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CAUSES OF DYNAMIC POSITIONING SYSTEM FAILURES AND THEIR EFFECT ON DP VESSEL STATION KEEPING

Master thesis

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PREFACE

This master thesis has been written during the winter and spring 2017/2018 as a graduation project in Estonian Maritime Academy. The aim of this thesis was to highlight the most common causes of DP system failures and their effect on DP vessel position keeping. This thesis is first of this kind in Estonia and will hopefully act as a starting point for further researches in a field of vessel Dynamic Positioning.

Conducting the research and writing this thesis has given me the opportunity to gain theoretical knowledge and collect experience without experiencing the incidents themselves. I will be happy if this thesis and the information it contains will reach the reader and raise the awareness of possible incidents as well as their effects on station keeping.

While working on this thesis, I experienced a tremendous feeling of dedication, which sometimes affected my overall performance as a colleague, husband, father, and friend. I promise that I will make it up. I am also grateful to my colleagues and my supervisor for their valuable advises, suggestions, and explanations.

I also would like to thank IMCA for providing me with incident data required for this thesis.

ANNOTATION

A widely used way to identify the effects of dynamically positioning system failures on a vessel station keeping is to conduct 'Failure Modes & Effects Analyses' (FMEA) trials. Despite the fact that such trials are carried out periodically, loss of position incidents still occur. Loss of position incident reports, collected and published by International Marine Contractors Association (IMCA), contain useful information about the causes of incidents and details on the sequence of events which lead to the incident. Initial sorting of the reports revealed that over 72% of loss of position incidents in a period 2007-2015 were caused by failures within the propulsion, position reference, computer, or power systems. By conducting inductive content analysis of the related incident reports, the main causes of such failures were identified and an associative relationship between the main causes and the type of incidents was established. As a result, the conceptual models of loss of position incidents were built. Conceptual models provide an overview of main causes and their effects on station keeping in accordance with the frequencies of their occurrence.

Key words:

Dynamic positioning, loss of position, incident analysis, incident frequencies, conceptual model, trends, dynamic positioning system failure.

Table of contents

PREFACE 3

ANNOTATION 4

Table of contents 5

List of figures 8

List of tables 10

Introduction 11

1 Dynamic positioning system 14

  1.1 Introduction and history 14

  1.2 DP system classification 16

  1.3 DP system principles 17

    1.3.1 Redundancy, reliability, capability 17

    1.3.2 DP system structure 19

    1.3.3 Theory and mathematical model 20

    1.3.4 Operational modes 22

  1.4 Main components of DP system 22

    1.4.1 Computers and control console 22

    1.4.2 Position reference system 23

    1.4.3 Environment reference system 25

    1.4.4 Propulsion system 26

    1.4.5 Power system 27

2 Methodology 29

  2.1 Literature overview 29

  2.2 Selecting data 29

  2.3 IMCA categories 31

  2.4 Research methods 31

  2.5 Credibility and limitations 34

3 Results 35

  3.1 Propulsion failures 35

    3.1.1 Initial sorting 35

    3.1.2 Failure groups and causes 36

    3.1.3 Incident types and frequencies 40

    3.1.4 Potential LOP Incidents 41

3.1.5 Drift off ... 44

3.1.6 Drive off ... 47

3.1.7 Trends ... 49

3.2 Position Reference system failures ... 49

3.2.1 Initial sorting ... 49

3.2.2 Failure groups and causes ... 51

3.2.3 Incident types and frequencies ... 55

3.2.4 Potential LOP incidents ... 56

3.2.5 Drift off ... 58

3.2.6 Drive off ... 61

3.2.7 Trends ... 63

3.3 DP system computer failures ... 64

3.3.1 Initial sorting ... 64

3.3.2 Failure groups and causes ... 66

3.3.3 Incident types and frequencies ... 69

3.3.4 Potential incidents ... 70

3.3.5 Drift off ... 71

3.3.6 Drive off ... 73

3.3.7 Trends ... 75

3.4 Power system failures ... 75

3.4.1 Initial sorting ... 75

3.4.2 Failure groups and causes ... 77

3.4.3 Incident types and frequencies ... 81

3.4.4 Potential incidents ... 82

3.4.5 Drift off ... 85

3.4.6 Trends ... 88

4 Conclusion ... 89

5 Lühikokkuvõte ... 91

6 Bibliography ... 93

Appendices ... 96

Appendix 1 DP system operational modes (Guide to Dynamic Positioning of Vessels“, Alstom 2000) ... 96

Appendix 2 Characteristics of different reference systems. (Guide to Dynamic Positioning of Vessels“, Alstom 2000) ... 97

Appendix 3 Example of incident report published by IMCA (IMCA) 98
Appendix 4 Sorting file in Microsoft Office Excel (by author) 99
Appendix 5 Incidents caused by “Propulsion system” failure (by author)............... 100
Appendix 6 Incidents caused by “Reference system” failure (by author)................ 101
Appendix 7 Incidents caused by “Computer system” failure (by author)................ 102
Appendix 8 Incidents caused by “Power system” failures (by author).................... 103

List of figures

Figure 1.1 First ships using dynamic positioning (Shatto, 2011) 15

Figure 1.2 Example of vessel redundancy concept (Global Maritime, 2018) 18

Figure 1.3 Schematic diagram of DP system *(Chas and Ferreiro, 2008).* 19

Figure 1.4 Forces acting on dynamically positioned vessel. (Kongsberg Maritime) 20

Figure 1.5 Kalman filter application (Holvik, 1998) 21

Figure 1.6 Different types of position reference systems *(Chas & Ferreiro, 2008)* 24

Figure 1.7 Simplified single line diagram of the DP vessel power system (Sørfonn, 2007) 28

Figure 3.1.1 Failure groups of "Propulsion system" *(by* author*)* 38

Figure 3.1.2 LOP Incident frequencies caused by propulsion system failure (*by author*) 40

Figure 3.1.3 Propulsion failures leading to potential LOP incidents *(by author)* 41

Figure 3.1.4 Propulsion failures leading to "drift off" incidents (*by author*) 44

Figure 3.1.5 Conceptual model of "drift off" incident caused by propulsion failure (*by author*) 46

Figure 3.1.6 Propulsion failures leading to „drive off "incident (*by author*) 47

Figure 3.1.7 Conceptual model of "drive off" incident caused by propulsion failure (by author) 48

Figure 3.1.8 Trends of LOP incidents caused by propulsion system failure *(by author)*49

Figure 3.2.1 Failure rate of position reference systems (*by author*) 52

Figure 3.2.2 Failure groups of "Position reference system" *(by author)* 54

Figure 3.2.3 Incidents caused by "reference system" failure (*by author*) 55

Figure 3.2.4 Position reference system failures leading to potential LOP incidents (*by author*) 56

Figure 3.2.5 Failures of different position reference systems leading to potential LOP incident (*by author*) 56

Figure 3.2.6 Position reference systems causing "drift off" incidents (*by author*) 58

Figure 3.2.7 Main causes of failures leading to drift off incidents (*by author*) 59

Figure 3.2.8 Types and number of reference systems online before "Drift off" (*by author*) 59

Figure 3.2.9 Conceptual model of Drift off incident caused by Position reference system failure (by author) 60

Figure 3.2.10 Position reference systems causing “drive off” incidents (*by author*)..... 61
Figure 3.2.11 Main causes of position reference failures leading to “drive off” (*by author*) 61
Figure 3.2.12 Types and number of reference system online before “Drive off” (*by author*) 62
Figure 3.2.13 Conceptual model of “Drive off” incident caused by Position reference system failure (*by author*)........ 63
Figure 3.2.14 Trends of the LOP incidents caused by position reference system failure (by author) 63
Figure 3.3.1 Failure groups of “Computer system” (*by author*) 67
Figure 3.3.2 Failure rate of DP controller and operator workstation (by author)........... 68
Figure 3.3.3 LOP Incident frequencies caused by computer system failure (by author) 69
Figure 3.3.4 Propulsion failures leading to potential LOP incidents (by author)........... 70
Figure 3.3.5 Causes of DP computer failures causing potential LOP incidents (*by author*) 70
Figure 3.3.6 Computer failures leading to “drift off” incidents (*by author*) 72
Figure 3.3.7 Conceptual model of “Drift off” incident caused by computer system failure (by author)........ 73
Figure 3.3.8 Computer failures leading to “drive off” incidents (*by author*)........ 73
Figure 3.3.9 Conceptual model of “Drive off” incident caused by computer system failure (*by author*)........ 74
Figure 3.3.10 Trends of LOP incidents caused by DP computer failure (*by author*)..... 75
Figure 3.4.1 Failure groups of “Power system” (*by author*) 78
Figure 3.4.2 Failure groups of “Power system” (by author) 80
Figure 3.4.3 Mechanical failures vs electrical (*by author*)........ 80
Figure 3.4.4 Incidents caused by Power system failure (*by author*) 81
Figure 3.4.5 Power system failures leading to potential incidents (*by author*)............. 82
Figure 3.4.6 Power system failures causing “drift off” incidents (by author)................ 85
Figure 3.4.7 “Drift off” incidents caused by power system failure (by author)............. 87
Figure 3.4.8 Trends of the LOP incidents caused by power system failures (by author)88

List of tables

Table 1. Equivalent classification society DP class notations (by author)..................... 17

Table 2. Main cause of DP incidents IMCA 2007-2015 (by author) 31

Table 3. Workflow of the research (by author) 33

Table 4. Propulsion failure groups and related causes (*by author*) 37

Table 5. Online reference systems based on 99 reports (*by author*) 51

Table 6. Causes of reference system failures (*by author*) 53

Table 7. Causes of "computer" failures (*by author*).. 66

Table 8. Power system common failures causes (by author) 77

Table 9. Power system groups (*by author*).. 79

Introduction

When the oil and gas industry was expanding further offshore, shallow water techniques that were successfully used for years to recover hydrocarbons were becoming less and less attractive. The industry required new methods for positioning vessels and other offshore installations in deeper waters. The development of Dynamic Positioning (further DP) systems made it possible to automatically keep the vessels or the floating offshore structure in a stable position using thrusters and position reference systems. DP is described as an automatic control of vessel's position and heading by coordinated use of thrusters with respect to one or more position references. A DP system is the collection of all the equipment that supports automatic position keeping control. (IMCA M 103 Rev. 3, 2017)

Reliable station keeping is essential to many offshore operations. Working in close proximity to another vessel or structure, supporting diving operations, anchor handling and drilling are just some examples of the tasks which require precise position keeping.

Despite the offshore oil and gas industry being the main user of dynamically positioned vessels, the growing number of different types of ships are now being fitted with DP systems. The 'Wärtsilä Dynamic Positioning unit' reported a successful test of the remote control of ship operations. The test involved driving the vessel through a sequence of manoeuvres using a combination of DP and manual joystick control. The test vessel was in the North Sea while the remote-control navigating was carried out from the 'Wärtsilä' office located in San Diego, California, 8000 km away (Wärtsilä Corporation, 2017). This important step towards developing the remote operated vessels indicates that DP system and associated equipment will have the place in the shipping industry for the years to come.

The success of DP supported operations depends on the reliability of the equipment, training levels and skills of operators, as well as mitigation of associated risks. When performing such operations, there is always a certain risk of incidents due to operational or technical error. Despite the myriad of regulations and rules that have been produced and applied in the recent years by regulatory bodies, loss of position (further LOP) incidents still occur. The consequences of such incidents may be disastrous, including fatalities, or they have an irreversible effect on the environment as well as financial charges to the operator.

It is common knowledge that DP system failure may lead to two types of loss of position: drive off and drift off (Hansen, 2011). The vessel may drift off position due to insufficient thruster capacity or if the DP control system believes the vessel is maintaining position (IMCA M 115, 2016). Alternatively, if the DP control system believes the vessel to be off position, it will issue the command and the vessel will drive off position using its own thrusters. A worst-case scenario for drive off is generally full thrust directed with the resultant environment forces (Hansen, 2011). Forces involved during drive off are greater; it is more likely that damage will occur in a drive off situation than in a drift off situation. The type of the LOP incident depends on the type of failure that occurs. Knowing the possible effect of failure, the DP operator will be better prepared to take appropriate actions to avoid possible consequences. Additionally, such information may have a high value in risk assessment process in a situation, where a vessel has to conduct the task with faulty equipment or components.

Many available studies and publications regarding reliability and performance of DP systems rely on theoretical knowledge and aim to assist in the development and manufacture of reliable and redundant DP systems. They are mostly around the question of ‘What may happen?’ and not around ‘What has happened?’. From the DP operator’s point of view, such information is overcomplicated and offers little or no help in operating and maintaining the dynamic positioning system and associated equipment on a day to day basis. Conducting FMEA (Failure Modes & Effects Analyses) and DP trials is a good way to keep the crew knowledge fresh and periodically monitor the condition of the vessel and DP system. However, such trials are developed to identify potential design and operation failures before they occur (IMCA M 166, 2016). They do not concentrate on the reliability of a single component. The system is only as strong as its weakest link; in the end, the reliability of any system comes down to the quality and condition of a single components. Information about which components and subsystems fail the most may be useful when carrying out planned maintenance. Higher attention can be given to the components with potentially higher failure rate.

The aim of this thesis is, by analysing the incident reports, to determine the causes of main failures leading to loss of position incidents, discover trends and common patterns, and to find the connection between the failures and which type of incident they cause. This thesis focusses on the most common technical failures causing the vessel to lose the desired position. A discussion of human factor falls outside the scope of this thesis, as it has been widely studied elsewhere.

The research relies on incidents reported to International Marine Contractors Association (further IMCA) on a voluntary basis in a period 2007-2015 and kindly provided to the author by the IMCA organisation in order to conduct this study.

Using inductive content analysis, the incidents are sorted by the main cause and categorised into content related groups. Also, effects of such failures on the vessel station keeping capability and incident scenarios are discussed. As a result of this study, conceptual models of LOP incidents are created.

In this thesis, author will cover the following tasks:

- Give an overview of dynamic positioning systems and related equipment
- Identify the most common DP system failures and their causes
- Determine the connections between failures and incident types
- Conduct frequencies analysis
- Build the conceptual models of LOP incident

The thesis consists of three parts. First, the theory, introduces the principles of the dynamic positioning system along with a description of the major sub-systems. In the second part research methodology, data mining, and limitations are discussed. Obtained results of this study are then introduced and discussed in part three.

1 Dynamic positioning system

1.1 Introduction and history

Dynamic positioning is a station keeping technique consisting of on-board thrusters that are automatically controlled to maintain a floating structure's position and/or heading. The propulsive force produced by the thrusters/rudders counteract the mean and slowly varying actions due to wind, waves, and current so as to maintain the structure within pre-set tolerances at a desired point above the sea floor and on a pre-defined heading (ISO19901-7, 2013). In the other words, dynamic positioning is the means of holding a vessel in a relatively fixed position with respect to the ocean floor, without using anchors, and accomplished by two or more propulsive devices controlled by inputs from sonic instruments both on the sea bottom and on the vessel by gyrocompass, by satellite navigation, or by other means (Holvik, 1998, 1). A collection of the equipment supporting dynamic positioning is called a Dynamic Positioning system (DP system). The main function of the DP system is to maintain the vessel at a specified position, or on a specified track, within a set heading, and each within tolerable limits. The system must be able to handle transient conditions such as changes in external forces, failure of a signal from sensors and position measurement equipment, and system hardware failures. The additional functions of the system are to control the vessel so as to minimise fuel consumption as well as keeping the thruster wear to a minimum. (Alstom, 2000)

DP systems are widely used on vessels and other floating structures which are mainly utilised by the offshore hydrocarbon exploration and production industry. Also, the popularity of the DP system is growing within the other industries such as on cruises and in the navy.

At the end of the 1950s and early 1960s, the exploration for oil was rapidly moving offshore into the deeper waters. Use of anchors was becoming increasingly problematic which meant that a new approach was required. Willard Bascom had the idea of mounting thrusters on the CUSS 1 to see if their position could be held without anchors to drill in 3000 meters of water.

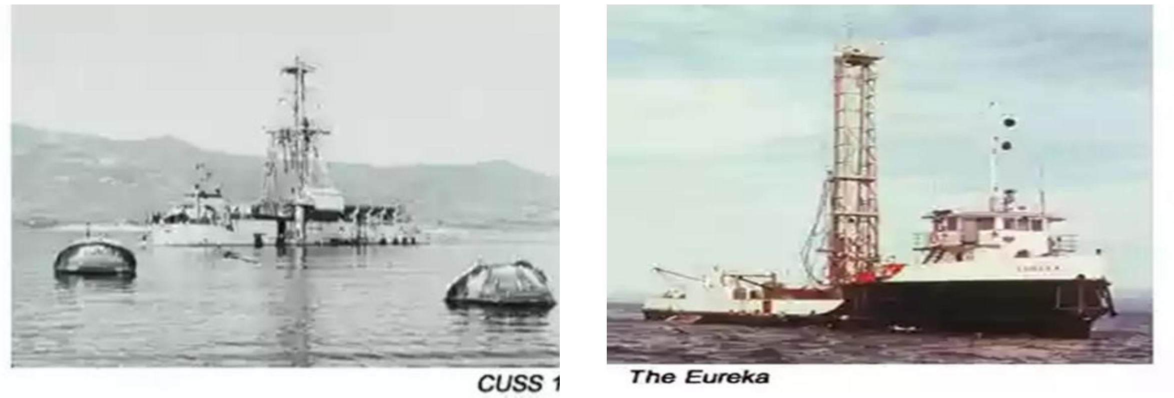

Figure 1.1 First ships using dynamic positioning (Shatto, 2011)

The ‘CUSS1’ (Figure 1.1) was the first drillship in the modern sense of the word. It was equipped with four rotating thrusters, one at each corner, and was the first vessel to use dynamic positioning. Direction and engine speed were controlled manually from a central location.

The first vessel to use the automatic position control was called the ‘Eureka’ (Figure1.1). The control machine was design and built by ‘Hughes Aircrafts’ and was based on the Honeywell process controllers. One of each controller was used to control surge, sway, and yaw. The position was viewed as a dot on an oscilloscope provided from a ‘tilt meter’ which measured the angle of a taut wire having lowered a heavy weight to the ocean floor. The heading was gained from a gyrocompass. (Shatto, 2011)

The first DP systems introduced in the early 1960s used conventional PID controllers. From the mid-1970s, more advanced control techniques were proposed based on linear optimal control as well as Kalman filter theory (Samad & Annaswamy, 2011).

1.2 DP system classification

The necessary reliability of the DP system is determined by the consequences of loss of position keeping capability. The larger the consequence, the more reliable the DP-system should be. The equipment classes are defined by the effect of failure and the nature of the failures which must be considered (DP vessel design philosophy…, DPC, 2011).

International Maritime Organisation (further IMO) defines three DP equipment classes which are intended to provide different levels of station keeping reliability (Circular 645, 1994, 5):

1. *For equipment class 1, loss of position may occur in the event of a single failure in any active component or system*
2. *For equipment class 2, a loss of position is not to occur in the event of a single fault in any active component or system. Normally static components will not be considered to fail where adequate protection from damage is demonstrated and reliability is to the satisfaction of the administration. Single failure criteria include:*
   - *Any active component or system (generators, thrusters, switchboards remote controlled valves, etc.).*
   - *Any normally static component (cables, pipes, manual valves, etc.) which is not properly documented with respect to protection.*
3. *For equipment class 3, a single failure includes:*
   - *Items listed for class 2, and any normally static component are assumed to fail.*
   - *All components in any watertight compartment, from fire or flooding.*
   - *All components in any one fire subdivision from fire or flooding*

Classes can be matched to the consequences of loss of position. Basically, with the DP2 class, all active components like generators, thrusters, switchboards, remote controlled valves, etc. are needed to be redundant. Class 3 requires redundancy of all active components and normally static components plus the physical separation of the components.

The main classification societies have used the IMO principles of equipment class and redundancy requirements as the basis for their own DP rules (IMCA M 182 2009, 8). Some of these are shown in table 1.

Table 1. Equivalent classification society DP class notations (by author)

IMO	**DNV-GL**	**ABS**	**BV**	**RS**	**LR**
International Maritime Organisation	Det Norske Veritas	American Bureau of Shipping	Bureau Veritas	Russian Register of Shipping	Lloyds Register of Shipping
Class 1	DPS 1/ DYNPOS-AUT	DPS-1	DYNAPOS AM/AT	DYNPOS-1	DP (AM)
Class 2	DPS 2/ DYNPOS-AUTR	DPS-2	DYNAPOS AM/AT R	DYNPOS-2	DP (AA)
Class 3	DPS 3/ DYNPOS-AUTRO	DPS-3	DYNAPOS AM/AT RS	DYNPOS-3	DP (AAA)

It is important to mention that DP rules and guidelines require only that the DP vessels be able to maintain position following a single failure for long enough to safely terminate the work in progress (DNVGL-RP-E306, 2015).

1.3 DP system principles

1.3.1 Redundancy, reliability, capability

In order to understand the DP system design philosophy, it is necessary to define the three basic principles on which the DP system is based: reliability, redundancy, and capability.

Reliability is the probability that an item can perform a required function under given conditions for a given time interval (DP vessel design philosophy…, DPC, 2011, 10). DP vessels should have a sufficient level of station keeping reliability. *Reliability is a product of the quality of the equipment and suppliers selected, the competence of the engineers, who design and build the DP vessel, the competence of the crew and* *management who maintain and operate it* (DNVGL-RP-E306, 2015, 19). DP rules and guidelines do not specify the levels of reliability.

Redundancy is the existence of more than one means of performing a required function (DP vessel design philosophy…, DPC, 2011, 10). Redundancy in the DP systems (single fault tolerance) is achieved by the provision of redundant systems; reliability and redundancy are not the same. DP class rules have redundancy requirements stipulated in order to achieve fault tolerant systems and meet the objective of preventing a single failure which leads to a loss of position. They often do not address the ability of the vessel to continue its industrial mission (DNVGL-RP-E306, 2015).

DP capability defines a DP vessel's station keeping ability under given environmental and operational conditions. DP capability analyses are used to establish the maximum weather conditions in which a DP vessel can maintain its position and heading for a proposed thruster configuration.

The groups into which generators, thrusters, and auxiliary services are divided largely determines the vessel's worst-case failure and therefore its post-failure DP capability. *The worst-case failure is the failure that has the greatest effect on station keeping capability* (DNVGL-RP-E306, 2015, 24). Generally, the worst-case failure is determined through FMEA study. The worst case single fault with respect to class requirements DP2 or 3 is a fault on one of the main bus-bar sections or a fault in a main propulsion motor.

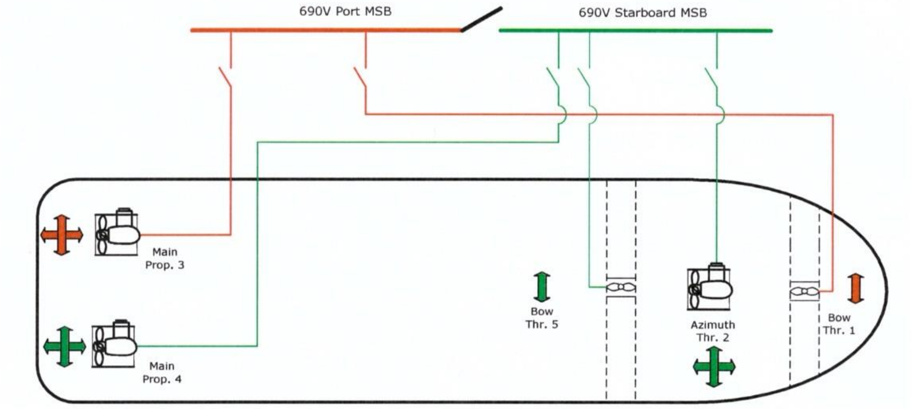

Figure 1.2 Example of vessel redundancy concept (Global Maritime, 2018)

As an example, the worst-case failure of the offshore supply vessel (figure 1.2) will be the loss of the starboard bus-bar section which will result in the loss of three thrusters.

1.3.2 DP system structure

Dynamic positioning system is a combination of six sub-systems:

- Position reference system
- Environment reference system
- Heading reference system
- Propulsion system
- Power system
- Control system

Each system in turn includes different components, sensors, and equipment which are required to perform the task (Figure 1.3)

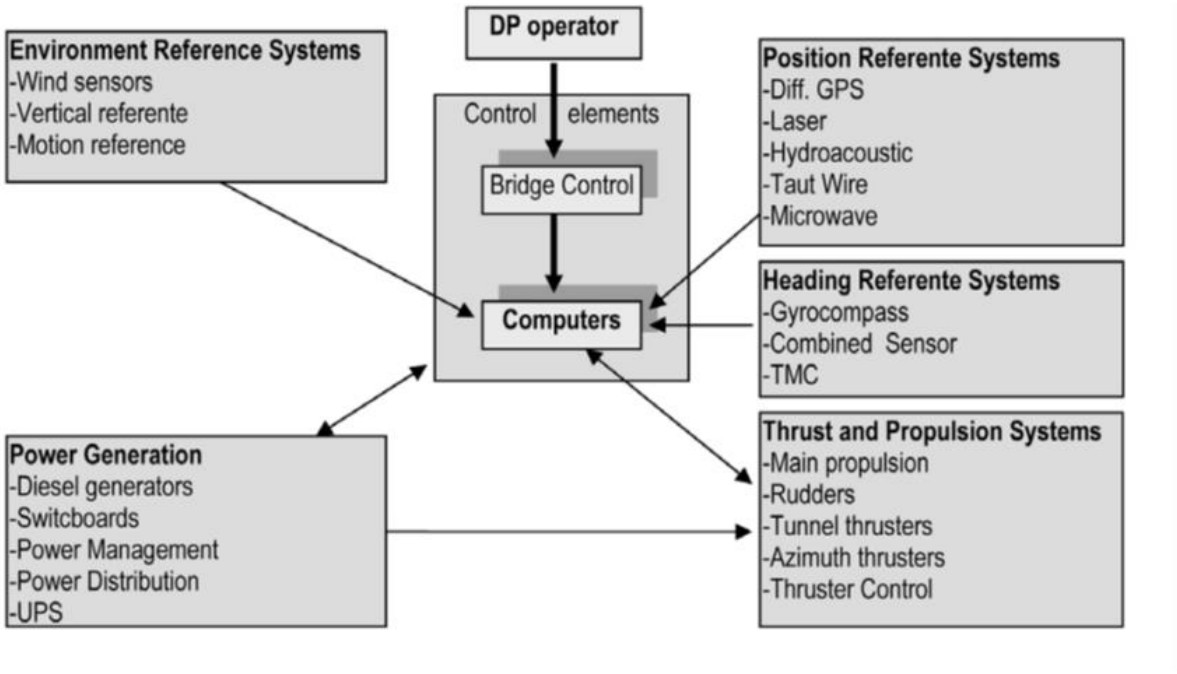

Figure 1.3 Schematic diagram of DP system *(Chas and Ferreiro, 2008).*

A DP control system uses the data from vessel's position and heading reference sensors, environment reference sensors and operator commands as an input. DP computers then analyse the input data and provide commands to the propulsion systems in order to maintain the position of the vessel at the desired location. Required power is delivered by a power generation system.

