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DYNAMIC POSITIONING SYSTEM – A DEFINITIVE STEP TOWARDS AUTONOMOUS SHIPS

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Abstract

Ask a seafarer and he will tell you how difficult it is to make a ship stand at one spot in the sea. Though difficult, this need of standing at a spot became a requirement when petroleum production went offshore. Initially, it was merely the recovery of retrieved oil from the rigs by the tankers which was managed with difficulty using anchors. Later, when the oil rigs moved to deeper waters, use of anchors became impossible and the dynamic positioning system was developed that provided vessels the necessary corrective control to withstand the forces of wind, current, and wave, thereby providing a fixed position and heading. Since then, this technology has been used by a variety of platforms such as oil rigs, scientific research vessels, cruise vessels, cable laying ships, oil tankers, and offshore wind farms.

With the refinement of the control systems, a capability to provide greater reliability and functional autonomy in unknown environments has been achieved that has ensured human and environmental safety, paving the way for autonomy in ships. Discussing the developments made for the dynamic positioning system over the years, the paper traces the developments that are helping in the conceptualisation of autonomous ships.

Keywords: Dynamic Positioning System (DPS); Autonomous ships; Kalman controller; PID;

1. Introduction

With an ever growing population and diminishing resources on land, mankind has been forced to move into the sea to meet his requirements of food and energy. This ‘forced’ movement made mankind to realise the inadequacy of his knowledge about the oceans thus necessitating the need for developing technologies for responsible extraction and use of the ocean resources. This thought spurred by the discovery of offshore oil, began the journey of technological development for exploration and exploitation of the ocean resources. One such technological development is the design of the dynamic positioning (DP) system which was motivated by the need of keeping a ship stationary at a place in extreme seas of the North Sea to facilitate safe transfer of recovered oil from the oilrigs to oil tankers. Such a development required automatic sensing and associated controls working in tandem to keep the ship stationary even when the sea was rough.

As a unit, a DP system consists of sensors, controls, a thruster, and a power system. The sensors sense the forces of wind, current, and wave against a position reference which is used as information for the controls that calculates the correction required to the position and heading of the ship. This desired correction, as a signal to the power system of the ship, eventually steers the required actuators (thrusters, propellers, rudders, or fins) to achieve the visible ‘stationary’ position.

With the DP system being a mix of systems and controls, its development evolved with the availability of technology. It is because of this that though the development of controls actually happened more than 100 years ago when the gyroscope-aided autopilot was invented in 1911, followed by the invention of the proportional-integral-derivative (PID) controller in 1922 the DP system could not be used commercially till the 1960s as computers that were essential for making the system to work, was not available till then.

Though the first DP system used only thrusters, control engineers have been developing larger and more complex systems to achieve higher levels of autonomy. Today, control systems are capable of providing reliability and functional autonomy in unknown environments thereby ensuring human and environmental safety. The time is not far when the technology behind DPS could be used for fully autonomous ships.

It is with this thought that the paper traces the development of the DP system over the years and the definitive steps of development it is taking to become a building block in the making of autonomous ships.

2. Development over the years

A DP system includes operator stations, positioning monitoring systems [that include sensors (to provide position reference[1] and the forces acting on the ship that eventually influence its direction), its own internal model of the ship[2], and one or more gyrocompasses (that provides the heading information)], controllers[3], and thrusters. Since the system has the capability to take over the entire responsibility of the crew on the bridge it is considered for automation of navigation and hence a possible replacement of humans in autonomous ships. In the context of the present paper, the *development of the controllers* for dynamic positioning and *efforts towards automation* over the years will be discussed individually to better appreciate as to how this technology is taking definitive steps towards the making of autonomous ships.

2.1 *Development in controllers*

In the late 1960's and the early 1970's the demand for petroleum-related products increased rapidly leading to the petroleum industry to go offshore. This led to new requirements with new operations and hence new types of vessels such as anchor handling-, supply-, seismic- and cable laying -vessels. When drilling commenced offshore, traditional anchors were used to maintain the ship's position in limited water depths while for deep water, vessels manually manipulated the propulsion system. This 'manual' manipulation was vulnerable to human errors, and hence the need for a more reliable method was felt which eventually led to the invention of the DP system.

A real-time control structure of a DP system is divided into levels that include the *guidance system*, the *high-level motion control algorithm*, the *thrust allocation (TA) algorithm* and the *low-level thruster controller*.

