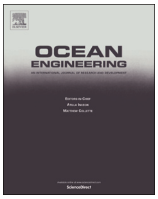
Ocean Engineering 109 (2015) 454–478

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng



Dynamics and control of underwater tension leg platform for diving and leveling

Yingkai Xia[a], Guohua Xu[a,1], Kan Xu[b], Ying Chen[a], Xianbo Xiang[a], Zengsheng Ji[a]

[a] *School of Naval Architecture and Ocean Engineering, Huazhong University of Science and Technology, Wuhan 430074, China*
[b] *Wuhan Second Ship Design and Research Institute, Wuhan 430064, China*

ARTICLE INFO

Article history:
Received 17 December 2014
Accepted 18 September 2015

Keywords:
Underwater tension leg platform
Diving and leveling
Joint space
Backstepping sliding mode control
Field trials

ABSTRACT

This paper focuses on high-precision diving and leveling control of an underwater tension leg platform, which uses hydraulic winches as the actuation mechanism. First, dynamic model is established based on joint space. Then, decoupled double closed-loop control strategies for diving and leveling are proposed and internal closed-loop controllers are designed and tested based on backstepping sliding mode control (BSMC) method. Finally, winch tests and field trials are carried out to verify the efficacy of our approach. Simulation and experimental results show that the controllers designed in this paper can achieve speed control and displacement control with high precision and strong adaptability, thus leading to successful diving and leveling control of the underwater tension leg platform.

1. Introduction

With the depletion of land resources, ocean exploration has been steadily growing as a major topic over the last two decades. However, it still faces great challenges because of complex underwater environment and the lack of necessary observation and communication means. Fortunately, the costs and risks associated with various underwater tasks can be greatly reduced by underwater equipment (You et al., 2012), which has led to an increase in the demand for underwater capabilities to perform high-precision tasks.

Recently, tension leg platforms have found wide-spread utilization in ocean exploration. The unique structure of tension leg platform makes it superior to similar products. For example, it is better than semi-submersible platform in anti-jamming ability, also more convenient and economical when compared with fixed platform.

1.1. Applications and problem description

Lately, as the oil industry moves toward deeper offshore areas, considerable interests have been developed in the use of compliant structures, especially tension leg platforms (Kim et al., 2007), which are generally constituted of a semi-submerged structure and pre-tensioned tethers anchored to the ocean bed (Lee et al., 1999). Muren et al. (1996) developed a three column TLP for 800 m water depth, which can easily be extended to 1500 m under shorter development schedule with significant reduction in cost. Teigen and Niedzwecki (1998) conducted numerical and experimental studies on a four column mini TLP with 10320 t displacement (Bhattacharyya et al., 2003). Snorre A and Heidrun were successfully used in 350 m water depth in the North Sea (Randolph et al., 2011). Since the broad application prospect of underwater tension leg platform was found out, different derivatives of TLP have been developed. Among them is a mini TLP called “SeaStar”, which was proposed by Kibbee et al. (1994). It consists of a sea surface piercing cylinder supporting the deck and accessories with the excess buoyancy offered by three fully submerged cylindrical hulls well below the surface. Vertical tension legs are attached to these buoyancy chambers. It has a low water plane area and hence less environmental loads and good response characteristics. Although tension leg platform has been one of the proven technologies (Yang and Kim, 2010), there are still many drawbacks to be overcome.

In this paper, a flexible-drive underwater tension leg platform is proposed for scientific research. Compared with general tension leg platforms, the platform we proposed is very unique because of its flexible drive branches, which makes its control more difficult. Four tension winches and four mooring winches are installed on the corners acting as its actuation mechanism. The tension winches are connected to the anchors through vertical cables, while mooring winches are connected to the anchors through oblique cables. Anchors, winches and cables all together form the flexible

---

E-mail address: hustxu105@126.com (G. Xu).
[1] Tel.: +86 27 87540234; fax: +86 27 87540234.

http://dx.doi.org/10.1016/j.oceaneng.2015.09.038
0029-8018/

tension legs of the platform. Eight ballast tanks are laid within the platform to adjust buoyancy. Two capsules are distributed on both sides of the platform, in which the controlling devices are installed.

Owing to special requirements of scientific research, the platform is ordered to implement high-precision diving within specified time at first, then, the attitude of platform should be leveled. Considering large inertia, parallel structure and flexible driving condition, the control objectives are rather difficult. To illustrate how the work is done, the dynamic modeling and controller design of the tension leg platform for diving and leveling are presented in this paper, as well as the simulation and experimental results.

1.2. Proposed approach and related works

Since the platform is essentially a big flexible underwater parallel robot, a lot of related works can be used for reference. However, considering the unique structure and controlling targets of this platform, the dynamic modeling and controller designing are quite difficult, and the main approaches used in this paper will be explained in the following three aspects.