1.3.3 Theory and mathematical model

When in the open water, the vessel is subject to environmental forces which include wind, current, and waves. Task specific vessels may also be a subject to task dependent forces such as a cable, pipe, anchors, tow ropes, or fire monitor reactions. Additionally, the vessel is subjected to moments which are generated by the vessel's own propulsion system. All forces affecting the vessel are variable and have different effects on the vessel's motion. As a result of such forces, the vessel's position, heading, and speed are constantly changing. Listed changes are measured by a position-reference system and fed into the DP control system. Additional data from environmental reference system is used to correct the reference system readings for roll, pitch, wind force, and direction. The DP control system then calculates the forces that the thrusters must produce in order to control the vessel's motion.

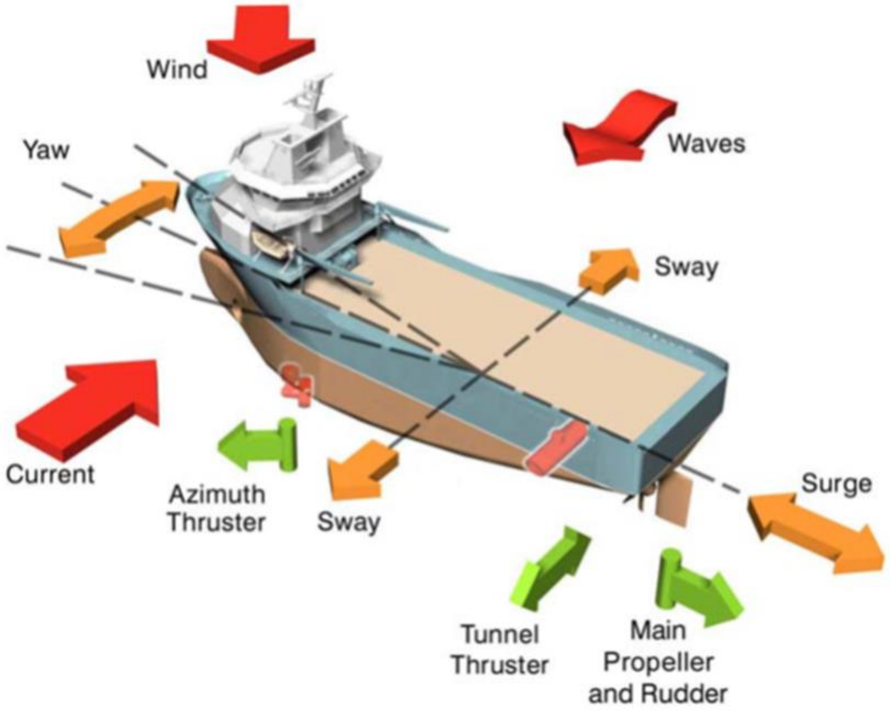

Figure 1.4 Forces acting on dynamically positioned vessel. (Kongsberg Maritime)

A DP vessel positions itself within the desired degrees of freedom (orange arrows) by counter-acting the environmental forces (red arrows) through its propulsors (green arrows) (Figure 1.4).

The DP system controls the vessel within three degrees of freedom - surge, sway, and yaw - in the horizontal plane. The vessel also moves in three vertical degrees of freedom: pitch, roll, and heave. The pitch and roll motions are not controlled by the DP system, however, in order to allow the position-reference system to correct for these motions, the system must have information about them. Dynamic positioning is only concerned with the automatic control of surge, sway, and yaw. Surge and sway are related to the position of the vessel, while yaw is defined by the vessel heading (Chas & Ferreiro, 2008).

In a simple closed feedback loop control system, a change of a sensed condition causes an action to counteract the change; the effect of the change is then sensed again and so on. Forces acting on vessel are variable in nature. To reduce oscillations in the data, some sort of filtering is required. The control system therefore incorporates a mathematical model of the vessel along with a Kalman filter. The mathematical model is an accurate description of the vessel's response to any external forces. Even if the mathematical model of the vessel is as accurate as possible, it will never be 100% correct. For this reason, measured data and data received from the mathematical model are used together and are processed by the Kalman Filter algorithm.

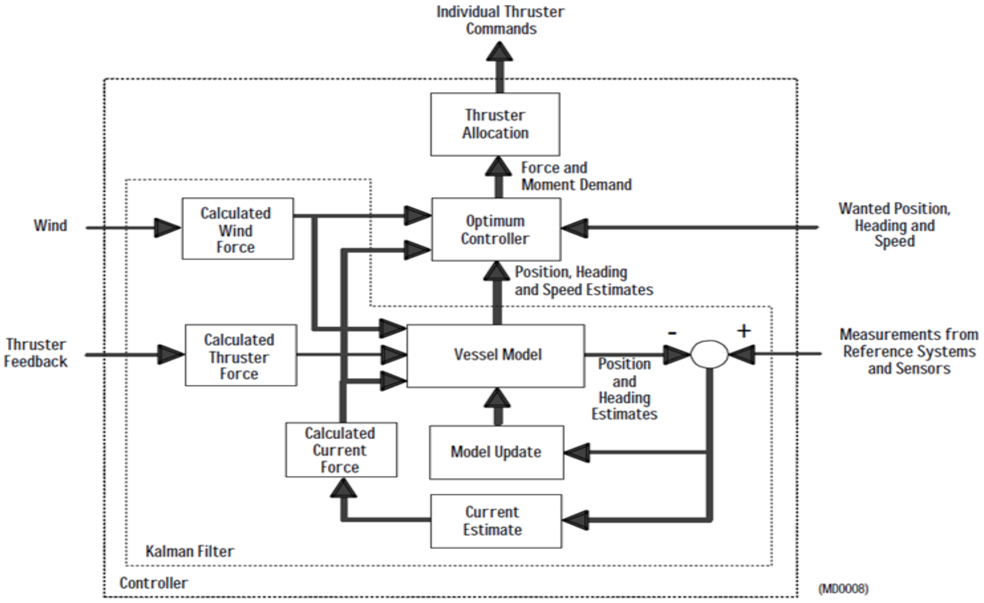

Figure 1.5 Kalman filter application (Holvik, 1998)

Kalman filter is able to distinguish between the rapidly-varying oscillations which cancel each other out over time along with the slowly-varying forces. Data from the different sensors, processed by a filter, are weighed in accordance with their noise levels and then used to update the state of a ship, received from the mathematical model. This data is compared with the required position of the vessel, input by the operator, the speed, any other forces, and the thruster demand that is created (Figure 1.5). The result of the thrust is then fed back to update the model vessel. (Alstom, 2000)

Over a period of time on location, the mathematical model adapts itself to the environmental forces. This process is often referred as ‘building up the model’. It helps to improve vessel station keeping capabilities, reduces fuel consumption, and the active use of thrusters. In the case of reference system failure, the DP system will go into ‘dead-reckoning’ mode and will use the created environmental model as a position reference input. The Kalman filter also provides the optimum combination of data from the different position-reference systems. (Holvik, 1998)

1.3.4 Operational modes

Today, DP Systems are not only designed for station keeping but also offer different operational modes with which to control the vessel. Each vessel, depending on its roles, may support several operational or control modes, however, the vessel can only be under the control of one operational mode at any one time. The difference between the modes is found in the way in which the position and speed are controlled (Alstom, 2000). The typical list of operational modes is given in Appendix 1.

Operation modes may vary between the manufacturers. Normally, before an operational mode can be selected, the system will check that the minimum set of equipment needed to operate the mode is available and that it has been selected.

1.4 Main components of DP system

1.4.1 Computers and control console

The processors operating the DP control software are generally known as DP computers. Depending upon the class notation of the DP vessel, computers may be installed in single, dual, or triple configurations. Modern systems communicate via intranet or local area network (LAN) which may incorporate many other vessel control functions in addition to dynamic positioning. In all DP vessels, the DP control computers are dedicated specifically to the DP function with no other tasks. A single-computer system or 'simplex' DP control system provides no redundancy. A dual or two-computer system provides redundancy and auto-changeover if the online system fails. A triple or 'triplex' system, usually installed on DP3 vessels, provides an extra element of redundancy and an opportunity for 2-out-of-3 voting.

The control console, or so-called operator station, is the DP system interface and provides the facility for the DP operator to send and receive data. Console incorporates control buttons, switches, indicators, alarms, and screens. Important parameters from the power, thruster system, and DP control systems are displayed to ensure that those systems are functioning correctly. Information necessary to operate the DP system safely should be visible at all times. Other information should be available upon operator request. In a well-designed and ergonomic DP control station, the position reference system control panels, thruster panels, and communications are ergonomically located close to the DP control console.

1.4.2 Position reference system

Accurate, reliable, and continuous position information is essential for dynamic positioning. There are many different Position Reference Systems (further PRS) available for DP systems; the selection of position measuring equipment for a vessel is based on the role of the vessel (Alstom, 2000). Position reference may either be absolute or relative systems. An absolute system gives the vessel’s geographical position. A relative system gives the vessel's position in relation to a non-fixed reference.

A position reference system may incorporate different types of position measuring equipment. It is possible to use just one type, however, for reliability, two or more types of position references are usually used.

Characteristics of different reference systems are shown in Appendix 2. When several PRS are online, a voting system can be used to pool the position values which weights the values as appropriate. If only one position reference system is enabled in the DP then it is simply checked, filtered, and used.

There are five main types of position reference systems currently in use on DP vessels (Figure 1.6).

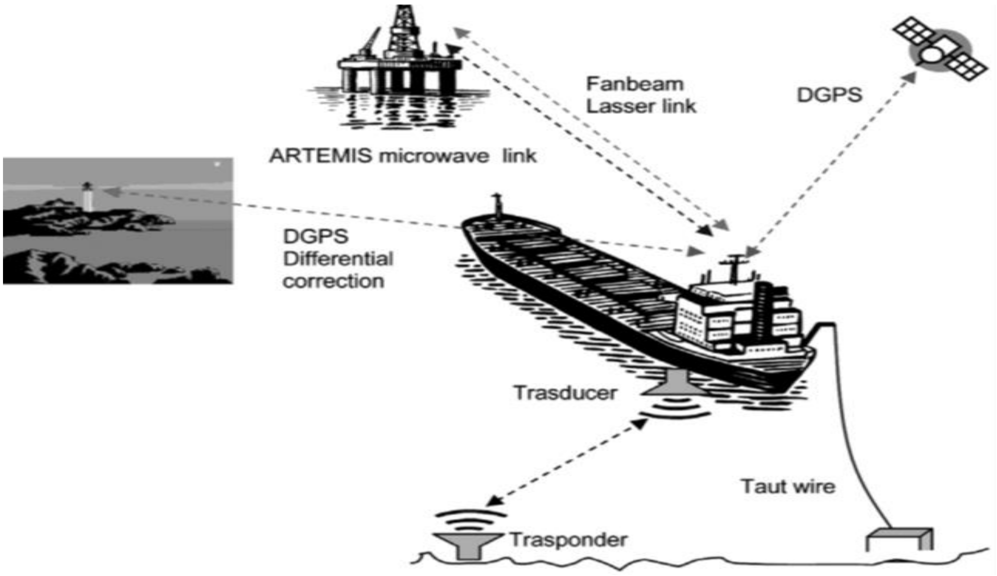

Figure 1.6 Different types of position reference systems *(Chas & Ferreiro, 2008)*

1. *Taut Wire* – The position is determined by lowering the depressor weight to the seabed and measuring the variation in the angle of the wire of a fixed point on the vessel relative to a fixed point on the seabed. The accuracy of the system depends upon the depth of the water, the mooring tension, the wire angle to the vertical, and the strength of tide. (Chas & Ferreiro, 2008)
2. *Radio-based position reference* – The position is determined by measuring the absolute distance and relative angle between the vessel and object of position reference by using radio waves. RADius, RadaScan, and Artemis working principles are based on radio waves.
3. *Differential Global Navigation Satellite System DGNSS* - GNSS stands for Global Navigation Satellite System and is the standard generic term for satellite navigation systems that provide autonomous geographical positioning with global coverage. In order to improve GPS accuracy, differential corrections are applied to GNSS data. DGPS is by far the most common mode of GNSS used in offshore vessel operations. The geographical position of the vessel can be determined within 2-5 m accuracy range. Some service providers are quoting 0.5-1 m of achievable positioning accuracy in 95% confidence regions (IMCA M 170, 2003).

   A relative DGPS system is used when vessel operation requires accurate positioning between moving vessels. The first vessel uses a standard DGPS to monitor its position. The second vessel receives GPS data on its own receiver and also receives GPS data from the first vessel over an Ultra high frequency (UHF) link. The second vessel then compares the two positions before deriving a range and bearing which is fed to the DP system. (Alstom, 2000).

4. *Hydro-acoustic Position reference HPR* - Hydro-acoustic systems (HPR) provide positioning with transponders placed on the seabed and a transducer placed in the ship's hull; using the propagation of sound through water in the same way as radio waves above the water. (Alstom, 2000). Disadvantages of this is the vulnerability to noise by thrusters or other acoustic systems. Also, the use is limited in shallow waters (Chas & Ferreiro, 2008).
5. *Laser-based systems* - there are two major laser DP position references in use: Fanbeam and CyScan. Both systems lock onto a single target and/or a number of targets on the structure, from which position must be maintained. Light pulses are sent and received in order to measure range and bearing (IMCA M 170, 2003).

1.4.3 Environment reference system

An environment reference system measures the environmental forces acting on the vessel including wind, current, and waves. The systems consist of sensors which are feeding the environmental information into the DP system. The vessel sensors are:

- *Gyrocompass* – The gyrocompass is used for heading control.
- *Vertical Reference Unit (VRU)* - The VRU on the vessel determines the difference between the 'local' vertical and reference plane of vessel. Although a DP system does not control a vessel in the pitch, roll, and heave axes, pitch and roll must be measured to provide accurate compensation for some position measurement equipment.
- *Anemometer/Wind sensor* - An anemometer is a device for measuring both the speed and direction of the wind. Wind is a major disturbing element on a vessel. The wind speed and direction are used to improve position control by modifying thruster demands.
- *Doppler Log* - The Doppler log measures the vessel's speed over the seabed. It uses sound and the Doppler Effect that is produced by a moving sound source having an altered reflected frequency which varies in proportion to the speed of that sound source (Alstom, 2000).

1.4.4 Propulsion system

The propulsion system is critical for the overall performance of the vessel, including the vessel's station keeping capability. *Diesel electric propulsion is now almost universal amongst medium and large DP vessels but direct driven and hydraulically driven thrusters are still used on some vessels* (IMCA M 206 Rev. 1, 2016, 3).

Generally, four common types of thrusters are used on dynamically positioned vessels:

1. Conventional propellers with rudders
2. Tunnel thrusters
3. Azimuthing thrusters
4. Azipod thrusters

A propeller is the traditional method of vessel propulsion. Propellers may be in either single or twin configurations. Two types of propellers are used: controllable pitch propellers (further CPP) or fixed pitch propellers (further FPP). Propellers provide thrust in both directions, however, due to the shape of the blades and the effect of the hull, the amount of thrust in the reverse direction is only 40-60% of that which is available in the forward direction (Alstom, 2000). Rudders provide sway force to the vessel in conjunction with the propeller. Generally, rudders are considered inefficient when side thrust is required. DP vessels with conventional shafted propulsion will have stern tunnel thrusters for improvement of manoeuvrability.

Tunnel thrusters are mounted in the bow and/or stern of the vessel. These enable the vessel to be moved sideways and provide a turning moment. Similar to a main propeller, thrusters may be of the CPP or FFP type. Tunnel thrusters are only effective at very low speeds and when located as far below the waterline as possible.

While tunnel thrusters are located in the tunnel and can only provide thrust in two directions, Azimuth thrusters are able to rotate. By rotating the thruster, the direction of thrust can be controlled within 360^0. The magnitude of thrust can be controlled in pitch or speed (CPP or FPP with variable speed drive). Azimuth thrusters are positioned so that they interfere as little as possible with each other as well as to avoid becoming damaged by touching the sea bed. They can also be retractable.

Azipod is a complete propulsion unit suspended below the ship. The pod contains an electric motor, the drive end of which is attached to a fixed pitch propeller. Azipod can also be rotated through 360^0 providing high manoeuvrability.

1.4.5 Power system

Power system reliability has a very high importance to DP operations. Power needs to be supplied to the thrusters and all auxiliary systems, as well as to the DP control elements and reference systems.

The design of today's offshore vessels and installations is driven by different environmental regulations, where emissions to the air are important. The majority of the offshore support vessels use Marine Diesel oil (further MDO). MDO is also preferred due to its readiness for use. For medium size installations, piston engines are normally used. Larger DP operated offshore oil & gas production vessels and semi-submersible units will normally be designed with an electrical propulsion system (Sørfonn, 2007, 5). The thrusters are the biggest consumers of the generated power. While in operation, the power demand depends on the environmental conditions and the mode in which system is operated. Due to this fact, the power system of DP vessels should be flexible and able to handle short power surges. The power systems are also required to comply with the relevant rules for the vessel's mandatory classification notations. All essential services for generators and their prime movers such as cooling, fuel, air, and lubricating systems are to be arranged in accordance with vessels DP notation.

After power is generated, it needs to be safely delivered to consumers. The electrical systems of today's vessels require extensive use of power electronics and a sophisticated Power Management System (further PMS). A PMS is designed to control and monitor the electric power production and consumption on-board a vessel. The system controls and monitors the engine driven generators, switchboards, and consumers. In the case of an electrical system fault, the power management system restores power in the smallest amount of time possible. On a typical diesel-electric installation, the power is produced by gen-sets (generator driven by diesel engine). The number and configuration of the gen-sets depends on the DP notation requirements and considering capability needs.

A simplified line diagram of the offshore support vessel power system consisting of four gen-sets connected to the common bus-bar. Gen-sets provide power to thruster electrical drives through the transformers. Thruster speed is controlled by using frequency converters. By opening the bus-tie, the bus-bar can be divided into two different sections, providing the required redundancy (figure 1.7)

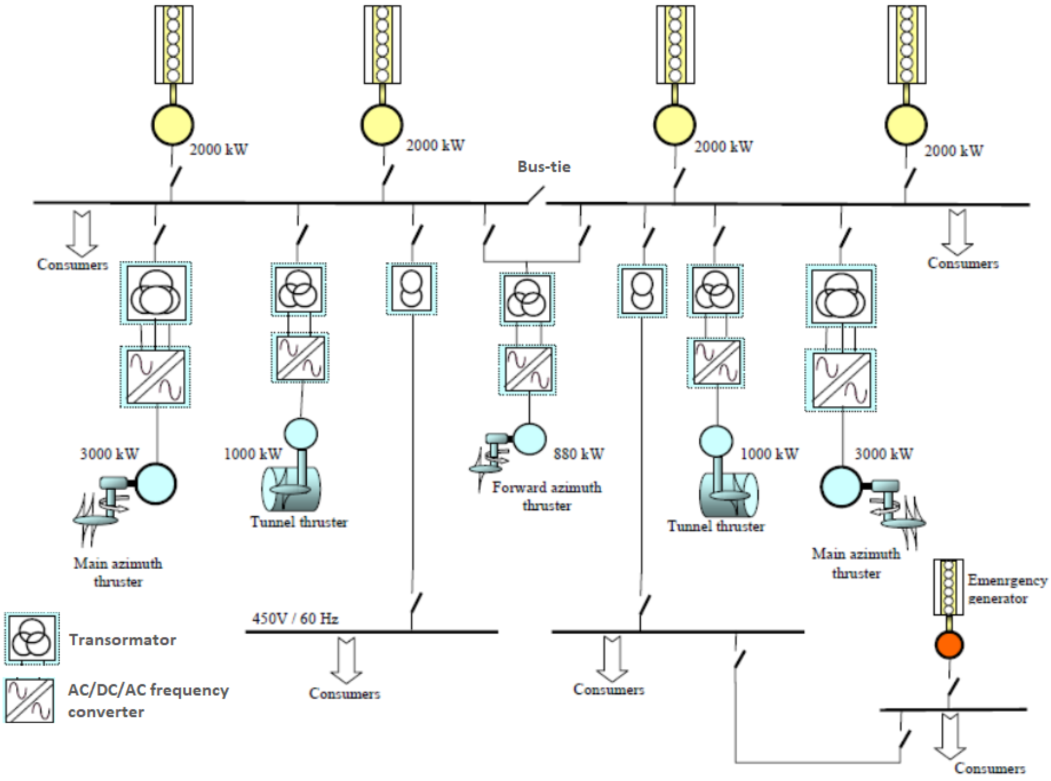

Figure 1.7 Simplified single line diagram of the DP vessel power system (Sørfonn, 2007)

There are extensive requirements to the reliability and redundancy of the power systems due to their importance and vulnerability. Most important of them are discussed in the next chapters.

2 Methodology

2.1 Literature overview

To ensure the reliable and safe operation of dynamically positioned vessels, regulations are necessary. The history of DP regulation can be widely found elsewhere, however, today there are two main regulatory bodies producing guidelines designed to improve safety and operational performance associated with dynamic positioning:

- International Marine Contractors Association (IMCA)
- Dynamic Positioning Committee (DPC)

The first formal guidance for vessels with dynamic positioning systems was issued by IMO in 1994, providing an international standard for dynamic positioning systems on all types of new vessel. While IMO circular outlines the minimum requirements for DP vessels, more detailed guidelines are produced by IMCA. ‘Guidelines for the design and operation of Dynamically Positioned Vessels’ addresses the different aspects of dynamic positioning systems including the associated operational hazards and safe design of the equipment. The Dynamic Positioning Committee produced ‘DP vessel design philosophy guidelines’ to outline detailed requirements and design suggestions for DP vessels. Training and experience of key DP personnel is addressed in IMCA circular M117 (former IMO MSC 738).

In addition to all above listed documents, both IMCA and DP committees take an active role in developing and publishing the detailed guidelines, addressing various components of dynamic positioning as well as associated equipment. Some of them rely on past incidents and statistics, whilst others concentrate on the theoretical study of this complex system.

2.2 Selecting data

To achieve the goals set in this thesis, historical incident data is required. In maritime industry, accidents are required to be reported to the flag state and/or to the governing body of the territorial waters where the event took place. Generally, the accident is the event or sequence of events what has resulted in a serious injury, death of a person, material damage to a ship, or pollution to the environment. According to legislation, the reporting of the ship’s equipment breakdowns, which do not lead to an accident, is not required. Such breakdowns can be classified as incidents. The Merchant Shipping (Accident Reporting and Investigation) Regulations describe incident as an “*event or sequences of events which has occurred directly in connection with the operation of a ship that endangered, or if not corrected would endanger the safety of a ship, its occupants or any other person or the environment”* (Merchant Shipping Regulations, 2012). Despite the fact that a failure of the dynamic positioning system, if not corrected, may lead to a serious accident, reporting of such events is not compulsory.

To improve safety, reliability, and operational efficiency of the dynamically positioned vessels, IMCA facilitates DP stations keeping event reporting systems and encourages its members and non-members to submit the information regarding such events. Reported events are then sorted and published on the IMCA website on a yearly basis. To preserve the anonymity of the reports, the events are assigned with numbers and are presented in a format of an incident tree (Appendix 3). Reports are available for members free of charge and non-members can purchase the publications. Incident data required to conduct this study was kindly provided by IMCA upon request with no charge.

The study is based on the events reported to IMCA in the period of 2007-2015, covering 9 years of DP operations. Reported events are categorised by IMCA into DP incidents, DP undesired events, and DP observations. For the purpose of this thesis, only DP incidents are studied. IMCA defines a DP incident as a major system failure, environmental, or human factor which has resulted in a loss of DP capability. DP vessel station keeping capability is the ability of the vessel to maintain position and heading in defined environmental conditions. In total, 619 events categorised as incidents by IMCA were reported during the given period.

2.3 IMCA categories

IMCA assign incidents with main and secondary causes. In order to define the scope of the study, the data for the period 2007-2015 was combined and reviewed (Table2).

Table 2. Main cause of DP incidents IMCA 2007-2015 (by author)

	2007	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**Total**
Computer	15	22	9	6	14	8	6	13	13	106
Electrical	2	10	10	12	3	4	0	0	1	42
Environment	3	3	2	4	5	2	3	2	11	35
External force	1	1		1		2	0	2	0	7
Human error	7	5	10	3	3	11	7	7	10	63
Mechanical		1								1
Power	10	9	13	5	7	6	13	9	10	82
Procedures		2		2						4
Propulsion	5	20	12	2	13	20	20	25	24	141
Reference	10	27	17	22	8	6	13	9	6	118
Unknown		1	2							3
Sensors			1		1	5	2	3	5	17
Total	53	102	75	56	54	64	64	71	80	619

The results reveal the fact that the majority of incidents are caused by a failure within propulsion, reference, computer, and the power systems. Combined, those failures cover over 72% of all reported incidents. To keep the scope of the research within reasonable limits, it was decided that concentrated attention would be given to incidents caused by the failures within propulsion, reference, computer, and power systems. In total, 447 reported incidents will form a base for this study.

