Study of the condition monitoring system for an autonomous unmanned vessel engine

Carlos Marqués Tatay

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Carlos Marqués Tatay

Department of Mechanical- and Marine Engineering
Western Norway University of Applied Sciences
NO-5063 Bergen, Norway

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Høgskulen på Vestlandet
Avdeling for ingeniør- og økonomifag
Institutt for maskin- og marinfag
Inndalsveien 28,
NO-5063 Bergen, Norge

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Author, student number:	Carlos Marqués Tatay,
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Supervisor at HiB:	Maneesh Singh
Assigned by:	uSEA Ocean Data
Contact person:	Carlos Marqués Tatay
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ABSTRACT

The maintenance of a ship engine can be carried out in different ways, as in all kinds of machines. The marine industry has evolved during the history, with different maintenance policies being implemented and new techniques being developed, with the sector moving towards remote and intelligent maintenance.

This thesis reviews this evolution in the maintenance tasks for marine power units, with special focus on condition monitoring, which consists of controlling the state of one or more characteristic parameters of the engine in order to notice abnormal changes that can be indicative of a potential failure, so measures can be taken to avoid it. The relevance of the Failure Modes and Effects Analysis is also studied in the thesis, as well as the method to transmit the obtained data.

All this information, however, is quite generic for all kinds of marine engines. This thesis focuses on the engine maintenance for the project developed by uSEA Ocean Data. This startup is creating an unmanned vessel that will operate for 30 days collecting data from the seabed and the offshore petrol installations.

The challenge then is to perform the maintenance on the engine, which will be a D7A-B TA (AUX) diesel genset provided by Volvo Penta, without the needs of human interaction. The proposed solution is the implementation of a condition monitoring system formed by various sensors and devices, that can ensure the safety of the vessel's operations without having a crew onboard.

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1. INTRODUCTION

1.1. Background

The use of condition monitoring is one of the most important practices in predictive maintenance between all kinds of industries and machinery. It allows to schedule the maintenance and to take preventive actions in order to avoid failure, by measuring different relevant parameters of the machine and comparing them to the normal or advisable values.

In the case of the marine industry, more precisely in its power systems, the use of condition monitoring has been fundamental for the correct operation of all kinds of vessels. The application of condition monitoring not only affects the safety and reliability of ships, as it can prevent the engine's failure from happening. It can also increase the efficiency of the operations, as it reduces the expense in changing broken pieces and the workforce that these replacements imply.

Many articles have been published about condition monitoring and fault diagnosis, from both theoretical and applied approaches. In the beginning of this practice, the signal acquisition was based on various field-testing techniques, and with the development of the technologies and communications, the sector has moved into more complex manners of data-acquisition and failure prediction. Nevertheless, most of the current condition monitoring system still require the human intervention in some stage of the process. This is where the challenge of this project lies.

The company uSEA Ocean Data is developing an unmanned vessel that will operate for 30 days collecting data for subsea operations, such as marine mineral and geophysical seabed mapping, bathymetric and hydrographic survey, and pipeline and cable inspection. The boat will sail with no crew onboard, being controlled remotely, and will deploy underwater unmanned drones that will perform the survey of the seabed.

This unmanned vessel will have a pair of diesel gensets as a power source, in particular, the D7A-B TA (AUX) manufactured by Volvo Penta. The purpose of this thesis is to propose a maintenance system based on condition monitoring to ensure the proper preservation of the engine and the safety of the vessels operations, without the presence of people onboard.

1.2. Motivation

During the years of my university studies, I have obtained lots of knowledge from the different courses I have taken, but it is really exciting to be able to put all the information that I have learned into a real project.

It has been a fantastic opportunity to work with uSEA Ocean Data, and to be able to help them during the development process of the autonomous vessel. It is really motivating working with such a new and innovative company, and to push the limits of the marine sector incorporating the new technologies that are available and continuously evolving.

Being able to have a fully unmanned vessel in the sea doing the task that would normally require a crew on board, not only will increase the company effectiveness and results, which is always important, but it will also reduce the risks of having people on-board when difficult weather conditions take place. In addition, being part of this project that will help reduce the impact of these operations in the environment is really gratifying, as it is our responsibility to make sure that we lead the new technological advances into a greener future.

1.3.Aim of the thesis

The objective of this project is to set the initial description of a condition monitoring system for an unmanned vessel that guaranties that the ship can be operated without human intervention during the 30 days that are planned.

1.4.Scope of work

This thesis focuses on the following points:

- Introduction to the different maintenance policies
- Review of the existing condition monitoring systems for ship engines.
- Survey of Failure Modes Effects Analysis
- Data logging and data transmission.
- Study of the required human interaction for the Volvo engine maintenance and operation.
- Proposal of the relevant types of sensors for the motor monitoring.

1.5.Limitations

Developing a whole condition monitoring system is a really complex task, even for the case of manned vessel engines that have access to the crew intervention. Also, it can be developed in various ways, as different parameters can be monitored: vibration, temperature, pressure, etc.

In addition, the fact that the uSEA vessel navigation will be unmanned suppose additional challenges for the development of a condition monitoring system, as there is no possibility on basing the procedure on previous monitoring works due to the fact that this project is a major innovation in the industry.

For these reasons, this thesis will focus on the survey of existing condition monitoring techniques developed in the industry. Also, how these methods can be adapted to this project with the implementation of different kind of sensors and devices. The development of each one of these proposed alternatives will not be addressed in this thesis. The data analysis of the information obtained by the sensors won’t be object of study of this project either.

1.6. Structure of the thesis

The thesis is divided into eight different chapter, whose content is summarized below:

- Chapter 1 contains the introduction of the thesis, including the background, motivation, aim, scope of work and limitations of the project.
- Chapter 2 presents the results obtained from the literature survey on the following topics: condition-based maintenance, condition monitoring in marine engines, failure modes effects analysis, maintenance of boat engines and data transmission.
- Chapter 3 explains the methods and methodology followed for the development of this thesis.
- Chapter 4 contains the analysis of the human interaction required in the Volvo Penta engine.
- In Chapter 5 some solutions for the tasks presented in the previous chapter with the implementation of sensors and other devices.
- In the Chapter 6 some conclusions are extracted from the work done.
- Chapter 7 includes some suggestion for future work in this project from uSEA Ocean Data.
- Finally, Chapter 8 presents the references for the different sources of information used for the development of the thesis.