Guidance system

A guidance system is responsible to 'sense' the forces that are trying to move the ship from its designated position while filtering out the noise and disturbances of the ocean from the actual disturbance. Over the years, two acceptable solutions have been developed as guidance system. The first one depends on model control (that uses filters) while the second one depends on PID regulator (that uses the three controllers proportional, integral, and derivative to provide a single output). While the PID based system corrects the deviation after it has happened, the model system can predict the possible deviation and apply corrections to avoid the deviations.

The PID controller was the first to be developed for 'task specific' ships of the 1960s when 'dynamic positioning' for ships started out as an exotic control technology. These PID controls consisted of separate PID loops and notch filters tuned in a heuristic[4] fashion. Subsequently, using the theory propounded by Kalman (1960) in 1960, Balchen et al. (1976, 1980) and Sælid et al. (1983) in 1976 gave a new and advanced method that used the Kalman filters[5] (to provide the optimum noise filtering of heading and position measurements) along with the Linear Quadratic Gaussian (LQG) optimal controllers (to provide the minimal deviation required to bring the ship to the original position thus consuming minimum power). Both the Kalman filters and the LQG controllers required multiple computations to be effective. Though developed in 1976 and more sophisticated than the PID controller, lack of computers (Teknikum29, 2017) that were small in size and could be used on ships did not permit the use of model control till the 1990s.

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[1] The most commonly used position reference for DPS is DGPS (Differential Global Position System) which provides greater accuracy than a GPS. Other position reference systems used in dynamic positioning include Hydroacoustic Position Reference, Global Navigation Satellite System (GNSS), Inertial Navigation System (INS), Taut Wire, Laser-based systems and Artemis. For DP of Class 2 or Class 3, it is necessary to use three different position monitoring systems as with two systems if one malfunctions, the error would go un-noticed, while if three are used the possibility of noticing the malfunction would be higher.

[2] The ship model is a set of equations of motion, based on the horizontal motion of the ship, that is used to predict the ship's motion when know hydrodynamic forces and moment are applied. The hydrodynamic and derivative coefficients in the equations of motion are obtained by undertaking tests in towing tanks, rotating arm tanks and Planar Motion Mechanism (PMM) as they cannot be calculated analytically. However, since the model so developed is an approximation, to achieve good performance of the DPS this model needs to be as detailed as practically possible.

[3] Controllers allow a ship to maintain a specified position and compass heading unaffected by the disturbances. They use algorithms such as multivariable PID algorithms, the H∞ design approach, and various non-linear techniques.

[4] Hands-on approach

[5] Motion of high frequency and relatively low amplitude which are a result of the first order wave loads do not need to be compensated by the DP systems. Such wave frequency components are removed from the position and heading measurements and estimated velocities, by the use of Kalman filters. If the DP system tries to compensate these wave-frequency motions it results in high power compensation and potential wear of actuators.

With the availability of digital computers in the 1990s[6], there was a renewed interest to develop control strategies for DP ships. New designs such as those based on *H∞-control*[7] (Katebi et al. 1997; Donha et al. 2001), controller *minimising self-induced rolling and pitching* (Sørensen, 1996, 2000), control strategies based on *non-linear methods*[8] (Fossen, 1996, 1999, 2001), *nonlinear feedback linearization* and *backstepping* (Aarset et al. 1998, Strand and Fossen 1998, Fossen and Grøvlen 1998, and Bertin et al. 2000), and *nonlinear sliding mode control* (Agostinho et al. 2009 and Tannuri et al. 2010) were developed. A timeline indicating these developments is given in Figure 1.