2.4 Research methods

To categorise the incidents and make sense of the data, the inductive content analysis is used. This content analysis technique uses a set of codes to reduce volumes of verbal or print material into more manageable data from which researchers can identify patterns and gain insight (Hall, n.d). Through content analysis, it is possible to distil words into fewer content-related categories. It is assumed that, when classified into the same categories, words, phrases, and the like will share the same meaning (Cavanagh, 1997). Content analysis can be used in an inductive or deductive way. The purposes for using an inductive approach are to condense extensive and varied raw text data into a summary format, establish clear links between the research objectives, and to develop a model or theory about the underlying structure of experiences or processes which are evident in the raw data. (Thomas, 2003) If there is not enough former knowledge about the phenomenon or if this knowledge is fragmented, the inductive approach is recommended (Lauri & Kyngäs, 2005). Inductive content analysis is a qualitative method of content analysis that researchers use to develop theory and identify themes by studying documents, recordings, as well as other printed and verbal material. (Hall, n. d) An approach based on inductive data moves from the specific to the general, so that particular instances are observed and then combined into a larger whole or general statement (Chinn &Kramer, 1999).

By applying inductive content analysis, the main causes of incidents are identified, coded, and categorised into similar content categories until common patterns are identified. *Usually the purpose of categories is to build up a model, conceptual system, conceptual map or categories* (Elo & Kyngäs, 2008). Results of the research are presented in the form of conceptual models that show categories of main causes leading to different LOP incidents.

The following table (table 3) explains the workflow of the theoretical inductive analysis based on Elo & Kyngäs (2008) and associated steps within this research.

Table 3. Workflow of the research (by author)

Phase	**Theoretical**	**Practical**
Preparation	Selecting the unit of analysis	Reviewing of the historical DP incident data in order to: – define the scope of research, – identify the main causes of common failures, – identify the connection between failures and type of incidents they cause.
Preparation	Making sense of the data	Reading through the incident reports to get a whole picture of the upcoming research.
Organising data	Open coding	Studying the incident report and assigning each incident with the major cause.
Organising data	Categorization	Main causes are classified into similar content categories
Organising data	Abstraction	Tables, showing causes and associated categories are created.
Reporting	Model, conceptual system	Failure models are created.

The process of data organisation was carried out using Microsoft Excel software. Each row represented an incident and columns were populated as follows: group, incident number, what happened, main cause, and type of incident (drift off, drive off, potential incident). Some additional data was also entered regarding the types of equipment which were online during incident (Appendix 4).

In order to quantify the data, the frequencies of failures and causes were calculated. Created conceptual models represent the failures according to the frequencies of their occurrence in descending order with more frequent failures being on top.

2.5 Credibility and limitations

Data used to conduct this research originated from a secondary source and has been pre-sorted by IMCA. The information presented on the reports is limited to the incident tree and a brief description of the incident. Reports also provide the main cause and a secondary cause of the incident. To identify the cause and assign it into a category, three aspects were taken into account: data available from reports, author's experience, and literature review. Additionally, consultations were held with experienced DP operators. All incidents, where available data was insufficient to identify the main cause, were excluded from this study.

Reports are also sorted by incident type into 'drift off' and 'drive off' categories. Reports, in which the fact of actual loss of position was not definite, were categorised as 'potential incidents'. For reasons of space, the conceptual models of potential LOP incidents were not built, but general models of incident are given in the appendices.

No attempt was made to categorise the incidents by DP class. Despite DP class notation being an essential factor regarding position keeping, IMCA reports do not provide such information.

Also, all incidents in which the human factor played a key role were excluded from this study.

3 Results

3.1 Propulsion failures

3.1.1 Initial sorting

The propulsion system is a key part of a Dynamic Positioning system. The consequences of propulsion failures directly affect the station keeping performance of the DP vessel. According to the American Bureau of Shipping (further ABS) guide for DP vessels, the propulsion, or in the other words ‘thruster system’, is defined as a combination of components and systems necessary to supply the DP system with required thrust force and thrust direction. The thruster system includes:

- Thrusters with drive units and necessary auxiliary systems including piping.
- Main propellers and rudders if these are under the control of the DP system.
- Thruster control electronics.
- Manual thruster controls.
- Associated cabling and cable routing.

When the main propulsion propellers are included under DP control, they are considered as thrusters and all relevant functional requirements are applied (ABS 2013, 24).

In addition to a vessel’s common requirements, the dynamically positioned vessel has to be able to provide the forces required to execute manoeuvres in surge, sway, and yaw. The total forces must be controllable in magnitude from zero to full power as well as in direction through 360° (DNVGL-RP-E306, 2015, 43). IMO and classification societies stipulate the redundancy requirements for each DP class. The vessel with DP1 notation should have thrusters in number and of a capacity sufficient enough to maintain position and heading under the specified maximum environmental conditions. Vessels with DP2 or DP3 notation are to have thrusters in number and of a capacity sufficient to maintain position and heading, in the event of any single failure, under the specified maximum environmental conditions. This includes the failure of any one or more thrusters. (ABS, 2013) DP rules and guidelines generally include requirements that thrusters should have a fail-safe and not develop uncontrolled thrust or reverse the direction of thrust as the result of a single failure. Potential fail-safe conditions include: fail as set, fail to zero thrust, or motor stop (IMCA M 206 Rev.1, 2016).

In this section, all reported incidents that were caused by some sort of propulsion system failure are analysed. In total, 141 reported incidents are transferred from IMCA publications into the research Excel worksheet. After initial sorting, some adjustments were made with regards to the failures and reports were moved as follows:

- Moved to ‘Power’ section – 15 reports
- Removed from the list – 3 reports
- Removed as ‘Human error’ – 9 reports
- Added from ‘Power section’- 2 reports

The available data does not provide accurate information regarding the type of propulsion. By analysing the reports, it was possible to identify wherever the engine was used to generate electrical power or wherever it was powering the thruster units directly. Incidents what were caused by the failure of the prime movers within the gen-sets were moved to the ‘power’ section. Uninterrupted power supplies (further UPS) failures, electrical network earth faults, and unidentified power supply problems were also moved to the ‘Power’ section. Incidents caused by the engines which were part of the propulsion (main engines) and thrusters driven directly by engine remained in the ‘Propulsion’ subsection.

In a complicated socio-technical system such as DP, it is often difficult to distinguish between human error and technical failure. In some reports, the human factor played a significant role. Wrong set-up after repairs, incorrect maintenance procedures, and installation of faulty or incorrect components are just a few examples of how human action may affect the performance of the propulsion system.

3.1.2 Failure groups and causes

By analysing remaining 116 reports, the possible main causes of the failures were identified, grouped, and the frequencies of their occurrence calculated. Results are shown in table 4. Due to insufficient information, the main cause of 24 incidents was not identified.

Table 4. Propulsion failure groups and related causes (*by author*)

Failure group	**Cause**	**Potential incident**	**Drift off**	**Drive off**
Thruster unit and drive	Drive short circuits	2		
	DC motor field problem	2		
	Loose wires	1		
	Bearing overheating	1		
Control system	Pitch or RPM anomalies	4		4
	Control units PLC	5		
	Network, communication	4		
	Loose wires	2		
	Fuses, relays, PCB, signal amplifiers	5	1	2
	Outstation internal power distribution	1		
	Faulty emergency stop button	1		
Feedback signal	Loose wires	4		
	Loose or broken linkages	1		1
	Faulty potentiometers	1		1
	Incorrect feedback signal	1	1	5
	Feedback breaker	1		
	Speed sensor	1		
Hydraulics (CPP, clutch)	Control valves, proportional, solenoids, limit switches	7	1	3
	Low hydraulic oil pressure	3		
	Hydraulic oil leaks	2		
	Gearbox, clutch	3		
Propulsion auxiliary systems (cooling, lubrication, air, ventilation)	Lubricating, cooling pumps	4		
	Thruster brake	3		
	Cooling, water leaks, thermostats	2	1	
	Oil leaks	1		
AC converter	AC converter unknown	4		
	Rectifier	1		
	Inverter	1		
	DC link	1		
Main engine	Scavenge air fan, high exhaust temp	3		
Unknown	All incidents were cause not identified	20	3	1

The main causes of the propulsion failure were categorised into 7 groups as follows:

1. Thruster unit and drive
2. Hydraulics (CPP, clutch)
3. Main engine
4. AC/DC Frequency converter
5. Thruster control system (network and controllers)
6. Feedback signal
7. Propulsion related systems (hydraulic, cooling, lubrication)

Figure 3.1.1 details the failure rate of each group.

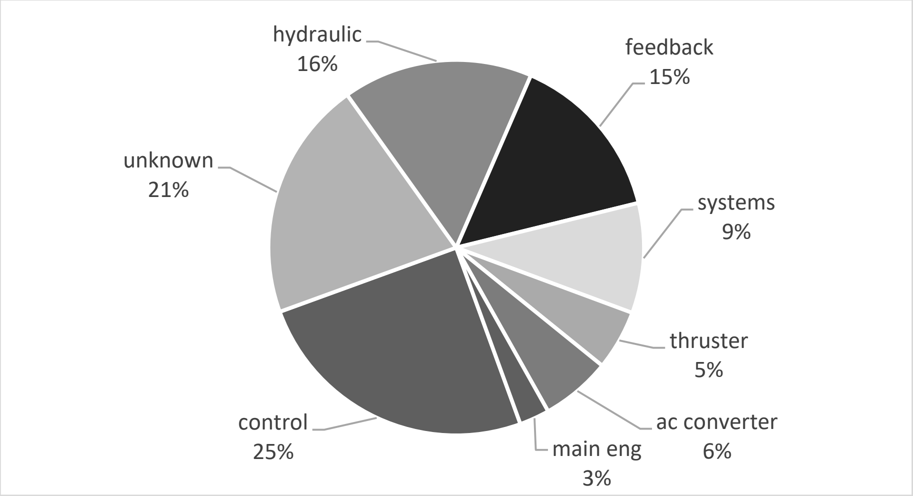

Figure 3.1.1 Failure groups of “Propulsion system” *(by* author*)*

The network and network switches are used for communication between thruster control units and the DP computer. Despite that the network may be considered as a separate system, for the purpose of this study, it was merged with the ‘thruster control’ group. Also, all reports where pitch and speed behaved erratically were assigned to the same group.

Feedback signal and related equipment are important parts of the control system. To show their significant role in, and effect on, station keeping, the feedback was considered as a separate group. If feedback problems are to be counted as a part of the thruster control system, the control system then becomes, by far, the biggest source of the ‘propulsion’ failures.

“There has been a noticeable reduction in failure rates of thrusters since the introduction of variable frequency drives with fixed pitch propellers” (DP vessel design philosophy…, DPC 2011, 30). An attempt was made to sort the incidents by the type of the propeller into FPP and CPP. Unfortunately, the information provided within the reports was insufficient to control the above statement. However, the problems with controllable pitch propellers were clearly mentioned in 31 reports. Also, the amount of hydraulic and feedback failures may suggest that the CPP failure rate is rather high.

In general, control and feedback signals may be affected by loose or damaged wires, poor contacts in terminals, and blown fuses, amongst others. Also, errors within the network or local thruster programmable logic controller (further PLC) may lead to thruster failure. In case of a power supply failure, control, or feedback signals errors, the thruster is designed to fail safe. It is supposed to stop or speed/thrust should be reduced to zero. By doing so, the vessel’s station keeping capability will be affected but ‘drive off’ may be prevented. Additionally, feedback signal failure may cause the converter to increase motor speed on some units and stop the others.

Hydraulic systems are normally used to control the CPP and steering. Generally, if hydraulic pressure is lost, the protection system is designed to stop the thruster (IMCA M 206 Rev. 1, 2016). Jamming of proportional control valves is another common cause of hydraulic system failures (Phillips, 1998).

Failures within the variable speed drives that may affect the station keeping are centred around frequency converter and electric drive. Wire break, bad contact, or a blown fuse within the converter may cause under or over-voltage and, as a consequence, the thruster will trip. Overheating or failure of the thyristor will lead to load reduction and, if not rectified, will eventually trip the converter. Short circuits, earth faults, or open circuits within the drive will take the thruster out of operation for extended period of time.

Auxiliary systems failures may also have a significant effect on position keeping capability (IMCA M 206 Rev.1 2016, 121). Leaks, pump failures, and power supply failures are just some examples of the possible causes.

Diesel engine driven thrusters or propellers also have issues which may influence the station keeping capabilities of the DP vessel (IMCA M 206 Rev.1, 2016). In addition to common engine and auxiliary system failures, they may also be affected by clutch and related equipment errors.

3.1.3 Incident types and frequencies

After analysing and sorting the reports, 116 incidents in a period between 2007- 2015 were recognised to be caused by 'Propulsion failure'. All reports where actual loss of position did not occur were assumed to be 'potential LOP incidents'. Relying on this principle, 92 reported incidents were considered as potential LOP incidents and actual loss of position or heading caused by propulsion failure took place 24 times. The vessel drifted off position 7 times and drove off position 17 times (Figure 3.1.2)

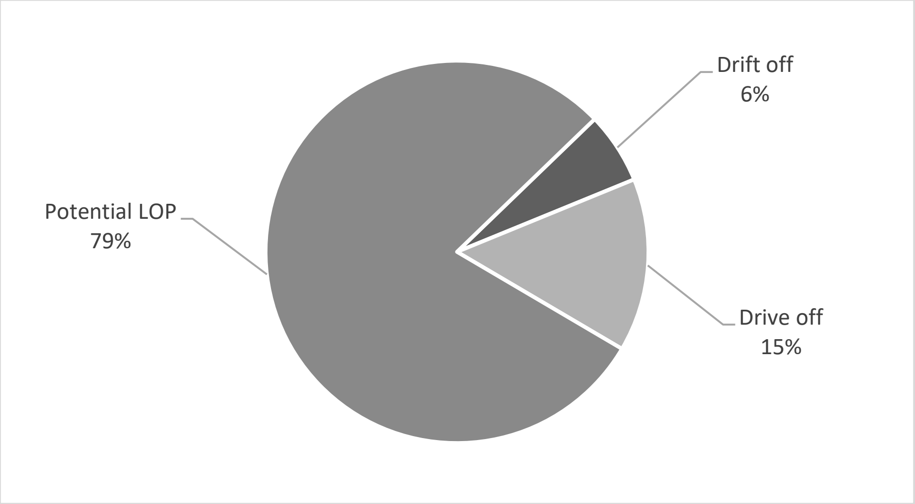

Figure 3.1.2 LOP Incident frequencies caused by propulsion system failure (*by author*)

The high number of the potential LOP incidents suggest that the propulsion system is not fault proof but, if this number is compared to the number of actual LOP incidents, it becomes obvious that reliability of the propulsion system, in regard of the station keeping, is high. The numbers also suggest that 'propulsion' failure is causing more 'drive off' incidents than 'drift off'.

3.1.4 Potential LOP Incidents

The control and hydraulic sections of the propulsion system are the biggest contributors to the potential LOP incidents (Figure 3.1.3). Due to insufficient information, the main cause of 20 potential incidents was not identified.

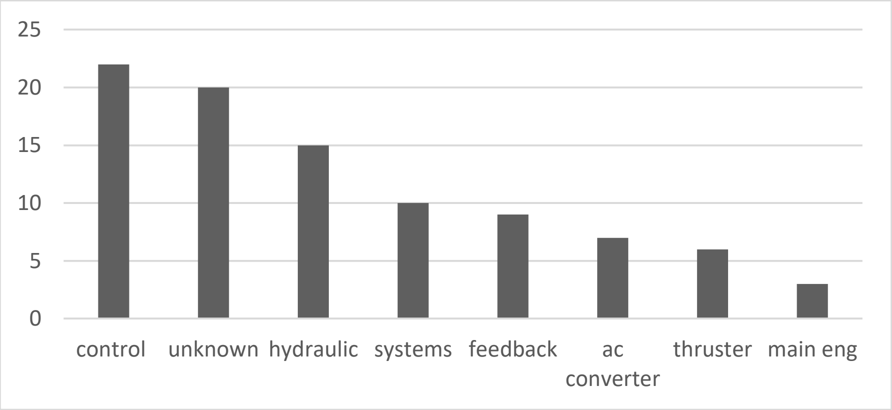

Figure 3.1.3 Propulsion failures leading to potential LOP incidents *(by author)*

Analysis shows that PLC and small electrical components cause the most problems within the control system of the thrusters.

PLC is a link between the DP controller and thruster; it constantly monitors the health of the thruster and sends the 'available' signal to the DP controller. Normally, DP system will send a command signal to the thruster only if the 'available' signal is present and the thruster has been selected. The thruster will become deselected only in the event that the operator deselects it or if the 'available' signal is lost. Loss of the 'available' signal means that there is either a loss of the digital input from the thruster due to active interlock or that there is a loss of communication between thruster controller and DP controller (Mason, 2009). Loose wires, faulty relays, network problems, or controller power supply failures may affect the 'available' signal. Additionally, PLC itself is an advanced microcontroller and may suffer from software error or another internal fault. Analysed data indicates that software faults are often resolved by rebooting the controller.

A control system also incorporates a large amount of electric/electronic equipment: relays, signal amplifiers, and circuit boards amongst others. Such components are sensitive both to temperature and environment; they are also prone to vibrations. Malfunction of such components may affect the command or feedback signals and, as a result, the thruster will trip or produce incorrect thrust. Pitch and speed anomalies may be caused by the failure of different components. Relying on the information available from the reports, it is impossible to identify exact causes of such errors. In general, voltage irregularities or current leaks may affect the command or feedback signal and thus cause anomalies or erratic behaviour in such a way that speed or direction of thrust are changed without a related command from the DP computer or operator.

Faults within the emergency stop system may cause the spurious loss of a thruster. Propulsion related emergency stops for DP2 equipment are usually ‘normally open’ contacts (IMCA M 206 Rev.1, 2016). However, if a system is designed with ‘normally closed contact’, then the wire brake will stop the thruster. To prevent shutdown of the thruster on emergency stop, cable faults, such as open circuit or short circuit, line monitoring may be used.

High rate of hydraulic system failures indicates that CPP is still widely in use. Analysis revealed that the pitch control valves are the most common cause of the hydraulic system failures. When in DP, the vessels propulsion system works under variable conditions and as a result the pitch control valves are operated very frequently. Poor maintenance and degraded oil quality may also contribute to the unexpected failure. Data also shows that pitch control or thruster azimuth angle control valves may fail in any position. That makes this error unpredictable. Most todays DP control systems are arranged to provide a prediction error if the thrust magnitude or direction is not as expected, this can occur if hydraulic systems are not capable of turning the thruster or changing blade pitch in the expected time (IMCA M 206 Rev.1, 2016).

Thrusters have numerous protections which are designed to prevent any damage to the equipment. The protection system will normally stop the thruster should lubricating oil pressure or cooling temperature readings exceed the pre-set limits. Lubricating oil systems are usually dedicated to the single thruster and failure within the system will affect only one thruster. Providing fully independent cooling systems for each thruster is considered to be good practice to avoid the risk of losing multiple thrusters due to leaks or maintenance related activities (IMCA M 206 Rev. 1, 2016). If central cooling is used, the cooling system failure may affect several thrusters on the same loop depending on the configuration. Analysis shows that the most vulnerable parts of the auxiliary systems are cooling and lubricating pumps. Failure of the lubricating oil pump will affect the oil pressure and, in turn, trip the thruster. Some thrusters can operate without forced lubrication for extended periods, however, they may be limited to a lower load under these conditions. The load reduction may be automatic; in this case, the DP control system should recognise that the thruster is no longer capable of its full power (IMCA M 206 Rev.1, 2016). A lubricating oil leak may also cause the pressure to drop in the system and, as a consequence, the thruster may trip. Failure of the cooling pump usually will not have an immediate effect on the thruster and there will be enough time for controlled, manual deselection and stopping of the defective thruster. If, for some reason, the cooling problem is not detected within reasonable time, the thruster will be stopped by high temperature protection. Water cooled drives may also experience a cooling medium leak. If such a leak is detected by the protection system, the thruster may trip or will be stopped by the crew and taken out of operation for repairs. In the worst case, the drive will encounter an earth fault or short circuit which may affect the rest of the equipment on the same network.

According to the analysis, the common cause of the feedback signal errors are loose wires and bad connections in terminals. Speed, angle sensors, linkages, and connection terminals for the feedback are normally situated on the thruster itself and may suffer under constant vibration. Poor maintenance may also contribute to this sort of failure.

An AC frequency converter is used to control the speed of a variable speed drive. In this analysis, the exact causes of converter failures were not identified.

Thruster internal faults, like short circuits and earth faults, are very rare. Short circuit may be caused by over-voltage spikes from the converter or internal fault of the motor windings. Such failures shall trip the breaker without affecting the network, however, if severe, the big voltage dip may also trip the breakers of the other equipment connected to the same network.

There is very little information available from the reports about the actions taken during or after the LOP potential incident. Some reports stated that the vessel had to abort the task to rectify or investigate the problem. Small errors can be rectified without the vessel abandoning the task, usually by rebooting the controllers or by restarting the thruster.

3.1.5 Drift off

Based on the data from 4 reports, the malfunction within control, feedback, hydraulic, or auxiliary systems may cause the propulsion to fail in such a way that will make the vessel to drift off position (Figure 3.1.4). Due to insufficient information, the main cause of three 'drift off' incidents was not identified.

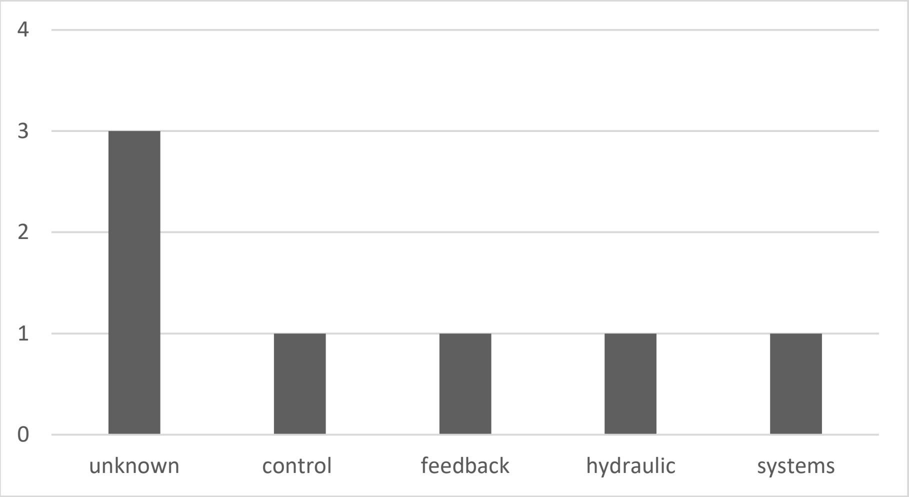

Figure 3.1.4 Propulsion failures leading to "drift off" incidents (*by author*)

Three common scenarios for most 'Drift off' incidents caused by propulsion failure were discovered:

1. Thruster becomes unresponsive with 'zero' or low pitch.
2. Thruster fails to 'zero' and is rejected by DP computer.
3. Thruster is stopped by the protection system or becomes unavailable to DP.

As a result, the vessels propulsion system cannot generate enough thrust to maintain the position and the vessel drifts off position.

Some errors may cause the thruster to 'freeze' at low, zero pitch, or low speed. Such conditions may also be caused if thruster is designed to 'fail safe' to as it is. If, by coincidence, the feedback signal is also incorrect or if such error goes undetected by the DP computer or operator, the vessel station keeping capability will be reduced. As a result, the environmental conditions will prevail and the vessel will eventually start drifting off position. This scenario is almost impossible with today's DP systems, however, it did occur in the past. The thruster was freezing at 10^0 and feedback was indicating 60^0. Thrusters were operating in bias mode. After the healthy thruster was stopped in good weather conditions, the vessel began drifting off. The feedback signal is usually not used by a DP controller for calculations and is only monitored by local thruster controller. If, for some reason, deviation between command and feedback signal goes undetected, the thruster will keep on the ‘available’ status and DP controller will operate it as usual. The vessel will remain in position as long as other thrusters are able to compensate.

An uncommon scenario for ‘drift off’ incident caused by propulsion feedback failure, is when the thruster stays online but the thrust direction is not as expected. This may be caused by combination of different factors. Such unusual ‘drift off’ occurred when actual thrust direction of an azimuth thruster was 180^0 opposite of what was indicated. As a consequence, thrusters were cancelling each other out, resulting in ‘drift off’. Azimuth thrusters typically have three angle measuring devices; one device provides feedback to the thruster control unit, one provides feedback to the DP control system for indication purposes, and the third provides angle indication at the local control station (IMCA M 206 Rev.1, 2016). Some thruster manufacturers use a single mechanical drive for all three angle indicators. If this drive slips, the thruster may be pointing in the wrong direction with no indication to warn of this.

An internal oil leak within the controllable pitch propeller may cause the pitch control valves to become slow to respond to the DP computer demands. It may result in the deviation between command and feedback signal. Such deviation will be detected by local controller and if the limits are exceeded, the thruster will be stopped or rejected by the DP controller. Station keeping capability will be reduced and the vessel may drift off the position.

Cooling system failures should not affect station keeping however, if undetected, the drive’s windings or bearings temperature will rise and thruster will trip. Depending on the system configuration, the multiply thrusters may be affected.

Analysis shows, that most of the ‘drift off’ incidents were caused by a loss of a single thruster. The general rule states that, “*a single fault in the thruster system is to be such that the thruster fails to a safe mode so that the vessel’s position and heading are not affected*” (ABS 2013, 23). According to this requirement, the loss of one thruster should not affect the station keeping of DP 2 or DP3 class vessels under normal conditions.

Strong currents and bad weather conditions were mentioned in some reports. If a DP2 or 3 class vessel operates within degraded conditions and outside its 'worst case failure limits', then the risk of losing position after thruster failure will be increased. To avoid this, the 'degraded conditions' risk assessment should be carried out (IMCA M 182, 2009).

Single thruster failure on DP1 vessel will have more severe effect on a station keeping and may result in a 'drift off' also under normal conditions.

As a result of the analysis, the conceptual model of drift off incident was created (Figure 3.1.5).