1.7. List of abbreviations

Abbreviation	Meaning
CM	Corrective Maintenance
PM	Preventive Maintenance
OEM	Original Equipment Manufacturer
TBM	Time-based Maintenance
CBM	Condition-based Maintenance
CM’	Condition Maintenance
CCEB	Current Condition Evaluation-based
FCPB	Future Condition Prediction-based
CMFD	Condition Monitoring and Fault Diagnosis
RMS	Root Mean Square
EMD	Empirical Mode Decomposition
FMECA	Failure Modes, Effects and Criticality Analysis
RPN	Risk Priority Number
SCC	Shore Control Center
VSAT	Very Small Aperture Terminals
ADU	Above Deck Unit
BDU	Below Deck Unit
CIR	Committed Information Rate
IMO	International Maritime Organization
TAN	Total Acid Number
TBN	Total Base Number

IRT	Infrared Thermography
UV	Ultraviolet

2. LITERATURE SURVEY

2.1. Introduction to Condition Based Maintenance

2.1.1. Definition of maintenance and types of maintenance policies

We can define maintenance as all technical and managerial actions that are taken during the usage of a product or an asset in order to maintain or restore its functionality (Shin and Jun, 2015). There are various ways of classifying the types of maintenance policies, but we can simply distinguish between Corrective Maintenance (CM) and Preventive Maintenance (PM).

With Corrective Maintenance, also called breakdown, run-to-failure or reactive maintenance, the actions taken to restore some equipment happen after it has already failed. Thus, this strategy leads to an increase in the costs associated with the repair or replacement of the malfunctioning part, as well as important levels of loses in the production time.

The Preventive Maintenance strategy, on the other hand, requires performing the maintenance task prior to the equipment breakdown. Its goal is, then, to reduce the rate of failure of the machinery. This technique contributes to minimizing the production time loss and failure-associated costs, as well as increasing product quality.

2.1.2. Preventive Maintenance strategy

Focusing on the PM strategy, it can be applied in the industry through either experience or original equipment manufacturer (OEM) recommendations, and it is based on a scientific scope.

With the experience approach, the company does not follow any specific or standard procedures, hence knowledge from experienced engineers in this field becomes really valuable. Nevertheless, the PM through experience approach implies some important drawbacks, as the company may face some problems if the experienced employee leaves the company, or if he/she is not available when a maintenance problem happens.

On the other hand, when PM is performed through OEM recommendations, the maintenance tasks are carried out at a specific time, but this is usually not optimal when trying to maximize equipment performance and minimize operation costs. This is due to the fact that each equipment works in different conditions so it would need different maintenance schedules. Also, OEM companies are experts in the design process, but are usually less experienced when it comes to maintaining a machine working without failure. Finally, these companies could try to maximize spare parts replacements by recommending PM schedules that are too frequent.

The scientific approach means implementing specific processes that utilize different analytical techniques, like statistics, artificial intelligence, or mathematical programming. Therefore, decision making will be based on real data analysis and not subjective appreciations. This scope of work can be divided into two techniques: comprehensive-based and specific-based techniques. In this last one, we find two different examples: time-based (TBM) and condition-based maintenance (CBM) (Ahmad and Kamaruddin, 2021). We will focus on this last technique.

2.1.3. Condition-based maintenance

2.1.3.1. Definition and goals

Condition-based maintenance, also called predictive maintenance, is the most modern and popular technique is the industry nowadays. It can be defined as a maintenance policy which performs maintenance tasks before the machinery failures happen, by assessing equipment condition including operating environments, and predicting the risk of failure in real-time by gathering data of the product. The main goal of this real-time assessment is to make maintenance decisions in order to reduce unnecessary repairs and minimize maintenance related costs.

The basis of CBM is the condition monitoring (CM) process, which consists of the acquisition of information of one or more parameters of the machine by different types of sensors or other appropriate indicators. The goal of the CM process is to indicate the condition of a system based on the values of health-indicating parameters, in order to prevent the failure before it happens.

2.1.3.2. Condition Monitoring process types

The CM process can be classified in two types, depending on how the data acquisition is performed: on-line and off-line. On-line CM implies that the process is carried out while the equipment or machinery is at operating or running state. The off-line process, on the other hand, is carried out while the product on which we are doing the maintenance is not on its working state.

Moreover, we can also distinguish two types of CM processes depending on the timing of the data acquisition: periodical and continuous monitoring.

In the case of periodical monitoring, the process is carried out at specific time intervals, like every hour, every *x* hours, or at the end of each labor shift, making use of tools like portable indicators such as acoustic emission units, hand-held meters, etc. Additionally to the data obtained with sensors and tools, the CM process also implies some evaluations based on the human intervention and senses, like assessing the degree of dirtiness, abnormal smells, or weird sounds. This last bit of information is really important in this thesis, as the maintenance of the boat engine will be performed without any human participation, so all these kinds of appreciations need to be substituted for some different ones based on sensors and not on human senses.

With continuous monitoring, as its own name implies, the process is carried out in a continuous and automatic manner with the use of special measurement devices like acoustic and vibration sensors. Even though this kind of monitoring gives us more data to work with, it has some limitations. The devices and sensors required to implement this kind of monitoring are quite expensive. Also, the continuous flow of data can lead to wrong deductions as the signal noise can experiment an increase. However, with the real-time data acquisition, we avoid missing out important information that can be lost between monitoring intervals in the case of periodical monitoring (Ahmad and Kamaruddin, 2012)

2.1.3.3. Condition Monitoring techniques

Condition Monitoring is based on the evaluation of a certain parameter of the working device, so we can distinguish different techniques depending on the parameter that is monitored (Ahmad and Kamaruddin, 2012)

- Vibration monitoring

  It is the most frequently used technique in Condition-based maintenance, especially in the case of rotatory machinery. It tests the health of the equipment *in situ*, which means in place, by using special tools like vibration sensors in order to detect any frequency changes in the vibration signal that can be indicative of some damage or degradation. This technique is of course performed on-line, as the machine must be at its operating state, and the data acquisition can either be periodical or continuous.

- Sound monitoring

  Sound or acoustic monitoring is also a very popular practice in CBM, having a strong link with the vibration monitoring technique. However, unlike vibration monitoring, which implies having the sensors attached to a specific vibrating component of the machine, acoustic monitoring simply listens to the whole equipment. The technique is also performed on-line, and the monitoring can also be carried out periodically or in a continuous way.

- Oil analysis or lubricant monitoring

  This technique consists of analyzing the oil to determine if its quality is still good enough to continue using it. With the result of these analysis, we can also deduct the health of the component that are lubricated with this oil, like engine shafts. The purpose of this technique is then to make sure that the quality of the oil is still acceptable and that the related components are in a good condition.