1.2.1. Modelling

Conventional modeling methods used in underwater robots include: Lagrangian (Abdellatif and Heimann, 2009), Newton–Euler (Mukherjee et al., 2007), Kane (Yun and Li, 2008) and Principle of virtual work (Zhang and Song, 2007). Fichter (1986) derived dynamic equation of Stewart platform according to the force and moment equilibrium equation of moving platform. Dasugpta and Mruthyunjaya (1998) used Newton–Euler method to establish the dynamic equations of 6-DOF parallel robot, with frictions of the agency joints considered. Geike and Mcphee (2003) analyzed the automatic modeling dynamics of full mobility parallel mechanism using principle of virtual work and symbols law. Codourey (1998) established the dynamic model of parallel mechanism based on Lagrange equation and the principle of virtual work. Liu et al. (1991) built the dynamic model of parallel robot based on Lagrange equation under the generalized coordinates of position and attitude, then obtained the driving force in joint space using Jacobian matrix. Piras et al. (2005) studied the dynamics of a 3-PRR planar parallel robot with flexible rods based on Finite Element Theory and KED analysis method, with axial elasticity of flexible rods considered.

The tension leg platform discussed in this paper is a complex underwater system with multivariable. Compared with serial mechanism, it has better performance in stability, carrying capacity, and controlling precision. However, due to the complex work space and parallel structure, detailed analysis and complete dynamic modeling of this platform is fairly difficult. In order to solve these problems and develop a reasonable dynamic model for subsequent controlling, both the dynamic models of platform and hydraulic system should be concerned. Furthermore, the method “joint space” is adopted to seek for a more concise model, based on which, the controlling of platform can be transferred directly into controlling of specific hydraulic winches. In contrast with general dynamic modeling method, “joint space” is much more conventional, and the control of platform can be decoupled based on that. Hence, the control instructions can be implemented separately for each drive branch, with couplings between branches neglected (Feng and Allen, 2004; Desanj et al., 1997).

Except couplings, the deformations, nonlinearities and uncertainties are also the main problems that need to be considered, which mainly exist in the platform and external environment. Actually, we have to admit that this is the first-stage work of tension leg platform, which mainly aims at achieving the basic diving and leveling control in the lake. Compared with the future application in the sea, the working environment in the lake is much better with few current and waves. Considering along with the rigid structure and reinforcement measures of platform, which are specially designed to keep the platform still underwater, simplified treatments with deformations, nonlinearities and uncertainties are tolerable. Therefore, a series of assumptions are made in Section 2, based on which, deformations, nonlinearities, and uncertainties are ignored.

Specifically, the modeling process of platform is divided into three steps. First, dynamic model of platform is developed based on kinematic analysis and Newton–Euler method; second, working principle of hydraulic drive system is analyzed, based on which the dynamic model is established; finally, “joint space” method is proposed to obtain the decoupled mathematical control model.

1.2.2. Controller design

Researchers have made considerable efforts to solve the control problem of similar products. The most widely used algorithms include: Lyapunov's direct method, backstepping technique, sliding mode control, feedback linearization, robust control, switching control, etc. Li and Salcudean (1997) proposed a link space pressure-feedback controller for an inverted, ceiling-mounted Stewart platform to pursuit high performance with good stability and robustness. Lee et al. (2003) designed a linear $H\infty$ control method based on computed torque to realize the precise control of Stewart platform. An integrated sliding mode control approach is adopted by Jantapremjit and Wilson (2008), Rhif (2011) and Kima and Shin (2007) to conduct a robustness motion control. Ge et al. (2012) provided a decoupled adaptive control method based on the model-predictive and data-driven technique. Li and Lee (2005) designed an adaptive nonlinear controller for depth control of underwater vehicles with fins without restriction on the *pitch* angle of diving. Antonelli et al. (2003) proposed an adaptive control law which takes into account the hydrodynamic parameters affecting the tracking performance.

In order to achieve control objectives of the platform, not only control algorithm for actuation mechanism should be concerned, but also the comprehensive planning for diving and leveling. Since the dynamic model has been established based on joint-space, the controlling of each drive branch can be implemented separately. Therefore, a decoupled double closed-loop control strategy is proposed, of which, the external controllers (include diving controller and leveling controller) are responsible for process planning, while the internal controllers (include speed controller and displacement controller) are designed for actuation mechanisms controlling.

Speaking of the external controllers, their strategies differ a lot since the goals are different. The diving controller is responsible for diving speed setting during the diving process to ensure the platform can dive to specific depth within limited time. To accomplish that, the whole diving process is divided into three stages, besides, in order to alleviate the speed bumps in ascending period and descending period of the ideal speed curve, the membership function of fuzzy logic is employed. While, the leveling controller is designed for the attitude adjustment after the diving process is finished, which concerns more about the precision and efficiency. To obtain the most suitable leveling method, three leveling strategies are proposed, among which, the method “Two-step chasing with lowest point fixed” is chosen at last.

Honestly, the external controllers only solve the problem, on a higher level, of how the work should be done. But, how to implement specifically and whether the targets can be reached still need to count on the internal controllers. To achieve high-precision control of actuation mechanism, a backstepping sliding mode control (BSMC) method is proposed, which combines both