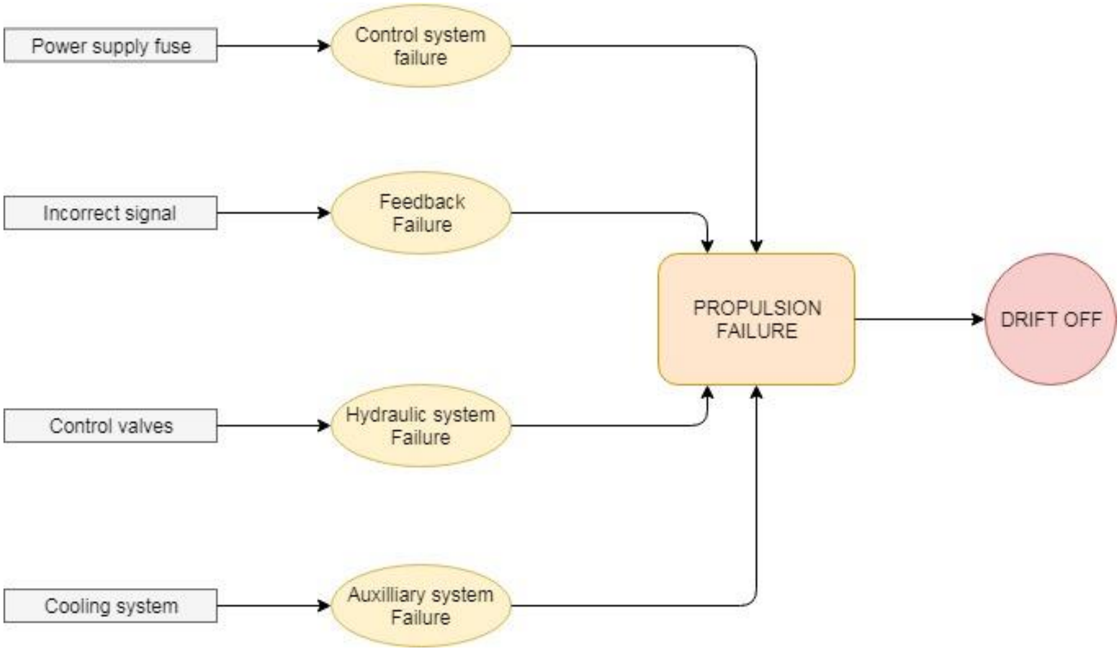

Figure 3.1.5 Conceptual model of "drift off" incident caused by propulsion failure (*by author*)

On this model, each failure occurred once, suggesting that there is no common pattern for drift off incidents caused by propulsion system failure.

3.1.6 Drive off

Analysis of the historical incident data revealed that propulsion feedback, control, and hydraulic errors may cause the vessel to drive off position (Figure 3.1.6). Due to insufficient information, the main cause of 1 ‘drive off' incident was not identified.

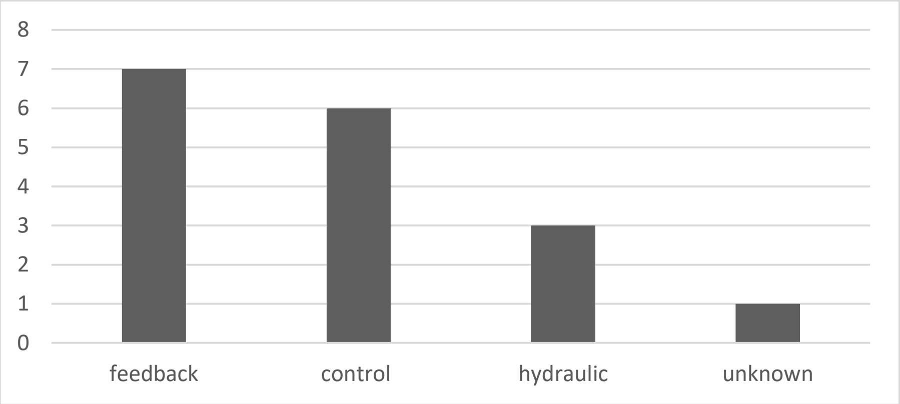

Figure 3.1.6 Propulsion failures leading to „drive off "incident (*by author*)

The thruster failing to full thrust (pitch or speed) is the most common scenario for ‘drive off’ caused by propulsion malfunction. Vessel may also drive off the position if thruster behaves erratically.

The feedback signal and command signal errors were the most common causes of propulsion system failures leading to a ‘drive off’ incident. The command signal is sent by a DP controller to the thruster controller. Thruster controller operates the thruster according to the command. Thruster movement is then measured by the feedback sensor and sent back to thruster controller. If there is a failure in one of these signals, the thruster controller cannot decide which of the signals is wrong and it may cause erratic behaviour of the thruster pitch or speed and, if other thrusters are not able to compensate, may result in the ‘drive off’ (Løkling, 2007). Yet, if such deviation occurs, the thruster controller shall detect it and make the thruster unavailable to a DP controller. In theory, if the feedback loop is faulty, the performance should be nearly unaffected. The system will use estimated feedback instead of measured feedback. Historical data shows, however, that feedback signal is the major cause of propulsion failures leading to ‘drive off’ incidents. Unfortunately, the information provided within the reports is insufficient to establish the exact causes of feedback signal errors.

The other factor what may contribute to 'drive off' if a thruster fails, is an operator incorrect intervention. Thrusters can fail in various ways and develop high unexpected levels of thrust or incorrect thrust direction. Since other thrusters will try to counter-balance the failed thruster, it is sometimes difficult for an operator to quickly determine which thruster has failed so that it can be stopped before vessel position is affected. By mistake, the healthy thruster may be stopped instead of the faulty one and, as a result, the faulty thruster will cause the vessel to drive off the position.

Malfunction of the CPP control valves is another possible cause of 'drive off' incidents. If pitch control jams in full pitch, or any other significant thrust position, and the other thrusters are not able to compensate, the vessel will drive off position. DP rules and guidelines require that single failures should not cause uncontrolled increase in thrust magnitude or direction. *Failure to full speed (significantly increased thrust) is generally not accepted in DP rules and guidelines and should be addressed appropriately in the design* (DNVGL-RP-E306, 2015, 48). Modern variable speed drives generally fail to zero speed if a significant discrepancy is detected between command and feedback signals. The only way to achieve the above requirement when CPP fails is to manually stop the thruster. The operator correct intervention is of a high importance.

As a result of the analysis, the conceptual model of the drive off incident was created (Figure 3.1.7)

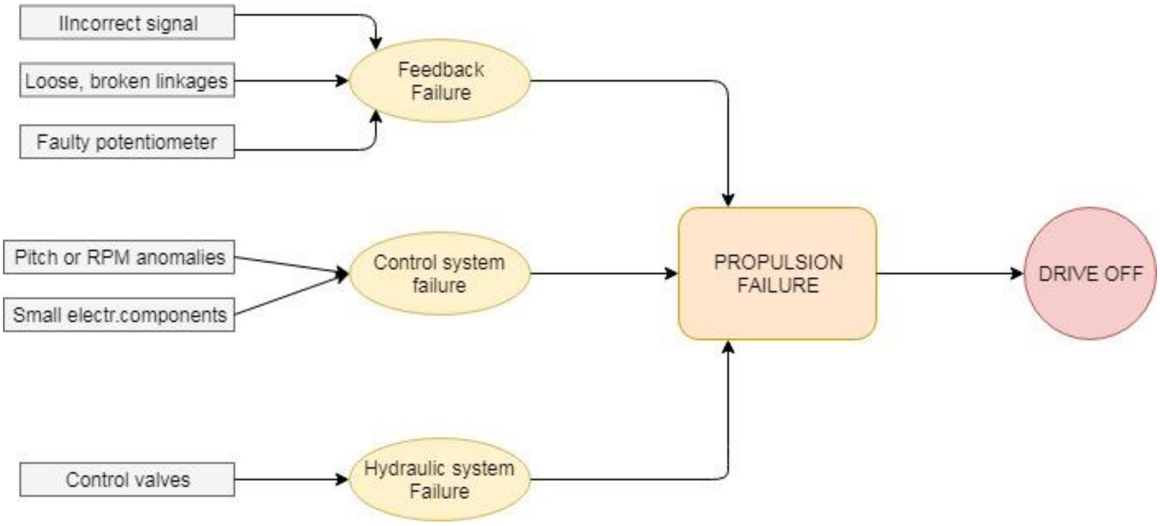

Figure 3.1.7 Conceptual model of "drive off" incident caused by propulsion failure (by author)

On this model, the failures and their causes are placed depending on the frequencies of their occurrence with the most frequent failure being on the top.

3.1.7 Trends

Types of the LOP incidents and their frequencies over the period 2007-2015 are shown on the figure 3.1.8

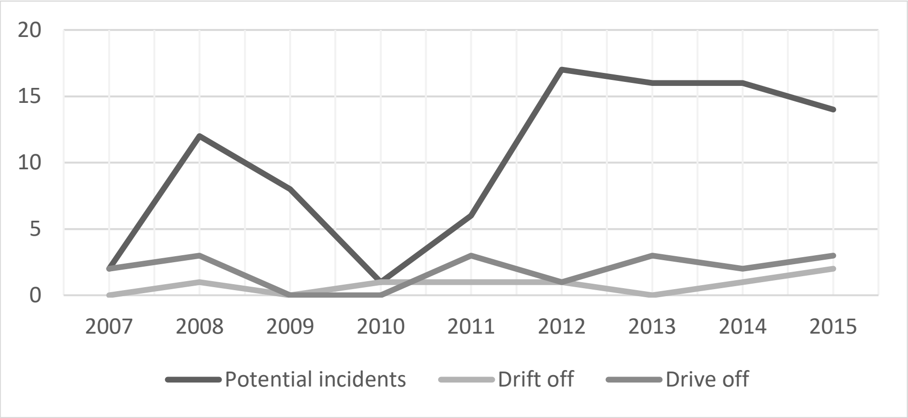

Figure 3.1.8 Trends of LOP incidents caused by propulsion system failure *(by author)*

In the recent years, the number of actual loss of position incidents caused by propulsion is showing a rising trend, while number of potential incidents is falling. Rising trends of the LOP incidents and causes of failures causing them may suggest that the vessels are getting older or that the quality of the maintenance is affected. In the bigger picture, the number of LOP incidents has been stable over the period of 9 years, varying between 2 and 5 per year.

3.2 Position Reference system failures

3.2.1 Initial sorting

International Maritime Organisation and Class rules give minimum requirements for the number of position references to be installed on the DP vessel. According to the IMO DP guide, for equipment classes 2 and 3, at least three position reference systems should be mounted and simultaneously available to the DP control system during the operation. For equipment class 3, at least one of the position reference systems should be connected directly to the back-up control system and separated by A.60 class division from the other position reference systems (IMO, Circ.645, 1994). Also, IMO does not address the operations and industrial mission of the vessel. The only requirement is that the position reference systems should produce data with adequate accuracy for the intended DP operation. Det Norske Veritas (DNV-GL) DP guidance states that the DP vessel should be equipped with a suitable position reference and sensors in accordance with the vessel's DP class notation and operational requirements (DNVGL-RP-E306, 2015). Choice of position reference systems should consider the vessels mission and the expected performance in a range of operational conditions. It is also recommended that the amount of references installed on the vessel should exceed the minimum sensor requirements stipulated by class rules in order to maximise operational uptime and achieve industrial mission requirements. (DP operations guidance part 1, 2012) *If the vessel is required to operate in close proximity to a floating facility, where the risk for shadowing of DGNSS signal may present, the redundancy in relative position reference sensors should be considered* (DNVGL-RP-E306, 2015, 114). Position reference systems online should be based on different principles. The rules also require that the performance of position reference systems should be monitored and warnings provided when the signals from the position reference systems are either incorrect or substantially degraded (IMO, Circ.645, 1994). The amount of references to be online during one or another operation is not regulated by class societies but can be found in a different DP operation guidance and vessel operator's manuals. For instance, the operational guidance on position reference systems and sensors for different operations in a form of a table was published by Marine Technology Society Dynamic Positioning Committee in 'DP Operations Guidance Part 2 Appx 2' (DP Operations Guidance…, 2012).

In this section, all incidents, caused by some sort of position reference system failure are analysed. In total, 118 IMCA reports are transferred into the Excel file. After initial sorting, adjustments were made in regard of the failures and moved as follows:

- Moved to 'Computer' section -2 reports
- Removed as 'Human error' – 4 reports
- Removed from the list – 14 reports
- Added from 'Computer' section – 1 report

In this research, environmental sensors including gyrocompass, anemometer, vertical reference unit (further VRU), and Doppler log are not considered as a part of the position reference system and all events caused by any of the environmental sensor error were excluded from the list. Reports, in which failure was recognised to be caused by the DP main controller rather than reference computer, are moved to the computer section. All reported incidents where human factor played a key role were excluded from the list. Inadequate service contracts affecting differential corrections, misplacement of the transponders, or incorrect settings causing the DP computer to reject the position reference system are just some examples of human factor affecting the performance of the reference system.

3.2.2 Failure groups and causes

The remaining 99 reports were first sorted by the type of the failed reference system. In some reports, the type of Differential Global Navigation Satellite System (further DGNSS) was specified, however, due to lack of information, it was decided not to categorise DGNSS by type. Also, based on the working principle similarities, the laser-based systems and radio wave-based systems were considered as one category. This category incorporates ‘Fanbeam’, ‘CyScan’, and ‘RadaScan’ reference systems. Artemis PRS utilises microwaves and despite being a radio wave-based system, due to its unique design, it was assigned into separate category.

In total, five reference system types were mentioned in the reports:

1. DGNSS
2. Taut wire
3. Artemis
4. HPR
5. Laser-based, radar-based system

In order to evaluate the reliability of each position reference system, the failure rate shall be adjusted by utilisation frequency. Such approach was used by K.S. Hauff (2014).

Taking 99 reports, as a base, the utilisation frequency of each reference system that was observed (Table 5).

Table 5. Online reference systems based on 99 reports (*by author*)

Type	**Online**	**Failures**
DGNSS	78	65
Taut	9	2
Laser & Radar	21	8
Artemis	19	14
HPR	28	10

Using obtained utilization frequency, the adjusted failure rate of each reference system was calculated using the formula (Hauff, 2014):

$$Adjusted\ failure\ rate = \frac{Number\ of\ failures}{Reference\ online}$$

For example, out of 99 reports, “Artemis” was mentioned to be online 19 times and failed 14 times. That gives the absolute failure rate of 0,736 or approx. 73%.

Failure rate shows PRS failure rate related to each other; adjusted failure rate may indicate the reliability of the each systems. Adjusted failure rate cannot be applied to evaluate reliability of the DGNSS reference system. DGNSS is widely used on all DP offshore vessels. It is an absolute reference system which can be used anywhere in the world. Relying on the fact that ‘DGNSS’ is the most widely used reference system, it may be assumed that the most commonly used equipment leads to a higher failure frequency.

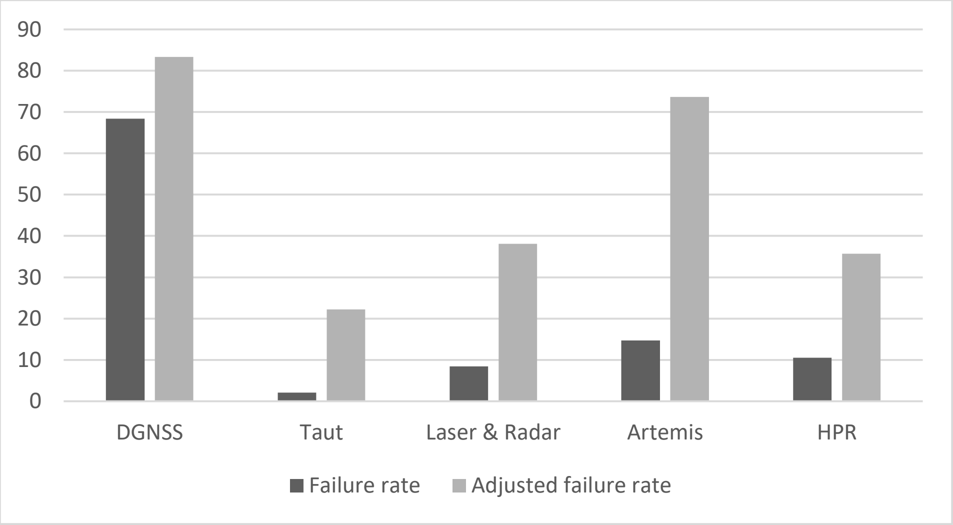

Figure 3.2.1 Failure rate of position reference systems (*by author*)

Other reference systems are used occasionally and the adjusted failure rate may give an approximate estimate into reliability of those systems (Figure 3.2.1).

By studying the incident reports, failure causes were identified and grouped allowing frequencies of their occurrence to be calculated. Results are shown in table 6. Due to insufficient information, the main cause of 29 incidents was not identified.

Table 6. Causes of reference system failures (*by author*)

Group	**Cause**	**Potential incidents**	**Drift off**	**Drive off**
Interference	Sun activity	7	2	
	Interference from other telecommunication systems	4		
	Physical obstruction	2	2	
	Near operations		1	2
	Water Aeration	2		
	False target	1		
	Unspecified atmospheric interference	2		1
Software	Software error, ok after reboot	5		
	Software “Freeze”	2		1
	Software “bug”			1
	Wrong settings, IP address	3		
	Calibration	1		
	Update required	4		
	Unknown failures of the software	7		
Mechanical	Damage due to corrosion and wear	2		
	Antenna errors	2		
	Damaged sensor unit or deployment equipment	3		
	Heat and fumes from funnel, position	1		
Communication	Poor differential correction signals from ground station	4		
	Ground station computer failure	1		
	Signal error due to satellite maintenance	1		
	Loss of satellite feed	2		
Electrical, hardware	Defective card	2		
	Loose Connector			1
	Low feed voltage	1		
Unknown	Causes unknown	16	6	7

The main causes of reference system failures were sorted into 5 different groups, regardless the type of the reference, as follows:

1. Interference
2. Software
3. Mechanical
4. Communications
5. Electrical and computer hardware

Figure 3.2.2 details the failure rate of each group.

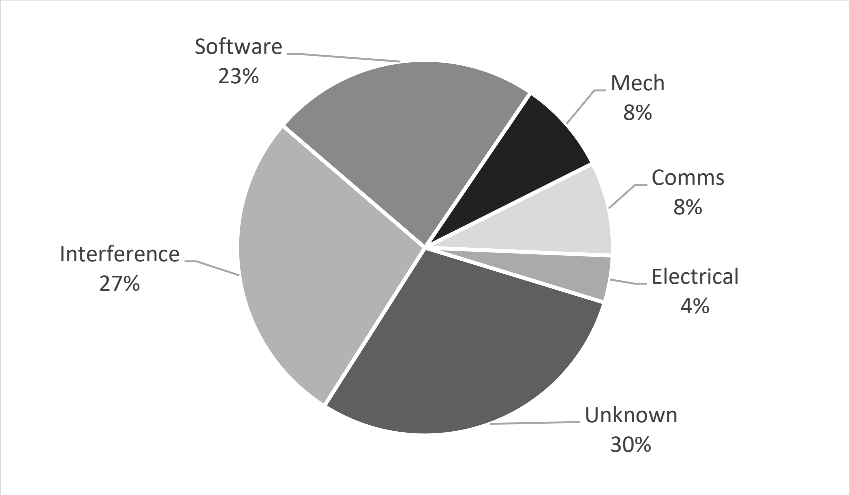

Figure 3.2.2 Failure groups of “Position reference system” *(by author)*

The reference system consists of many different parts and components. Environmentally exposed, external equipment may include antennas, signal transponders, signal receivers, cabling, junction boxes, sensors, and cranes, amongst others. Internal parts are computers, monitors, interface hardware, and other related components. External parts of the reference system experience wear and tear over the time and often encounter physical damage or corrosion due to environment. In addition, the poor installation, increasing the likelihood of failure, is common. They can also be damaged by lightning strikes, water ingress, or physical interactions. Internal hardware, like PCs, GNSS receivers, and demodulators etc. are subject to normal failures as are all other electronic devices. Software may cause the incorrect inputs due to software bugs or incorrect settings. Also, unexpected updates and software ‘freeze’ may cause the partial rejection or total loss of the position references. GNSS signals are extremely weak at the Earth’s surface and are susceptible to interference. Mostly, in the offshore environment, interference is unintentional; however, intentional interference, for example GNSS jamming and spoofing, can occur (DGNSS position reference sensors, DP committee 2015, 35). For DGNSS, the interference may be caused by sun activity, space weather, other telecommunication systems, and physical obstructions. Other position references may be affected by the operations in proximity, water aeration, or false target.

3.2.3 Incident types and frequencies

After analysing and sorting the reports, 99 incidents in a period between 2007- 2015 were recognised to be caused by 'reference system' failure. Actual loss of position occurred 24 times, of which 13 incidents were 'drive off' and 11 times the vessel drifted off position. The rest of the reported incidents, 75 in total, were assumed to be a potential LOP incidents (Figure3.2.3).

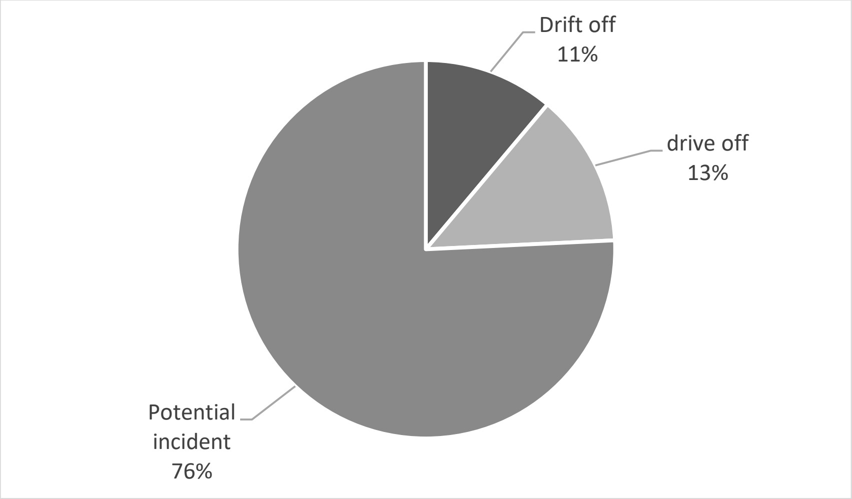

Figure 3.2.3 Incidents caused by "reference system" failure (*by author*)

The numbers of 'drift off' and 'drive off' incidents caused by reference system errors are very similar. It shows that this error is unpredictable and creates additional difficulties in the process of risk assessments. A high number of potential incidents suggests that many LOP situations were prevented as per DP redundancy concept.

3.2.4 Potential LOP incidents

Relying on the data based on the research, the most common causes of reference system failure leading to potential loss of position are: software errors and interference (Figure 3.2.4). Due to insufficient information, the main cause of 16 potential incidents was not identified.

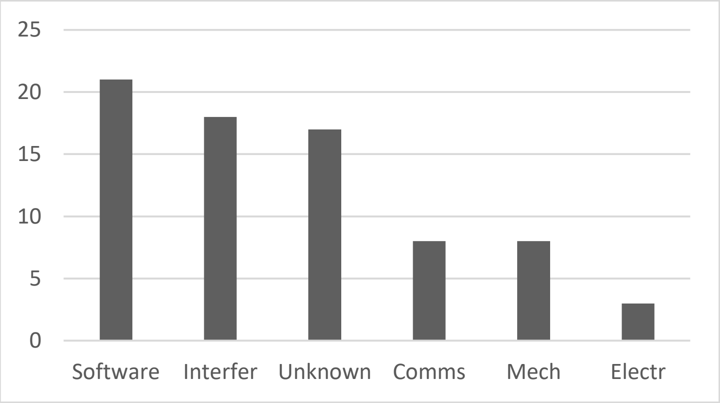

Figure 3.2.4 Position reference system failures leading to potential LOP incidents (*by author*)

To reveal the dependencies between the position reference system and possible failures, further analysis was conducted. Analysis revealed that software error is the most typical failure of the DGNSS type of reference system but may also affect any other position references (Figure 3.2.5). Software may fail as a result of different errors within the code. Such errors usually cause 'freeze' of the reference system or may corrupt the data.

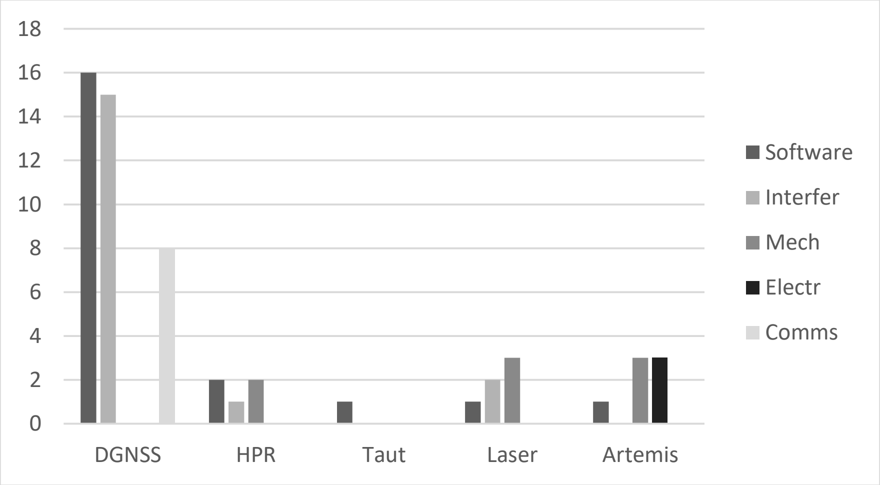

Figure 3.2.5 Failures of different position reference systems leading to potential LOP incident (*by author*)

Relying on the obtained data, many software errors are rectified by rebooting the reference system or DP controller.

DGNSS, hydro-acoustic, laser, and radar-based reference systems may be affected by some sort of interference resulting in potential LOP incidents. Hydro-acoustic interference is usually caused by water aeration created by the vessel’s own propellers, or by nearby operations, and mainly affects HPR type references. Laser reference system requires an optical line of sight between the signal sender and reflector. Line of sight is most usually affected by physical obstruction such as smoke or snow (IMCA M 170, 2003). The laser beam may also jump on another target. RadaScan is more reliable, however, it still requires a clear view of a responder in order to operate successfully (IMCA M 209 Rev 1, 2017). Incorrect installation may cause interference with x-band radar. However, no such interference was discovered during analysis.

