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Modeling Techniques and Control Strategies for Jack-Up Rig: A State of the Art and Challenges

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ABSTRACT In recent years, for many offshore projects, including offshore oil and gas exploration and offshore wind farm construction, it is necessary to control the position of elevating of Jack-up Rig (JuR) in stable and balanced control. Designing the elevating control systems of JuR is an upcoming technology, which is extensively used in offshore drilling and other marine structures. To maintain the position of platforms from displacement, the jacking system is used automatically to control and stabilize the position of the JuR in sea state disturbances. In recent years, the theory of modern control has been studied and developed in terms of robustness and stability to achieve greater accuracy and reduce the movement of the platform caused by environmental disturbance and other affecting factors. This paper presents a state-of-the-art review of approaches for JuR control strategies and architectures. In addition, it recommends possible control principles and makes a matching between the advantages and disadvantages of existing literature. Some details for future research on control challenges are discussed in this paper.

INDEX TERMS Adaptive robust control, dynamic positioning, environmental loads, jacking control, rig move.

I. INTRODUCTION

A. PROBLEMS AND MOTIVATIONS

Jack-up drilling platforms have been used for exploration, drilling, and work-over near offshore oil and gas fields for decades. There are many methods utilized to balance control within reducing the affecting factors in the process of elevating of Jack-up Rig (JuR). However, the study of modern control algorithms still motivates researchers to develop academic and applied applications to help the system operate more stably and safely control system and has many more operations possible that were not feasible before even though each method has its own advantages. In contrast, during the previous 30 years, the combination of mobility, the ability to lift the platform above sea level for a variety of water depths, and the ability to function as a fixed platform addressed them as valuable in the offshore field. In essence, a jack-up platform is a mobile device used in any place around the world by certain maximum water depths and sea states, as well as varied sea bottom conditions. Moreover, the platform is often transported, with the legs in the fully raised position, from one

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TABLE 1. List of abbreviation.

Number	List	
	Abbreviation	Description
1	JuR	Jack-up Rig
2	JuRs	Jack-up Rigs
3	TLP	Tension Leg Platform
4	FPSO	Floating Production Storage and Offloading
5	JS	Jacking system
6	JSs	Jacking systems
7	RP	Rack-and-pinion
8	RBFNN	Radial basis function neural network
9	RAC	Robust Adaptive Control
10	IMO	International Maritime Organization
11	OIMM	Offshore Integrated Meteorological Mast
12	DP	Dynamic Positioning
13	DPS	Dynamic Positioning Systems
14	GA	Genetic Algorithm

offshore location to another, resulting in completely different loads on the structure Yin *et al.* [1], and Shabakhty *et al.* [2].

The DeLong Rig No. 1 for Magnolia Petroleum, which consists of a barge with six legs, was developed in 1950 during the off-shore oil and gas industry's era. Thereafter, the DeLong-McDermott No.1, which was built in 1954 and seems to be the first ten-leg offshore drilling platform, developed spudcans to keep the spuds from digging into the

deep ocean. The JuR is a type of mobile platform that consists of a floatable hull outfitted with several detachable legs, it is regular to use 3-legs and 4-legs types, competent in raising the hull over the surface of the sea [3], [4]. For instance, the 3-legs JuR are triangular barges, totally outfitted during the drilling processes and motivating of three truss legs while other forms are used less usually because of the complexity in structure and arrangement. Moreover, JuR is also named because they have established the self-elevating control system with three, four, six, and eight movable legs that can be extended upward or below the hull. However, recent surveys on the laboring environment, the JuR can drill in waters up to 350 feet depth, but for the deep water, less than 600 feet depth, the overall economics and operational efficiency of the deep-water JuR commonly make them more favorable than shallow water semi-submersibles [5]–[8]. Since the JuR will always be favored over a semi-submersible rig assuming both are capable of drilling the well in the conception of jack-up and semi-submersible rigs. For general assessment, we classify and characteristics of offshore types as shown in the following Table 2.

In reality, many types of offshore platforms have been designed based on various factors: technological and scientific development, economics [40], the necessity to employ deeper natural reservoirs [41], [42], environmental constraints [43]. Developing more high-speed technology and implementing more powerful research activities [44]–[46] are considered offshore constructions for the aforementioned problems, but more costly investments and system design changes are obliged. Meanwhile, these solutions can be alternated by content economically and task techniques that can simultaneously be kept unchanged for cost-saving that utilize the existing system infrastructure, and satisfy the standards and regulations. Lately, offshore engineering has drawn significant attention from researchers in both academic and industrial to benefit the service providers and technology providers [47], [48] to meet the high demand requirements for an offshore platform. Eventually, newly designed systems must ensure to safe for the human, marine, and coastal environments, and to maintain the very considerable investments of time and resources associated.

However, recent surveys on offshore platforms have focused on general issues, i.e., benefits, characteristics, types, and the various structural concepts (such as fixed, gravity, and compliant, floating, and sub-sea platforms) [49]; motivations, potential, applications, challenges, promising technologies, and open problems [49], [50]; practical aspects, standardization advancements, regulation, and instruments [51]; offshore power generation, transmission, distribution, consumption, energy storage, offshore intelligence and environment [52], multi-body dynamics in the applications of offshore structures [53], [58], advances and trends [49], [54], [55]. Additionally, others have investigated particular topics such as nonlinear analysis of Jack-Up structures [53], Jacking system (JS) [56], data and engineering assessments [51], Dynamic positioning (DP) [59], Jack up legs [56], Jetting

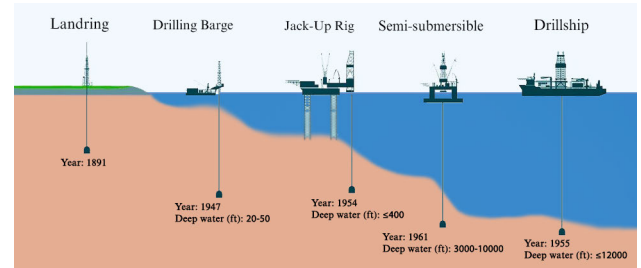


FIGURE 1. Different water depths of offshore structures through the years.

system of the spudcan [57], floating Spar platform [22], vibration control [17], modeling and control [50], moving system, and pre-loading, and factors influencing the correct positioning of the JuRs [59], [60]. It can be observed that the general issues about the JuR are quite completed, meanwhile the specific issue about challenges on modeling and control strategies for the JuR has not been investigated yet.

B. TAXONOMY

As can be observed, there are several difficulties concerning the research of the JuR model, methodologies, and applications, as well as financial issues, but they all revolve around two questions: 1) Which system metrics should be improved (quality, unit cost, scheduling, hourly rate, safety, communication, and technology, etc.) and 2) by which solutions to ensure JuRs survival in a harsh environment and at the same time keeping the operation and maintenance costs as low as possible during the whole of its life cycle, including model optimization design, advanced intelligent control, and loads (permanent and operation load, environmental loads, etc.). The modeling and control of JuR taxonomy are given based on the system performance metrics shown in Table 3 and the solutions with added techniques as performed in Table 4.

C. CONTRIBUTIONS

Offshore engineering is a segment of civil engineering concerned with the construction far from the coast of sea structures. They are normally employed in the oil industry, but there are also platforms for broadcasting, navigational lighting, radar surveillance, space operations, oceanographic study, and so forth. The JuRs are special mobile platforms ordinarily used for drilling processes in about 500 feet water depth (400 feet is from sea level to the bottom, and elevating the rig from 100 to 150 feet above the water). Nevertheless, several considerations will be analyzed, such as dynamic modeling, and wind and wave force, and so on, concern as robust mobile platforms. In this paper, based on the fundamental role of the JuRs aforementioned and to satisfy the specific points during an operation on the sea waters, we handle a survey on the state-of-the-art in terms of modeling and control strategies of the JuRs. The contributions of the paper in association with the related topics are presented as follows:

1. Introduction: This topic provides the readers an overview from shallow-water steel jackets, jack-up barges,

TABLE 2. A classification and characteristics of offshore platforms.

Number	A classification and characteristics									
	Type	Fixed offshore platforms	Mobile offshore platforms	Water depth (feet)	Ref.	Authors	Year	Ref.	Authors	Year
1	Stell jacket	Yes	No	60-300	[9] [10] [11] [12] [13]	Liaqat Ali Bao-Lin Z. E. Cao Hossein G. B. Zhang	(2021) (2020) (2020) (2018) (2014)	[14] [15] [16] [17] [18]	Karadeniz H. Mostafa Y.E. M. Esteban Ramkumar K. Dehghani A.	(2010) (2004) (2019) (2016) (2019)
2	Stell tower	Yes	No	≤ 1300	[14] [15] [16]	Karadeniz H. Mostafa Y.E. M. D. Esteban	(2010) (2004) (2019)	[17] [18]	Ramkumar K. Dehghani A	(2016) (2019)
3	Stell gravity	Yes	No	≤ 800	[15] [16]	Mostafa Y.E. M. D. Esteban	(2004) (2019)	[17] [18]	Ramkumar K. Dehghani A	(2016) (2019)
4	Concrete gravity	Yes	No	≤ 1300	[17] [18]	Ramkumar K. Dehghani A	(2016) (2019)	[19] [20]	Kabir Sadeghi Khaled A. H.	(2017) (2013)
5	Standing tower	Yes	No	≤ 1600	[17] [18]	Ramkumar K. Dehghani A	(2016) (2019)	[20]	Khaled A. H.	(2013)
6	Guyed tower	Yes	No	2000-2500	[17] [18]	Ramkumar K. Dehghani A	(2016) (2019)	[20]	Khaled A. H.	(2013)
7	Spar tower	Yes	No	≤ 7820	[17] [18] [20]	Ramkumar K. Dehghani A Khaled A. H	(2016) (2019) (2013)	[17] [18] [20]	Ramkumar K. Dehghani A Khaled A. H	(2016) (2019) (2013)
8	TLP	Yes	No	1500-4900	[17] [18] [20] [23] [24]	Ramkumar K. Dehghani A Khaled A. H Z. Wu A. M. Rayan	(2016) (2019) (2013) (2020) (2012)	[25] [26] [27] [28]	A. El-gamal A. A.Rayan M. Horoub J. Tang	(2014) (2013) (2020) (2016)
9	JuR	No	Yes	≤ 400	[17] [18] [20] [29]	Ramkumar K. Dehghani A Khaled A. H ZHU. Yazhou	(2016) (2019) (2013) (2015)	[30] [31] [32] [33]	Bogdan R. Z. T. Feng Jiang Tao Yi X.J. Tian	(2018) (2014) (2020) (2019)
10	Semi-submersible	No	Yes	3000-10000	[17] [18] [20] [34]	Ramkumar K. Dehghani A Khaled A. H P. Yadav	(2016) (2019) (2013) (2012)	[35] [36] [37]	J. M. Gregor T. Ishihara Seung J. K.	(2019) (2019) (2018)
11	Drilling ship	No	Yes	≤ 12000	[17] [18] [20]	Ramkumar K. Dehghani A Khaled A. H	(2016) (2019) (2013)	[38] [39]	S. O. Yoo Sivabalan P.	(2019) (2018)

TABLE 3. Performance metric taxonomy.

References	System performance metrics					
	Quality	Cost	Technology	Communication	Safety	Others
[17]		✓			✓	
[18]	✓	✓	✓		✓	
[22]		✓	✓			
[52]		✓	✓		✓	
[50]		✓	✓	✓	✓	✓
[61]	✓	✓	✓			✓
[62]		✓			✓	
[63]		✓	✓	✓		✓
This Paper	✓	✓	✓	✓	✓	

TABLE 4. Solution taxonomy.

References	Solutions		
	Model Optimization	Loads	Advanced Intelligent Control
[17],[50],[52],[63]	✓	✓	✓
[18]		✓	✓
[22]		✓	
[61]	✓		✓
[62]			✓
This Paper	✓	✓	✓

and JuR to floating Semi-submersibles and drilling ships capable of operating in quite deep seas. In addition, it is

means there are numerous types of platforms for offshore drilling activities. Focusing on the JuR types, the contents

related to modeling and control are systematically mentioned before detailed analysis in the following contents.