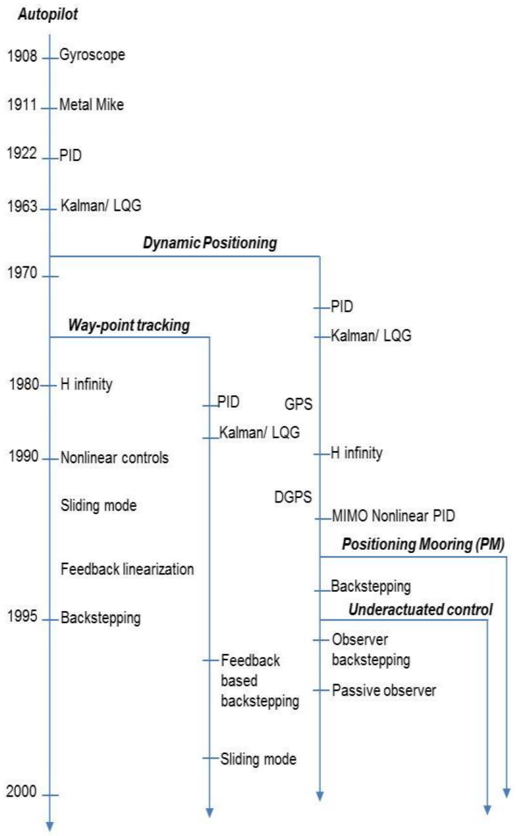

Figure 1: Time line of development of guidance system (Fossen, 1999)

[6] Timeline of Computers, Available at http://www.computerhistory.org/timeline/1990/ (accessed 28 August 2018)

[7] With the main objective of providing a design that is more robust than that can be obtained with LQG/ Kalman filtering methods or other techniques

[8] One of the motivations using nonlinear passivity theory was to reduce the complexity in the control software getting rid of cumbersome linearization and the corresponding logics.

The modern day's controller has the capability to select wind feed-forward (to improve performance), gain adjustment (for higher precision by manipulating how hard the controller must try and maintain position and heading) and operational mode through the use of computers (which may be manual, semi-auto and automatic). Today, even though the model controls are available, PID regulators continue to be used for cheaper DP systems as they are easy to tune and commission the controllers. In most systems, single-input-single-output (SISO) PIDs is used. However, a true multivariable PID methodology is preferable as a ship exhibits significant interactions between the various loops. A comparison of the existing multivariable PID methods and their assessment in regard to DP control problems is discussed in greater detail by Martin and Katebi (2005).

Though the DP system was originally conceived to assist the vessel in maintaining its heading and position, the technology so developed has been found to be useful to manoeuvre the vessel precisely over short or long distances. From the simple technology of the 1960s, this technology has developed to today's advanced system which covers multiple redundancies such as:

(a) **Class 0:** Manual position control and automatic heading control

(b) **Class 1:** Both position and heading control are automatic and manual with no redundancy and where loss of position can occur in the event of a single fault.

(c) **Class 2:** Both position and heading control are automatic and manual, but a loss of position due to a single fault of an active component or system such as generators, thrusters, switchboards, remote control valves etc. is not permitted. However, loss of position can occur after failure of static components such as cables, pipes, manual valves etc.

(d) **Class 3:** Both position and heading control are automatic and manual, and loss of position to occur from any single failure including a complete burn, fire, subdivision or flooding is not permitted. The components have redundancy and are separated from each other.

High-level motion control

Based on the signals inferred by the guidance system, a *high-level motion control algorithm*, also called the DP control algorithm, determines the total force and moment required to bring the ship back to its desired position and heading. This generalized force is used as input by the *thrust allocation (TA) algorithm* to determine the force to be produced by individual thrusters. The output from the TA algorithm is sent to the *low-level motion controller* (the local thruster controller) which eventually provides the actual motion and hence the correction. For the high-level motion controller, it is possible to use three independent PID controllers while assigning one for each degree of freedom.

2.2 *Development in automation*

Development in the field of guidance, navigation and control through advancements in the field of satellite navigation, sensors, communication, and computers has permitted automation on ships in areas such as auto-piloting, collision avoidance, docking, station-keeping through dynamic positioning, roll stabilization, and remote control of the platform. This development has been a result of a focused approach of marines through ages in an effort to detect the exact orientation and position of ships in open seas using instruments. The first baby step towards automation was taken by Bohnenberger in 1810 who developed the gyroscope, with the electric version being given by Hopkins in 1890 which subsequently became the heart of the to-be-developed gyrocompass. Though the magnetic compass was considered accurate, it was erratic and unreliable for metal hulls. To resolve this problem, many non-magnetic solutions were proposed but the most successful of them was the *Gyrocompass*, the development of which began in the mid to late 1800s with Jean-Bernaurd-Leon Foucault, a French inventor, developing the first model in 1852. Other attempts included several failed attempts by William Thomson in 1880 and an effort by Arthur Kreb that had actually helped a French submarine to travel in a straight line in the 1880s akin to an autopilot. The first non-practical form of the gyrocompass was patented in 1885 by Marinus Gerardus van den Bos of Netherland followed by the first usable gyrocompass, using the already developed gyroscope, by Hermann Anschutz-Kaempfe of Germany in 1906 who is credited to have patented the first North seeking gyrocompass. It was not until 1908 that this compass was mass produced by the Germans for their Navy. At nearly the same time Elmer Ambrose Sperry of the USA patented his design for 'ballistic[9] compass' including vertical damping in 1908 and gave the US Navy its gyrocompass for the World War I.