According to the data, the most common type of the interference disturbing the DGNSS signal is solar activity. Also, other operations in proximity as well as physical obstructions will affect the quality of the satellite signal.

Analyses suggests that an unstable communication link between the vessel and ground station may interrupt differential correction signals and, as a result, DGNSS will be unreliable. Correction signals may also be affected by ground station local errors.

Mechanical breakdowns, occurring within HPR deployment equipment and external parts of the laser and Artemis systems, are also known to cause the potential LOP incidents; corrosion and wear are usually the main causes. Electrical failures within the ‘Artemis' system may be caused by a faulty card or internal power supply problems. There were no strong patterns discovered within electrical and mechanical failures. Such failures may affect any external and internal equipment and are usually instigated by lack of maintenance, poor design, or a combination of those two.

A DP 2 or DP 3 vessel is likely to use three or more position references simultaneously. When working with three or more position references on-line, failure of one alone should not cause any loss of station as the other position references are able to compensate (IMCA M 242, 2017). Use of two position references is also reasonable and safe for many types of DP activity; failure of one may not cause concern unless that failure goes undetected. Redundancy of the system in this case will be reduced and the operation will be most likely terminated. If the operation requires three position references, and the vessel is reduced to two position references, the operation will also be most likely terminated. If one of the references fails while vessel is close to an installation or with divers in the water, termination of the work can also be expected (IMCA M 242, 2017). The above listed scenarios characterise the majority of analysed potential LOP incidents.

A high number of potential LOP incidents suggest that many LOP incidents were prevented or mitigated by a DP operator or a DP control system. Nevertheless, it is obvious that reference failures are an inevitable source of risk during offshore operations.

3.2.5 Drift off

In total, 11 ‘drift off’ incidents were discovered being caused by a reference failure. Most of the drift off incidents were caused by DGNSS failure (Figure 3.2.6). The main cause of 6 incidents was not identified.

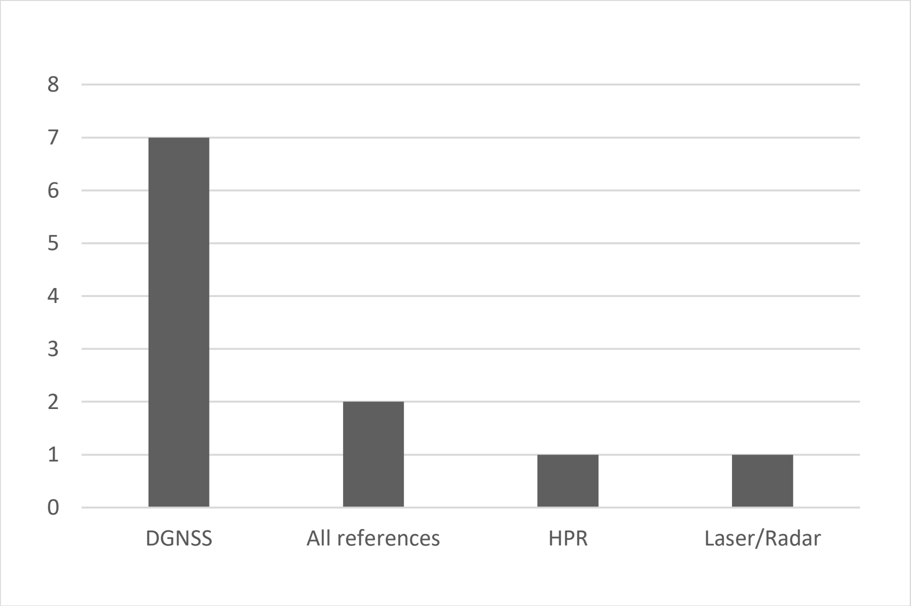

Figure 3.2.6 Position reference systems causing “drift off” incidents (*by author*)

According to the data, interference was the only known cause of reference systems failure leading to drift off incidents.

Sun activity, physical obstructions, and operations in close proximity are the main sources of the interference leading to ‘drift off’ (Figure 3.2.7).

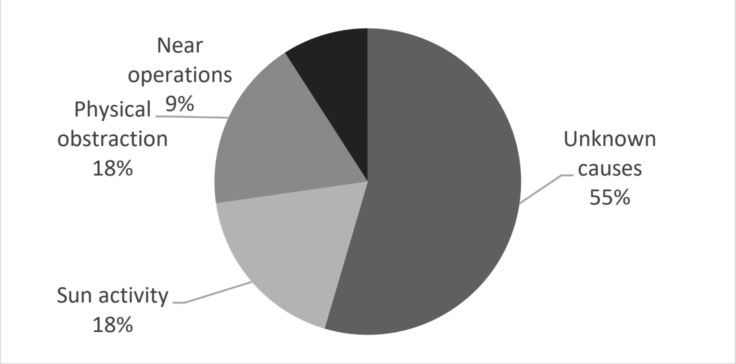

Figure 3.2.7 Main causes of failures leading to drift off incidents (*by author*)

DGNSS signals were mainly affected by solar interference, while laser system failed when a container crossed the line of sight between the signal sender and the receiver. Interference, produced by diving support vessel operating nearby, affected all online reference systems causing the vessel to drift off position.

Analysis shows that drift off will most likely occur if set-up include two reference systems online of the same type and they both fail simultaneously (Figure 3.2.8)

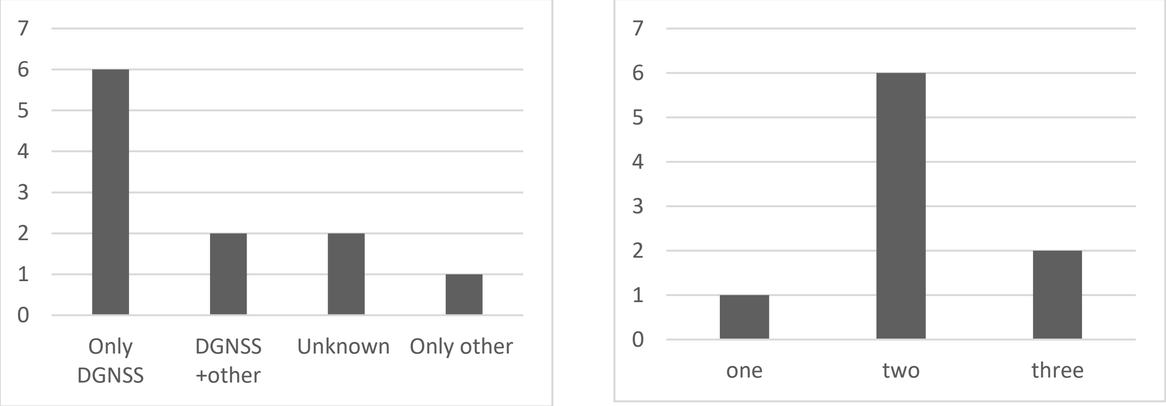

Figure 3.2.8 Types and number of reference systems online before “Drift off” (*by author*)

If all position reference systems fail at once, the vessel will remain in position relying on the last calculated mathematical model. Under normal conditions, dead reckoning should provide enough time for an operator to take over control of the vessel in manual or joystick mode. If no actions are taken by the operator, then the vessel will start drifting off position due to environmental changes.

DP vessels very rarely use only one reference system at a time. However, use of only one position reference may be reasonable in some DP modes such as: track follow or follow-sub. Under such operations, the operator shall be ready to take over control of the vessel if system fails.

Under normal operation, the DP vessel will have at least two position reference systems online. Data from the reports verifies this fact (Figure 23). The partial loss of reference signal (any one of two, or any one or two of three), if undetected, may cause drift off or a series of small jumps caused by weighting. The potential for an unacceptable excursion depends on the acceptance windows for position references in the DP control system software (IMCA M 242, 2017).

Drift off severity depends on the environmental conditions and the amount of time before the operator can take control over the vessel. Under normal conditions, the drift is considerably slow and the time to react is sufficient to get the situation under control.

As a result of the analysis, the conceptual model of drift off incident was created. (Figure 3.2.9)

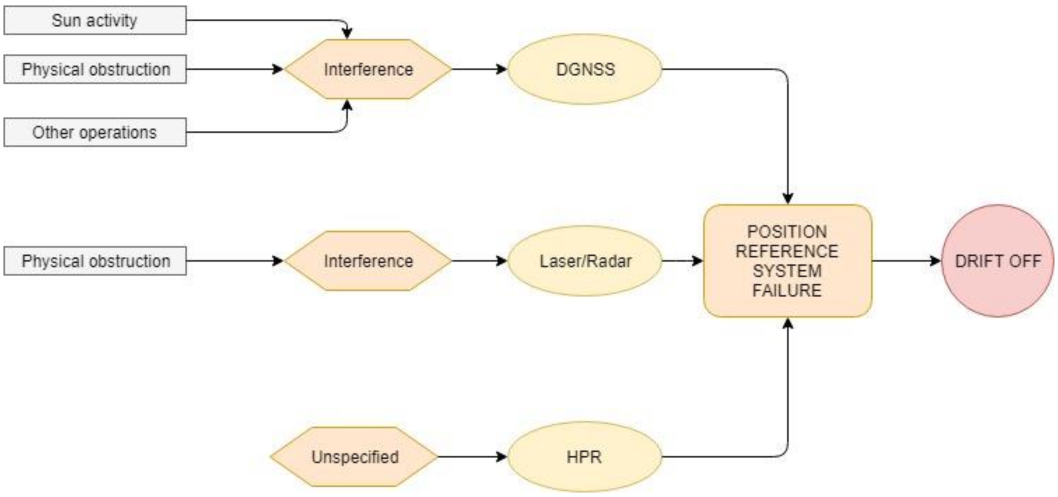

Figure 3.2.9 Conceptual model of Drift off incident caused by Position reference system failure (by author)

The model shows types of the reference systems leading to drift off but also the common failures and causes of those failures.

3.2.6 Drive off

In total 13 ‘drive off’ incidents were caused by position reference system failure. Most of the ‘drive off’ incidents were caused by DGNSS failure (Figure 3.2.10). Main causes of 7 incidents were not identified.

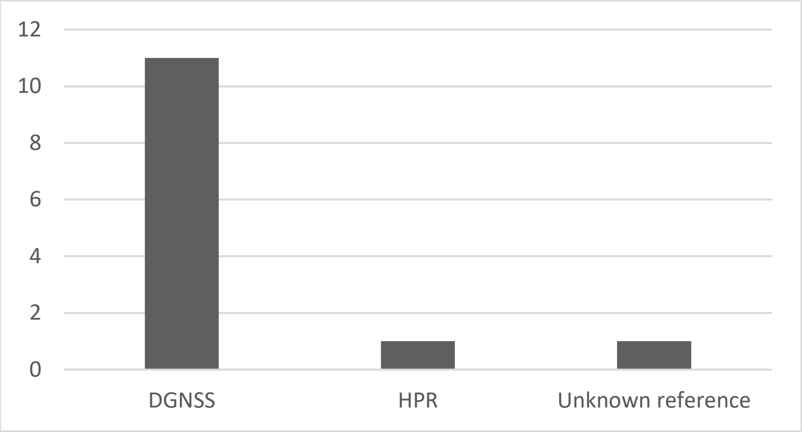

Figure 3.2.10 Position reference systems causing “drive off” incidents (*by author*)

Data shows that interference, software, and electrical errors within the position reference systems caused the most drive off incidents. Interference is mostly caused by other operations in proximity, however, also by the unspecified source. Unfortunately, information available from the reports is insufficient to identify the sources of unknown interference. It may be assumed that unknown atmospheric interference may refer to solar activity as it is the major type of interference affecting DGNSS signals.

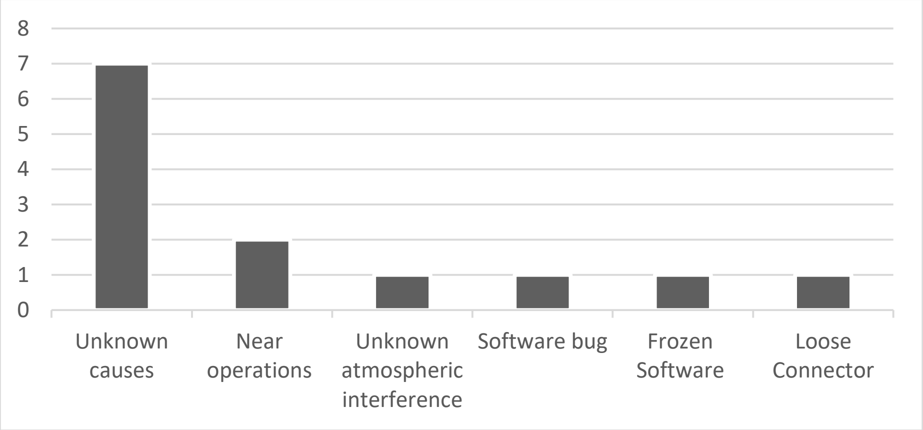

Figure 3.2.11 Main causes of position reference failures leading to “drive off” (*by author*)

There are no trends or common patterns within the position reference system failures leading to drive off incidents. The causes are all different and frequencies of occurrence are not persistent (Figure 3.2.11).

Few scenarios leading to a 'drive off' incident discovered during analysis are as follows:

- incorrect data input from reference system
- 'freeze' reference input

Incorrect data input may be a result of interference or software bug. With one position reference system online, the vessel will follow the position reference input and will drive off the position. If two position reference systems are online, depending on the weighting settings, the vessel will follow a position reference which has more weight. For example, if the DGNSS system has 70% weight and laser system 30% weight, the DP controller will rely more on DGNSS and the mean position will be closer to the DGNSS position input. If the DGNSS signal fails, the vessel will commence a drive off in direction of the incorrect reference input. The same may happen if additional position references with higher weighting settings are brought online. If three position references are simultaneously online, then the mean position will be between them depending on a weighting setting. If deviation increases, the DP system will choose two references which are showing the similar position and reject the offset one. By mistake, the healthy position reference may be rejected and the vessel will follow an incorrect reference.

Some sort of software error may cause position reference system to 'freeze'. 'Freeze' position references will provide the perfect reference and, if another reference has been taken offline, drive off situations may occur. The vessel will move to the position provided by 'freeze' reference system.

Analysis shows that the most common set-up before 'drive off' is a DGNSS plus other reference system (Figure 3.2.12). The maximum number of DGNSS systems in three reference setup is usually two. It is also important to mention that majority of incidents occurred while three or more systems were online simultaneously.

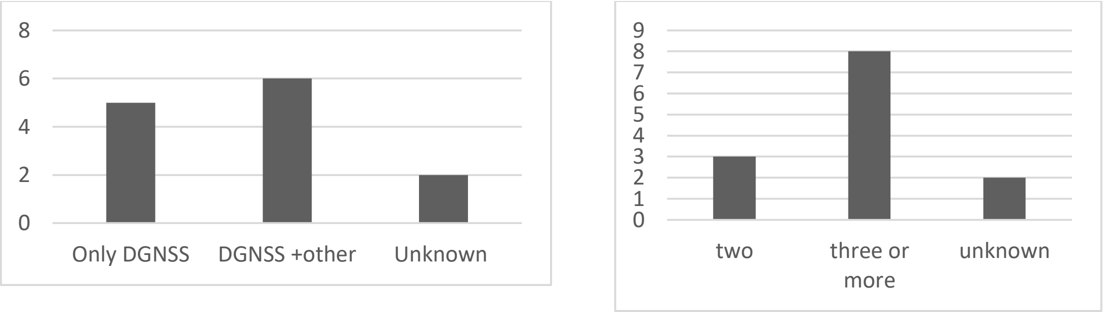

Figure 3.2.12 Types and number of reference system online before "Drive off" (*by author*)

Severity of the drive off depends entirely on the data provided from failed position reference systems and reaction times of the operator. To stop the drive off, an operator will have to take over control of the vessel.

As a result of the analysis, the conceptual model of drift off incident was created (Figure 3.2.13).

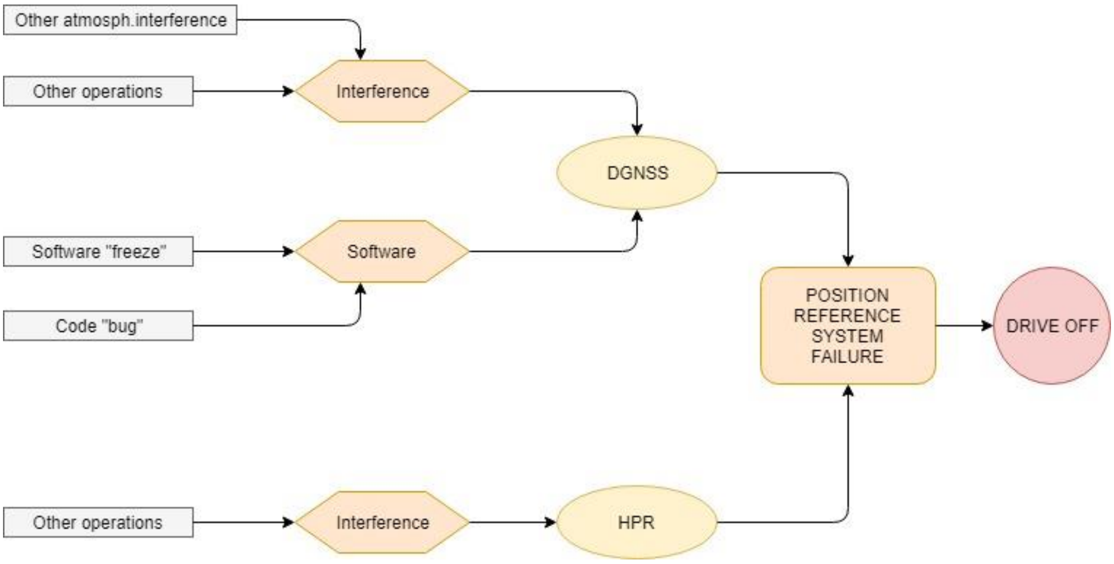

Figure 3.2.13 Conceptual model of “Drive off” incident caused by Position reference system failure (*by author*)

3.2.7 Trends

Types of the LOP incidents and their frequencies over the period 2007-2015 are shown on the figure 3.2.14

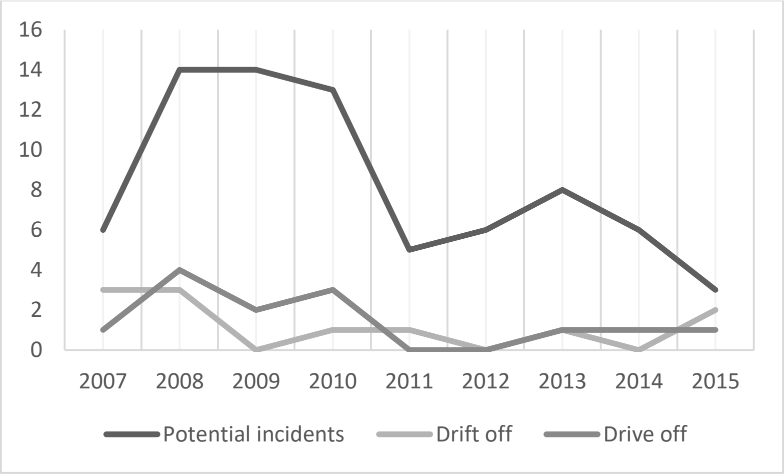

Figure 3.2.14 Trends of the LOP incidents caused by position reference system failure (by author)

Trends suggest, that number of potential incidents is decreasing while number of actual LOP incidents is rather stable. It may indicate, that procedures for using reference systems are improving. Also reliability of related equipment is getting better.

3.3 DP system computer failures

3.3.1 Initial sorting

A DP control system is designed to keep the vessel at a specified position, with a set heading, each within tolerable limits. To achieve this, the system continuously performs the following tasks:

- Measures the deviation of the vessel from its target position and calculates the forces needed to restore the target position.
- Measures the environmental forces acting on the vessel and calculates the forces needed to counteract their effect.
- Transforms the calculated counteracting forces into commands to the individual thrusters.

To perform the above tasks, the control system requires a human interface through which to enter the target position, sensors to monitor the position and environment, sensors for measuring vessel heading, and a controller to calculate the commands (Alstom, 2000). To implement the commands, the network and local field PLC are also necessary.

IMCA defines ‘computer’ as DP system related hardware and software (IMCA). For the purpose of this thesis, only DP control computer (controller) and operator control station computer related failures are covered under this section. The other parts of the control system are discussed elsewhere.

The heart of the control system is the DP controller. The Controller receives data from the various sensors and the operator then calculates and outputs the command signal to the propulsion system in order to generate the required thrust to keep the vessel at the desired location. Operator input is entered using the operator control station. All essential information regarding system status is also available through this interface. Control station consists of a display unit, a control panel and a control processor.

The general requirements for control systems of DP vessels set by IMO include arrangement of the operator stations, availability of the information required to monitor the state of the DP system, alarms and warnings, and also record keeping of their occurrences. Control systems should be arranged in a way which allows the operator to control propulsion in manual mode if the DP system fails. To achieve this, the manual control of the thrusters should be truly independent. (IMO, Circ.645, 1994)

IMO and Class rules stipulate the redundancy requirements according to the vessel DP class notation; redundancy of the DP1 control system is not required. The control system of DP2 equipment should consist of at least two independent computer systems. Common facilities such as self-checking routines, data transfer arrangements, and plant interfaces should not be capable of causing the failure of both or all systems. In addition to all listed DP2 requirements, DP3 system should be provided with a back-up DP-control system. This system should be arranged in a room separated by A60 class division from the main DP-control station. It is important to mention that DP2 and DP3 computer systems should be arranged so that an automatic transfer of control occurs after a detected failure in one of the computer systems. (IMO, Circ.645, 1994)

In this section, all LOP incidents and potential LOP incidents caused by ‘DP computer’ failures are analysed. In total, 106 incidents are transferred from IMCA reports into Excel workbook. After initial sorting, some adjustments were made with regard to the main failures as follows:

- Moved to ‘Reference’ section – 3 reports
- Removed as ‘Human error’ section – 10 reports
- Added from ‘Reference’ section – 3 reports

All failures that are caused by position reference related equipment are moved to the ‘reference’ section. Additionally, all reports where human error led to the computer failure are removed. Unintentional stopping or de-selection of thrusters, unauthorised tuning, and incorrect installation of the software are just a few examples of a human factor, what was mentioned in the reports, affecting the DP computer.

3.3.2 Failure groups and causes

By analysing computer failure reports, the causes were identified, grouped, and the frequencies of occurrence were calculated. Results are shown in the table 7. Due to insufficient information, the main cause of 16 incidents was not identified.

Table 7. Causes of “computer” failures (*by author*)

Section failed	**Cause**	**Potential LOP incident**	**Drift off**	**Drive off**
Software	Software upgrade, tuning	5	2	3
	Software bug	2	3	3
	Computer "freeze"	6	0	0
	Anomaly	26	3	4
	Virus	2	0	0
	Unknown software problem	2	1	1
Hardware	Motherboard	2	0	0
	Hard drive	3	0	0
	Card	2	0	1
	Insufficient cooling	2	0	0
	Power supply failures	4	0	0
	Loose wire	1	0	0
	Unknown hardware components	2	0	0
Unknown	Unidentified errors	13	0	3

Many incidents are assigned with the cause ‘computer freeze’. Such errors are usually caused by software malfunction. Most of the ‘freeze’ errors within the research were rectified by rebooting the computer. Any unexpected movements of the vessel, of which the exact cause cannot be identified, are considered to be caused by computer anomaly. Usually the anomalies are also resolved by rebooting the computer.

After analysing the reports and evaluating the causes of computer system failures, it was decided to categorise the causes as hardware and software related. On the author’s opinion, such categorisation provides a good overview of the errors causing computer system to fail.

Computer hardware is defined as a collection of physical parts of a computer system; this includes the computer case, monitor, keyboard, and mouse. It also includes all of the parts inside the computer case such as the hard disk drive, motherboard, video card, power supply block, and cooling fans. Failures within listed components are considered as a 'hardware failure'.

System software is a program that manages and supports the computer resources and operations while it executes various tasks such as processing data and information, controlling hardware components, and allowing users to use application software. Information provided within the reports does not specify the type of the software which failed. All reports where software error was mentioned are considered as a 'software failure'.

Analyses suggests that software is causing almost four times more failures than hardware within the controllers and operator stations (Figure 3.3.1).

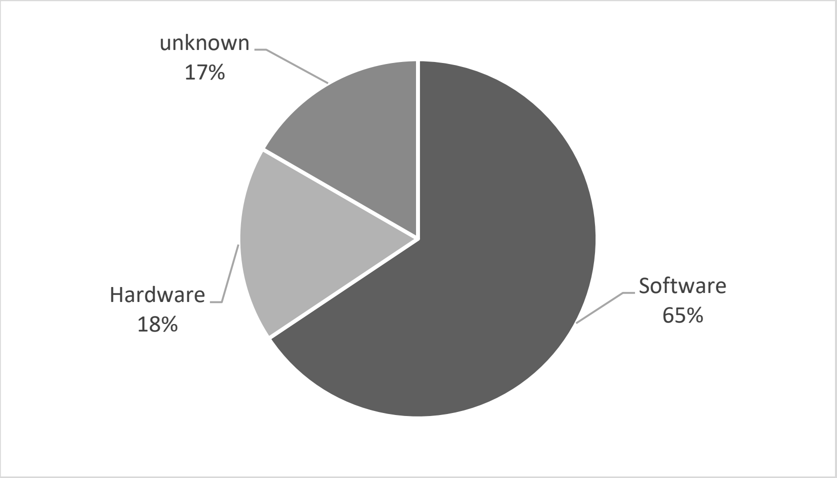

Figure 3.3.1 Failure groups of "Computer system" (*by author*)

Such a difference may indicate that the hardware, used within the DP computer system, is relatively reliable. Also, hardware failures can be detected in the earlier stages and dealt with accordingly. On the other hand, software errors may be totally hidden from the user until it suddenly fails (Skogdalen & Smogeli, 2011).