- Electrical monitoring

  This practice focus on controlling the correct functioning of the electrical and electronic component of the machinery, by monitoring different indicative parameters such as resistance, potential or conductivity. The data acquisition for this practice can be carried out is a lot of different ways, as there are many parameters that can be relevant for the maintenance, and each one of them may imply a different information-obtaining method. Any unusual changes on these kinds of parameters can be indicative of a fault in the electrical insulation, broken components on the motor, or deterioration in the electrical components, so monitoring and analyzing these values can help us prevent the failure of the equipment.

- Temperature monitoring

Almost every kind of machine is going to experience some heating on its components, being it due to electrical, mechanical, or chemical reasons. Therefore, temperature monitoring is often used to prevent the failure of the equipment, as the over-heating of any component usually is going to be an indicative of some malfunctioning in the machine. The equipment to acquire this data can go from more simple thermocouples to more advanced thermographic techniques.

- Physical condition monitoring

This technique focuses on checking the state of the materials in the machine, to see if there has been any cracks or corrosion in the components. To carry out this process, the monitoring should be off-line.

- Other monitoring techniques

A CM system is going to be different depending on the type of the machine and its operating conditions. For this reason, there are plenty of other monitoring techniques that can be implemented to check relevant parameters of our specific equipment. These could be, for example, performance analysis of some different parameters: compressor or turbine efficiency, air and fuel flow rate, cylinder and exhaust pressure, torque, coast down time, power consumption, etc.

In conclusion, there are many techniques which can be used to perform the condition monitoring of a parameter. So, depending on the specific machinery on which we want to carry on the maintenance, it will be interesting to focus on some techniques and not others, as it can be seen in *Table 1*.

Performance parameter	Machine type								
	Electric motor	Steam turbine	Aero gas turbine	Industrial gas turbine	Pump	Com-pressor	Electric generator	RIC engine	Fan
Temperature	•	•	•	•	•	•	•	•	•
Pressure		•	•	•	•	•	•	•	•
Pressure (head)					•				
Pressure ratio			•	•		•			
Air flow			•			•		•	•
Fuel flow			•	•				•	
Fluid flow		•			•	•			
Current	•						•		
Voltage	•						•		
Resistance	•						•		
Input power	•				•	•	•		•
Output power	•	•		•			•	•	
Noise	•	•	•	•	•	•	•	•	•
Vibration	•	•	•	•	•	•	•	•	•
Oil pressure	•	•	•	•	•	•	•	•	•
Oil consumption	•	•	•	•	•	•	•	•	•
Oil (tribology)	•	•	•	•	•	•	•	•	•
Torque	•	•				•	•	•	
Speed	•	•	•	•	•	•	•	•	•
Length		•							
Angular position		•	•	•		•			
Efficiency (derived)		•	•	•	•	•		•	
• Indicates measurement of performance parameter may be applicable for condition monitoring.									

Table 1: Performance parameters by machine type (ISO 13380, 2002)

2.1.3.4. Decision making under the CBM policy

The decision making in the maintenance process can be divided into two parts: diagnosis and prognosis (Ahmad and Kamaruddin, 2012). We can define diagnosis as finding where a fault comes from, while prognosis is the process of predicting when the fault is going to happen. The diagnosis is based on detecting signs that warn the engineers that the equipment is working in an abnormal state. This, however, doesn't mean that the machine has failed, as it may still be able to continue working in this condition. In order to predict when the machine is going to finally fail, prognosis must be performed, so that we can determine how much time can the machine continue working and when to perform the maintenance tasks.

In the case of Condition Based Maintenance, the decision making can be done attending to two methods: current condition evaluation-based (CCEB) and future condition prediction-based (FCPB).

The first one, the CCEB method, analyses, as its own name says, the condition of the machine at the present time and compares it to a preestablished failure limit. If the current state exceeds this limit, then the decision will be to perform the appropriate maintenance tasks, while if the condition of the equipment is under the limit, no other actions are needed. The visual representation of this method can be seen in *Figure 1*.

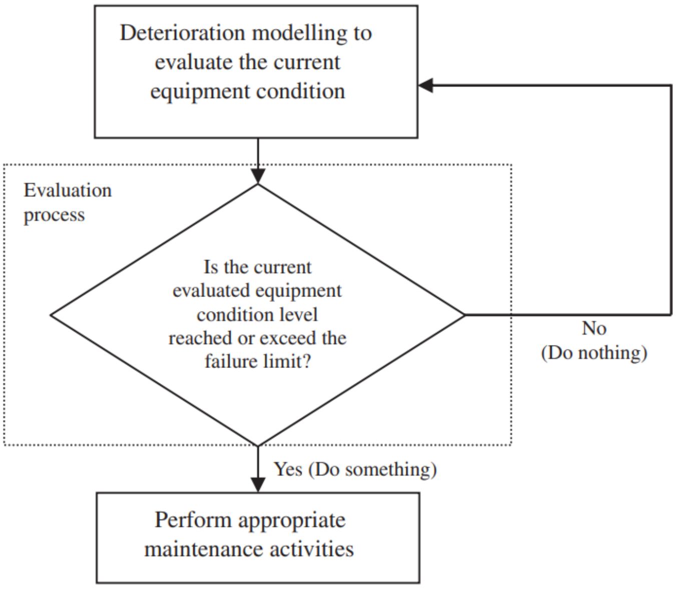

Figure 1: Current condition evaluation based (CCEB) method (Ahmad and Kamaruddin, 2012)

On the other hand, the FCPB method focuses on analyzing the trend of the equipment condition and tries to predict its future state. Then, like the previous method, if the predicted condition of the machine exceeds the failure limit, then some maintenance actions should be performed, and if the equipment state is under the limit, then no further action is required. Unlike the CCEB method, in this case the decision to take is not only whether or not to carry on maintenance tasks, but also plan and schedule them so that the machine can continue its function, but without getting to the failure point. The schematic representation of this methodology can be seen in *Figure 2*.