2. **Structural modeling:** In this topic, we provide the readers with a comprehensive structural and foundation modeling of the JuR. Focus on the regular structure of the JuR which has 3-legs and 4-legs types, competent in raising the hull over the surface of the sea. Because the accurate estimation of extreme response of offshore structure the JuR subjected to storm load pattern is complex, extreme control response of jack-up platforms in sea environment requires improving the understanding of the effect of nonlinearities such as environmental forces, drag-dominated, loading random waves, dynamic amplification, nonlinear structural response, and nonlinear foundation systems. Nevertheless, the JS of the JuR is an important system to do so this section details how legs can be lifted or lowered by motors and the related emerging techniques and mechanisms of the JuR. In addition, some mathematical models of the JuR structure and loads are presented to assist in computation, study, simulation, as well as application. However, to understand the types of equipment and control systems on the JuR, we need to understand an overview of the JuR's automatic operating systems and the main functions associated with the actuator and its mechanical structures. The details are presented in Section II.

3. **Loads:** The previous section deals with system modeling where the loads are a very important part that influences the performance of the system. Loads include permanent loads (dead loads), operating loads, environmental loads, and installation loads. Some of them are unstable in nature depending on weather, working conditions and modes, etc., especially environmental loads. The content of Section III deals with different types of loads and analyzes their forced effects on the JuR.

4. **Automated and control systems:** This topic aims to introduce that automated and control systems are always designed to depend on operation modes to ensure safety and accuracy in extreme environmental conditions. Thus, we divide into three groups of basic systems serving the main functions: maneuvering (rig move process), elevating (jacking process), and drilling (the systems of Power, Hoisting, Circulating, Rotary, and Well control) of which two most important systems are the dynamic positioning system (DPS) and the JS. The details of automated and control systems with assisted techniques can be found in Section IV.

5. **JuR move:** This topic provides the readers with functions of rig move in one of two ways: in self-floating mode, using either its propulsion system in a dry-towing operation or floating on their decks and being towed to the new location by tugs or barges in a wet-towing operation. In the scope of the work, we are more interested in the self-propelled Jack-ups with the DPS. Then, an overview of a DPS control theory, the nonlinear motion are investigated in Section V.

6. **Jacking control system:** In this topic, we introduce the emerging control techniques to gain a higher system performance that focused on the JS working under the effect of nonlinearities of the model and weather disturbances. This is the

main point that we investigated in this survey. The presence of errors (i.e., mechanical error in design and manufacture, error in the position of the bases, control time delay, random error) can enable the new mechanisms and novel strategies of control, especially in the field of nonlinear control. The details of the jacking control system are presented in VI.

7. **Challenges and research directions:** This topic presents the ongoing challenges the JuR faces including uncertain environmental impacts and technical issues. The offshore system design challenges showed us that the deployment of control designed system must guarantee the basic requirements by following a specific set of laws regulated. Meanwhile, the discussed technical challenges enable us to further propose more promising research directions in studying and applying the novel solution achieving the best performance in the control process of JuR.

The rest of this paper is organized as follows. In Section II, we introduce the structural modeling with the effect of nonlinear errors and some remarks. An overview of the JuR's loads is presented in Section III. Next section we deal with the automated and control systems. Section V is dedicated to showing the JuR move with analysis, and evaluation. Section VI are detailed the jacking control system. The discussion of challenges and research directions is given in Section VI and the conclusion in Section VI.

II. JACK-UP STRUCTURAL MODELING

A. COMPONENTS

The JuRs included three main components: the Hull, the Legs and Spud-can footings, and the equipment used on the Jack Up. These components are described below

- 1. **The Hull:** The hull of the JuR is waterproof, and it contains or supports the equipment, systems, and personnel required for regular operations. The hull of the Jack Up provides the required buoyancy to keep it from sinking while it is afloat. Moreover, the hull's specifications might change based on the unit's varied modes of operation [53], [72]. Wind, current, and wave loads are most often directed to the hull. Furthermore, the freeboard of a Jack Up unit has the most impact on its afloat stability.
- 2. **The Legs and the Spud-can footings:** Steel legs and Spud-can footings help to maintain the hull when the unit is elevated as well as provide the required stability to resist lateral stresses. Because Spud-can footings are utilized to enhance the soil bearing area, the Jack Up can be employed in places where the soil strength is lower than if the bearing area was smaller. Additionally, both the legs and the Spud-can footings have numerous features that influence how the unit performs in elevating and floating modes, therefore it's crucial to understand them. Table 5 shows the typical types of Legs [1], [2], [4], [6], [17], [18], [20], [29]–[33], [49], [53], [56], [64]–[66], [68]–[71], and Spud-can footings [57], [59], [68].
- 3. **The JuR's Equipment:** To fulfill its mission, each JuR unit will require appropriate equipment. As a result, the

total rig's hull size and lightship weight are impacted by this equipment. Moreover, Marine Equipment, Elevating Equipment, and Supporting Equipment are the three primary categories utilized on the rigs. There are several hydraulic systems [73], [74], [101], and dynamic [75], [107] related equipment, most of which are electrical and automatic systems, which are cited in Table 6.

Moreover, these components are critical to the safe operation of a jack-up unit as each mode of operation may impose its limiting design criteria on certain parts of the structure.

B. MAIN FUNCTION IN THE OPERATION OF JuR

The JuR was primarily intended for shallow waterways with limited water depth capabilities, thus the most difficult issues are the transportation schedule and establishing the legs in harsh weather. The foundation of the JuR serves as support for the legs as well as defining the stiffness qualities that determine the weather conditions that of the JuR can withstand. Soil characteristics such as lower bound and upper bound friction angles were determined and analyzed on the geo-technical investigation data. Furthermore, the evaluation for the leg penetration was analyzed before moving the JuR to the installation location. Related to the foundation, when preload is applied, the foundation must be strong enough to prevent the spud-cans at the base of the legs from penetrating too far into the seabed and have enough resistance to prevent the spud-can from sliding. The slot type drilling is often used format supported footing units, whereas cantilever drilling is typically used for units with independent footings, as shown in Fig. 2.

For preparation, leg and hull support, the unit's watertight integrity in general, and properly securing all cargo and equipment are all issues that must be handled in advance. When the installation location is reached, the working conditions are safe, the steps to be performed along with its function below:

1. Arriving at the location: The transit mode is used to transport from starting point to the installation position. The unit could either be afloat on its hull (DPS) or be carried as cargo aboard another vessel [59].

2. Lowering the Legs: the JuR keeps the hull in a fixed position, and its legs are subjected to penetration below the seafloor by using the JS [56].

3. The preloading operation: the procedure's purpose is to provide loads to the jack-legs up to a predefined load level. Guaranteeing the soil resistance is sufficient for the foundation to handle the maximum design loads (included environmental loads) for running in that position. After achieving supreme spud-can penetration below the seafloor while applying prescribed preload to the legs [57], the extra load (usually seawater ballast) is discharged. In this process, pumping saltwater into large tanks of the JuR progressively increases the load to the desired maximum preload. This puts greater vertical pressure on the spudcan foundations, causing them to sink deeper until the preload is balanced by the soil bearing capacity. The foundations are preload proofed

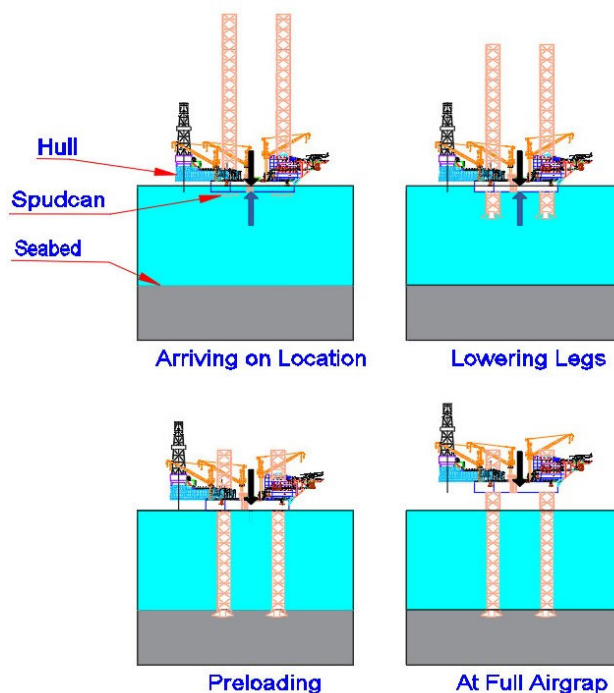


FIGURE 2. Operations steps of a JuR from arriving at a site to be in full operation.

by subjecting them to a larger vertical load than would be expected during operations [76].

4. At the Air gap: the hull is elevated to a higher position from the water surface to its ultimate position at an air gap between the hull and water surface. Fixation system used to secure the leg after jacking.

C. LEGS AND SPUDCANS

The JuR generally can be classified into two basic categories: independent leg jack-ups and mat supported jack-ups. The former are normally used in areas of firm soil, coral, or uneven seabed [81] described above, the kind of components such as legs, spudcans, and equipment depending on the type of JuR. In which the spudcans regularly be at the base of each leg to support the weights of the whole structure.

The legs and spudcans are the critical mechanical components that hold the Jack-Up hull in its raised position and provide the strength to resist the environmental forces of waves, current, and wind, along with the jacking or fixation system [77]. The most common JuR has three or four legs within two main types of legs. Table. 5 compares the advantages and drawbacks of the four-legged placed in a rectangular shape against the three-legged arranged in a triangular form. Moreover, the three-legged JuR are lighter for a given hull size and may carry more cargo. They also eliminate the need for an extra leg, decreasing the number of lifting mechanisms required (racks, pinions, etc.). This helps to cut down on energy and maintenance costs. They do, however, require preload tanks onboard, which take up useful space, unlike the four-legged JuR.

TABLE 5. The Legs and Spud-can footings typical types.

Unit types	Advantages	Disadvantages	References
Four-legged arranged in a rectangular form	The lack of tank saves on money for piping and equipment, while adding more usable space within the hull; Little to no pre-load tanks required; More redundancy as the unit can stand on three legs; Units are stiffer in elevated mode.	Loss of deck load in the Afloat mode due to increased windage and additional weight of extra leg; Adds more wind, wave and current loads.	[17], [18], [20], [49], [56], [64],
Three-legged arranged in a triangular form	Less weight, parts and power needed; Allows for more deck load to be carried in the; Afloat mode due to less windage and reduced leg weight.	Required preload tankage; No leg redundancy.	[1], [2], [4], [6], [17], [18], [20], [29], [30], [31], [32], [33], [49], [53], [56], [64], [65], [68], [69], [70], [71]
Cylindrical legs (hollow steel tubes)	Small Gear Units; Legs take up less deck area; Easier and cheaper to construct.	Limited to shallow water; Require more steel to achieve the same resistance to environmental loads and to provide the same elevated response as a truss leg; Less stable and cannot adapt to stress in water like a truss structure.	[17], [18], [20], [49], [56], [64], [66]
Truss legs, X or revised K-braces	Optimal steel utilisations; Lighter and stiffer legs; Reduced drag load.	Larger in size and hence they take up larger deck area and hence not suitable for shallow water or smaller units.	[1], [2], [4], [6], [17], [18], [20], [29], [30], [31], [32], [33], [49], [53], [56], [59], [65], [66], [70], [71]
Mat supported footing	Minimising risks on soft or muddy soils (creates a lower bearing pressure by a distributed weight on a large area; Small penetrations; Can carry more load; Afloat due to buoyancy chambers; Quicker installation and extraction; Limited sea floors (not suitable for uneven seabed or seabed with largest slopes); Complicated flooding and emptying sequence.	Limited sea floors (not suitable for uneven seabed or seabed with largest slopes); Complicated flooding and emptying sequence.	[17], [18], [20], [49]
Spud-can footing	Better stability; More versatile (A spud-can can be placed on uneven seabed and other difficult sea floors).	Can cause deep impressions in softer soil, due to deep penetrations.	[1], [2], [4], [6], [17], [18], [20], [29], [30], [31], [32], [33], [49], [57], [59], [64], [66], [68], [69], [70]

In terms of leg types, the first is cylindrical legs, which are easier to manufacture but require more steel to reach the same level of environmental resistance and enhanced responsiveness as a truss leg. Truss legs are composed of crisscrossed tubular steel pieces, which make them robust but lightweight. Furthermore, because they are larger in dimension, they take up more deck space and are not appropriate for shallow water or smaller units. Additionally, the JuR is also assisted by spudcan-based stabilizing devices on the seafloor. Spudcans are steel cleats with pointed ends and a cylindrical form joined to the bottom of each leg. However, the can's spike pushed to the seafloor to supply the rig more stability during operations.