DP controllers and operator workstations are the main parts of the DP computer system. Reports were also analysed in order to determine the reliability of those parts.

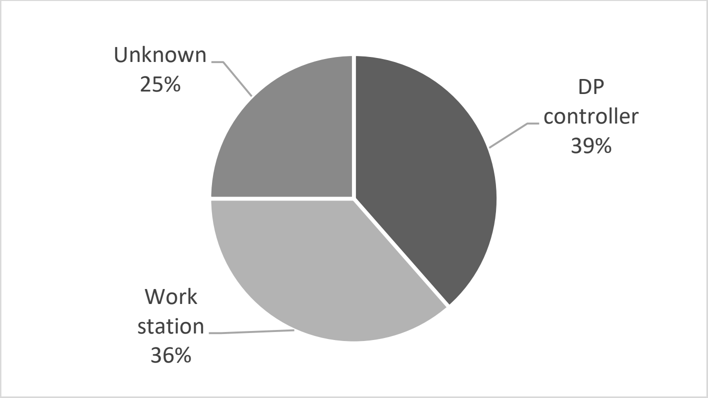

Figure 3.3.2 Failure rate of DP controller and operator workstation (by author)

The failure rates of controller and workstations are very similar (Figure 3.3.2). Despite both being computer systems, there are some variances between controllers and operator stations. Operator stations normally run on operating systems such as ‘Windows’ or ‘Linux’ and comprise the hardware typical of a desktop computer; including a keyboard, mouse, and screen. Controllers include software algorithms such as mathematical models, state gains, thruster allocation logic, and many others. Controllers are usually enclosed into dedicated compartment without permanent human interface.

Generally, computer system failure may occur as a result of a hardware issue or a severe software error which causes the system to freeze, auto-reboot, behave erratically, or stop functioning altogether. Causes of the computer failures are typical to all computer systems. All mechanical components are subject to normal ageing and wear and should be monitored and replaced accordingly to prevent unexpected failures. Computers require a source of power supply. Despite being connected to the main power supply network, computers incorporate an internal power supply unit (further PSU). PSU converts mains alternated current (AC) current to low-voltage direct current (DC) current for internal components of the computer. Overheating and overloading are the typical causes of PSU failures. Electronic components are temperature sensitive. Temperature raise will slow down the processing speed of the computer and may cause electronic circuits to fail. Poor cooling is the common cause of such failures. Motherboards and different cards contain an enormous number of electronic components. Sudden change of voltage or an electrical spike can cause damage to the delicate circuits of the motherboard. Hard drives are mechanical devices and may fail due to a failure of the electric motor or the drive itself. Vibration and overheating are the contributing factors. Logical failures of the hard drive may also occur. They are caused by corruption in the file system through a virus or if an important registry entry were to be accidentally deleted. Loose wires and poor connections may cause short circuits or earth faults.

System failures due to software issues may be caused by a bad line of code or ‘bug'. A software bug is an error in a computer program or system that causes it to produce an incorrect or unexpected result or to behave in unintended ways. Viruses and improper installation processes may also affect DP controllers and workstations.

3.3.3 Incident types and frequencies

After analysing and sorting the reports, 96 incidents in a period between 2007- 2015 were recognised to be caused by ‘Computer’ failure. All reports, where actual loss of position did not occur, were assumed to be ‘potential LOP incidents’. Relying on this statement, 72 reported incidents were recognised as potential LOP incidents while actual loss of position or heading caused by propulsion failure occurred 24 times. Vessels drifted off position 9 times and drove off position 15 times.

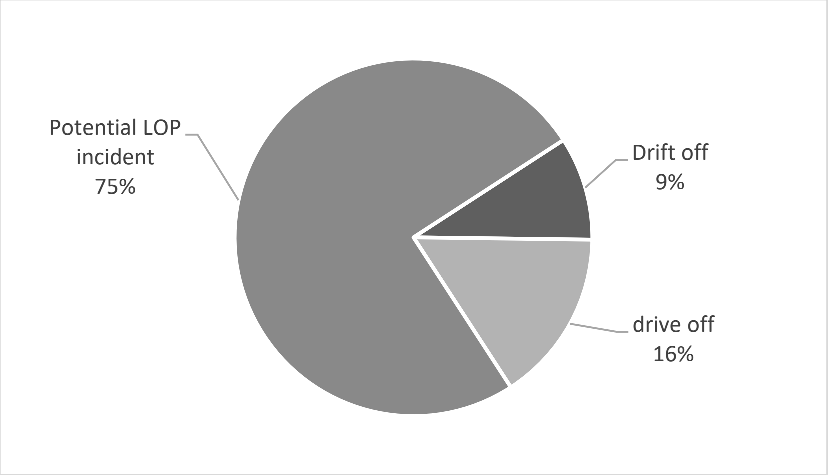

Figure 3.3.3 LOP Incident frequencies caused by computer system failure (by author)

Data shows that ‘computer’ failure, if not prevented, will more likely cause a ‘drive off’ incident (Figure 3.3.3). The number of the potential incidents suggests that many LOP situations were avoided and that the DP redundancy concept actually worked.

3.3.4 Potential incidents

Most of the potential incidents were caused by software error (Figure 3.3.4). Due to insufficient information, the main cause of 13 incidents was not identified.

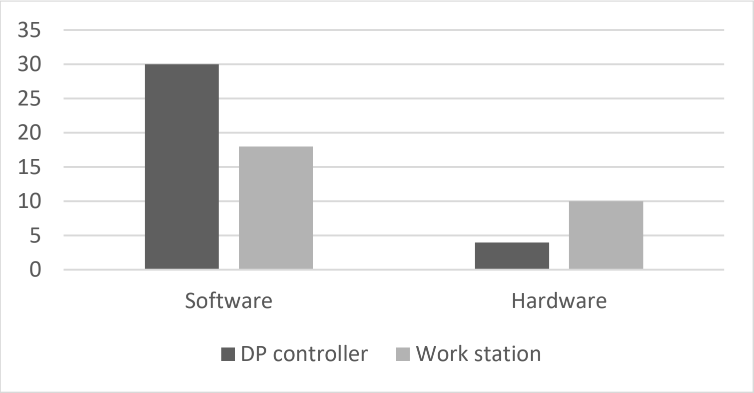

Figure 3.3.4 Propulsion failures leading to potential LOP incidents (by author)

Operator stations normally include components used as a system interface; due to this fact, they may suffer hardware failures more frequently than DP controllers.

A unidentified computer anomaly is the dominative cause of the computer software failures (Figure 3.3.5). Such software errors are very unpredictable and usually occur without warning; as a result, DP controller or the operator station may become unresponsive or misread the command signals.

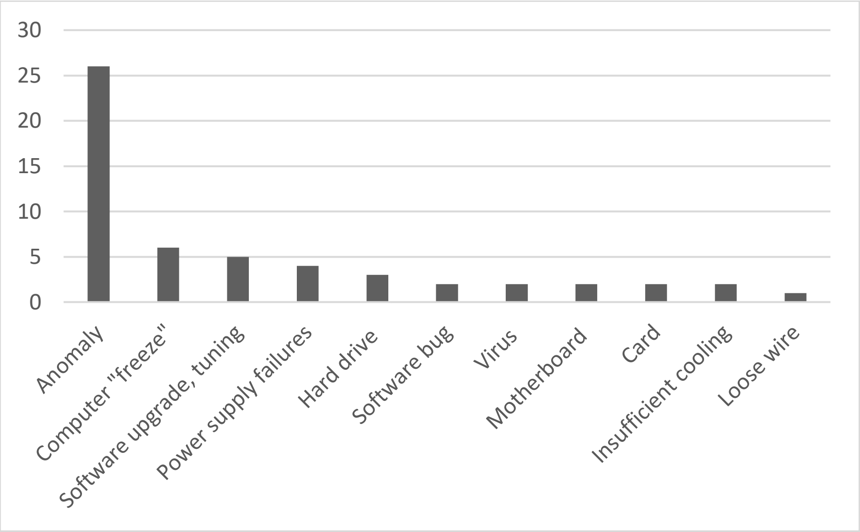

Figure 3.3.5 Causes of DP computer failures causing potential LOP incidents (*by author*)

While an unknown ‘anomaly’ affects mainly DP controllers, the ‘freeze’ error is more typical to operator stations. Generally, station screen or other interface hardware become unresponsive and the operator is unable to monitor or control the movements of the vessel. It was noticed that, during potential incidents, only one workstation or one DP controller are affected at a time.

Software updates are also a considerable source of threat to DP software sustainability. There are many parameters that can be adjusted in accordance with the task, environment, or operator requirements. Very often, after updating software or rebooting the computers, a control system resets to default settings. Those changes may go unnoticed by operator and the vessel may behave unexpectedly in DP mode.

A software‘bug’ may exist within the software for a long time without being noticed. Only a particular sequence of the events may reveal the deficiency of the code and cause the DP computer to act unexpectedly.

Viruses and antivirus software were mentioned in some reports causing computers to fail. Viruses can be uploaded into the DP systems from external USB devises, usually by entering auto track data. Also, some potential incidents were caused when an antivirus program conducted an automatic update, later activating a computer automatic reboot. Human error and poor procedures play a key role during such episodes.

In normal circumstances, the first remedy after a software failure is a computer system partial or full reboot with a reset to default settings. It is worth mentioning that most of the potential incidents reported during this period caused by computer software were rectified by rebooting the system. If a reboot does not help, then further investigation is required. Normally, DP vessels have qualified personnel on-board to conduct fault finding and system assessment in situ. Manufacturer remote assistance through communication channels is also available.

Computer PSU and hard drives are the source of the most hardware failures. To rectify hardware failure, some components will have to be replaced; it is more time consuming than a system reboot in case of this software failure. Also, availability of computer spare parts on-board is rather limited. Analysed data shows that, if hardware fails, the operation or ongoing task is aborted.

3.3.5 Drift off

Relying on the analysed data, there is a higher possibility that computer software error rather than ‘hardware’ malfunction will lead to the ‘drift off’ incident.

It was also noticed that ‘drift off’ is more often caused by the failure within a DP controller rather than failure within operator station.

Analyses revealed the two common patterns for a ‘drift off’ situation caused by software error:

- DP control system lose control of one or several thrusters and vessels remaining propulsion system is not able to generate required counterforce.
- All reference systems are rejected and vessel remains on mathematical model (dead reckoning).

Software bugs or other anomalies are affecting the station keeping by causing irregularities within the DP system (Figure 3.3.6).

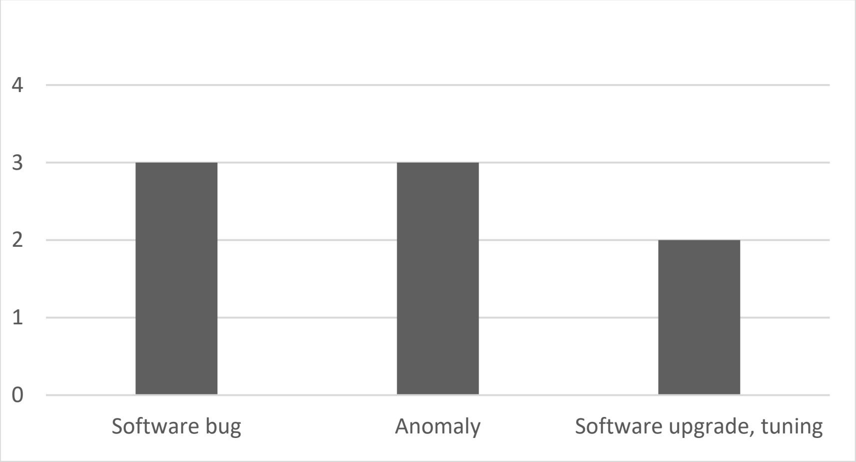

Figure 3.3.6 Computer failures leading to “drift off” incidents (*by author*)

Irregularities such as unexpected change over between different modes, unexpected reduce of demand on bus-bar, or rejection of the healthy thrusters may affect the station keeping capability. As a result, vessel will drift off the desired position.

New software or some sort of software update may contribute to communication errors between the controller and position reference system. If this happens, the system will use the ‘vessel mathematical model’ to estimate the vessel position and velocity. If the DP model is functioning correctly but the external conditions change, then the vessel may drift off position in a very short time. If the rejected position reference systems have corrupted the DP model, the vessel may be forced off position quickly. Such incidents may be avoided by conducting an appropriate risk assessment and by carrying out tests every time the system updates or an upgrade is performed. To achieve this, it is necessary to increase the focus on software as a safety critical component and also to work to improve the understanding of the functionality as well as the criticality of the control system software amongst vessel owners and crew (Skogdalen & Smogeli, 2011).

To illustrate the obtained data, conceptual model of 'drift off' incident caused by DP computer failure was created (Figure 3.3.7).

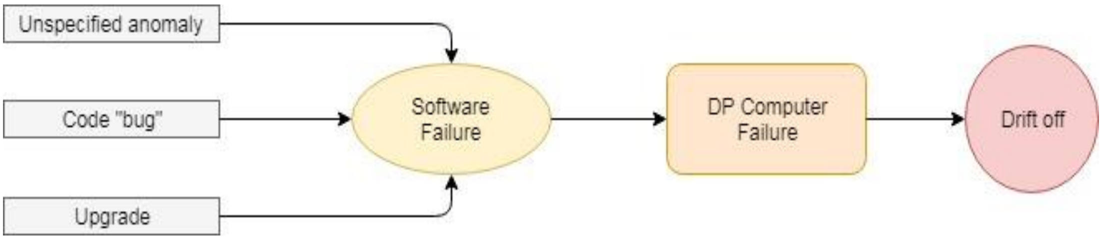

Figure 3.3.7 Conceptual model of "Drift off" incident caused by computer system failure (by author)

One of the only available barriers against computer software caused 'drift off' is taking over control of the vessel in manual mode. The DP controller or operator station is then rebooted and tested. The majority of the reports stated that all errors cleared after reboot.

3.3.6 Drive off

Analysis of the incidents showed that the 'drive off' incident will most likely occur due to computer software error within the DP controller. The main cause of 3 'drive off' incidents was not identified. Unspecified anomaly, software update, or error within the code are the main causes of software malfunction leading to a 'drive off' incident. A faulty card caused one such incident (Figure 3.3.8).

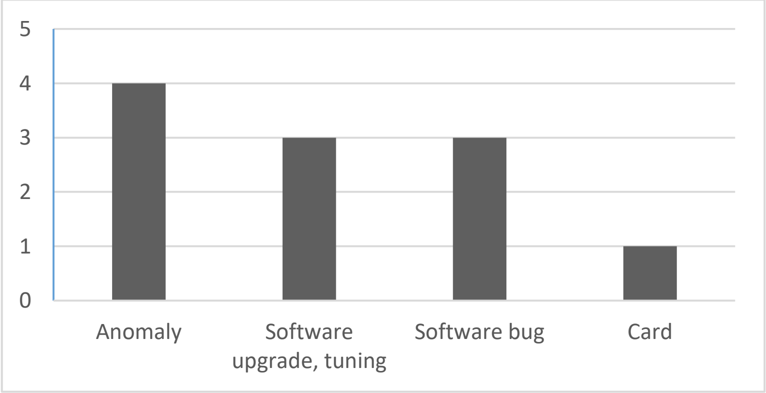

Figure 3.3.8 Computer failures leading to "drive off" incidents (*by author*)

The analyses revealed two main scenarios for a ‘drive off' incident caused by computer software error:

- Single or all thrusters produce the unexpected full or excessive thrust.
- Overshooting of requested position.

No common patterns were discovered between drive off scenarios and the software errors causing them. Thrusters producing full or excessive thrust is the most common scenario for a drive off and can only be stopped by operator intervention. It was noticed that sudden change of parameters or other operator interaction with DP control system, after a continuous and steady operation, seems to be the common cause of ‘drive off’ incidents. Usually rebooting the controllers solves the problem.

Software updates as well as inadequate tuning of the DP system or mathematical model may cause the vessel to overshoot the required position or even cause the vessel to surge in any of the directions. A reboot has usually had no effect on rectifying such errors and often requires the software provider to be contacted for assistance.

Conceptual model of a ‘drive off’ incident caused by computer failure is shown on the figure 3.3.9.

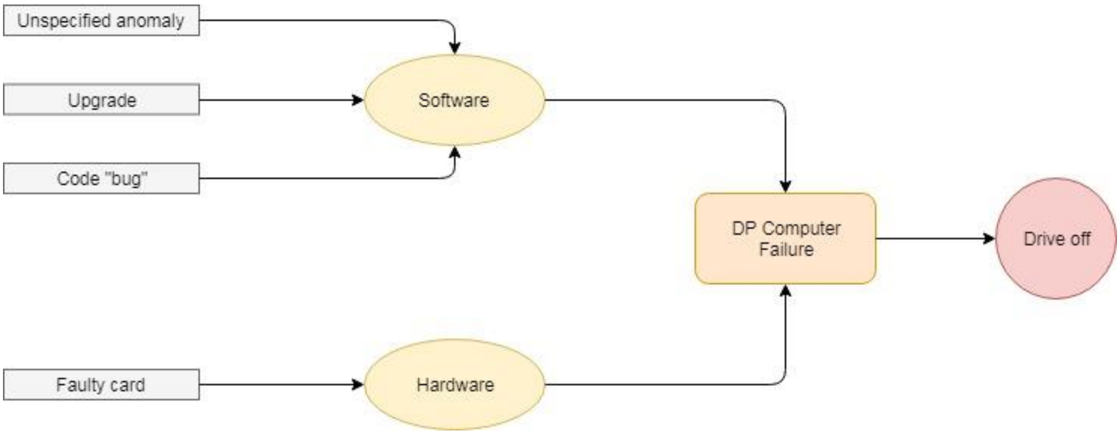

Figure 3.3.9 Conceptual model of “Drive off” incident caused by computer system failure (*by author*)

Only one 'drive off’ incident was discovered to be caused by a hardware failure. Network card failure within the operator station affected the commands and caused the vessel to slowly drive off the position.

3.3.7 Trends

To identify the trends in incidents caused by DP computer failure, the data for the period 2007-2015 was combined (Figure 3.3.10).

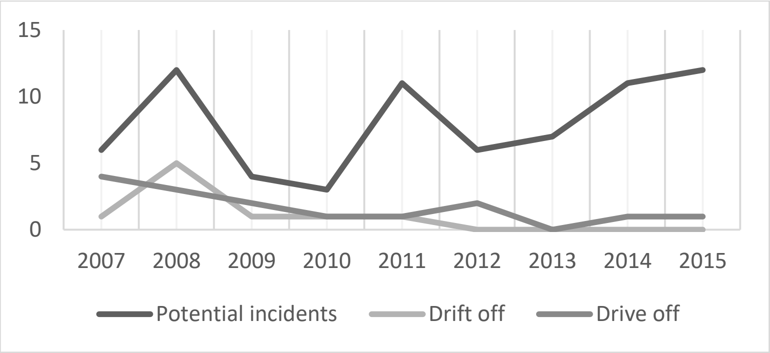

Figure 3.3.10 Trends of LOP incidents caused by DP computer failure (*by author*)

The number of reported potential incidents is on the rising trend. The last ‘drift off’ incident occurred in 2012. This may indicate that the redundancy concept has reached the desired performance. Also, the number of drive off incidents is considerably low, suggesting that major code and software problems have been eliminated by manufacturers.

3.4 Power system failures

3.4.1 Initial sorting

The power system is one of the most complicated and extensive systems on-board of the vessel. In addition to all of the common shipping regulations related to power systems, the power system of the DP vessels are required to comply with the redundancy requirements in accordance with the DP class notation. IMO provides the general redundancy requirements for the power systems according to the vessel’s Class notation. For Class 1 DP vessel the power system need not be redundant, for class 2 the system should be divisible into two or more systems in such a way that, in the event of failure of one system, at least one other system will remain in operation. For class 3 power system, all class 2 requirements apply; additionally, the divided power system should be located in different spaces separated by A60 class division. Where the power systems are located below the operational waterline, the separation should also be watertight. (IMO Circ.645, 1994) Requirements of the classification societies are usually more specific and address each subsection of the power system separately. For the instance, the ABS guide for DP vessels divides power system requirements into 4 different sections (ABS, 2013):

1. Power generation,
2. Power distribution,
3. Power management system,
4. Uninterruptible power supply systems.

Power generation addresses the generators and prime movers whilst the power distribution section stipulates the requirements of the switchboards and cabling network. To assist the designers of the DP systems in fulfilling all of the requirements related to redundant power systems, the recommended practises and design philosophies are available from different class societies and other DP related associations.

Many of the new DP operated offshore vessels are equipped with diesel-electric propulsion (Sørfonn, 2007, 5). Electrical propulsion system consists of the prime mover and a generator, commonly called the gen-set. Gen-sets produce all necessary electrical energy required on-board. Produced energy is then distributed to consumers including propulsion thrusters. The number of gen-sets installed on-board depends on the vessel's power and its redundancy requirements. Typical DP vessel power plants have four, six, or eight gen-sets connected to two or more switchboards. Engines for an electric power plant are most commonly liquid fuelled, four-stroke, turbocharged medium speed diesel engines (IMCA M 206 Rev.1, 2016). Synchronous alternating current generators, more commonly called alternators, are the most commonly used on board DP ships.

In this section, all incidents caused by power system failure are analysed. In total, 82 IMCA reports are transferred into the Excel file. After initial sorting, some adjustments were made with regard to the main failures and were moved as follows:

- Moved to 'propulsion' subsection – 2 reports
- Removed as 'human factor' – 10 reports
- Removed from the list – 2 reports
- Added from 'Propulsion' subsection – 15 reports

Not following the procedures, when operating the switchboard or unintentional stopping of the gen-sets through accidentally pushing the stop or emergency stops, are just some examples of human errors what may lead to loss of position incident.

3.4.2 Failure groups and causes

By analysing 83 reports, the main causes of failures were identified, grouped, and the frequencies of their occurrence were calculated (table 8). The main cause of 18 incidents was not identified.

Table 8. Power system common failures causes (by author)

Failure group	Cause	Potential incidents	Drift off
PMS	Breakers disconnecting automatically	2	
	Faulty controller	1	
	Incorrect set-up	1	
Control equipment	Governor actuator failure, overspeed	1	3
	Governor incorrect settings	1	
	Sensor (speed, other)	3	
	Protection equipment failure	2	1
	Loose wire	2	
	Air supply	1	
Excitation Systems	Voltage and frequency fluctuations		1
	Unspecified AVR errors	2	1
	Faulty Diode plate or exciter	1	
	Exciter anomaly	1	
UPS	Unspecified errors	2	
	Cooling fan	1	
	Voltage control	1	
	Loose connection	1	
	Faulty switch	1	
	Chargers		1
Fuel system	Fuel pump failure	3	1
	Blocked filters	1	3
	Fuel HP pipe leak		1
	Water contamination in fuel tanks	1	
Oil system	Oil seal failure	1	
	Oil pressure sensor failure	1	
	Oil leak causing low pressure	1	
Cooling system	Blocked SW strainers		1
	Thermostat failure	2	
	SW pump failure	1	
	Leaks	1	
Electrical	Generator Internal short circuit	2	3
	Consumer short circuit, earth fault	3	2
	Distribution, cabling, blown fuses	2	
	Transformer failure	1	
Engine component	Bearing	1	
	Rocker gear	1	
	Fuel injector failure	1	
Unknown		12	6

In total, 9 failure groups were formed (Figure 3.4.1):

1. Power management system (PMS)
2. Engine control and protective equipment
3. Automatic Voltage regulators (AVR)
4. Uninterruptible Power Supply (UPS)
5. Fuel system
6. Lubricating oil system
7. Cooling system
8. Engine hardware component
9. Short circuit

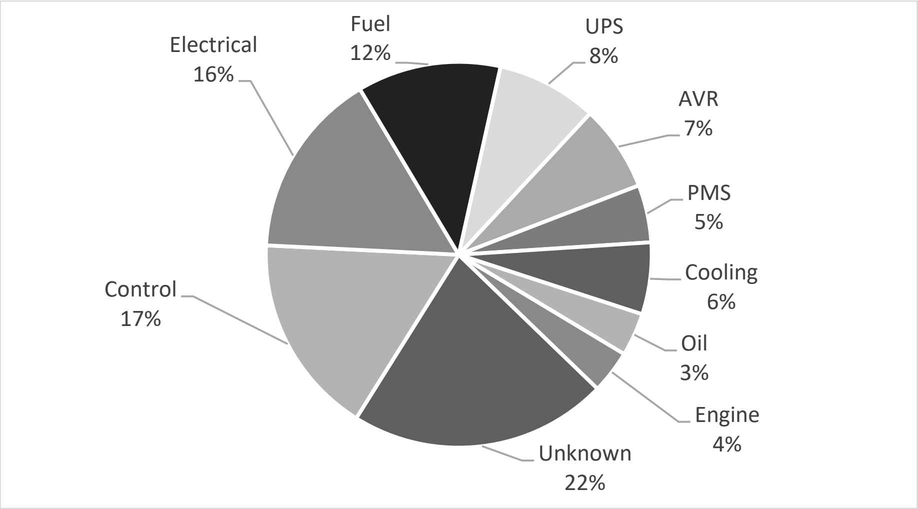

Figure 3.4.1 Failure groups of "Power system" (*by author*)

There are many power system failures that can affect the operation of DP related systems in any power plant configuration. Power system is the most extensive DP related system and incorporates an enormous amount of equipment and components. Alternators and the prime movers are both complicated machines which work under a high thermal and mechanical load for extended periods of time. This makes them vulnerable to all kinds of failures and errors. Power system also incorporates a large amount of auxiliary systems including cooling, fuel, lubricating oil as well as compressed air, just to mention a few. Mechanical breakdowns of the engine or any essential auxiliary system component may affect the power plant power output. *Fuel system faults are associated with blockages, leaks and contamination by water* (IMCA M 206 Rev. 1, 2016, 28). Low oil pressure will initiate an automatic 'stop' of the engine. Cooling problems may contribute to the overheating of the engines and, as consequence, the engine will be stopped. Engine control systems including governors, actuators, speed sensors, and other related components may affect the power plant in many different ways. There is also a large number of other protection equipment for the prime mover and alternators; the failure of which may trip the related machine. Electrical failures such as short circuits, earth faults, transformer failures, may have a strong impact on the integrity of the electrical system depending on the severity. Electrical cables may suffer from mechanical or/and environmental damage.