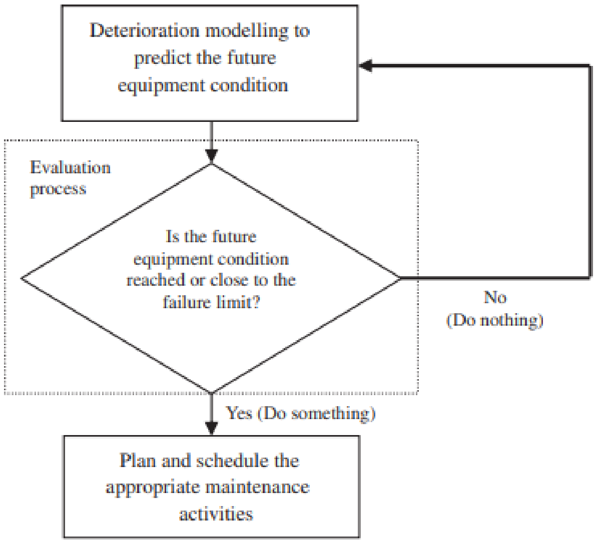

Figure 2: Future condition prediction based (FCPB) method (Ahmad and Kamaruddin, 2012)

2.1.3.5. Advantages and disadvantages of CBM

There are many different possibilities when it comes to deciding what kind of maintenance policy implement in each specific case. One of these possibilities is Condition Based Maintenance, which is has a lot of advantages compared to other options, but it also has some cons.

On the side of the advantages, there has been many reports and industry cases where the CBM has been successful. In the first place, implementing this policy will give us a more precise and earlier warning of future failure than other techniques. In addition, when applied correctly, it can reduce the equipment failure. Consequently, the safety is significantly increased, as avoiding the failure leads to also avoiding the problems it can cause, both to the workers and the industry installations. In addition, as less failure happens, the customer satisfaction is improved. This is not only interesting from the customer's point of view, but also from the maintenance service provider, as they usually offer a warranty period during which they cover the costs related to failure of the system. So, with CBM there is a decrease not only on the times failure occurs, but also on the costs related to these failures.

Moreover, as it is a predictive maintenance, it allows the users to plan the maintenance tasks in a better way. The time-based maintenance intervals can then be reduced and, as a result, there is a decrease in the costs associated to unnecessary and inefficient maintenance.

In addition, as the unusual condition of the machine is detected before the failure occurs, the production time can be increased, as it is possible to modify the working conditions to continue operating without reaching the failure. This of course leads to an increase in the productivity of the process, as unnecessary stops in the labor are avoided.

Nevertheless, CBM also has some disadvantages and limitations. Firstly, the initial investment is quite high, not only in terms of the hardware and equipment costs, but also in terms of developing a decision-making model and training the staff to be capable of performing the required actions and decisions. In addition, the available technologies are quite undeveloped in some areas, which can lead to limitations when it comes to ensuring the accuracy of the acquired data. In conclusion, CBM can be a really interesting option when it comes to maintenance systems, but it will depend on the company resources and equipment. In fact, almost 30% of industrial equipment is not benefited by CBM (Shin and Jun, 2015).

2.2. Condition Monitoring in marine engines

2.2.1. Introduction

Nowadays, almost the totality of large merchant ships uses marine diesel engines as their power source, because they have a rapid start and can offer a wide power range and high efficiency. In addition, as the technology in diesel engines has evolved through lots of years, the reliability is ensured.

Marine engines have to face difficult and variable operating environments, and some faults and damages may appear when working in high humidity, high temperatures and vibrational conditions. As any major fault in the power source can lead to serious accidents, as well as safety issues, Condition Monitoring and Fault Diagnosis (CMFD) is an interesting option when implementing a maintenance system for a marine engine.

Applying these CMFD techniques brings many advantages to the maintenance of a marine engine. As commented, the safety is increased, as avoiding failure of the machine also means avoiding dangerous accidents. The efficiency is also increased, as unnecessary stops and reparations are reduced, saving not only money but also time. The efficiency is also increased due to the fact that the workload of the crew can be reduced, so the mistakes in the fault detection process caused by the fatigue are decreased. Moreover, implementing these techniques pushes the industry to move forward to more complex and advanced maintenance methods, which will not only make the operations more efficient but also less environmentally harmful.

2.2.2. Development of CMFD for marine power systems

The CMFD techniques have been applied to marine power systems since some time ago, and there have been lots of advances in the technology and a lot of research has been done. This evolutive process can be divided into three generations (Xu *et al.*, 2021): the first one based on the application on field-testing techniques, the second one focused on online and remote condition monitoring, and the third one looking towards the intelligence fault diagnosis.

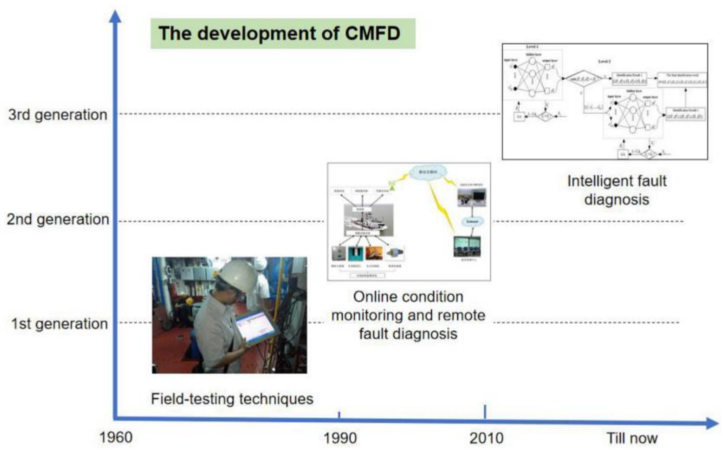

Figure 3: CMFD evolution for marine power systems (Xu et al., 2021)

2.2.2.1. First generation of CMFD

This first generation focuses on the application on field-testing techniques for monitoring different parameters. These techniques are appropriate for periodic inspections, and then the acquired data should be processed in order to extract the possible faults in the system.

- Signal acquisition

In this first generation, the data acquisition includes the obtainment of performance, oil, and vibration parameters.

The analyzed performance parameters in marine diesel engines comprehend the power, and the temperature and pressure of the different fluids running through the engine (fuel, air, coolant, and oil). To evaluate the condition of the engine, these values are compared to the standard ones that the machine should show in its normal condition. Then, the fault diagnosis is usually performed through simulation models, whose objective is to predict how different faults could affect the performance parameters in the future and take maintenance decisions according to this information.

Regarding the acquisition of the lubricating oil parameters, it first started with offline methods that implied taking samples out of the machine and testing them in a lab. This offered high precision, but as the time between the sample extraction and the obtention of the results was so long, the conclusions could be not useful for the real time monitoring of the machine condition, so the correct time for changing the oil could not be precisely determined. For this reason, the techniques evolved towards portable testing, which required much shorter testing times, so the condition of the oil could be determined in the field in almost real time.