Related to the effect of factors on the afloat stability of the elevating process, when the JuR is towed, legs may stretch up to 500 feet above the water's surface, even when fully retracted. The stability of the JuR is mainly influenced by larger and longer legs. Different legs have varying degrees of lateral stiffness depending on their design and size. Furthermore, the unit is in the raised position, and leg stiffness directly connects to Jack Up stiffness influenced the hull wobble and the JuR's natural period. Therefore, all the above

issues should be considered and analyzed carefully when designing the control model for the JS.

D. EQUIPMENTS AND SYSTEM

The legs of the jack-up rise up via holes in the hull of the drilling rig, regardless of the type of leg employed in the construction. The drilling derrick and associated equipment are supported by a deck. We only discuss automated equipment and systems fitted onboard of the JuR in three categories in this article: Marine Equipment, Elevating Equipment, and Supporting Equipment. In Table. 6, the majority of the systems are listed along with the citations.

Furthermore, the problem of equipment installation is critical, as it directly affects the structure, loads, and stability of the JuR during the whole working period. The drilling equipment can be mounted on the hull in two ways. A cantilevered jackup is the most common configuration for drilling equipment. In the standard, the drilling derrick is mounted on an arm that thus extends forth from the drilling deck. Moreover, drilling can be done through existing platforms, as well as without them, using a cantilevered JuR [3], [78]–[80]. Most JuRs produced in the last ten years have been cantilevered

jack-ups because of the range of motion provided by the cantilever. The last but not least, the other type of JuR is the slot-type jack-up, also known as a keyway JuR. But these JuR designs, though still mentioned here, are hardly used today.

E. MATHEMATICAL MODELING AND ANALYSIS

The direct finite-element technique [82] and the simple beam approach [83] are the two most used methods for static or dynamic analysis of the JuR. The rig is regarded as a spatial lattice frame structure in the first approach, with the forces and displacements in each constituent member taken into account, whereas in the second approach, the whole rig is replaced by a uniform beam carrying a lumped mass, designed to allow its static or dynamic behavior to be predicted utilising simple theoretical formulas. Both of the aforementioned approaches, however, are inappropriate for use in the early stages of design since the first is too sophisticated to offer fundamental design data and the second is too simple to provide trustworthy information.

Nevertheless, the mass matrix is another attribute matrix of a structural part, in addition to the stiffness matrix. All mass matrices are calculated using lumped-mass models for simplicity. In theory, consistent mass matrices should lead to improved accuracy in outcomes, but in actual, this increase is frequently little, and the benefit seldom exceeds the extra work required [84]. Furthermore, the equations of motion for the JuR can be easily obtained by first deriving the equations of motion for each leg and the upper hull separately, then integrating them by imposing the constraints of deformation compatibility and force equilibrium at the junctures of the legs and the hull, as well as the specified support condition of the legs at the seabed in the form of six rigid body motions:

- Translational: Surge, sway, and heave.
- Rotational: Roll, pitch, and yaw.

Each nodal point's six degrees of freedom are taken into account. The mode superposition method and Duhamel integral [85] were used to determine the wave excited dynamic responses, while the Jacobi approach [86] was employed to find the rig's native frequencies and mode shapes.

1) THE EQUATIONS OF MOTION OF EACH LEG

By constructing the corresponding matrices $[k_{s1}]$ (or $[k_{s2}]$) and $[m_{sA}]$, the overall stiffness matrix $[\bar{K}^L]_i$ and mass matrix $[\bar{M}^L]_i$ for the i th leg may be derived. The three-legged JuR's equations of motion are determined by

$$[\bar{M}^L] \{\ddot{\delta}^L\} + [\bar{K}^L] \{\delta^L\} = \{F^L\} + \{R^L\} \quad (1)$$

In the equation (1), $\{R^L\}$ is the interaction force vector at the junction of the three-legged and hull, where $\{F^L\}$ is the external force vector due to environmental loading on the legs. Thus, we have the equation (2) as follows:

$$[M^L] = \left[\begin{matrix} [\bar{M}^L]_1 & & \\ & [\bar{M}^L]_2 & \\ & & [\bar{M}^L]_3 \end{matrix} \right] \quad (2)$$

$$[K^L] = \left[\begin{matrix} [\bar{K}^L]_1 & & \\ & [\bar{K}^L]_2 & \\ & & [\bar{K}^L]_3 \end{matrix} \right] \quad (3)$$

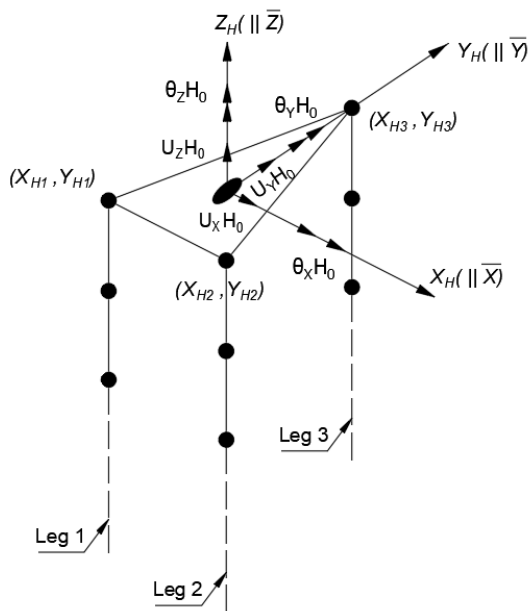


FIGURE 3. Simplified lumped-mass model of the 3-legs JuR type [81].

$$\{X^L\} = \left\{ \left\{ X^L \right\}_1 \left\{ X^L \right\}_2 \left\{ X^L \right\}_3 \right\}, \quad X = \delta, F, R \quad (4)$$

$$\{\delta^L\} = \left\{ \left\{ \delta^L \right\}_1 \left\{ \delta^L \right\}_2 \left\{ \delta^L \right\}_3 \right\} \quad (5)$$

The damping forces are temporarily ignored in equation just for simplicity (1).

2) THE EQUATIONS OF MOTION OF THE UPPER HULL

Because the stiffness of the hull of a typical JuR is significantly greater than that of the legs, it is fair to assume that the hull is a rigid body with all of its masses concentrated at its center of gravity Fig. 3. The following equations of motion for the hull are derived from the previous assumption:

$$[\bar{M}^H] \{\ddot{\delta}_0^H\} = \{F^H\} + \{R^H\} \quad (6)$$

where

$$\{\ddot{\delta}_0^H\} = \{\ddot{u}_{xH0} \ddot{u}_{yH0} \ddot{u}_{zH0} \ddot{\theta}_{xH0} \ddot{\theta}_{yH0} \ddot{\theta}_{zH0}\} \quad (7)$$

The equation (7) is the acceleration vector of the hull, and $\{F^H\}$ and $\{R^H\}$ are the external and interactive force vectors, respectively. The latter $\{R^H\}$ is the resultant force vector with respect to the center of gravity of the hull imposed by the three legs. Moreover, the hull's acceleration vector is given by the equation (7), while the external and interaction force vectors are given by the equations $\{F^H\}$ and $\{R^H\}$, respectively. The resulting force vector $\{R^H\}$ imposed by the three legs with regard to the hull's center of gravity. Additionally, the mass matrix of the hull can be calculated as follows:

$$[\bar{M}^H] = [m_{xH} m_{yH} m_{zH} I_{xH} I_{yH} I_{zH}] \quad (8)$$

3) THE EQUATIONS OF MOTION OF THE JuR

The interaction forces (and moments) between the three legs and the hull are represented by the force vectors $\{R^L\}$ and $\{R^H\}$ in equations (1) and (6). At the junctures of the three legs and the hull, there is a specific relationship between them that satisfies the requirements of force balance and deformation tolerance. When $\{R^L\}$ and $\{R^H\}$ are removed from equations (1) and (6) and the support conditions of the three legs at the seabed are enforced, the equations of motion of the whole JuR will be derived. If indeed the rigid hull's displacement vector, $\{\delta_0^H\}$, and the nodal displacements at the junction of the i^{th} , ($i = 1, 2, 3$) leg and rigid hull, $\{\delta_{Hi}^L\}$, are indicated in Fig. 3. $\{\delta_0^H\}$ and $\{\delta_{Hi}^L\}$ can be calculated as follows:

$$\{\delta_0^H\} = \{u_{xH0} u_{yH0} u_{zH0} \theta_{xH0} \theta_{yH0} \theta_{zH0}\} \quad (9)$$

$$\{\delta_{Hi}^L\} = \{u_{xHi} u_{yHi} u_{zHi} \theta_{xHi} \theta_{yHi} \theta_{zHi}\} \quad (10)$$

Deformation compatibility between the three legs and the stiff hull necessitates by

$$\{\delta_{Hi}^L\} = [r_{Hi}] \{\delta_0^H\}, \quad i = 1, 2, 3 \quad (11)$$

where

$$[r_{Hi}] = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & -y_{Hi} \\ 0 & 1 & 0 & 0 & 0 & x_{Hi} \\ 0 & 0 & 1 & y_{Hi} & -x_{Hi} & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (12)$$

The equation (12) indicates the transformation matrix between $\{\delta_0^H\}$ and $\{\delta_{Hi}^L\}$, where (x_{Hi}, y_{Hi}) are the coordinates of the i^{th} junction's centroid in the $x_H y_H z_H$ coordinate system shown in Fig. 3. Let

$$\{\delta_H^L\} = \left\{ \left\{ \delta_{H1}^L \right\} \delta_{H2}^L \left\{ \delta_{H3}^L \right\} \right\} \quad (13)$$

$$[r_H] = \begin{bmatrix} [r_{H1}] \\ [r_{H2}] \\ [r_{H3}] \end{bmatrix} \quad (14)$$

Equation (11) can thus be rewritten as

$$\{\delta_H^L\} = [r_H] \{\delta_0^H\} \quad (15)$$

That is the deformation compatibility equation. Because $\{R^H\}$ and $\{R^L\}$ are interaction forces (and moments) between the three legs and the rigid hull, one may derive $\{R^H\}$ and $\{R^L\}$ as

$$\{R^H\} = -[r_H]^T \{R^L\} \quad (16)$$

This is the force equilibrium equation, thus (1) should be rewritten as

$$\begin{bmatrix} [\bar{M}_{pp}^L] & [\bar{M}_{pq}^L] \\ [\bar{M}_{qp}^L] & [\bar{M}_{qq}^L] \end{bmatrix} \begin{Bmatrix} \{\delta_p^L\} \\ \{\delta_q^L\} \end{Bmatrix}$$

$$+ \begin{bmatrix} [\bar{K}_{pp}^L] & [\bar{K}_{pq}^L] \\ [\bar{K}_{qp}^L] & [\bar{K}_{qq}^L] \end{bmatrix} \begin{Bmatrix} \{\delta_p^L\} \\ \{\delta_q^L\} \end{Bmatrix} \\ = \begin{Bmatrix} \{F_p^L\} \\ \{F_q^L\} \end{Bmatrix} + \begin{Bmatrix} \{0\} \\ \{R^L\} \end{Bmatrix} \quad (17)$$

where $\{\delta_q^L\}$ and $\{\delta_p^L\}$ are the displacement and acceleration vectors at the three junctures, and $\{\delta_p^L\}$ and $\{\delta_q^L\}$ are the displacement and acceleration vectors at the three legs' other nodal points. $\{F_q^L\}$ and $\{F_p^L\}$ are the equivalent environmental force vectors in the same way. Using the connections $\{\delta_q^L\} = \{\delta_H^L\}$ and those given by equations (6), (15) and (16) and expanding equation (17), we have equation (18) as below

$$[M^*] \{\delta^*\} + [K^*] \{\delta^*\} = \{F^*\} \quad (18)$$

where

$$[M^*] = \begin{bmatrix} [M_{pp}^*] & [M_{pq}^*] \\ [M_{qp}^*] & [M_{qq}^*] \end{bmatrix} + [\bar{M}^H], \\ [K^*] = \begin{bmatrix} [K_{pp}^*] & [K_{pq}^*] \\ [K_{qp}^*] & [K_{qq}^*] \end{bmatrix}, \\ \{\delta^*\} = \left\{ \left\{ \delta_p^L \right\} \left\{ \delta_0^H \right\} \right\}, \quad \{\delta^*\} = \left\{ \left\{ \delta_p^L \right\} \left\{ \delta_0^H \right\} \right\}, \\ \{F^*\} = \left\{ \left\{ F_p^L \right\} \right. \\ \left. [r_H]^T \left\{ F_q^L \right\} + \{F^H\} \right\}, \\ [M_{qp}^*] = [r_H]^T [\bar{M}_{qp}^L], \\ [M_{qq}^*] = [r_H]^T [\bar{M}_{qq}^L] [r_H], \\ [K_{qp}^*] = [r_H]^T [\bar{K}_{qp}^L], \\ [K_{qq}^*] = [r_H]^T [\bar{K}_{qq}^L] [r_H], \\ [M_{pp}^*] \equiv [\bar{M}_{pp}^L], \quad [K_{pp}^*] \equiv [\bar{K}_{pp}^L], \\ [M_{pq}^*] = [\bar{M}_{pq}^L] [r_H], \quad [K_{pq}^*] = [\bar{K}_{pq}^L] [r_H] \quad (19)$$

