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A survey of dynamic positioning control systems

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ABSTRACT

Offshore exploration and exploitation of hydrocarbons have opened up an era of dynamically positioned (DP) vessels. DP control systems maintain floating structures in fixed position or pre-determined track for marine operation purposes exclusively by means of active thrusters. There are more than 2000 DP vessels of various kind operating worldwide. This paper gives a survey of some of the major technology advances in the DP controller design having taken place during more than 30 years of research and development. In addition some perspectives for the future with corresponding research challenges will be addressed.

1. Introduction

This paper is an updated version of the plenary paper by Sørensen (2010) presented at the IFAC Workshop CAMS 2010. A dynamically positioned (DP) vessel is by the International Maritime Organization (IMO) and the certifying class societies (DNV, ABS, LR, etc.) defined as a vessel that maintains its position and heading (fixed location or pre-determined track) exclusively by means of active thrusters. The real-time control hierarchy of a marine control system (Sørensen, 2005) may be divided into three levels: the *guidance system*, the *high-level plant control* (e.g. DP controller including thrust allocation), and the *low-level thruster control*. Description of DP systems including the early history can be found in Fay (1989). In the 1960s the first DP system was introduced for horizontal modes of motion (surge, sway and yaw) using single-input single-output PID control algorithms in combination with low-pass and/or notch filter. In the 1970s more advanced output control methods based on multivariable optimal control and Kalman filter theory were proposed by Balchen, Jenssen, and Saelid (1976). This work was later improved and extended by Balchen, Jenssen, Mathisen, and Sælid (1980), Jenssen (1981), Sørheim (1982), Saelid, Jenssen, and Balchen (1983), Fung and Grimble (1983), Grimble and Johnson (1988), Fossen (1994), Sørensen, Sagatun, and Fossen (1996), Fossen, Sagatun, and Sørensen (1996), Katebi, Grimble, and Zhang (1997, 1997), Mandzuka and Vukic (1995), Kijima, Murata, and Furukawa (1998), Tannuri and Donha (2000), Volovodov, Chernjaev, Kaverinsky, Volovodov, and Lampe (2004) and Perez and Donaire (2009). The introduction of observers with wave filtering techniques based on Kalman filter theory (Fossen & Perez, 2009) by Balchen, Jenssen and Sælid is regarded as a breakthrough in marine control systems in general, and has indeed been an inspiration for many other marine control applications as well.

In the 1990s nonlinear DP controller designs were proposed by several research groups. Stephens, Burnham, and Reeve (1995) proposed fuzzy controllers. Aarset, Strand, and Fossen (1998), Strand and Fossen (1998), Fossen and Grøvlen (1998), and Bertin, Bittanti, Meroni, and Savaresi (2000) proposed nonlinear feedback linearization and backstepping for DP. In the work of Fossen and Strand (1999), Strand and Fossen (1999) and Strand (1999) the important contribution of passive nonlinear observer with adaptive wave filtering is presented. One of the motivations using nonlinear passivity theory was to reduce the complexity in the control software getting rid of cumbersome linearizations and the corresponding logics. Pettersen and Fossen (2000), Pettersen, Mazenc, and Nijmeijer (2004) and Bertin et al. (2000) addressed DP control of under-actuated vessels. Agostinho, Tannuri, and Morishita (2009) and Tannuri, Agostinho, Morishita, and Moratelli (2010) proposed to use nonlinear sliding mode control for DP. Volovodov, Smolnikov, Volovodov, and Lampe (2007) proposed a controller for 3 dimensional DP operations of sea mobile objects (underwater vehicles) using a Lyapunov approach. DP of underwater vehicles like remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) has lately received increasing interest from offshore contractors, vendors and the research community.

As the DP technology became more mature research efforts were put into the integration of vessel control systems and the refinement of performance for the various vessel types and missions by including operational requirements into the design of both the guidance systems and the controllers. Sørensen and Strand (2000) proposed a DP control law for small-waterplane-area marine vessels like semisubmersibles with the inclusion of roll and pitch damping. Sørensen, Leira, Strand, and Larsen (2001) recommended

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the concept of optimal setpoint chasing for deep-water drilling and intervention vessels. Leira, Sorensen, Berntsen, and Aamo (2006) extended this work and proposed to use structural reliability criteria of the drilling risers for the setpoint chasing. Jensen (2010) showed how proper modeling of pipe dynamics can be included in the DP guidance system. Fossen and Strand (2001) presented the nonlinear passive weather optimal positioning control system for ships and rigs increasing the operational window and reducing the fuel consumption.

Most of the current DP systems have been designed to operate up to a certain limit of weather condition limited by the thrust and power capacity. Due to the accuracy and availability of the inertia measurement units (IMU), Lindegaard (2003) proposed acceleration feedback (AFB) to increase the performance of DP systems in severe seas. AFB denotes here output acceleration feedback in addition to output PID controller. Sørensen, Strand, and Nyberg (2002) and Sørensen (2005) proposed passive nonlinear observer without wave-frequency (WF) filtering for output PID-controller in extreme seas, especially where swell becomes dominant.