Lastly, the analysis of the vibration parameters is really significant for all rotatory machines, and specially for marine diesel engines. As all manufacturing processes, the assembling of a marine power system implies some installation and manufacturing deviations. This generates gaps between the components of the engine that make the machine unbalanced, generating centrifugal forces that cause vibration in the different parts of the equipment. The analysis of this vibration is then really important for this kind of engines, as studying the velocity, acceleration, frequency, or phase can help to accurately locate and diagnosticate faults in the system.

- Fault feature extraction

In order to determine the wear states and wear faults in the equipment, the wear-particles images are processed to extract the characteristics of this particles.

On the other hand, there are three approaches for feature extraction from vibration signals: time domain analysis, frequency analysis and time-frequency domain analysis. The time domain analysis method includes both dimensional (variance, maximum and minimum amplitude, RMS value, etc.) and nondimensional parameters (crest or corrugation factor). For the frequency domain analysis, a visualized spectrum analysis is used to relate the operation conditions with the vibration signals. Lastly, time-frequency domain analysis can process non-linear and non-stationary signals, with method such as a Fourier transform or the Wigner-Ville distribution.

2.2.2.2. Second generation of CMFD

With the advance in sensor technologies, together with the progress in computer and network communications, the CMFD systems evolve towards online and networked setups.

In this second generation, online CM becomes really important as it offers real-time fault diagnosis. This way, the monitoring can be automated, and faults and abnormal situations can be detected between inspection periods. For example, with the vibration signals from the engine the pressure in the cylinders can be obtained, and with this data and the angular speed of the engine, we can calculate the variations of the pressure inside the cylinder, and then predict possible failures in the system. With regards to oil monitoring, lots of advances were made to create online wear particle sensors and physicochemical oil sensors, with important applications in the tribology field.

Also, with the evolution of the internet and network communications, many remote CMFD systems have been successfully developed, with onshore control centers that obtain data directly from the vessel engine and can then analyze it and make the pertinent maintenance decisions.

2.2.2.3. Third generation of CMFD

With the advances in automation, AI, and big data, this third generation of CMFD appears, focusing on intelligent fault-diagnosis methods. The objective is to replicate the human thought process with intelligent algorithms, in order to analyze multiple and big amounts of data to evaluate the health of the engine and develop smart maintenance plans.

Nowadays, these kinds of approaches are based in quantitative models, data-driven fault diagnoses and expert systems-based diagnoses.

Firstly, in order to implement fault diagnosis based on quantitative models, the values given by the sensors are compared to the diagnostic models, which can be either physical or mathematical. However, for these models to work properly, it is needed to estimate an excessive quantity of relevant parameters, so this approach is difficult to apply for fault detection in marine engines.

Then, with the evolution of big data technology, the data-driven fault diagnosis models appear, whose objective is to analyze big packs of data and distinguish abnormal values or trends to predict the failure of the system. These models can be based on statistical analysis (univariate or multivariate analysis), signal processing (wavelet transforms, EMD and spectral analysis), machine learning (for non-linear relationships between fault features and fault modes), or information fusion (multi-source information integration).

Finally, current investigation on expert systems focuses on system optimization and the combination with other algorithms. This expert knowledge is fundamental in fault diagnosis as there is little high-quality fault data available.

With this generation being the current one, there are many potential approaches that could lead the CBM towards new stages, like in the case of this thesis. It is interesting to focus on different ways of developing smart ships that can be managed in an automated and unmanned way.

2.3.Failure Modes, Effects and Criticality Analysis

2.3.1. Introduction

Failure modes, effects, and criticality analysis (FMECA) is a technique to identify and analyze all the potential failure modes of the different components of a system, the consequences theses failures may cause on the system and how to avoid these failures, and/or soften the effects of the malfunction on the machinery. The goal of this methodology is to identify and prioritize the failure modes and the consequences linked to these failures and apply the most appropriate maintenance techniques to avoid or minimize catastrophic and critical consequences.

The purposes of the FMECA are not only related to maintenance tasks. It can also be useful to assist in designing alternative options for the system, ensuring future reliability and safety. In addition, by following this methodology it can be ensured that all failure modes and their effects have been considered, as well of their relevance according to the criticality of their consequences. In addition, it can serve as a basis for not only maintenance planning, but also quantitative reliability and availability analyses, as well as developing criteria for test planning and demands for test equipment.

Three types of FMECA can be distinguished: design, process, and system FMECA. Design FMECA is performed to avoid failures during the design of an equipment. Process FMECA focuses on the problems that can occur during the machine manufacturing, operation, and maintenance. Lastly, system FMECA tries to avoid the problems that can happen in larger processes or production line operations.

We can also differentiate between two different approaches to FMECA: bottom-up and top-down. The bottom-up approach when the concept of the system is already finished, so each component and its possible failure modes is studied. The top-down approach, on the other hand, is performed in the early steps of the design process, so it is more focused in what functions should the system perform and what failures may occur while performing these functions, in order to avoid them (Rausand, 2005).

2.3.2. FMECA procedure

To carry on the FMECA of a system the following steps must be followed: analysis of the system, study of the system structure, failure analysis and preparation of FMECA worksheets, team review, and corrective actions (Rausand, 2005).

First, the system to analyze must be defined, decide which components should be included in the analysis, what are the system functional requirements and study the conditions in which the system is going to operate. Then, it is interesting to look at all the available information that can describe the system, as well as investigating about previous similar designs that can be useful for the current project.

Then, the structure of the system must be analyzed. This is done by dividing the system into different units in a hierarchical order, usually according to the function of the elements and subsystems. The depth of this breakdown process will depend on the objective of each specific analysis. The analysis should be started then from the top of the hierarchical structure, as it can then be divided into different subsystems in order to identify the failure modes and causes of the lower-level elements.

Thereafter, the worksheet on which the analysis will be recorded should be prepared. There are many different worksheets that can be used, depending on the requirements of the customer, but it usually covers some common aspects on its different columns. The first one should include the element reference. Then, all the different functions of the element are displayed. Next, the distinct operational modes of the element are listed, e.g., running, standby, etc. The following column should identify the potential failure modes of each function and operation mode. Afterwards, a description of the failure causes and mechanisms is included, studying all the failure modes in the previous column one by one. Then, the different methods for detecting each failure mode are listed. The next two columns may include the effects that each failure mode can cause on the subsystem and on the whole system. After that, the failure rates for each failure mode are displayed, with a pre-established scale. Then, the worst potential effect of the failure is ranked, which also requires a pre-decided scale. Finally, the last column contains the possible actions that can be taken in order to correct the different failure modes and restore the normal condition or prevent severe consequences.