The equation of motion of the JuR under no restrictions is (18). Because all of the legs are bent at the seafloor for support, so rewrite equation (18) as follows:

$$\begin{bmatrix} [M_{ss}^*] & [M_{sr}^*] \\ [M_{rs}^*] & [M_{rr}^*] \end{bmatrix} \begin{Bmatrix} \{\delta_s^*\} \\ \{\delta_r^*\} \end{Bmatrix} + \begin{bmatrix} [K_{ss}^*] & [K_{sr}^*] \\ [K_{rs}^*] & [K_{rr}^*] \end{bmatrix} \begin{Bmatrix} \{\delta_s^*\} \\ \{\delta_r^*\} \end{Bmatrix} \\ = \begin{Bmatrix} \{F_s^*\} \\ \{F_r^*\} \end{Bmatrix} \quad (20)$$

which are the hinged rig's motion equations in case of all legs of the JuR are fixed at the seabed, however, $\{\delta_r^*\} = \{\delta_t^*\} = 0$ and $\{\delta_r^*\} = \{\delta_r^*\} = 0$ are obtained, then the equation of motion of a fixed rig (21) is obtained.

$$[M_{ss}^*] \{\delta_s^*\} + [K_{ss}^*] \{\delta_s^*\} = \{F_s^*\} \quad (21)$$

III. JACK-UP RIG LOADS

Seabed features, environmental circumstances, waves, ocean currents, and the depth of the water layer are only a few of the elements that influenced the JuR's control process. Similarly, a wide range of marine platforms is utilized for oil and gas exploitation, and energy production in offshore areas. The scope of this study is limited to the aspects of oceanographic environmental factors that influence JuR's jacking system's control process. As a result, the JuR must be made to withstand the following types of loads:

a) Permanent loads (dead loads)

- Weights of equipment and related structures permanently placed on the platform, as well as the structure's weight in the air (including ballast).
- Hydrostatic forces on the members below the waterline and forces pressures.

b) Operating loads Loads include the weight of all non permanent equipment or material, as well as forces generated during the operation of equipment.

- Drilling, production facilities, living quarters, furnishings, life support systems, heliport, consumable supplies, liquids, and other items carry a lot of weight.
- Forces are generated during the operation, drilling, mooring, helicopter landing, crane operations.

c) Environmental loads

- Wind load: The most significant consideration in the design of the JuR is the wind load [78], [87]–[89]. Moreover, the influence of risk wind speeds and directions on different platform working circumstances must be thoroughly explored.
- Wave load: Waves are largely generated by the impact of wind on water, which converts wind energy into wave energy through friction. The wave loads (gravity waves) were applied sideways to the primary columns, creating moment resistance on the fabrication. Gravity waves discharge the remainder of wave energy. The highest wave should be used in the design of offshore infrastructures. Moreover, the maximum wave height and significant wave height are shown in [90]. The forces experienced by structures exposed to waves are significantly greater than those experienced by structures exposed to wind. The forces are caused by the dynamic pressure and the movements of the water particles. There are two distinct situations that may be differentiated. Diffraction and reflection impact the wave field in large volume bodies, referred to as hydrodynamic compact structures. Calculations based on diffraction theory must be used to calculate the forces on these substances [92].
- Current load: Wind activity on the water surface, temperature gradients, density gradients, tidal movements, and other factors all contribute to ocean currents in the open sea. The kinematics of water particles are dramatically altered when current is present. It also creates drag pressures on offshore buildings' submerged sections [91], [92].

- Earthquake load: Earthquake loads should be computed using the appropriate code for the country in which the JuR is located. When an earthquake is combined with other loads such as tsunamis [94], winds, and/or waves, the total displacement response is larger than the displacement response of the earthquake load alone [93].

d) Installation loads

Generally, these are each loads that occur during the fabrication and installation of the platform or its components. During fabrication, lifting forces are created by erection lifts of various structural components, but during installation, forces are generated by platform load out, transportation to the site, launching and upending, as well as lifts connected to installation. All components and connections of a raised component must be engineered to withstand the forces generated by the lifted weight's static equilibrium and the sling tensions. When the jacket is loaded from the fabrication yard onto the barge, load out forces are created. It is determined by the friction coefficient.

e) The load combinations The load combinations are determined by the design process, i.e., limit state or allowed stress design.

- Normal operations: The load combinations suggested for usage with acceptable stress procedures are dead loads plus operational environmental loads plus maximum live loads. Living loads plus dead loads plus operating environmental loads are the minimum living loads.
- Dead loads, extreme environmental loads, and maximal live loads are all part of extreme activities. Dead loads plus extreme environmental loads plus a bare minimum of living loads equals dead loads plus extreme environmental loads plus minimum live loads.
- Environmental loads should be aggregated in a way that reflects their combined likelihood of occurrence.
- Earthquake stresses must be applied separately from other environmental pressures, such as waves, wind, and so on. Because of their rarity, earthquakes, although being a major load condition for the design of maritime structures, are not typically a factor during the operating process of the JuR.

In addition, all loads are converted into force components acting on the JuR, the external and interaction force vectors are given by the equations $\{F^H\}$ and $\{R^H\}$, respectively. $\{F_q^L\}$ and $\{F_p^L\}$ are the equivalent environmental force vectors. The sum of the loads is characterized by the components in the equation (19), while the equations (17), (18), (20) and (21) are the combined equations of the whole JuR model with the above-mentioned types of loads. In the study, these loads must be carefully analyzed, both in simulation and model building. It also affects the selection of control algorithms in the future. In particular, the loads caused by the environment needs to be taken care of, which will be presented in the next subsection.

A. ENVIRONMENTAL FORCE

When an earthquake occurs, the state of the sea is intensely strong, then no control-related activities are allowed, and the control processes do not be executed. Control execution condition is no earthquake similarly as the environmental force vectors include the wave force, wind force and current force, named F_{emi} , which is presented by Fossen [97], and expressed as [96]:

$$F_{emi} = F_{wave} + F_{wind} + F_{current} \quad (22)$$

1) THE WAVE FORCE

The most obvious environmental problem for offshore activities is waves. They induce a floating structure or vessel to heave, pitch, roll, sway, surge, and yaw in six degrees of freedom. They are the leading source of downtime and decreased operational efficiency. When it comes to permanent JuR structures, the forces exerted by waves are generally the most important design criteria. There are numerous classifications for ocean waves. The wave period or corresponding wavelength is the most natural and often used classification.

Table. 6 shows an overview of the various forms of surface waves as a function of wave period. The equation of the wave force F_{wave} for the control problem [96] is described as follow:

$$\begin{aligned} F_{wave} &= \zeta(x, y, t) \\ &= \sum_{q=1}^N \sum_{r=1}^M \sqrt{2S(\omega_q, \psi_r) \Delta\omega \Delta\psi} \sin(\omega_q t \dots \\ &\dots + \phi_{qr} - k_q(x \cos \psi_r + y \sin \psi_r)) \end{aligned} \quad (23)$$

where ψ_r , ω_q , ϕ_{qr} and S denote direction, frequency, phase angle, and wave spectrum, respectively, with the phase angle ϕ_{qr} of wave components ranging from 0 to 2π . The harmonic amplitudes of wave frequency ω_q are represented by the $\Delta\omega$ and $\Delta\psi$ factors. On the other hand, the number of waves is $k_q = 2\pi/\lambda_q$, where λ_q is the wave length and the dispersion relation $\omega_q = \sqrt{k_q g}$ with g is the gravity acceleration.

Related to the current in deep sea area, deep-water waves generate oscillatory currents on the bottom, resulting in minimal net soil particle translation owing to waves alone. When a wave current is superimposed on a steady-state current, however, the sediment transport is significantly increased, as the amplitude of the wave current changes as the cube of the instantaneous current velocity.

2) THE WIND FORCE

The JuR deck, which is supported by several pillars or other temporary supports, is a massive structure that will expand and contract with the temperature and rotate as added weights. Therefore, it is usually supported on heavy laminated neoprene and steel pads, allowing shear deformation and rotation. At the same time, the deck must be adequately secured against a windstorm. Stops must be provided so that the structure cannot possibly slide off. Noted that wind forces can reach 500–1000 tn or more under a severe storm.

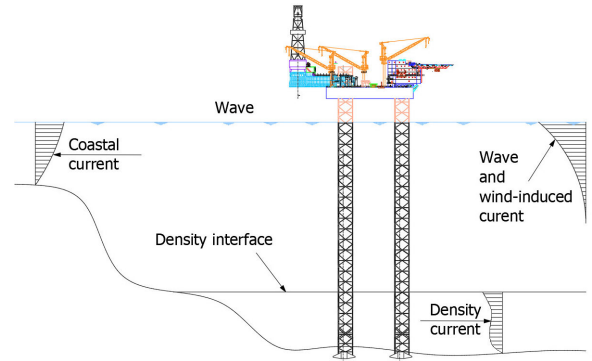


FIGURE 4. The wave-current flow field in the JuR installation position.

An overview of the International standards of wind power classification described on Table. 7 [98].

The different variables are the low frequency (V_w) and direction (β_w) of wind modeled. Wind forces are generated by

$$\begin{aligned} F_{wind} &= [X_{wind}, Y_{wind}]^T \\ X_{wind} &= 0.5 C_X g_R \rho_w V_R^2 A_T \\ Y_{wind} &= 0.5 C_Y g_R \rho_w V_R^2 A_T \end{aligned} \quad (24)$$

The wind traction into the ichnography region A_T is represented by C_X and C_Y . Furthermore, V_R defines wind speed and g_R denotes wind direction.

$$V_R = V_w ; \quad g_R = \beta_w - \psi_L - \psi_H \quad (25)$$

3) THE CURRENT FORCE

Oceanic circulation, geostrophic, tidal, wind-driven, and density currents, as well as currents caused by river discharge, are all examples of currents as showed on Fig. 4. As offshore structures are planned and constructed in deeper seas, requiring precise measurements at all depths for both vertical and horizontal components of the current. Furthermore, the current is invariable in both direction and amplitude, therefore the current speed V_c and direction β_c are represented as slow variable parameters in the earth axis to correct the current speed V_c and direction β_c . The current velocity is presented by Dang *et al.* [97] and Fossen [96]:

$$\begin{aligned} u_c &= V_c \cos(\beta_c - \psi_L - \psi_H) \\ v_c &= V_c \sin(\beta_c - \psi_L - \psi_H) \\ F_{current} &= [u_c, v_c, 0]^T \end{aligned} \quad (26)$$

where u_c and v_c are current velocity compositions, and ψ_L and ψ_H are angular compositions impacted by high and low frequency values, respectively.

B. THE EXTERNAL AND INTERNAL FORCE

1) THE INTERACTIVE FORCES

In addition to the nodal displacements $\{\delta^L\}$ and external loads $\{F^L\}$ acquired in the previous subsections, the interaction forces $\{R^L\}$ of legs and hull may be calculated using equation (27) as shown below

$$\{R^L\} = [\bar{M}^L] \{\delta^L\} + [\bar{K}^L] \{\delta^L\} - \{F^L\} \quad (27)$$

TABLE 6. An overview of the various forms of surface waves as a function of wave period [95].