Use of hybrid control theory as proposed by Hespanha (2001), Hespanha and Morse (2002), and Hespanha, Liberzon, and Morse (2003) and fault-tolerant control by Blanke, Kinnaert, Lunze, and Staroswiecki (2003) enabled the design of proper control architecture and formalism for the integration of multi-functional controllers combining discrete events and continuous control. Sørensen, Quek, and Nguyen (2005), Nguyen (2006), Nguyen, Sorensen, and Quek (2007, 2008) and Nguyen and Sørensen (2009b) proposed the design of supervisory-switched controllers for DP from calm to extreme sea conditions and from transit to station keeping operations. The main objective of the supervisory-switched control is to integrate an appropriate bank of controllers and models at the plant control level into a hybrid DP system being able to operate in varying environmental and operational conditions. Implementing the hybrid control concept will increase the so-called weather window making it possible to conduct all-year marine operations, such as subsea installation and intervention, drilling, and pipe laying in harsh environment. Concerning large changes in environmental conditions, in particular, when conducting marine operations in deep-water, the feature of hybrid control is important as the operations are more time consuming, and hence more sensitive to changes in sea states. Lately, with increasing interest for hydrocarbons in the arctic DP operations in various ice conditions like level ice, managed ice and ice ridges have been studied. In Nguyen, Sørbø, and Sørensen (2009) DP in level ice is presented. For DP vessels operating partly in ice and open water, see Fig. 1, switching between controllers and control settings on both the plant-level and low-level will be necessary.

Fig. 1. DP operations in arctic hydrocarbon exploration.

The number of the safety critical and demanding DP operations is increasing. As a consequence of this the system integrity and requirements to further physical and functional integration between the DP system, marine automation system, thruster and propulsion system and power plant will follow accordingly. It is believed that more research efforts will be directed into diagnostics and fault-tolerant control, see Blanke et al. (2003), Nguyen, Blanke, and Sørensen (2007), and Fang and Blanke (2009). As a part of this proper testing and verification of the DP system software are crucial for the safety and profitability (Johansen, Fossen, & Vik, 2005, 2007; Johansen & Sørensen, 2009; Smogeli, 2010).

The importance of the DP control system for the closed-loop performance of the station keeping operation is clearly demonstrated in several studies. Morishita and Cornet (1998), Morishita, Tannuri, and Bravin (2004), Tannuri and Morishita (2006), and Tannuri, Saad, and Morishita (2009) have conducted detailed performance studies of the DP operations for shuttle tanker and Floating Production Storage and Offloading (FPSO) units.

This paper will give a survey of some of the major technology advances of the DP control system having taken place during more than 30 years of research and development. Important areas of guidance and navigation are not covered in this paper. For further references on these topics the reader is referred to Fossen (2011), Skjetne (2005), Ihle (2006) and Breivik (2010).

Detailed information with complementary references to the literature for the major contributions in the field of DP of marine vessels can be obtained from Fossen (2000), Fossen (2002), Fossen (2011) and Sørensen (2011).

The paper is organized as follows. Section 2 contains an introduction to DP systems. In Section 3 mathematical modeling of DP vessels is presented. Sections 4 and 5 present DP observers and controllers, respectively. In Section 6 a brief overview of thrust allocation is presented. Section 7 is about low-level thruster control. Section 8 is about hybrid DP control with experimental results. In Section 9 failure and functional testing in the sense of hardware-in-the-loop (HIL) testing are shown. Finally, conclusions are made in Section 10.

2. Introduction to dynamic positioning

While in DP operated ships the thrusters are the sole source of station keeping, the assistance of thrusters are only complementary to the mooring system in the case of thruster assisted position mooring (PM) systems. Here, most of the station keeping is provided by a deployed anchor system. In severe environmental conditions the thrust assistance is used to minimize the vessel excursions and line tension by mainly increasing the damping in terms of velocity feedback control. Thruster assisted position mooring (PM) systems have been commercially available since the 1980s and provide a flexible solution for floating structures for drilling and oil&gas exploitation on the smaller and marginal fields. Modeling and control of turret-moored ships are treated in Strand, Sørensen, and Fossen (1998), Strand (1999), Sørensen, Strand, and Fossen (1999), Berntsen, Aamo, Leira, and Sørensen (2008), Berntsen (2008) and Nguyen and Sørensen (2009a, 2009b). For turret anchored ships without natural weather-vaning properties the thrusters are also used to automatic control of the heading, similarly to DP operated vessels.

DP systems have traditionally been a low-speed application, where the basic DP functionality is either to keep a fixed position and heading or to move slowly from one location to another. In addition specialized tracking functions for cable and pipe-layers, and remote operated vehicle (ROV) operations have been available. The traditional autopilot functionality has over the years become more sophisticated. Often a course correction function is available