Once the worksheet is completed, there is a way of presenting the risk related to the different failure modes: the risk ranking. It can be displayed by a risk matrix, which compares the frequency and the severity of the consequences of the failure mode (*Figure 4)*, or by a risk priority number (RPN), which is a combination of the rank of the occurrence (O), severity (S), and the likelihood of detection (D) of the failure mode. The RPN is then calculated as RPN = S x O x D, the greater this value is, the greater the failure risk is.

		Consequence				
		Negligible 1	Minor 2	Moderate 3	Major 4	Catastrophic 5
Likelihood	5 Almost certain	Moderate 5	High 10	Extreme 15	Extreme 20	Extreme 25
	4 Likely	Moderate 4	High 8	High 12	Extreme 16	Extreme 20
	3 Possible	Low 3	Moderate 6	High 9	High 12	Extreme 15
	2 Unlikely	Low 2	Moderate 4	Moderate 6	High 8	High 10
	1 Rare	Low 1	Low 2	Low 3	Moderate 4	Moderate 5

Figure 4: Standard Risk Assessment Matrix (Kaya, 2018)

After this, a review team studies the worksheets and the risk rankings and decides if the system is acceptable, or it needs some modification to reduce the risk. These corrective actions may include changes in the design, implementation of new safety features, use of safety and warning devices and development of new procedures. The reduction on the risk of a certain failure mode thanks to a corrective action can be obtained by comparing the RPN for the initial and revised system concept. An example of a worksheet including initial and revised RPN can be seen in *Figure 5*.

Phases	Professional figures	Procedure	Failure mode	Failure effects	Failure causes	Initial risk ranking				Corrective actions 2013–2014	Revised risk ranking				Corrective actions 2015–2016	Final revised risk ranking			
						S	O	D	Risk priority number (RPN)		S	O	D	RPN		S	O	D	RPN
3	Physicist	Pre treatment quality control and authorization	Wrong measure, insertion or reading of a delivery parameter	Wrong delivered dose	Violation of protocol limits for quality assurance	5	3	4	60	Adherence to instructions in quality assurance protocol	5	2	3	30	Adherence to instructions in quality assurance protocol—wider experience	5	1	1	5
9	Nurse	Patient positioning on the operating table	Patient displacement	Patient displacement, slipping and fall off	Non-adherence to guidelines/ protocol	5	4	3	60	Adherence to Hospital Policies and Procedures	5	2	3	30	Adherence to Hospital Policies and Procedures—wider experience	5	1	2	10
11	Surgeon–Nurse	Delivery of surgical specimen to the Pathology and/ or Radiology Department	Transcription error	Wrong patient identification	Communication defect	5	4	3	60	Procedure adherence	5	2	1	10	Procedure adherence-wider experience	5	1	1	5
				Wrong therapeutic decision	Communication defect	5	4	4	80	Surgeon confirmation required	5	2	1	10	Procedure adherence-wider experience	5	1	1	5

Figure 5: FMECA worksheet example (Videali et al., 2017)

2.3.3. FMECA for diesel engines

As commented in previous sections, almost the totality of large vessels uses diesel engines as their main power source unit. So, it is interesting to study what considerations are relevant when performing a FMECA for a diesel engine.

The process needed to perform the FMECA on a diesel engine is basically the same as in any other kind of machine. The first step is to define the engine application, doing a functional description of the system operation, structure, and boundaries, as well as establishing the functional relationships between the different elements. Then, establish safety and performance acceptance criteria. After, all potential modes and their causes must be identified, and the effects of each failure mode must be evaluated. Next, the failure detection methods must be stablished, the severity and frequency of each failure mode must be determined, and the Risk Index should be evaluated. Finally, the last step is to identify the corrective measures that can be implemented for each failure mode.

There has been a lot of research on this topic, which offers useful information about how to perform this analysis and knowing which are the most relevant components when focusing on failure modes. Many studies point that the fuel injection system is the fault area with the greatest rate of failure, followed by the cylinder head and valves, the charging and exhaust system, the cooling system, and lastly the engine components subjected to high levels of wear, like bearings, pistons, liners, etc. (Banks *et al.,* 2005). It must be taken into account that these last parts are more usually replaced, which explains why they are so low on the failure rate list, even though they face lots of wear.

2.4.Maintenance of boat engines

As we have seen in the previous sections, there are different ways of approaching the maintenance of a marine diesel engine. But for this part of the literature survey, we will focus on the general tasks that are usually carried out in all boat engines, so then later it will be easier to analyze and face how to carry out the maintenance of the specific engine for this project.

When planning the maintenance for a diesel power unit, the most important source of information is always going to be the manufacturer manual, as it contains instructions on what maintenance tasks are required and the intervals for them. These intervals are usually specified in regular time intervals (every month, every year, etc.), or in operation hour intervals (every 50 hours, every 250 hours, etc.). For this reason, most of the engines are equipped with an hour meter to keep track of the operation time of the machine.

Regarding the general maintenance for a diesel engine, there are three component groups that are usually the most critical: the lubrication, cooling, and fuel systems.

Oil in diesel engines works at high temperatures and under extreme pressures. Also, it may contain traces of sulfur, that can be transformed into sulfuric acid which is obviously not good for the engine's health. For this reason, it is important to recommendations from the manufacturer about the quality and the viscosity of the oil. Depending on these characteristics, the oil change intervals may differ.

The cooling system in diesel engines usually has at least three coolers: the oil and fuel cooler, the heat exchanger, and a transmission cooler. It is important, then, to make sure that the coolant meets the recommendations of the manufacturer, and that the level and quality of the fluid are checked according to the intervals on the manual.

Finally, with respect to the fuel system, it is important to make sure that the fuel that gets into the engine is clean, as the opposite would lead to important damages on the motor. To achieve this, the filters must be changed regularly according to the schedule, and the fuel injectors must be bled after every filter change.

2.5. Data transmission and optimization

2.5.1. Introduction

The vessel that is being worked on in this project must sail unmanned for 30 days until refueling is necessary. This means that all the data collected from the sensors of the engine has to be sent to a Shore Control Centre (SCC), so then it can be properly analyzed, and the necessary predictions and decisions can be made.

Even though, uSEA Ocean Data is still on the early stages of the project, some solutions for data transmission and communication have been proposed.