Classification	Period band	Generating forces	Restoring forces
Capillary waves	< 0.1 s	Wind	Surface tension
Ultragravity waves	0.1 – 1 s	Wind	Surface tension and gravity
Gravity waves	1 – 20 s	Wind	Gravity
Infragravity waves	20 s to 5 min	Wind and atmospheric pressure gradients	Gravity
Long-period waves	5 min to 12 h	Atmospheric pressure gradients and earthquake	Gravity
Ordinary tidal waves	12 – 24 h	Gravitational attraction	Gravity and Coriolis force
Transtidal waves	> 24 h	Storms and gravitational attraction	Gravity and Coriolis force

TABLE 7. The classification of the International standards of wind power [98].

Various HEIGHTS		At 10m Heights		At 30 m Heights		At 50m Heights	
#	Resource Class	m/s	W/m ²	m/s	W/m ²	m/s	W/m ²
1	Poor	0 – 4.4	0 – 100	0 – 5.1	0 – 160	0 – 5.4	0 – 200
2	Marginal	4.4 – 5.1	100 – 150	5.1 – 5.9	160 – 240	5.4 – 6.2	200 – 300
3	Moderate	5.1 – 5.6	150 – 200	5.9 – 6.5	240 – 320	6.2 – 6.9	300 – 400
4	Good	5.6 – 6.0	200 – 250	6.5 – 7	320 – 400	6.9 – 7.4	400 – 500
5	Excellent	6.0 – 6.4	250 – 300	7 – 7.4	400 – 480	7.4 – 7.8	500 – 600
6	Excellent	6.4 – 7.0	300 – 400	7.4 – 8.2	480 – 640	7.8 – 8.6	600 – 800
7	Excellent	> 7.0	> 400	8.2 – 11	640 – 1600	> 8.6	> 800

the interactive forces $\{R^L\}$ is nonlinear because the interaction process between the hull and the legs often generates an uncertain value.

2) THE INTERNAL AND EXTERNAL FORCES

Offshore structure footings, in particular, have finite stiffness in the horizontal, vertical, and rotational directions, with cross-coupling between the horizontal and rotational degrees of freedom and the possibility of nonlinearity caused by varying submergence, geometric, or a driving function that is important in jack-up structural reaction.

- Nonlinear loading components (i.e., drag force loadings, permanent loads, operating loads).
- Bottom restraint (nonlinear foundation characteristics).
- Damping is a term used to describe the process (i.e., due to the motions of the JuR structure, there may be significant hydrodynamic damping as a result of the relative velocity of the water particles and the leg member).
- The uncertain structure’s dynamics (since the structure’s natural period is often high, i.e., 5 – 8 seconds), there may be significant wave energy available to excite the structural system, resulting in quite large inertial forces.
- Structural interface nonlinearities (i.e., gaps between the leg structure and rack pinion).
- Time-delays of control process.
- Noise and disturbances in the mechanical and electrical systems.

A time-domain numerical integration approach is required to solve the equations of motion to accommodate a high degree of nonlinearities associated with the system.

IV. AUTOMATED AND CONTROL SYSTEMS ON JuR

A. AN OVERVIEW OF THE AUTOMATED SYSTEMS ON JuR

In general, to understand the control systems on the JuR, we need to keep in mind an overview of JuR’s automatic

operating systems associated with the actuator and its mechanical structures, of which two important systems are the DPS and the JS. The topic of models and metrics enables us to formulate the system, e.g., in the closed-form expressions and optimization problems, and then analyze for further optimization designs. First, we attended to complete an overview of The performance and inspections of these control systems: (i.e., dynamic positioning [128]; elevating [115], [116], [119]; drilling rig main systems [101], [114]; hoisting [110] and rotation [101]; power generation [120], [121]; mud circulating, pneumatic [113], [114]; and well control [108]) which are detailed on Table. 8 in this topic. However, due to limited energy resource, JuRs may be designed to operate in extreme environmental conditions at relatively large water depths, the automated systems are often designed to depend on operation modes to ensure safety and accuracy:

- 1. Maneuvering (Rig move process): it is necessary to consider in respect to any ultimate strength analysis of a jack-up in the transit condition as static load, inertia load (as a result of motion), and wind load components.
- 2. Elevating (Jacking process): it is essential for real-time control concerning safely and speedily lowering and positioning the legs of JuRs in all types of seabed. Moreover, It must also be able to hold the leg in an elevated position and absorb the forces generated by the leg’s roll and pitch motion when the Jack-Up in the undertow.
- 3. Drilling (The process including the systems of Power, Hoisting, Circulating, Rotary, and Well control): During drilling control operations, all of the circulating system, mud pumps, and prime movers are used to circulate the drilling fluids. However, it is also required to be able to ensure safety and accuracy under the effect of many influencing factors.

Furthermore, because each mode of operation may impose its own limiting design constraints on particular elements of

the structure, these modes are important to the safe operation of a jack-up unit. The major equipment and supporting systems for the rig's operation are detailed in Table. 8 to provide an overview of the overall automated systems aboard the JuR. Because group Electrical and group Safety systems are common serving systems, we will not discuss them within the scope of this study.

B. CONTROL TECHNIQUES AND APPLICATIONS

In general, control strategies directly affect the system performance performed an essential role in the development of marine science. However, different control strategies become continued fulfilled and investigated which bring numerous capabilities to offshore industrial and oceanic development. The corresponding control principles, objectives, fundamental strategies, unconventional approaches, methodologies, honors, and shortcomings need to reveal in detail, analyze and compare. Focus on marine mechatronic systems (i.e., the integration of mechanical and electrical, control, and artificial intelligent disciplines applied in the offshore marine environment), harmful consequences of multiple opposing factors such as hydrostatic pressures, element corrosion, hydrodynamic influence, and attenuation of electromagnetic signals, sensor signals, erroneousness, uncertain parameters of the system caused by the environmental and harsh working condition at sea, have to be circumvented in addressed.

It can be seen that there are many JuR's models, techniques, and applications, but all of them focus on answering two questions: 1) which system performance on the design and manufacture JUR's control systems specialize in safety, critical (to the safe operation, damping, stress, and loaded structural element, etc.), operational instrumentation and monitoring systems (JuRs are normally designed to function in several different operational modes) to improve and 2) by which solutions including how to deploy the control systems, i.e., modeling to designing and applying advanced control algorithms all the way to deployment with novel automatic code generation i.e., neural network, Genetic algorithm, Particle Swarm Optimization, and system verification, validation, and test; Last but not least, these challenges have been promoting the development control theories focused on marine science and technology toward a promising future.

V. JACK-UP RIG MOVE

The JuR is made out of a buoyant hull with numerous moveable legs that may raise the hull above the water's surface. The buoyant hull, on the other hand, allows the unit and any connected apparatus to be transported to the appropriate position. The JuR may transfer from one place to another in one of two ways: in self-floating mode, employing either its propulsion system in a dry-towing, or floating on their decks and being pulled by tugs or barges to the new position in a wet-towing. Although the dry-towing method is faster than the wet-towing method but almost all JuRs are not self-propelled and rely on tugboats or large ships to slowly move slowly. In this paper, we focus on control related issues, so other aspects will not be mentioned much here.



FIGURE 5. Three tugboats brought Tam-Dao 05 to position and maneuvered to correct direction of JuR before anchoring.

A. MANEUVERING THE JuR BY WET-TOWING METHOD

Towing activities of Floating Production, Storage, and Offloading systems, especially the JuR, have increased as deep-sea resources have improved. Because offshore buildings are usually pulled in the ocean, a towing system with a towline at the stern of the tugboat is employed. It is critical to ensure the structure's towing stability. Moreover, Towing operations that lack adequate towing stability can result in unanticipated planar motion of structures and marine mishaps like stranding or collisions with other ships. Thus, to avoid marine incidents when towing the structure to the installation location, the towing stability must be evaluated during the early design stage [123].

In works of literature, Wet-towing for offshore is described in the literature as using an offshore integrated meteorological mast (OIMM), which combines the offshore transportation of the foundation and steel mast into one operation. The OIMM's most important approach is a self-floating towing operation with appropriate subdivision inside the floating tank [122]. Ding *et al.* [125] conducted hydrodynamic studies in relation to sea conditions to determine the towing dynamic behaviors of the OIMM with varied drafts, mooring sites, towing velocities, and towrope lengths in various sea conditions. An effective approach for analyzing the hydrodynamic characteristics of fins and improving the FPSO's course stability during towing has been devised in [124], and to cross-check for comparison reasons, the result is an eigenvalue analysis be done using a linearized towing system model. Fig. 5 indicated the three tugboats brought Tam-Dao 05 JuR to installing position.

Most of the studies related to wet-towing gathered that the impact on the environment is huge. During wet towing operations, waves, wind, and currents are the main causes of floating structure disturbances. As a result, the dynamic reaction in a complex environment is the most crucial numerical challenge. To do so, we can conclude that the sea states have a greater impact on the towing speed than on motions responses.

In the scope of this work, wet-towing control is mainly concerned with the tugboat and the tugboat-mounted DPS that keeps the vessel moving accurately. Moreover, this DP system is also equipped on the JuR moving by the Dry-towing

TABLE 8. A comparison of different identifiers in terms of the control process.

Equipment /System	Control Unit	Main Purposes	Technique /Control methods	Features	References
Drilling	Draw works Brakes System	Controlling a winch cable for an oil well drilling	Adaptive	Direct feedback of actuator force	[106]
	Hydraulic-Driven Rotary Top Drive System	Relatively wasteful of power To drill a borehole, apply clockwise tension to the drill string.	Observed Intelligent control	Controlled by feedback pressure Control of torque and speed	[102], [103] [100], [101]
	Lifting Systems.	The drill string is raised, lowered, and suspended, while casing and tubing is lifted for insertion into the well. Pipe loading into and out of the derrick, as well as casing elevators.	Time driven Feed-back Intelligent control	Driven by air motor or hydraulic motor	[104], [105]
MUD Circulating Systems	Pressurized Mud Cap Drilling System	Using high pressure to circulate drilling fluid System For Drilling.	Time driven Feedback	Gear driven	[114], [115]
	Drill Strings	To transmit the torque and drilling fluids to the drill bit.	Real-time monitoring and intelligent control	Solid’s control PLC and HMI based design with control and monitoring features. Integrated control system with local control panel for real-time monitoring and control. PLC and HMI based design with control and monitoring features.	[107], [108]
Well system	Choke Control Units.	Systems are typically designed to actuate auto chokes or gate valves using single system pressures	Precise well control	Precise well control and Monitoring features	[109]
	BOP-Handling	To handle with the BOP stack’s lifting and traversing movements	Pendant or Radio Remote Control	Adjustable Load Limiter and Precise Control	[110]
Marine system	Bilge and Ballast Systems	To keep oil rigs afloat	Intelligent	Balance control	[113], [118]
	Mooring System	Used for station keeping of a ship or floating platform in all water depths	Intelligent	The mooring system forces are nonlinear time- and position-dependent restoring forces	[111], [112]
	Communication system	Used for communication	Intelligent	Object Linking and Embedding for Process Control	[119], [120]
	Jacking System	Designed to drive rack-and-pinion jacking systems	Precise speed control	Consists of variable speed drives and controls	[116], [117]
Power plant	Diesel Engines and Auxiliary Engines Control units	Power source	Real-time monitoring and Intelligent	Power Management	[121], [122]
Electrical system	Main Switchboard Emergency Switchboard Motor Control Lighting System Electrical Outlets Batteries and UPS Alarm Systems: Fire, Gas, General and Flooding Navigation Lights and Foghorns Communication: Telephone and PA System Electric Welding			Not mentioned in this paper	
Safety system	Automatic Fire Detection CO2 System Emergency Pump Deluge System Foam System for Helideck Lifeboats Flammable-Gas Detection H2S Gas Detection Alarm and Public Address Fire Protection			Not mentioned in this paper	

method. This problem is covered in the next subsection of this section.

B. MANEUVERING THE JuR BY DRY-TOWING METHOD

We keep in mind that some JuRs are self-propelled and some are not. Self-elevating units are known as jackup vessel,

liftboats, lift barges, or jackup barges, depending on their purpose and capability. Although there is no clear differentiation between these categories, each of these units has specific characteristics that are widely regarded as distinguishing elements in how the units are referred to in the offshore sector. Related to the dry-towing method, to facilitate the analysis

and based on the structure of the Jack-up, we classify it as follows:

- 1. Not self-propelled jack-ups: By transporting the JuR aboard another vessel, the unit is secured onto the other vessel (the usually used the heavy lift vessel) as deck cargo.
- 2. Self-propelled jack-ups: Jack-up vessels are platforms [128], [129] with the legs can be extended to the seafloor to lift the vessel's hull above the sea surface.