Elmer Sperry went ahead to extend his work to automation of the ship's steering and developed 'Metal Mike', a closed-loop ship control system (Allensworth, 2000 and Bennet, 1979) in 1911. This device captured the behaviour of a helmsman and compensated for varying sea states using feedback control and automatic gain adjustments. Later in 1922, Nicholas Minorsky (Minorsky, 1922) gave the first position feedback control system using a three-term control law known today as the Proportional-Integral-Derivative (PID) control which too was motivated by the helmsman and was the first 'auto-pilot' the shipping industry saw.

These auto-pilots were single-input-single-output (SISO) control systems where the heading (yaw angle) of the ship was measured by a gyrocompass and corrected if required. With the development of digital computers that were small in size and could be installed on ships, increased functionality could be added resulting into multiple-inputs multiple-outputs (MIMO) control systems and many sophisticated features such as wave filtering, environmental conditions, wind and reference feed were possible. This allowed a three-phase manoeuvre that included acceleration, turning at a constant yaw rate and de-acceleration to zero yaw rate. Such auto-pilots work on a three-level hierarchical system of *way-point tracking* which include weather routing including way-points generated from wind, wave, current and collision data, reference trajectories and tracking control and navigation systems, with the differential GPS (DGPS) in combination with roll and pitch angle measurement being used for navigation since the 1970s.

In 1998, ABB with an interest in fuel saving during station-keeping gave a new concept called the weather optimal positioning control (WOPC) system. This system uses virtual circle control which maintains the ship at a constant position while rotating the heading of the ship until the environmental loads on the ship in the sway direction and the yaw moment become zero and the surge forces are head-on.

Wärtsilä in 2017 reported[10] an advancement in the existing technology with their 'SmartPredict' which can display the expected position of a vessel multiple seconds in the future to avoid incidents and collisions, thus leading to greater levels of automation. Another product of a similar nature but of GE and targeted at smaller vessels is SeaLyte[11]

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[9] These compass use 'liquid ballast' to give a form of gravity since simple methods of control are not practical in commercial compasses due to problems encountered due to the ship's movement. The ballast liquid flows between north and south ends of the rotor under the influence of gravity when the gyro has an angle of tilt.

[10] Paul Fanning, 10 June 2017, Wärtsilä launches SmartPredict to provide safer ship manoeuvring guidance, Available at https://www.mpropulsion.com/news/view,wrtsil-launches-smartpredict-to-provide-safer-ship-manoeuvring-guidance_48036.htm (accessed 27 August 2018)

[11] Structured, Compact and Cost-Effective, GE Introduces Its New SeaLyte* Vessel Control and Dynamic Positioning Systems, 7 February 2017, Available at https://www.gemarinesolutions.com/content/structured-compact-and-cost-effective-ge-introduces-its-new-

which consists of *SeaLyte Vessel Control System (VCS)* [integrates functions such as machinery alarm and monitoring, machinery and auxiliary systems control, optional power management and cargo handling] and *SeaLyte DP* [that provides a manual and automatic position control, heading control, joystick maneuvering and a user-friendly interface to the ship's systems and reference equipment]. Reduced hardware embedded in the system brings reduced complexity, leading to a lower equipment cost. Other companies such as Bourbon Corporation through Kongsberg Maritime along with Bureau Veritas[12] are focusing on real-time advisory tools and streamlined operations onboard to reduce manning, increase safety, and to reduce fuel and maintenance costs.

3. The Ayes and the Nays

As seen in the preceding discussions, the focused and continuous development in technology especially navigation has helped the development of the DP system. Though this system has come to become a state of the art equipment, it is evolving continuously with advancements being made to make the technology 'autonomous' with a minimal human interface. This effort is allowing the realisation of the dream of an autonomous ship. Though the actual autonomous ship may be some years away, there are some positives that give confidence for its usage while there are other negatives which need focused development before the technology can eventually be used for autonomous ships. These ayes and nays will be discussed in the subsequent paragraphs.