2.5.2. VSAT technology

VSAT (Very Small Aperture Terminals) is a satellite communications technology that offers two-way Internet, data and telephony. The satellites of this network are located at the GEO orbital location. The combination of this position of the satellites, together with the moving vessels, creates the need for stabilized antennas, which usually consist of a circular antenna covered by a dome. This technology usually offers data rates from 64 Kbps up to 8 Mbps.

The remote maritime VSAT system consist of two parts: an Above Deck Unit (ADU), and a Below Deck Unit (BDU). The ABU is an antenna and transceiver located outside of the vessel. The BDU is a unit that is placed indoors and communicates and controls the antenna.

There are some important concepts when it comes to deciding what VSAT solution is the better fitted for each application:

- *Contention Ratios* are an indicator used in shared bandwidth VSAT environments. It represents the number of users with whom the client shares the bandwidth within the network. Therefore, a higher value of this ratio indicates a greater number of users sharing the same bandwidth and, thus, the lower the speed can be.
- *Committed Information Rate* (CIR) refers to the minimum bandwidth that is guaranteed to the client. It is usually measured in Kbit/s and is a minimum level of service that is ensured by the supplier.
- *Frequency band* in VSAT technologies divide in three possibilities: C-band, Ku-band, and Ka-band. C-band is mainly used for voice and data communication. Even though it requires a large antenna due to its weak power, it performs well under bad weather conditions as it works with lower frequency signals. Ku-band, on the other hand, require much smaller antennas, as higher frequencies are obtained easily without the

need of big antennas. As a disadvantage, it is more susceptible to rain effects and distortion. Finally, Ka-band offers the greatest power among the three possibilities, but, as a result of the higher frequency signals, the quality of the transmission can be compromised (What is Maritime VSAT, 2019).

2.5.3. Inmarsat

This company, created more than 40 years ago by the International Maritime Organization (IMO), is one of the world's leading satellite companies, offering service to all kinds of enterprises and organizations.

Inmarsat offer a variety of services depending on the necessities of each customer. For the purpose of this project the most interesting option is Fleet Data, as there is no need of voice communication with the boat, only data transmission. This technology allows information transmission to a central cloud-based database using its own dedicated bandwidth. But not only this, this service offers data pre-processing and analysis (Fleet Data, 2020). This is really interesting as it reduces the need of bandwidth and makes the communications more efficient, as well and easing the data analysis onshore for later maintenance predictions.

2.5.4. Iridium

Iridium is a global satellite communications company that offers voice and data transmission services. It offers a constellation consisting of 66 satellites located in the Low-Earth Orbit, which allows stronger signals and faster connections with the use of smaller antennas with lower power requirements (Iridium network, 2021).

These cross-linked networks provide reliable connectivity to the vessel regardless of the geographical location or weather conditions (Autonomous Vessels, 2021). This is really interesting for our application as the boat will face difficult climatology and a correct communication must be guaranteed for the proper operation of the ship.

3. METHODS AND METHODOLOGY

As seen in the literature survey, there are plenty of factors influencing the maintenance of a machine, in this case, a diesel engine. The development of the maintenance schedule and condition monitoring of a machine is an extensive process that requires lots of information about the equipment and its operating conditions.

The unmanned vessel project developed by uSEA Ocean Data is still on its starting steps, so there was not much specific data available about the monitoring system. In addition, the implementation of a whole condition monitoring system is a really complex task usually carried out by expert companies focused on this topic. Therefore, the purpose of this thesis has been mainly theoretical, with the goal of setting the basis for future research and implementation of the specific system that will monitor the parameters of the boat engine, as well as the data analysis to make the relevant maintenance predictions.

Consequently, the methodology utilized to develop this thesis can be divided into three main sources of information: the literature survey, the meetings with the company's engineer and the engine operator's manual.

3.1. Literature research

As commented before, the process of developing a condition monitoring system implies having some knowledge, not only in this topic, but also in lots of areas related to the CM. Consequently, the first step to develop this thesis was to gather information about the subjects included in the chapter two: condition-based maintenance, condition monitoring in marine engines, FMECA, maintenance of boat engines and data transmission and optimization.

In order to carry on this literature survey, the most important aspect was to ensure the reliability of information. This was accomplished by checking the authority of the scientific paper which served as an information source for the thesis, as obtaining the knowledge from a trustable and renowned organization or author, usually guaranties the quality of the information. In addition, I devoted time to read different documents about the same topic, so then I could make sure that the information obtained was veridical and trustable, as contrasting information is a great way of ensuring the reliability of the data. The usage of industry standards has also been a relevant method to ensure the trustworthiness of the information. Moreover, for some cases, the source of the data was not scientific documents and papers, but the information collected on the websites of companies that are relevant for this project. This last method has a disadvantage, as the details contained in these websites can sometimes be subjective and biased by the company's vision, and they can have the intention of selling their services more than informing about them. This have been solved by carefully analyzing the information and comparing it to the one obtained from other knowledge sources.

This surveying process has been fundamental to set the basis of this project and understand the maintenance sector. As a student finishing the studies in Industrial Engineering, I had received education in various areas, going from mechanical technologies to electrical systems. But this formation has been very general, without getting in depth into any particular application. Also, the knowledge obtained during these years has been very theoretical, with very little application examples on the real industry. For this reason, having no previous background on the fail-detection and maintenance industry, spending time reading documents and learning about the distinct factors that had to be considered for this thesis has been essential.

3.2.Meetings with uSEA engineer

After obtaining the background information for the thesis and setting the basis for the project, the next step was to focus on the specific engine that will be used in the unmanned vessel designed by uSEA Ocean Data.

To achieve this, the guidance from Hans Skaar, the engineer from uSEA, has been fundamental. He has been a major source of information for this thesis, as his knowledge as machine expert has been really helpful. As commented before, I faced this project with no experience on the industry, only theoretical and general knowledge. For this reason, the regular meetings with him have been really useful during the entire process, as he has provided suggestions about what it needs to be done in the engine to ensure its correct functioning.

As an engineering with many years of experience on-board, he offered really helpful information about the maintenance tasks that are usually carried out by the crew on the boat. Knowing this was essential for developing the alternatives for this tasks that can be implemented remotely in the unmanned vessel.

He suggested that a good approach to the implementation of sensors that would substitute the human interaction with the engine would be to think about the senses of the human being, and how could they be replaced by electronic devices and sensors. He emphasized that, apart from the maintenance tasks listed in the engine manual, there are some important checks that the boat crew do on a regular basis that needed to be carried out in an unmanned way.