In the scope of the work, we are more interested in the self-propelled jack-ups because the jack-up vessel provides a stable platform for offshore activities like drilling platforms [129] and wind farm [130] servicing platforms. Although a large percentage of the jack-up vessel are not self-propelled, tugboats or heavy lift vessels are utilized to transport the jack-up from one location to another, and they are also employed to accurately position the vessel over the seabed, coupled with an anchoring system. However, there is a growing trend for self-propelled jack-ups, which reduces the added costs of shipping and placement associated with un-propelled jack-ups. Self-propelled jack-ups are now being fitted with Dynamic Positioning Systems (DPS) to decrease operational costs and hazards even more.

C. DYNAMIC POSITIONING SYSTEM ON JACK-UP VESSELS

The DPS help to perform all of the activities such as transit, survival, and station keeping of the jack-ups. If it is self-propelled, dynamically positioned, or moored, the variations in needed electrical systems for propulsion are considerable. The power needs for DP that are the main consumers aboard self-propelled jack-ups will differ significantly based on the operational mission. Thruster units typically range in power from several hundred to several thousand HP with four, six, and eight variable-speed thruster configurations, as well as harsh conditions that necessitate the employment of all thrusters. Furthermore, Table. 9 shows the DPS class information by Craig and Islam [127], which includes a description of the four types of DPS discussed by IMO before. The severity of the effect of DP loss, including catastrophic events such as fires, flooding, and spills, is assessed by redundancy on system failure and enforced by the intensity of the impact of DP loss.

Concerning the feature, the DPs now allows for many more actions that were before impossible. DPS, in particular, makes it simple for boats to shift positions because of their great agility. Furthermore, DPS does not require anchor handling tugs, does not require water depth, and is not restricted by a blocked seabed. The DPS is largely focused on the control of the jack-up vessel includes surge, sway, and yaw. It calculates the necessary control actions to maintain position and corrects position mistakes by applying thruster forces to the vessels as the control system demand. As a result, under most sea conditions, the DPS control system plays a significant role in increasing the efficiency of the Jack-up vessel.

1) OVERVIEW OF DPS CONTROL THEORY AND OFFSHORE APPLICATION

Lately, Wang *et al.* [131] and Mehrzadi *et al.* [132] reviewed several prior study materials to present the start of the art of contemporary control theories to improve the quality of DPS. A traditional study of navigation is the nonlinearity and unpredictability of the disturbance taken into account in the controlling process of an offshore self-propelled vehicle. Last but not least, how these difficulties will be addressed by the DPS is discussed extensively in [133] and more recently by [131] and [132]. The analysis results showed the importance of DPS in the harsh working conditions when maneuvering with the Dry towing method. More significantly, we must address the certainty problem that self-propelled jack-up vessels often function in deep water, which is complicated and sensitive. Hence, we need a control system that can be adaptive to modifying the variables, and robust to uncertain factors. There are many solutions based on modern control algorithms to increase stability for the DPS, in which we have to mention adaptive control first.

In the process of adaptive control of the DPS, Piao *et al.* [134] used Adaptive Backstepping Sliding Mode controller to solve the problem of certain disturbances, but time-delay is not mentioned in this work. Meanwhile, the DPS for Accommodation Vessels considering the case of time-delay used to deal with bounded tracking error, input latency, and shielding effects by [135], the DPS was built with specified performance and a predictor-based method to enhance the quality of the system. A Finite-Time Output Feedback Control Scheme [136] and Robust Output-Feedback Control based High Order Sliding Modes [137] aimed to provide the robustness of standard Sliding Modes Controllers while keeping accuracy and chattering suppression. This is new nonlinear sliding schemes for DPS disturbed by wave action. In addition, there are some of adaptive control algorithms based on model predictive, such as Nonlinear Model Predictive Controller [138] and nonlinear cascaded control based on backstepping [139], to demonstrate that predictive control introduces the idea of adaptive control, which is suitable for uncertain structural and complex systems in ship motion control. In general, the adaptive control of the DP system focuses on improving control quality in the existence of nonparametric perturbations such as disturbances and parameter variations dynamics, but it really doesn't require any prior knowledge of the bounds on these uncertainties, or in some words, the adaptive control has no intent for robustness. Dang *et al.* [96] have developed the Robust Adaptive Fuzzy Control Using Genetic Algorithm model for the DPS in the caused by environmental effects and uncertainties. The application of H_∞ control is utilized to assure the robust boundless of GA parameters by Lyapunov stability analysis, while the Genetic Algorithm helped to enhance the optimization of the system.

For offshore application, by using a nonlinear estimation technique [140], a switching control perspective on the offshore construction scenario of Heavy-lift vessels [141],

TABLE 9. The IMO DPS class information [127].

Description	IMO Class	ABS	LRS	DNV
Manual position control and automatic heading control under specified maximum environmental conditions.	–	DPS-0	DP (CM)	DNV-T
Automatic and manual position and heading control under specified maximum environmental conditions.	Class 1	DPS-1	DP (AM)	DNV-AUT, DNV-AUTS
Automatic and manual position and heading control under specified maximum environmental conditions, during and following any single fault excluding loss of a compartment. (Two independent computer systems).	Class 2	DPS-2	DP (AA)	DNV-AUTS
Automatic and manual position and heading control under specified maximum environmental conditions, during and following any single fault including loss of a compartment due to fire or flood. (At least two independent computer systems with a separate backup system separated by A60 class division).	Class 3	DPS-3	DP (AAA)	DNV-AUTRO

a convolutional neural network for estimating sea's states [142], these are the latest works related to the DPS and the systems serving it to increase the ability to withstand the effects of weather and uncertain factors during the work. Moreover, three primary variables influence the quality and performance of DPS in the actual operating condition of the vessel, including imprecise system parameters, dead-zone inputs, time delay, and dynamic and environmental disturbance. With complicated vessel dynamics, dead-zone inputs and time-delay are expected to be the causes of DPS nonlinearity. As a consequence, the adaptive fuzzy control method provides an effective control that is quite desirable for coping with this nonlinear system [142]. In the next subsection, different relevant publications on DPS dynamics will be thoroughly examined.

2) DPS DYNAMIC

The nonlinear motion of a vessel in DPS mode is described by Fossen [98] and reused by some authors, as Dang *et al.* [96] for a class of service vessel, Ye *et al.* [141] for Heavy-Lift Vessels, Liang and Wang [135] Accommodation Vessels, and FPSO Vessels [143]. Two separate coordinate systems include: the first one is a vessel fixed non-inertial frame $O - XYZ$; and the other is the inertial system approximated to the earth $O_0 - X_0Y_0Z_0$, which showed by Fig. 6. Kinematics and dynamics describe the movement of the vessel in planar space with three degrees of freedom, namely, surge, sway, yaw and external force acting is defined as below [96]:

$$\dot{\eta} = J(\psi)v \quad (28)$$

$$M\dot{v} + Dv = F - F_{envi} \quad (29)$$

We rewrite the equation (22) in which vector F_{envi} represents the forces from environment, including wave, wind and current as follows:

$$F_{envi} = F_{wave} + F_{wind} + F_{current} \quad (30)$$

where position (x, y) and heading (ψ) of the absolute coordinate system $X_0Y_0Z_0$ are denoted as a vector from $\eta = (x, y, \psi)^T$. The vector $v = (u, v, r)^T$ describes velocities of the vessel motion in the relative frame of reference. The control vector F produced by thruster systems controlled by the DPS.

The vertical centering of the relative coordinate system XYZ is placed at the roll axis of vessel, x_G denotes the longitudinal position of the gravity central of the vessel towards the relative frame of reference [96].

The transformation matrix $J(\psi)$ and $M \in R^{3 \times 3}$ and $D \in R^{3 \times 3}$ are the inertia and damping matrix, respectively. The matrixes $J(\psi)$ are written as:

$$J(\psi) = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (31)$$

$$M = \begin{bmatrix} m - X_{\dot{u}} & 0 & 0 \\ 0 & m - Y_{\dot{v}} & mx_G - Y_{\dot{r}} \\ 0 & mx_G - N_{\dot{v}} & I_z - N_{\dot{r}} \end{bmatrix}$$

$$D = \begin{bmatrix} -X_u & 0 & 0 \\ 0 & -Y_v & mu_0 - Y_r \\ 0 & -N_v & mx_G u_0 - N_r \end{bmatrix} \quad (32)$$

where m is the vessel mass, I_z is the moment of inertia about the body-fixed Z -axis, x_G represents the location of G in x -axis direction, u_0 is velocity component at mid-vessel. The acceleration of the surge, sway, and yaw directions of transformation increase the inertia quantities represented as

$$X_{\dot{u}} \triangleq \frac{\partial X}{\partial \dot{u}}, Y_{\dot{v}} \triangleq \frac{\partial Y}{\partial \dot{v}}, N_{\dot{r}} \triangleq \frac{\partial N}{\partial \dot{r}}, Y_{\dot{r}} \triangleq \frac{\partial Y}{\partial \dot{r}}, N_{\dot{v}} \triangleq \frac{\partial N}{\partial \dot{v}} \quad (33)$$

where D represents the damping matrix and M represents the inertia matrix with additional mass effects. The equation(34) defines the damping compositions in directions of surge, sway, and yaw.

$$X_u \triangleq \frac{\partial X}{\partial u}, Y_v \triangleq \frac{\partial Y}{\partial v}, N_r \triangleq \frac{\partial N}{\partial r}, Y_r \triangleq \frac{\partial Y}{\partial r}, N_v \triangleq \frac{\partial N}{\partial v} \quad (34)$$

However, when M_0 and D_0 represent the nominal values, and ΔM and ΔD represent the uncertainties, then the structural parameters are rewritten $M = M_0 + \Delta M$ and $D = D_0 + \Delta D$. Depending on the type of vessels or jack-ups, the parameters are used differently in the calculation, simulation, and design of control algorithms, but the system of kinematics equations mostly experience the same form as mentioned above.

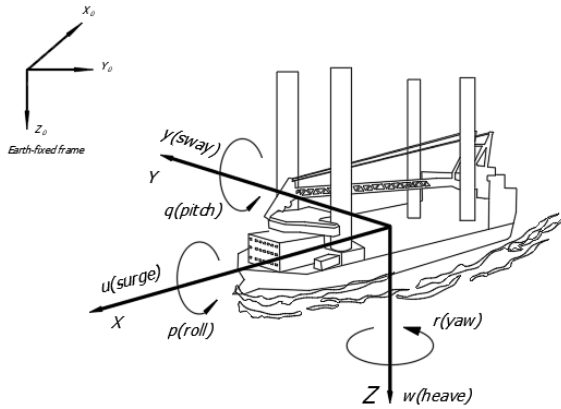


FIGURE 6. Definition of the vessel fixed non-inertial frame $O - XYZ$ and the inertial system approximated to the earth $O_0 - X_0Y_0Z_0$.

VI. JACKING CONTROL SYSTEM

A. RACK AND PINION

The jacking systems (JSs) is the mechanical system used to elevate the JuR. On the JuRs that are employed, there is a multiple jacking system (JS). Rack and pinion mechanical system, on the other hand, is a well-known way of elevating the jack-up hull and legs by distributed torque between all legs using numerous hydraulic or electric motors and gearboxes, thus it supported the entire platform raised or lowered smoothly and simultaneously. However, the holding system, incorporated with the JS or utilized as a separate machine, worked when the legs and hull attained the fixed position. Electrical, hydraulic, or pneumatic JS are available. Rack and pinion mechanical systems are the most applied methods because it allows for reasonably stable jacking.

Regarding the control problem, control solutions must depend on the mechanical transmission system, of which there are two types as follows:

- 1. Hydraulic system: the system used a hydraulic cylinder to exert force to elevate large objects, the forces generated by the pressure in the cylinder chamber to raise weights.
- 2. Electric system: Even in harsh marine conditions, electric motors provide a smooth and safe jack-up procedure. However, it is critical to guarantee that the motors that drive the rig’s legs are extremely dependable and capable of withstanding heavy loads with minimal current fluctuations.