After all incident reports were sorted and failure groups assigned, it became obvious that some of the failure groups can be categorised into fewer content-related categories (Table 9).

Table 9. Power system groups (*by author*)

Power system	**Associated equipment**
Power generation	Engine control equipment, AVR, fuel system, oil system, cooling system, engine component, alternator internal short circuits and earth faults
Power distribution	Electrical (excluding alternator internal faults)

The distribution system includes transformers, cables, switchboards, and switching equipment. Domestic and vessel specific electrical equipment, the failure of which may affect the electrical network, are also considered as a part of distribution system.

According to results, the power generation is the highest source of 'Power system' failures Figure 3.4.2).

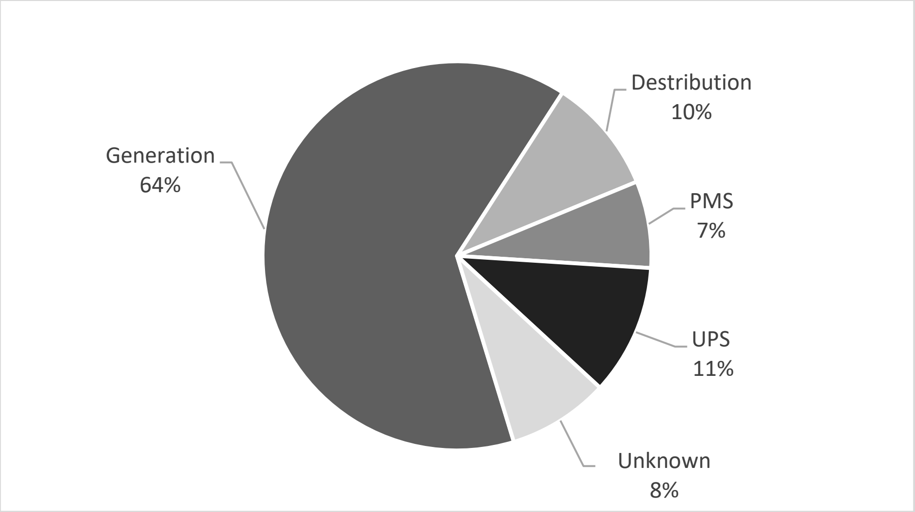

Figure 3.4.2 Failure groups of "Power system" (by author)

Despite integrated power management systems and uninterrupted power supplies are parts of the distribution system, the failures within those systems are very specific; for the purpose of this study, they are considered as a separate system.

To give an insight into the overall reliability of the mechanical and electrical equipment of the power system, the incidents were sorted by the type of the failure. The result is shown on figure 3.4.3.

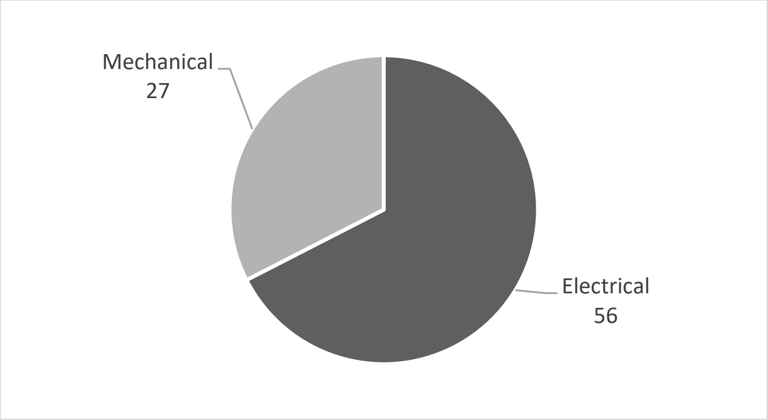

Figure 3.4.3 Mechanical failures vs electrical (*by author*)

Mechanical equipment incorporates power plant related equipment, what does not have a direct contact with electrical power. Engine parts, pumps, thermostats, filters, just to name a few. Those components are usually robust allowing failures to be prevented at the earlier stages. Electrical/electronic equipment of the diesel-electric power plant are very extensive and consist of many different elements. Preventative maintenance is achievable to some degree, however, many components may fail unexpectedly. Despite a small degree of a possible error in data interpretation, it is obvious that electrical components fail more frequently.

3.4.3 Incident types and frequencies

The ‘power system failure' incident frequencies, relying on the data based on 83 reports, are shown on figure 3.4.4. According to the analysed data, actual loss of position occurred 24 times causing the vessel to drift off position.

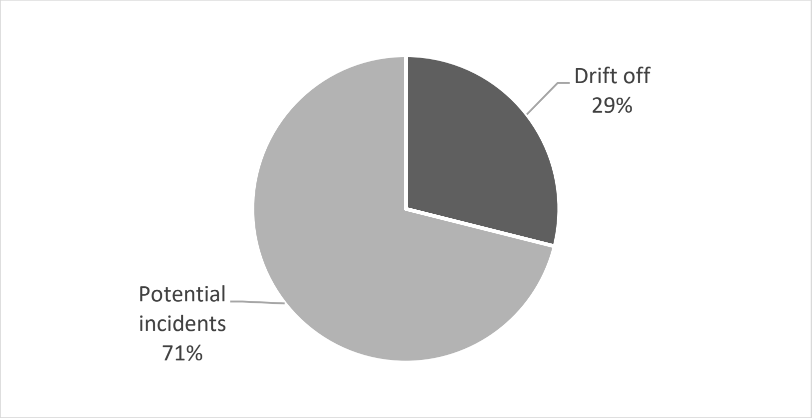

Figure 3.4.4 Incidents caused by Power system failure (*by author*)

The power system of the DP2 vessel is required to be a single failure tolerant. This means that any single failure on the power system shall not affect the vessel’s ‘station keeping’ capability. Even after a worst-case failure, the amount of available power as well as the control systems should be sufficient enough to safely abort the task or continue with reduced redundancy. The analysed data shows that, if not prevented or interrupted, the power system failure will lead to a ‘drift off’ incident. No ‘drive off’ scenarios, caused by power system failure, were found during this study.

3.4.4 Potential incidents

It total, 59 incidents were categorised as potential incidents. The cause of 12 incidents was not identified.

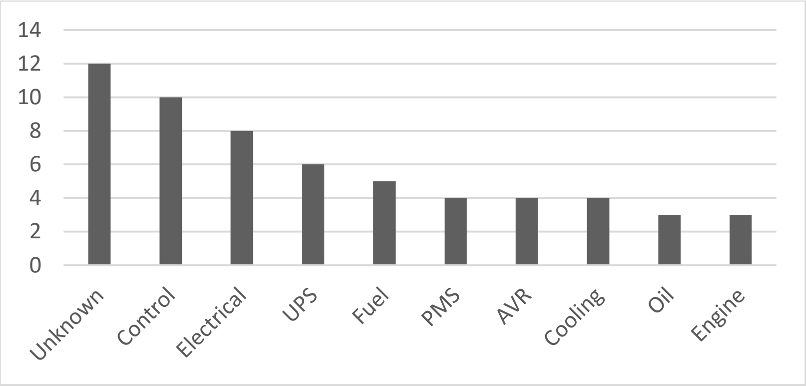

Figure 3.4.5 Power system failures leading to potential incidents (*by author*)

Failure within the control system caused the most potential incidents (Figure 3.4.5). Faulty speed pick-up sensors and charge air shut off proximity sensors may activate an auto-shut down of the engine. Usually, one engine is affected at a time. Depending on the configuration of the switchboard, loss of one engine may lead to reduced power output, reduced redundancy, or partial blackout. Protection equipment is designed to monitor different parameters of the machines and some are programmed to stop the gen-sets if any parameter is out of the pre-set limit. According to incident data, failure of a power protection system and failure of generator voltage differential protection may lead to partial blackout and loss of multiple thrusters. Loose connection within a 24V power supply to the engine or loose wire on the governor may cause a partial blackout. The control air pressure reducing valve and governor actuators may also be the reasons of potential incidents.

Damaged wires were mentioned as a cause of an alternator internal short circuit as well as short circuits within the network. Vibration and improper installation were the contributing factors. A short circuit, depending on the severity and location, might trip one or several breakers on the same line which would cause partial or full blackout and loss of thrusters.

According to the data, UPS failed after a short circuit occurred within the HPR power supply. As a result, essential DP equipment was left with no power. Earth fault or spikes within the network may blow the fuses and interrupt the power supply to the thrusters.

UPS are used to supply power to a vital part of the DP system. Errors within the UPS such as loose wires, faulty cooling fans, batteries, and switches may lead to total failure of the UPS and, as a result, related equipment would become unavailable.

Most of the potential incidents within the fuel system group were caused by the fuel pump failure. Engine automatic or manual shut down was initiated after such failures. Generally, only one engine was affected during the incident, meaning that fuel pumps were related to one particular engine. However, no information regarding stand-by pumps status were provided within reports. The main engine stopped and all thrusters connected to this engine tripped as a result of an automatic fuel filter failure (type unspecified). Water contamination of a fuel service tank was the cause of high exhaust temperature deviation on the engines. As a result, two generators and three thrusters became unavailable.

Failure within the power management system software left one half of the switchboard black by spontaneously opening the breakers. It was also reported that PMS was not able to cope with the increased power demand during bad weather due to an incorrect set-up. Human factor may be considered as a secondary cause of such incident. According to the incident data, PMS controller failed only once during a 9 year period.

Unspecified AVR errors were found to be the main cause of generators going offline. Also, anomalous behaviour of the diesel generator exciter left one part of the bus bar unresponsive to change in power demand. The engine was stopped for repairs after excitation system diode plate failed.

Failures within the cooling system were caused by faulty thermostats and sea water pump failures. The engine may overheat due to thermostat failure and will be automatically or manually stopped. *Control valves are generally designed to fail to full cooling. Fail ‘as set’ may not be sufficient to prevent temperature instability in the power plant. Wax element type valves may fail to open on rising temperature but the use of multiple elements means that failure is usually gradual, providing an opportunity for the degradation of performance to be noticed*. (IMCA M 206 Rev. 1, 2016, 32) Depending on the system configuration, failure of the sea water pump will reduce overall redundancy of the cooling system. According to one report, a cooling water leak caused the earth fault on the shaft generator and, as a result, the shaft generator and related thruster tripped.

Engines are protected against low oil pressure. Failure of the pressure sensor, or low oil pressure due to a leak, will initiate auto-stop of the engine.

Engine components failures were only reported three times during the entire period of 9 years, making the internal combustion engine the most reliable part of the power system.

For the DP vessel, redundancy in power supply system is fundamental. According to redundancy philosophy, a single failure shall not cause or prevent the vessel from station keeping (Sørfonn, 2007). The electrical system of a DP class 2 vessel is normally arranged as two separate systems with bus-tie being a point of connection between them. Bus-tie is normally closed during DP operation. Each system has dedicated thrusters and generators connected to it. If failure occurs on one system, the other will remain intact and the vessel will be able to maintain position or it will have enough power and propulsion to safely terminate the operation. The same principles apply to all sub-systems and they should be segregated in the same way. In reports, considered as potential incidents, vessels were able to maintain position and had enough capability to continue or safely terminate the operation.

3.4.5 Drift off

In total, 24 ‘drift off’ incidents were discovered being caused by ‘Power system’ failures. Causes of 6 ‘drift off’ incidents were not identified.

Failures within the fuel, electrical, and control groups cause most of the ‘drift off incidents; (Figure 3.4.6). AVR, UPS, and cooling system failures may also lead to such incidents.

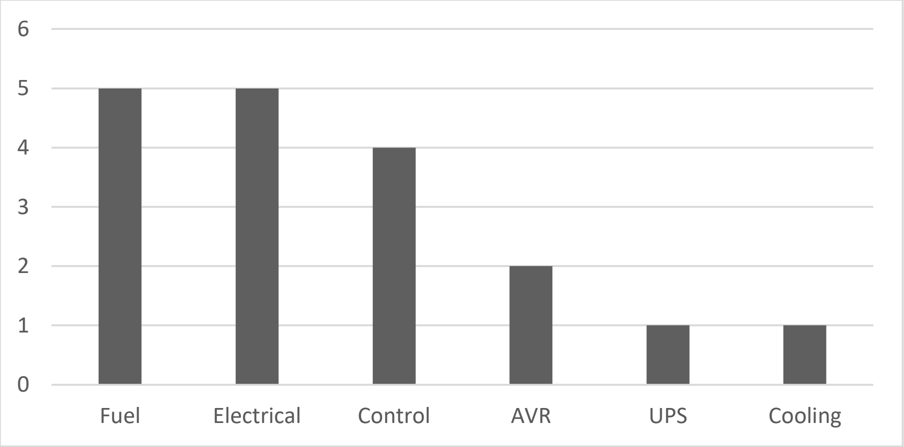

Figure 3.4.6 Power system failures causing “drift off” incidents (by author)

Most of the fuel system failures were caused by bad fuel quality, resulting in the blockage of the fuel filters. Blocked fuel filters may affect the power plant as follows:

- Fuel supply is not sufficient to maintain the load and engine stops on fuel starvation (main engine).
- Fuel supply is not sufficient to maintain the RPM and generator trips on ‘under frequency’ (gen-set).
- Fuel supply is not sufficient and generator trips on ‘reverse power’ (gen-set).

Also fuel pipe leaks caused the fire in the engine room and, as a result, the essential DP system cables were damaged; unfortunately, the report does not specify the type of the fuel line (high or low pressure). According to the SOLAS 74 convention, engines that do not have double high-pressure fuel piping must be converted (Solas Convention, 1974). IMCA publication ‘Fires in the machinery spaces’ states that the low-pressure side of the fuel oil system has proved to be a hazard as well (IMCA M 119 Rev.1, 2016).

A generator internal short circuit and short circuits within the domestic electrical network may lead to drift off. *Severe short circuits will induce a momentary voltage drop. If the complete network is connected together this voltage drop will be seen in the entire network. This kind of voltage drop will always be present during short circuit conditions and all consumers connected to these networks may trip or stall if the voltage cannot be maintained* (Sørfonn, 2007, 13). Analysed data shows that position is lost mainly due to the tripped thrusters after a severe short circuit. As a result, the vessel loses its capability to maintain position.

Control system failures leading to ‘drift off’ were caused by an error within the governor or actuator as well as by a faulty ‘reverse power’ microswitch. The engine governor controls the fuel admission to the engine. Conventional AC generators operate at constant speed and the governor is arranged to maintain this speed. The most common governor types are electronic governors with electric or electro-hydraulic actuators to control the fuel rack on the engine. Many older vessels are fitted with hydro-mechanical governors (IMCA M 206 Rev.1, 2016). Governor malfunction may cause severe active power sharing imbalance and voltage/frequency fluctuations in the network; these may trip the thrusters and other sensitive protective equipment. ‘Fail to full power’ is the failure mode of greatest concern as this can cause one generator to take the entire system load. Depending on the generator rating relative to the load size, the faulty machine may or may not trip on overload. If the machine rating is larger than the available load, the healthy generators connected to the system will trip on reverse power. (IMCA M 206 Rev.1, 2016) A fuel control error may also lead to the engine overspeed. In this case ‘overspeed protection’ will shut down the engine. Analysed incidents suggest that single governor or actuator malfunction may lead to a severe consequence and cause a serious ‘drift off’ incident.

A typical AVR failure affecting more than one generator may occur if the AVR causes over-excitation. This may disrupt reactive power sharing causing healthy machines to operate in the capacitive region and trip on under excitation (IMCA M 206 Rev.1, 2016). Such failure will lead to full blackout and vessel will drift off position.

Two main engines and two thrusters went offline after loss of DC chargers to the battery bank. Engine control power is typically 24Vdc which may be derived either from a DC power supply with battery backup or from a control system which is powered from a

UPS (IMCA M 206 Rev.1, 2016). Such incident may only occur if both engines have a common source of control power supply.

By analysing the reports, it was discovered that one serious ‘drift off’ incident was caused by the ingress of small fish into the power plant cooling system. As a result, all engines tripped on a ‘high water temp’ and the vessel experienced a total blackout. On a modern vessel, seawater is normally used to cool down the fresh water. Seawater enters the vessel through the strainers, passes through the heat exchangers, and then discharged back to sea. By providing several separate seawater intakes and segregating the system, such incident may avoided. If all sea water intakes become blocked simultaneously, the blackout can only be prevented by the crew taking the immediate and appropriate actions.

Conceptual model of drift off incidents is shown on the figure 3.4.7.

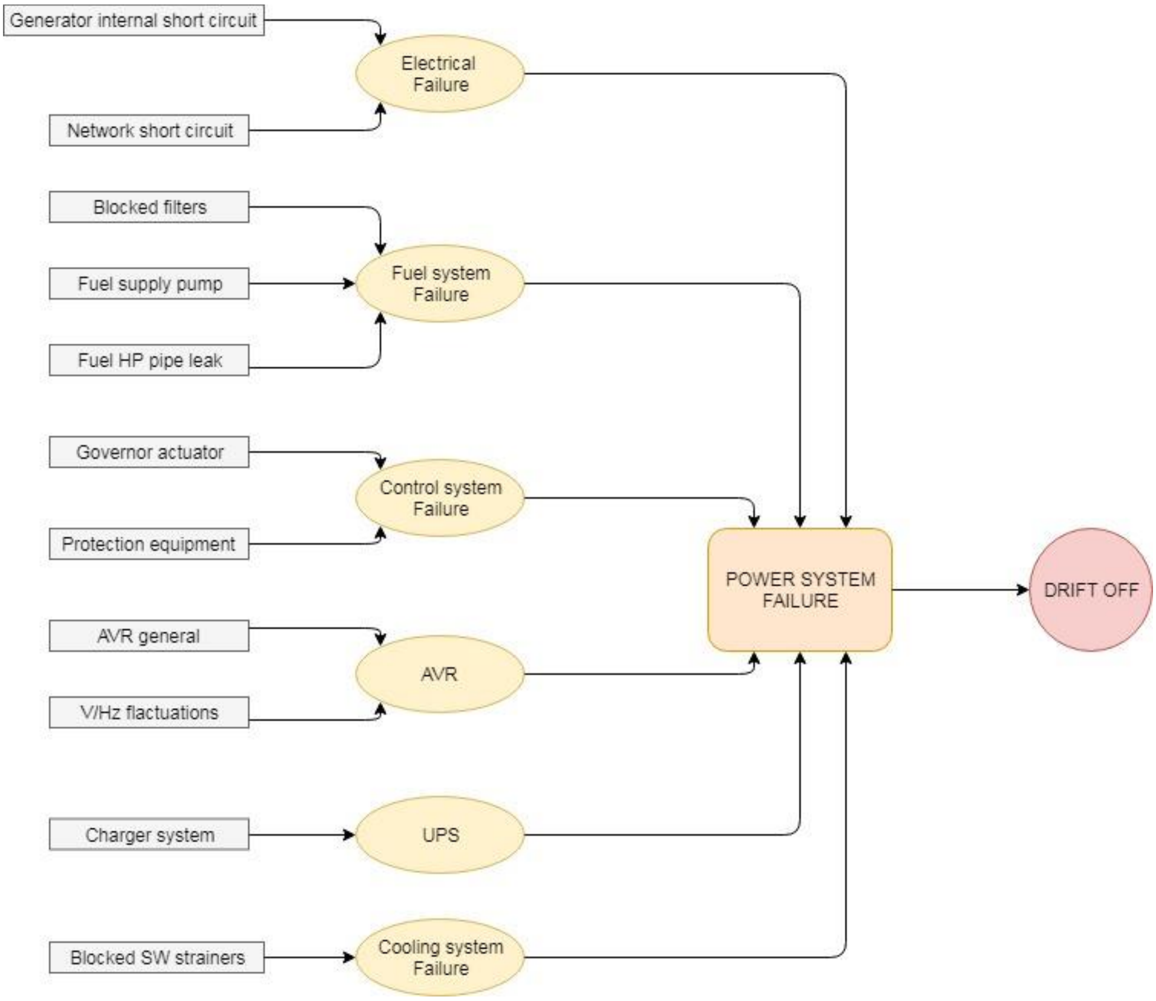

Figure 3.4.7 “Drift off” incidents caused by power system failure (by author)

3.4.6 Trends

To identify the trends of the incidents caused by DP computer failure, the data for the period 2007-2015 was combined (Figure 3.4.8).

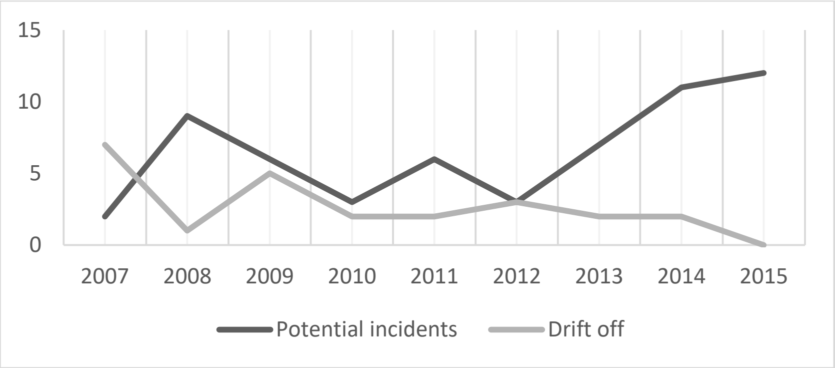

Figure 3.4.8 Trends of the LOP incidents caused by power system failures (by author)

The number of potential incidents has been rapidly rising in the recent years. The trend of ‘drift off’ incidents, on the other hand, is declining. This may indicate that, while equipment is getting older and fail more frequently, the redundancy and availability of the backup power reduces the number of actual LOP incidents.

4 Conclusion

The aim of this thesis was to determine the main causes of the most common failures of dynamic positioning system leading to loss of position incidents, discover trends and common patterns and find the connection between the failures and type of incident they cause. The task turned out to be more challenging than expected due to the fact, that information provided within the incident reports was limited and on some occasions controversial. However, by conducting indicative content analysis, the common patterns were identified and connections between failures and type of incidents discovered. Initial sorting of the incident reports revealed, that the failures within propulsion, power, position reference and computer systems cause the majority of loss of position incidents. Each aforementioned system was considered as a separate research topic. Such approach allowed to make adjustments to coding and categorisation process, in order to obtain structured and systematic results.

The main discoveries of the research may be summarised as follows:

- The main causes of the propulsion system failures lie within the control and feedback systems. Despite thrusters are designed to fail safe to low or zero thrust, drive off incidents occur more often than drift off incidents. This fact may be considered as a clear evidence that thrusters still fail to full thrust.
- Interference is the main cause of position reference system failures. The number of drift off and drive off incidents is very similar, making outcome of such failure rather unpredictable. This finding also indicates that procedures and recommendations for use of position reference systems are not followed.
- Computer systems fail mostly due to software errors and cause two times more drive off incidents that drift off incidents. It is very difficult to establish the real cause of software failure, as it usually lies within the code. However, software errors are normally resolved by rebooting the computer.
- Obtained data indicates that power system failure will lead to drift off incidents exceptionally. Short circuits and fuel system failures cause the most incidents. The most surprising results is that blocked fuel filters are among the most common causes of drift off incidents.

The conceptual models of the LOP incidents created as an outcome of this research provide a valuable information at a glance. They can be useful tools in a risk assessment process or when planning and carrying out planned maintenance of the vessels dynamic positioning system and other related equipment. Models show the most vulnerable components and most common causes of failures leading to LOP incidents. As a recommendation, more attention should be given to such components and sub-systems to avoid any future incidents and undesired events.

Data obtained as a result of the analysis also contains valuable numbers of incident occurrences and failure rates. Such information can be used in the future works to conduct quantitative analysis and prepare the base for probabilistic risk assessments.

5 Lühikokkuvõte

Laeva dünaamiline positsioneerimine on laeva automaatjuhtimise moodus, mida kasutatakse laeva paigal hoidmiseks või täpsust nõudvate manöövride teostamiseks, kasutades selleks laeva enda propulsiivseadmeid. See moodus võimaldab hoida laeva paigal kohtades, kus ankru kasutamine on vee sügavuse või muude asjolude tõttu võimatu. Dünaamilise positsioneerimise süsteem hõlmab enda alla kogu laeva seadmeid, mis on seotud dünaamilise positsioneerimisega.

Käesoleval magistritööl oli kaks eesmärki:

- määrata põhilised dünaamilise positsioneerimise süsteemi tehnilised rikked ja nende põhjused
- seostada DP süsteemi rikked positsiooni kaotamise tüübiga

Eesmärkide täimiseks analüüsiti „International Marine Contractors Association“ poolt avaldatud ajalooliste intsidentide raporteid ajavahemikust 2007-2015. Analüüsiks kasutati kvalitatiivset lähenemist ja rakendati induktiivset sisuanalüüsi.

Töömahu vähendamiseks keskenduti vaid põhiliste rikete uurimisele, milleks on propulsiivseadme, kohaviite süsteemi, DP arvuti ja laeva jõuseadmete rikked. Vastavalt IMCA andmetele põhjustasid just need rikked 72% kogu intsidentidest antud ajaperioodil.

Analüüs hõlmas enda alla põhiliste rikete ja nende põhjuste määramist ja grupeerimist. Lisaks uuriti rikete mõju laeva positsiooni hoidmisele, mille tulemusena grupeeriti intsidendid kolme rühma: kohalt ära triivimine, kohalt ära sõitmine ning potentsiaalsed positsiooni kaotamise intsidendid. Selleks, et määrata enam levinud rikked, viidi läbi rikete sagedusanalüüs. Tulemuste esitamiseks loodi kontseptuaalsed intsidentide mudelid, kus rikked ja nende põhjused on näidatud reastatuna vastavalt nende esinemise sagedusele.