3.1 *Reasons for confidence*: With reducing maritime skills, shipping companies are looking at investing in automation for more efficient operations and a smaller crew. This thought has been supported by the increasing sophistication in alarm and monitoring systems, navigation systems and propulsion control through dynamic positioning along with increasing competition between electronic companies allowing a reduction in cost. This has allowed shipowners to integrate their entire ship systems and operations to be able to monitor and control ships remotely from a single console either on the ship or from afar. Today, the propulsion and auxiliary plants can be run with increased safety from the bridge indicating the required confidence towards automation.

With dynamic positioning, the position and heading of the vessel can be maintained using computers with minimal human interference, which in effect is the start point for automation. The first such effort on a ship using an analogue control system, interfaced with a taut wire reference, and thrusters in addition to her main propulsion was the "Eureka" in 1961. As confidence grew, the DP capable ships grew to 65 in 1980 which subsequently increased to 150 by 1985 and currently stands at over 1,000 and is increasing constantly. Earlier the DP system was considered a luxury but with their proven track record of providing navigational superiority in harsh environmental conditions, they have become a necessity. Today, customised automation concepts allow control of propulsion and DP systems, power management, machinery automation and HVAC automation systems from the bridge.

3.2 *Reasons for concern*: Irrespective of the level of automation achieved, malfunctions cannot be resolved automatically and needs human interference. In order to avoid human involvement completely, failures resolving techniques such as predictive analytical techniques (that would collect operational data and recognise failure before they occur), Internet of Things (IoT) and personal assistants (such as Google assist and Siri) are being proposed for use, the technology for which is still in the development/ trial stages.

The associated cost of building such technologically advanced ships is nearly three times as much as a conventional ship of a similar size thereby making them more expensive to insure (the Yara Birkeland, the first crewless ship, will cost approximately $25 million[13]).

Further, lack of regulatory and legal developments are not supporting the cause of making unmanned ships a reality. Of concern are the legal issues related to safe manning requirements and product liability rules that will in return affect the maritime liability and insurance rules. It is believed that the required extent of regulatory change will depend on the level of autonomy. Accordingly, Lloyd's Register has published classification guidance for six autonomy levels.[14] The first three levels provide designers, builders and operators to define the desired level of autonomy while the other

sealyte-vessel-control-and (Accessed 27 August 2017)

[12] @2018 with courtesy of Bourbon, 08 February 2018, Available at https://www.bureauveritas.com/home/worldwide-locations/norway/news/2018+with+courtesy+of+bourbon (accessed 27 August 2018)

[13] The first crewless ship expected to start sailing in 2018, initially delivering fertilizer along a 37-mile route in southern Norway. David Z Morris, World's First Autonomous ship to launch in 2018, Fortune, 22 July 2017, Available at http://fortune.com/2017/07/22/first-autonomous-ship-yara-birkeland/ (accessed 27 August 2018)

[14] MFAME, 6 Autonomy Levels for Shipping, 30 Aug 2016, Available at http://mfame.guru/6-autonomy-levels-shipping/

three levels involve unmanned vessels with varying levels of remote operation including complete autonomy. The remote operation includes shore-based operators who can intervene, if required, to avoid navigational disasters. Since vessels operate under national and international regulations, before such ships operate, policy for both regimes is essential. While the national regulation may get developed, with the political will of a nation, the international regulations by IMO would require multilateral agreements between various countries which may take up to ten years for finalisation.[15]

4. Conclusion

The paper traces the need and the development of the dynamic positioning system over the years and the current advancements that are indicative of the fact that they are definitive steps of development towards the use of DP systems as building blocks for autonomous ships. The limitations in knowledge and technology along with policy voids that plague all out usage and development of such ships have also been discussed.

The dynamic positioning systems have improved significantly over the years, but need to be developed further to ensure safe operation in deep water applications. With both the airplanes and railways having become driverless, the focus is now moving to marine platforms. Though limited success has been achieved in the form of Unmanned Surface Vessels (USV) that for larger ships is a work in progress wherein the dynamic positioning system is playing an important role and possibly 'definitive' step towards automation in ships. One thing, however, remains certain is that 'autonomous ships' are no more a dream but a distinct reality which will be realised in the years to come.

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