General, popular JuR type is three-leg Jack-Ups which may have 36 pinions, while larger units would have 54, and extreme environment versions might have up to 72. An AC electric motor with a fail-safe disk brake drives each pinion through a sequence of gears. The motor characteristics will tend to equalize the load between all pinions on a chord preventing any of the individual pinions from it being overloaded. Hydraulic motors were used instead of electric drives in early JS’s designs. The main configuration of two sets of jacking units is shown in Fig. 7 [73].

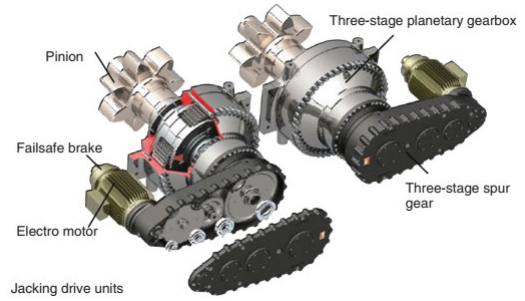


FIGURE 7. The principal arrangement of two sets of jacking units (GustoMSC jacking unit) [73].

The rack and pinion system is usually built and manufactured advanced high-capacity JSs, including jacking units and Jacking control, and then provided the data to the designer. Based on that, systems are calculated to match the provided equipment for various JuRs. Related to the recent studies of rack and pinion of the JS, the problem of stress and stiffness analysis of a 7-teeth are discussed by [116], the authors in [115] presented chaotic dynamics powered by the Casimir force. Moreover, the theoretical investigations were carried out [145] using the tooth wears model from scuffing of heavy-duty machine spur gears. Finally, bearing loads and stress analysis was performed for a failed pinion of a jack-up platform in [146], the author showed issues to explain the failure of the pinion. In general, there are many studies on this issue because of its importance in improving the quality of the JS.

B. KINEMATICS AND DYNAMICS

The movements of the hull and the interaction of forces are presented in Fig. 8. The hull moves up and down following the Z-direction, and vertical and horizontal shaking around the X-axis, Y-axis. In elevated mode, the hull is driven by electric motors mounted on three positions on the hull corresponding to the situation of the legs, the motors on each position have the same parameters and are synchronously controlled at the same speed. The diagram of the jacking control system is depicted in Fig. 9.

The hinged rig’s motion equations in case of all legs of the JuR are fixed at the seabed in equation (18) in section III of this paper. To move the hull to a fixed position, the elevating mechanism is used. According to the overall diagram in Fig. 9, we have the force components acting on the JuR’s body calculated in the system of differential equations describing the kinematics as follows [144]:

$$G \frac{d^2x(t)}{dt^2} + B \frac{dx(t)}{dt} + Ggx(t) = k\tau(t) + \tau_{envi}(t) \quad (35)$$

where $G = \sum_{i=1}^n g_i$ is total weight of JuR; $\tau(t) = \sum_{i=1}^n \tau_i(t)$ is total torque of motors with k is the inverted factor in rotary – translational drive (including the number of motors and transmission coefficients).

The displacement of the hull is calculated by

$$x(t) = R\theta(t) \quad (36)$$

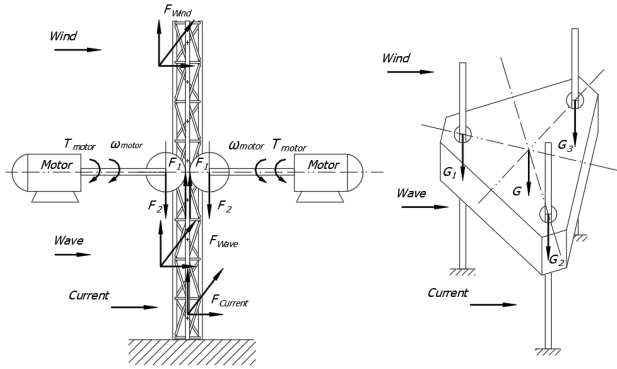


FIGURE 8. The movement in all directions of the hull.

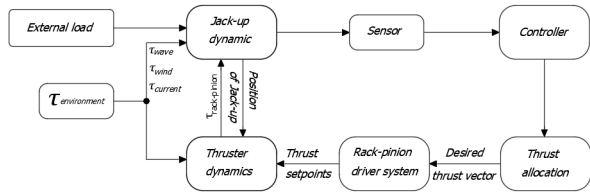


FIGURE 9. The diagram of jacking control system.

The sum of the effects of external and internal disturbances includes wave, wind, current, and external noise components, respectively. The equation is defined as follows:

$$\tau_{envi}(t) = \tau_{wave}(t) + \tau_{wind}(t) + \tau_{current}(t) + \tau_n(t) \quad (37)$$

Finally, the equation describing the kinematics of JuR is written as:

$$Rs^2 \theta(s) \left(\sum_{i=1}^n g_i \right) + RB\theta(s)s + \theta(s)gsR \left(\sum_{i=1}^n g_i \right) = k \sum_{i=1}^n \tau_i \quad (38)$$

where B is coefficient of friction, $R(m)$ is gear radius, $\theta(s)rad$ is the angle rotation of gear, and $g(m/s^2)$ is acceleration due to gravity. The above equations for use in study, simulation and technical calculations. The system will become a nonlinear system when the properties of the external forces and disturbances, acting on the jacking control process, are considered as the nonlinear functions.

C. ANALYSIS OF FACTORS AFFECTING THE ELEVATING PROCESS

1) ENVIRONMENTAL ELEMENTS

The wind load is generated when tiny waves occur on the water's surface, increasing drag and allowing short waves to form. However, these little waves will continue to build until they break, with the majority of their energy going to the legs of JuR. To model the wave surface construction and calculate the wave height, the mathematical wave model presented by [96], [147]–[149]. Equation (23) determines the wave factor impacting the JUR's structure.

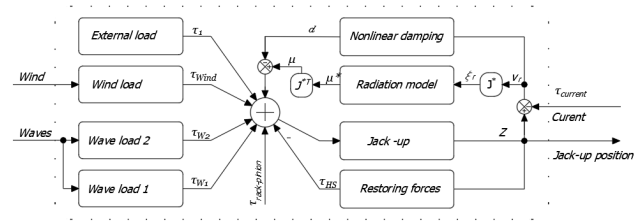


FIGURE 10. The kinematics of a JuR on control system design.

The wind load affects the floating stability of the legs, and it depends on the windbreak area, velocity, structure shape, height. Generally, there are four methods of calculating wind load: numerical simulation, using the formula synthesized from experiment, field test, and wind tunnel [29], [150]. However, the wind frequency and direction are modeled as slowly changing quantities, and the wind force is calculated by using equations (24) and (25).

The current load is considered to be stable even though the current velocity varies with time, space, depth, and vibration caused by whirl. Ignoring the above factors in the calculation process for offshore works, we only need to calculate the velocity and velocity profile of the flow on the water surface [96], [151]. The force acting on the legs of the JuR can be calculated separately according to the following equation (26).

The effects of weather conditions on the quality of the control system and the durability of the equipment, which mentioned in the previous sections. However, we are repeated here as an integral part of the system design calculation process, and it means that we always have to pay attention to this problem.

2) VIBRATIONS

General, the structural vibrations and the connections of Jul legs, [152], [153], are mainly caused by the periodic action of waves and currents. We have suitable methods such as dynamic factor amplification, frequency domain analysis, or time-domain analysis [154] for vibration analysis of marine structures. Using DAF (Dynamic Amplification Factor) method [155] where the inertial load is used to represent dynamic load, the ratio between dynamic response amplification and static response amplification is calculated as follows:

$$DAF = \frac{1}{\sqrt{\left[1 - \left(\frac{T_N}{T} \right)^2 \right]^2 + \left(2\zeta \frac{T_N}{T} \right)^2}} \quad (39)$$

where T is the wave excitation period. The T_N frequency is determined as follows:

$$T_N = 2\pi \sqrt{\left(\frac{M_e}{K_e} \right)} \quad (40)$$

M_e is the mass of one leg:

$$M_e = \frac{M_h}{N} + M_{la} + \frac{M_{lb}}{2} \quad (41)$$

where N is number of legs. M_h is the whole rig mass. M_{la} and M_{lb} are the upper and lower leg volume. K_e is the hardness of one leg is calculated as follows:

$$K_e = \frac{\frac{3EI}{L^3} \left(1 - \frac{P}{P_E}\right)}{1 - \frac{\frac{3L}{4} - \frac{12F_g I}{AF_v Y^2} \left(\frac{EI}{K_{rs}} + \frac{L}{2}\right) - \frac{3(EI)^2}{F_r L K_{rs} K_{rh}}}{\left(\frac{EI}{K_{rs}} + L + \frac{EI}{F_r K_{rh}}\right)} + \frac{7.8I}{A_s F_h L^2} \quad (42)$$

where F_g is the coefficient takes into account the geometry factor. K_{rs} is the stiffness at spud-can connection. K_{rh} stiffness at the position of connecting the legs to the hull. F_r is the stiffness coefficient of the hull. E is the modulus of elasticity of steel. A is a cross-sectional area of a leg. Y is the distance from the center of one leg to the line connecting the centers of the other two legs. L is the leg length. F_v is the stiffness coefficient of the ground in the vertical direction. F_h is the coefficient of stiffness of the ground in the horizontal direction. I is the second moment of area of the leg including contribution from rack teeth. P_E is the Euler buckling load and A_s is the effective shear area of one leg. We have:

$$P = \frac{M_h g}{N} \quad (43)$$

The inertial load is used to represent dynamic load, thus the accuracy of the calculated hydrodynamic coefficients will affect the mathematical model of the system because it is a formula consisting of many components, each of which has a certain tolerance, which may contain nonlinear elements.

3) MECHANICAL ERRORS

The rack-gear system used to raise and lower the rig is a complex elastic mechanical system, the gear system will generate vibration and noise during operating. Errors for basic gear systems included contact position errors, bearing assembly errors, axial errors, pitch errors, and gear radial errors. Gear geometry deviation in transmission the stress transmitted from the gear to the rack is related to the geometric parameters involved in contact position and tooth height of the rack, pitch, number of teeth, pressure angle [156]–[159]. Furthermore, errors in the shape and position of the contact surface affected the transmission error. Thus, the sum of the component errors is superimposed from the different geometrical errors and acting on the powertrain according to [160]. We have:

$$\begin{aligned} & (\Delta x_{0i}, \Delta y_{0i}, \Delta z_{0i}, \Delta \theta_{0i}, \Delta \beta_{0i}, \Delta \gamma_{0i}) \\ &= \begin{pmatrix} dx_{i1} + dx_{i2} + \dots, & dy_{i1} + dy_{i2} + \dots \\ dz_{i1} + dz_{i2} + \dots, & \delta x_{i1} + \delta x_{i2} + \dots \\ \delta y_{i1} + \delta y_{i2} + \dots, & \delta z_{i1} + \delta z_{i2} + \dots \end{pmatrix} \\ &= \begin{pmatrix} \sum_{j=1}^n dx_{ij}, & \sum_{j=1}^n dy_{ij}, & \sum_{j=1}^n dz_{ij} \\ \sum_{j=1}^n \delta x_{ij}, & \sum_{i=1}^n \delta y_{ij}, & \sum_{i=1}^n \delta z_{ij} \end{pmatrix} \quad (44) \end{aligned}$$

where: dx_{ij} , dy_{ij} , dz_{ij} , δx_{ij} , δy_{ij} , δz_{ij} are the j th error of the i th part, respectively. Δx_{0i} , Δy_{0i} , Δz_{0i} , $\Delta \theta_{0i}$, $\Delta \beta_{0i}$, $\Delta \gamma_{0i}$ are the displacement errors according to all 3 rotation errors of the same part under overlapping, respectively.

In general, the geometry of the gear and rack system determines the accuracy of the lifting or lowering operations of the rig. The performance of the gear and rack system is reduced at the teeth are geometrically faulty. However, gear and rack transmission systems have various classes of errors such as radial misalignment, axial misalignment, tooth profile misalignment, pitch, and some unspecified errors, etc. Finally, in order to improve the control performance, the calculation, estimation, and identification of these errors not only make the system more stable but also increase the stability, which is of particular interest to the JS.