Analüüsi tulemusena selgus, et propulsiivseadme, kohaviite süsteemi ja DP arvuti rikked põhjustavad suurema tõenäosusega kohalt ärasõitmise intsidenti. Jõuseadme rikked põhjustavad aga ainult äratriivimise intsidente. Propulsiivseadmete nõrgemaks lüliks on tagasiside ja juhtimissignaaliga seotud probleemid, aga ka hüdraulika juhtklappide rikked. Kohaviitesüsteemi probleemne koht on interferents ja selle mõju DGNSS-le ja teistele kohaviite süsteemidele. DP arvuti langeb rivist välja enamasti vaid tarkvara probleemide tõttu. Anomaaliad, tarkvarauuendused ja koodivead põhjustavad enamuse intsidente. Lühised ja kütuse kvaliteet on jõuseadmete rikete suuremad põhjustajad.

Uurimustöö tulemusena saadud andmed on võimalik rakendada DP süsteemi ja selle osade hoolduse planeerimisel ja riskide analüüsimisel erinevate DP operatsioonide ettevalmistamisel.

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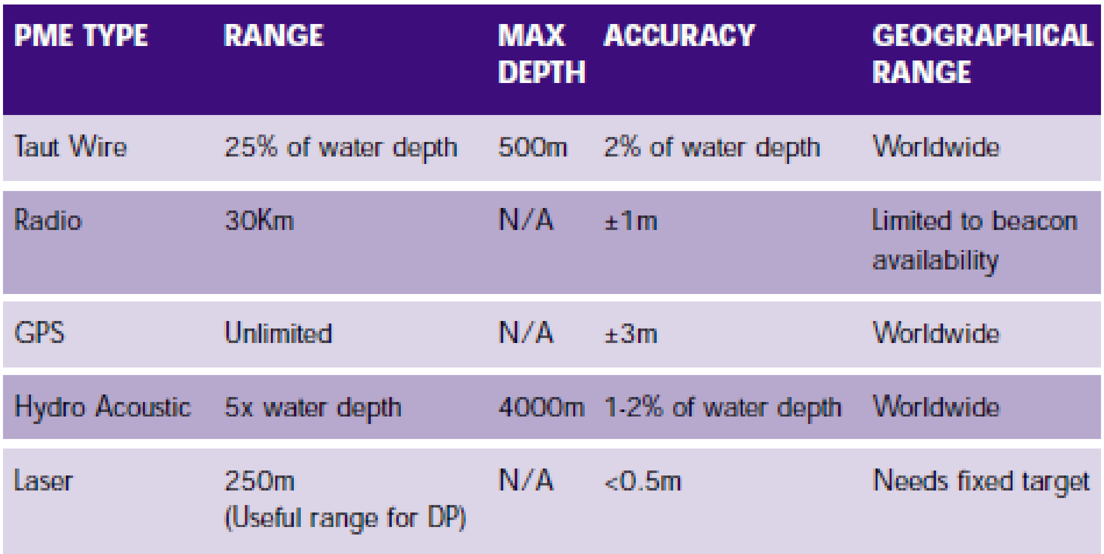
Appendices

Appendix 1 DP system operational modes (Guide to Dynamic Positioning of Vessels“, Alstom 2000)

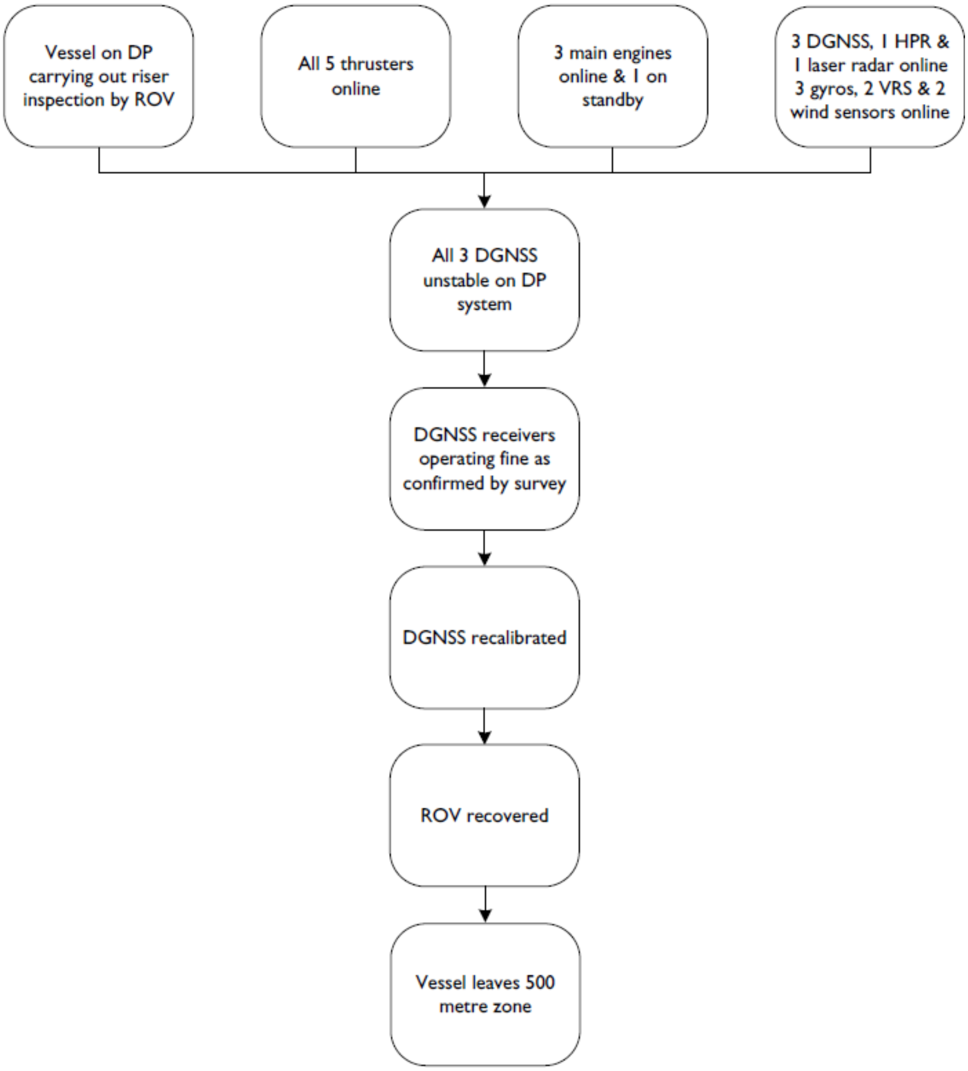
Joystick Manual Heading (JSMH)	The vessel is controlled by the joystick in fore/aft and port/starboard movement, and rotated by the turning control knob about its centre of rotation. This mode is used for totally manual vessel manoeuvring.
Joystick Auto Heading (JSAH)	The vessel heading is automatically controlled. The joystick controls fore/aft and port/starboard movement. This mode can be used for close manoeuvring.
DP	The vessel heading and position are both automatically maintained. This mode is used to maintain a fixed position in relation to a stationary target with a fixed heading.
Min Power/ Weathervaning	Maintains the heading of the vessel into the prevailing weather, while maintaining DP control.
ROV Follow	The vessel's position is maintained either relative to a moving target, such as a Remotely Operated Vehicle (ROV), or maintaining position until the ROV moves outside a defined area.
Auto Track	The vessel position is automatically moved along a track, at a set low speed, between two or more predetermined points (waypoints) with automatic heading control.
Auto Pilot	Normally uses main propulsion and rudder to move along a fixed course. Used as a transit mode. Azimuth thrusters can be used instead of main propeller and rudders.
Auto Sail	Providing forward movement along a track with automatic heading control to keep the vessel on track, normally uses main propulsion and rudder only. Used as a transit mode. Azimuth thrusters can be used instead of main propeller and rudders.
Auto Speed	Maintains zero or constant low fore/aft and port/starboard speeds using Doppler Log signals with automatic heading control.
Pick-up/Fixed Loading	Vessel heading determined by prevailing weather whilst position maintained at fixed point. Used for Shuttle Tankers.
Approach/Loading	Vessel heading determined by prevailing weather whilst position maintained at fixed distance (radius) from a reference (base) point. Used for Shuttle Tankers.
Riser Follow	Controls the position of the vessel so that the riser angle tends towards zero. Used for drilling vessels
Simulation	An offline mode providing simulated input/output data for training and testing in all modes.
Model Control	Maintains vessel in current operational mode in the case of position or heading sensor failure.

Appendix 2 Characteristics of different reference systems. (Guide to Dynamic Positioning of Vessels“, Alstom 2000)



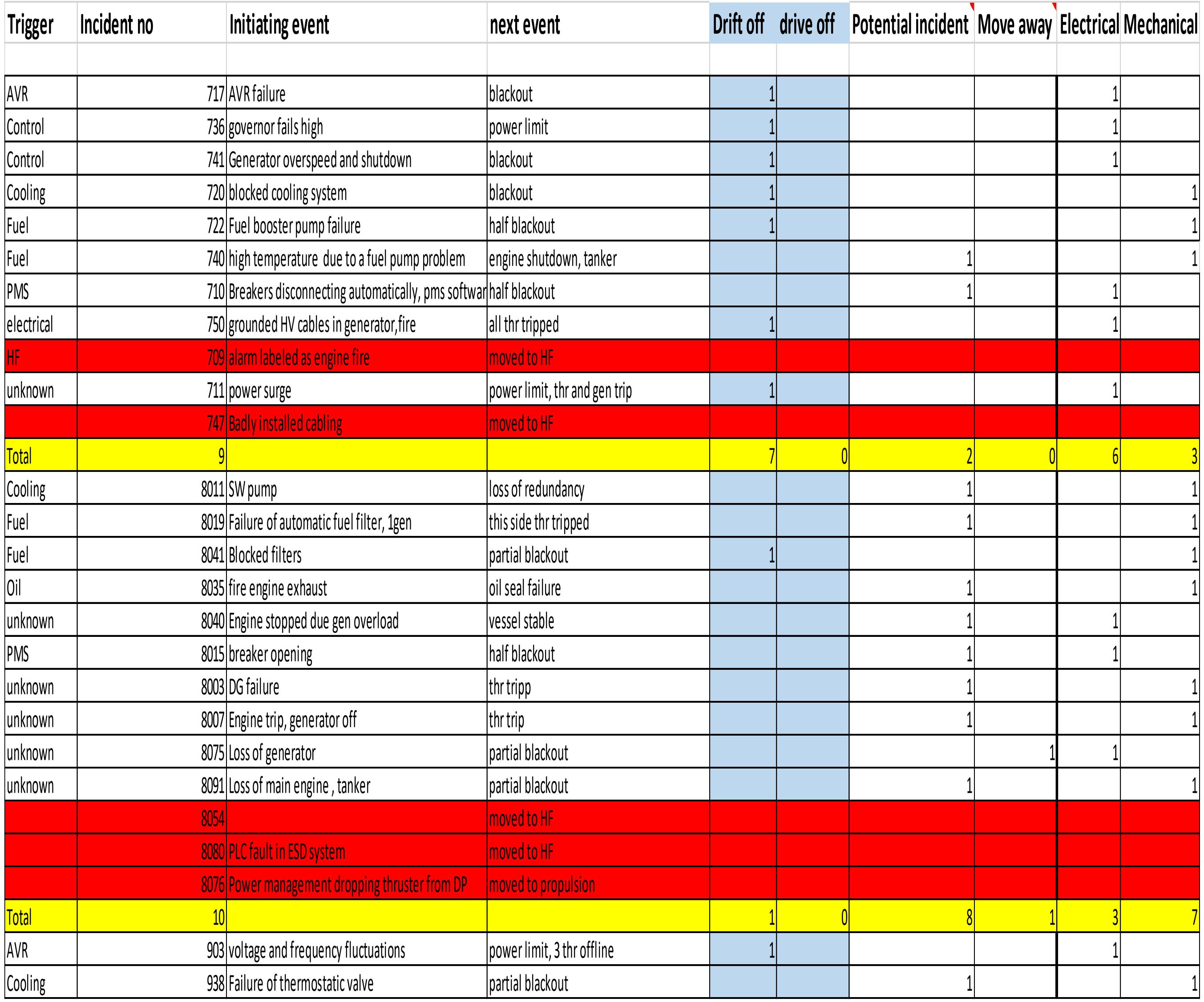
PME TYPE	RANGE	MAX DEPTH	ACCURACY	GEOGRAPHICAL RANGE
Taut Wire	25% of water depth	500m	2% of water depth	Worldwide
Radio	30Km	N/A	±1m	Limited to beacon availability
GPS	Unlimited	N/A	±3m	Worldwide
Hydro Acoustic	5x water depth	4000m	1-2% of water depth	Worldwide
Laser	250m (Useful range for DP)	N/A	<0.5m	Needs fixed target

Appendix 3 Example of incident report published by IMCA (IMCA)



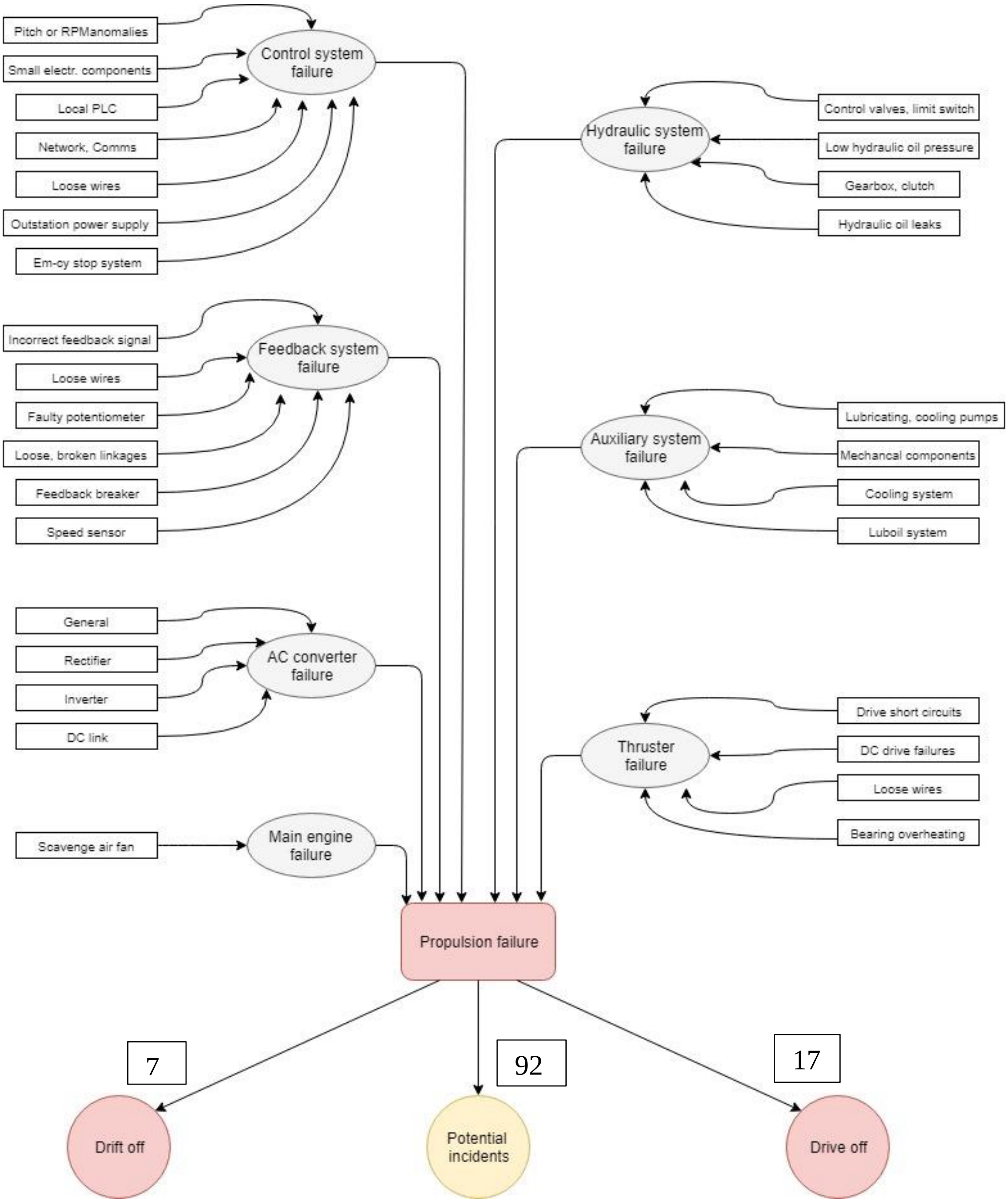
Comments	DGNSS and DP controllers rebooted after departure from 500 metre zone
Initiating Event	Instability in DGNSS
Main Cause	Reference – Poor DGNSS signals
Secondary Cause	Computer – Tuning of DP system

Appendix 4 Sorting file in Microsoft Office Excel (by author)

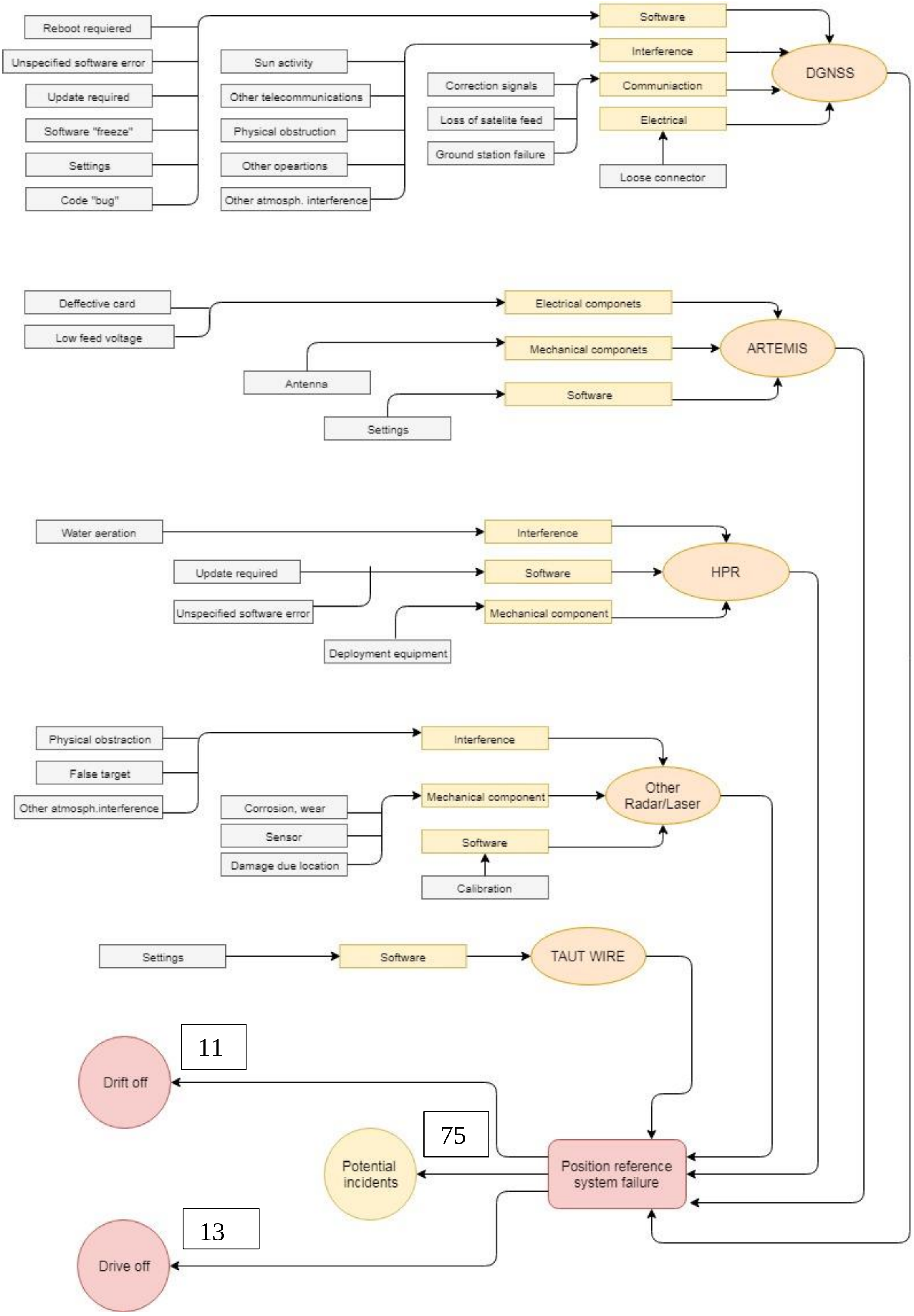


Trigger	Incident no	Initiating event	next event	Drift off	drive off	Potential incident	Move away	Electrical	Mechanical
AVR	717	AVR failure	blackout	1				1	
Control	736	governor fails high	power limit	1				1	
Control	741	Generator overspeed and shutdown	blackout	1				1	
Cooling	720	blocked cooling system	blackout	1					1
Fuel	722	Fuel booster pump failure	half blackout	1					1
Fuel	740	high temperature due to a fuel pump problem	engine shutdown, tanker			1			1
PMS	710	Breakers disconnecting automatically, pms softwar	half blackout			1		1	
electrical	750	grounded HV cables in generator,fire	all thr tripped	1				1	
HF	709	alarm labeled as engine fire	moved to HF						
unknown	711	power surge	power limit, thr and gen trip	1				1	
	747	Badly installed cabling	moved to HF						
Total	9			7	0	2	0	6	3
Cooling	8011	SW pump	loss of redundancy			1			1
Fuel	8019	Failure of automatic fuel filter, 1gen	this side thr tripped			1			1
Fuel	8041	Blocked filters	partial blackout	1					1
Oil	8035	fire engine exhaust	oil seal failure			1			1
unknown	8040	Engine stopped due gen overload	vessel stable			1		1	
PMS	8015	breaker opening	half blackout			1		1	
unknown	8003	DG failure	thr tripp			1			1
unknown	8007	Engine trip, generator off	thr trip			1			1
unknown	8075	Loss of generator	partial blackout				1	1	
unknown	8091	Loss of main engine , tanker	partial blackout			1			1
	8054		moved to HF						
	8080	PLC fault in ESD system	moved to HF						
	8076	Power management dropping thruster from DP	moved to propulsion						
Total	10			1	0	8	1	3	7
AVR	903	voltage and frequency fluctuations	power limit, 3 thr offline	1				1	
Cooling	938	Failure of thermostatic valve	partial blackout			1			1

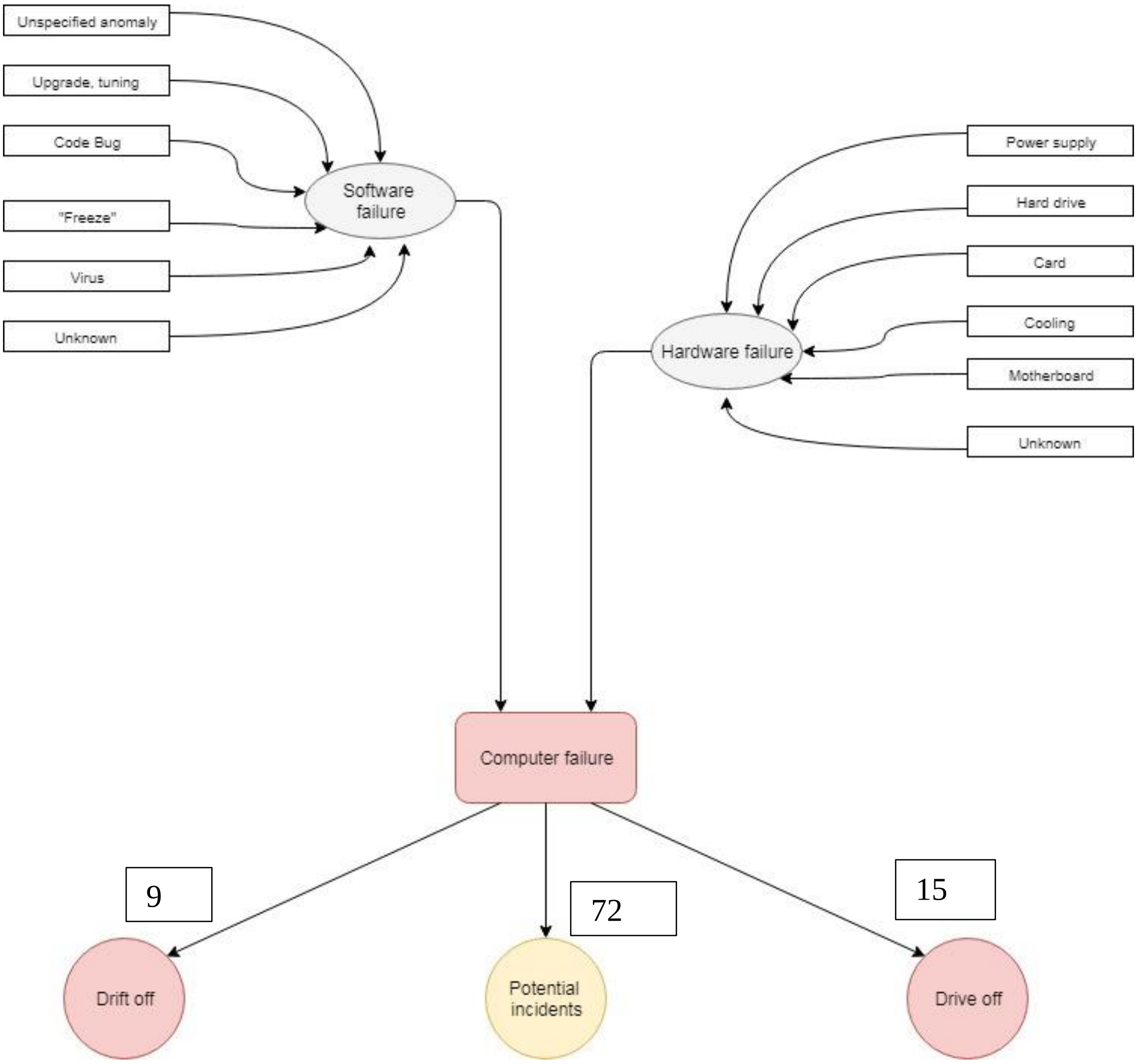
Appendix 5 Incidents caused by “Propulsion system” failure (by author)



Appendix 6 Incidents caused by “Reference system” failure (by author)



Appendix 7 Incidents caused by “Computer system” failure (by author)



Appendix 8 Incidents caused by “Power system” failures (by author)