D. APPLICATIONS AND SERVICES

1) MAIN FUNCTIONS OF JACKING SYSTEM

In the offshore construction and drilling industry, jacking devices are often used on Liftboats and JuRs for drilling and offshore wind turbine installation and maintenance. For each kind, the jacking mechanism must fulfill specified requirements. The two most common JSs are pin-and-yoke (PY) and rack-and-pinion (RP). In addition, this study focuses on RP, which is extremely satisfactory to high-speed operations and deep-water applications. However, Jacking units and jacking control systems were often incorporated in sophisticated high-capacity JSs, and the primary tasks are normally separated into two functional groups: control and monitoring, in detail, are as follows:

- 1. Speed Control: Variable frequency drives control the speed of the jacking motors in each leg. The controllers provide variable speed control between the minimum and maximum specified points.
- 2. Re-Torque Control: The Re-Torque Control distributes the weight evenly across the jacking units on one leg. The operator does not need to manually re-torque each motor using a torque wrench.
- 3. Rack Phase Differential (RPD) monitoring system: This system may also be used as a reference for automating jacking corrections to make processes more efficient and avoid operator mistakes (JS-specific). Furthermore, owing to the inaccuracy of the manual technique, limb injury might easily occur without this device.
- 4. Leg Position Indication: The encoder and supporting structure are permanently attached to each leg, and the length of the leg below the hull can be seen.
- 5. Air Gap Monitoring System: The system monitors the airgap in real-time and displays the current airgap between the hull and the water. This system can determine real-time wave height information and may be used to trigger alerts when the sea level and wave heights reach a predetermined threshold, signaling the need to evacuate the area.
- 6. Buoyancy Point System: This allows for the computation of buoyancy load estimations on legs and spud cans. This system indicates whenever a leg is released from the seabed instantaneously.
- 7. Inclination Monitoring System - This system is used to keep the JuR or vessel inclination during jacking

phases and to determine its movement during leg removal from the seabed even if there is strong wind and wave action oscillation.

- 8. Load Monitoring System - This system necessitates the incorporation of torque load sensors into the jacking tower and gears. Load monitoring may be done in a variety of methods, with differing degrees of precision. Live load monitoring enables load monitoring even when the system is not jacking, enabling continuous load readings. In order to take a measurement on the system, standard load monitoring may need the system to be actively moving.
- 9. Deck Load and Computation System - This system is extensible and can be integrated with a load monitoring system, but in its most basic form, it allows for the calculation of deck load and Preload information – computation and Gravitational force based on deck load placement.
- 10. Pinion Torque Monitoring Systems: These systems are designed to measure and communicate the exact torque exerted to each pinion to the jacking control system. The control system distributes the load delivered to the jacking units automatically, and torque re-torque may be done automatically.

In addition to the above systems, depending on the specific requirements of each JuR can be equipped with other auxiliary systems. Regarding control, Speed control and Re-torque control are the main systems, the application of new control algorithms to ensure stability and robustness helps JUR increase its ability to work in extreme weather conditions.

2) THE APPLICATION OF NEW CONTROL ALGORITHMS

In offshore industry, SCADA systems are used in the jacking control system by companies like ABB, Siemens, and TSC. The ease of programming and system design with industrial hardware is offset by the restricted applicability of contemporary control theories. The control methods employed in these systems, such as Fuzzy and PID, are ineffective under complicated working situations and are inconvenient to operate. Advanced control theories for industrial systems are researched, and there are numerous publications for reference, however, there are few papers regarding JSs in offshore projects. It can be noted that there are few articles on this topic in systems such as IEEE Explore, Elsevier, and others.

To handle the effects of external disturbances on a maritime system, a system utilized a backstepping method to create the control law based on Lyapunov function, as well as a radial basis function neural network (RBFNN) with dynamic surface control [161]. Reference [162] advocated a new control legislation method. Dynamic surface control and active disturbance rejection control were accomplished by the controller. The Lyapunov function was used to demonstrate stability, and the controller's performance was compared to that of the sliding mode control via simulation. When using contemporary control techniques such as neural networks

and disturbance rejection-based sliding mode control, the Lyapunov theory is an excellent tool for ensuring the stability of the control system under the influence of the environment.

The selecting technique of learning rate to ensure robust tracking in the face of noise and modeling errors, as well as guaranteed a quicker convergence speed, are described in [163] and [164] about the adaptability and resilience of the system. The capacity to resist external disturbances may be characterized as the control system's robustness and stability. Furthermore, the weight update technique is interpreted into a similar feedback structure, and the small gain theorem [165] is used to examine its stability and robustness. Using the adaptive learning rate established for the convergence and resilience of RBFNN, an adaptive learning rate for RBFNN using time-domain may be used. As mentioned, adaptive control under the influence of error and noise was implemented to overcome parameter uncertainties and nonlinear disturbances using adaptive sliding mode control [163]. Moreover, Adaptive neural networks including an active surface with minimal learning parameters were implemented to overcome parameter uncertainties and nonlinear disturbances using adaptive sliding mode control [164], [166]. The nonlinear dynamics and anti-sway tracking control [167] and active control [168], both related to offshore crane control systems, addressed the problem of payload sway suppression and trolley position track with disruptions of ship movements and parameters perturbation. This demonstrates that nonlinear control approaches are very useful for controlling offshore equipment.

As a result, control theories are currently being researched and applied to maritime industry in general, and the JSs in particular, with an emphasis on addressing errors and environmental disturbances utilizing contemporary methodologies and the Lyapunov criteria for stability. Researchers can rely on this attitude to create academic research.

VII. DISCUSSION

In this section, we specify and discuss the main challenges and the research directions about JuR motion, techniques, and applications toward modeling and control systems. The challenges include harsh working conditions and technical issues. In addition, the research directions focus on a promising JuR advanced and intelligent control design framework to ensure robustness, stability, quality, and safety for the overall automated systems, especially for the DPS and JSs.

A. MAJOR PROBLEMS

In general, through the contents that have been reviewed based on the circular citation references of reputable sources, we can orient four main issues as follows:

- Structural modeling and the effect of nonlinearities factors: the JuR subjected to storm load pattern is complex, extreme control response of jack-up platforms in sea environment requires improving the understanding of the effect of nonlinearities such as environment effect, drag-dominated, loading random waves, dynamic

amplification, nonlinear structural response, and nonlinear foundation systems. However, some mathematical models of the JuR structure need recommended to help in computation, study, simulation, as well as application.

- Outline of automatic operating systems on the JuR: To understand the control systems, we need to understand an overview of the JuR's automatic operating systems associated with the actuator and its mechanical structures and performance.
- Control Strategies to gain a higher performance: the emerging control techniques used to gain a higher system performance under the effect of nonlinearities of the model and weather disturbances. This is the main point that we investigated in this survey. The presence of nonlinear errors (i.e., mechanical errors in design and manufacture, error in the position of the bases, control time delay, random error) can enable new mechanisms and novel control strategies, especially in the field of nonlinear control.
- Applications and services: what is the difficulty when we applied the novel strategies of control into the application in building the JuR. A wide range of control methods (i.e., neural network, fuzzy control, Genetic algorithm) is investigated based on some offshore applications that can be studied in the future.

B. CHALLENGES

1) HARSH WORKING CONDITIONS

As analyzed before, the influence of the environment and working conditions is quite wide on the JuR control process, especially in the JuR maneuvering and elevating mode. Also, the following conclusions are extracted based on the predicted conditions and results:

- Rig move process is highly affected by the weather conditions.
- The safety of operations is improved by defining the processes for departure, transit, and installation at any emergency jacking position/standby location.
- The exactly weather forecast is a main method in determining the action of wind, and waves on JuR.
- Changing wind directions leads to a change in its velocity, height, and impact on JuR. And the same for waves.
- Wind loads on a derrick, drilling top is significantly changed by alterations of weather conditions.
- Earthquake stresses must be applied separately from other environmental pressures, such as waves, wind, and so on. Earthquakes have a huge effect on waves, winds and ocean currents.

2) THE NON-LINER ERRORS

The JuR footings have limited stiffness in the horizontal, vertical, and rotational directions, as well as cross-coupling between the horizontal and rotational degrees of freedom and nonlinearity. This nonlinearity, on the other hand, might be generated by changing submergence, geometric nonlinearity, or a driving function crucial in Jack-up structural response.

Thus, the errors and noise are the challenger which caused by:

- Nonlinear loading components (i.e., drag force loadings, permanent loads, operating loads).
- Nonlinear foundation characteristics.
- Uncertain damping (i.e., due to the motions of the JuR uncertain structure).
- The uncertain structure's dynamics.
- Structural interface nonlinearities (i.e., gaps between the leg structure and rack pinion).
- Time-delays of control process.
- Noise and disturbances in the mechanical, electrical systems, communication, and network.

The mentioned harsh working conditions and non-linear errors are the technical challenges enable us to propose the research directions in discussed in the sequel.

C. RESEARCH DIRECTIONS

- 1. Robustness and Stability for JuR control process: Harsh working conditions and the nonlinear errors caused by many factors are the main factors that cause the system to be difficult to control, unstable, and not abundantly robust. In many scenarios, depending on the missions to be completed of each automated system, operation mode, weather, loads, etc., the control solution chosen will determine the performance of the system, which includes: quality, unit cost, scheduling, hourly rate, safety, communication, and technology. The JuR are connected in some specific technologies such as optimization control, intelligent control (Neural network, fuzzy logic, genetic algorithm, etc.). The control systems are capable of collaborating with another existing control algorithm, e.g., PID control, LQR control, as well as with the model predictive control and Back-stepping Sliding Mode control. These solutions require the JuR model to be relatively accurately certain and the modeling error to be small. Thus, the adaptability and sustainability of these systems are also considered insufficient in the operational requirements of JuR. It means that the new research directions are equipped with not only stability and accuracy but also capable of ensuring safety in all the harshest working conditions. From this aspect, robust control solution combined with other algorithms such as adaptive, genetic optimization, particle swarm optimization, along with other intelligent algorithms, is considered suitable for automated systems of the JuR.
- 2. Robust Adaptive Control (RAC): Robust control is a controller design technique that explicitly addresses uncertainty, whereas adaptive control used a controller to adapt to a controlled system with parameters that fluctuate or are originally unknown. When we combine these controllers into a single solution, we say that an adaptive controller is resilient if it ensures global boundedness in the presence of "acceptable" classes of uncertain dynamics and bounded disturbances, as well

as performance error bounds on the order of the modeling error. In this case, the disturbance and errors are caused by waves, winds, currents, earthquakes, and the uncertain loads changed when the system is in operating. Finally, the system ensures not only optimal and stable control but also robustness within the limits of pre-calculated working conditions. However, a typical RAC design for the JuR, especially the JSs, has not been studied in the literature, this opens the opportunity to novel research ideas.

- 3. Intelligent Disturbance Observer-based Robust Control: Internal and external disturbances are calculated using recognized dynamics and quantifiable plant states in disturbance-based robust control, and system robustness is easily accomplished by getting feedbacks from the disturbance estimations. Moreover, the disturbance observer makes the performance more resilient in numerous working situations by employing intelligent methods such as a Neural network controller, Genetic algorithm, or Cerebellar model articulation controller. To enhance disturbance approximation and compensation, an artificial intelligence (AI) approach is combined with disturbance observer-based feedback linearization. Thus, the disturbances caused by loads of JuR are eliminated from the control process. Importantly, artificial intelligence is always attractive to researchers, the algorithms created by AI are always novel issues, so this is also a highly reasonable research direction.

VIII. CONCLUSION

This paper has presented a comprehensive review of the challenges of modeling and control strategies for JuR. First, it seeks to offer readers with background information on a variety of offshore drilling platforms, with a particular focus on the JuR with automated systems. Then, to comprehend the components and major functions in the operating of JuR, structural modeling is introduced, as well as the necessary mathematical equations in general. The JuR is then built to withstand a mixture of loads, including permanent loads, operational loads, and environmental loads. The loads that influence the JuR are described using theory and equations, and common system performance indicators are developed for informative assessments. After that, the automatic operating systems with different control strategies become continued fulfilled and investigated which bring numerous capabilities to offshore industrial and oceanic development. Thereafter, automatic operating systems with multiple control techniques are completed and studied, resulting in a wide range of capabilities for offshore industrial and oceanic development. Furthermore, the DPS and the JS, two of the most essential systems, are examined. Finally, ongoing challenges and open research issues are presented to provide the readers in both modeling and control sectors with promising suggestion solutions applied to JuR in the future.

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