3.3. Volvo Penta engine operator’s manual

The information contained in the D7A-B-TA (AUX) diesel engine operator’s manual, as well as in the Service Protocol document, has been the main source of information about the engine specific maintenance requirements.

The methodology used in this case has been reading the manual looking for the maintenance tasks and maneuvers on the engine that require the intervention from a person. Then, once these human actions were identified, some alternative needed to be developed so that the engine can operate normally without the presence of crew members on board. It was also relevant to research the maintenance schedule recommended by the manufacturer, contained in the Service Protocol, so only the necessary tasks would be addressed. This process is developed more in depth in the next chapter.

4. HUMAN INTERACTION ON THE ENGINE

4.1. Introduction

As the vessel from uSEA Ocean Data will sail unmanned for a period of 30 days, it is necessary that the boat engine can operate and be maintained without the presence of any crew members on board. The purpose of this chapter, then, is to identify from the Volvo Penta D7A-B-TA operator's manual all the human interaction required to run and maintain the engine.

4.2. Maintenance Schedule

The maintenance intervals recommended by the manufacturer, in this case Volvo Penta, is collected in the Service Protocol. This information is relevant as not all maintenance and operation tasks have to be addressed, but only the ones that must be carried out in an interval time less than the 30 days unmanned sail period.

Service activity	Action	
S At 500 hours		
Valve clearance	Inspection	●
A Every 12 months or 500 hours whichever occurs first		
Engine oil and oil filters / by-pass filter	Replace	●
Coolant level and antifreeze mixture	Inspection	●
Drive belts, belt tensioner and idler wheels	Inspection	●
Air filter	Inspection	● / ○
Fuel pre-filter, draining water / contamination	Clean	●
Seawater filter	Clean	● / ○
Anode, protection system	Replace	● / ○
Propeller shaft seal	Inspection	●
Impeller kit	Replace	● / ○
B Every 12 months or 1000 hours whichever occurs first		
Fuel pre-filter and fuel fine filter	Replace	●
Air filter	Replace	●
Wearplate and pin	Inspection	●
C Every 1500 hours		
Valve clearance	Inspection	●
D Every 48 months or 2000 hours whichever occurs first		
Drive belts	Replace	● / ○
Wear kit	Replace	●
E Every 48 months or 8000 hours whichever occurs first		
Coolant	Replace	●

Figure 6: Service Protocol of the Volvo engine (Service Protocol, 2022)

As seen in *Figure 6*, the smallest interval for maintenance is 12 months or 500 operating hours. During the 30 days the engine would operate for about 720 hours, which would mean that the tasks defined on the sections S and A from the table would have to be performed while the boat is sailing unmanned. Nevertheless, this is not the case, as there will be two or three identic engines on the boat and the load will be divided between them, so the engine will operate for about 500 hours before going back onshore for refueling.

Thereby, none of this maintenance actions that would require the intervention of a member of the crew have to be substituted by remote unmanned methods. The vessel will arrive for refueling just in time so that the pertinent maintenance tasks can be carried out on shore.

4.3. Operator's manual human interaction

Apart from the maintenance task mentioned above, which don't suppose any problem as explained before, there are some other actions that should normally be performed on the engine by a person. These operations are collected in the D7A-B-TA (AUX) manual (Operator's manual D5A/7A T/TA, 2022) and are presented below.

- ***Starting the Engine***

1 Turn on the power by putting the starter key in position "I".

2 Press the "Alarm test" button to make sure the warning lamps come on and the acoustic alarm sounds.

3 Turn the key to position "III". Release the key immediately after the engine has started.

4 Check the instruments and run the engine unloaded until it attains normal operating temperature.

As we can see, in order to start the engine, it is necessary to manipulate a key between different positions. Also, the crew members should use the alarm test button to make sure that the available alarms work correctly.

- ***During load operation make sure that:***

1 No engine related alarms occur.

2 There are no visible leaks of fuel, lube oil, coolant or exhaust gas

3 No abnormal noise or vibrations occur.

4 The color of the exhaust gas is normal.

5 Instrument readings are normal

In this case, the human interaction during the engine operation goes from checking the alarms display, make sure that there are no leaks, as well as being aware of weird noises, vibrations or gases.

- ***Alarm test***

When pushing the "Alarm test" button, the warning lamps will light up and the acoustic alarm will sound. Always perform an alarm test before starting.

For this task, as commented before, the crew presence is necessary to perform the verifications on the alarms system.

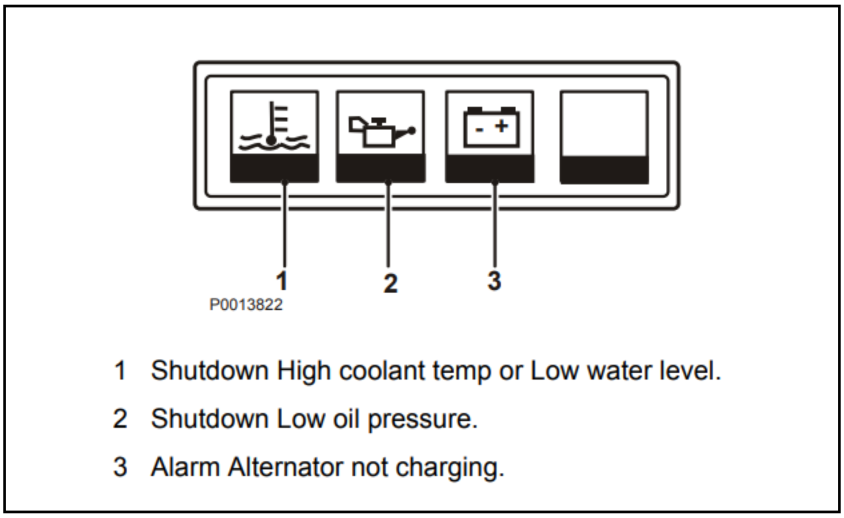

Figure 7: Warning handling display (Operator's manual, 2022)

- ***After Engine Shutdown***

1 Check the genset and engine room for leaks.

2 Close the fuel cock and seawater cock.

3 Read off the hour counter and carry out preventive maintenance according to the maintenance schedule.

4 Turn off the main switch if the genset is not to be used for a long period.

As the manual explains, the human presence after the engine is turned off is necessary for checking that there are no leaks in the system, closing valves and check the hour meter (this last part is not important in our case).

- ***General inspection***

Make a habit of visually checking the engine and engine bay before starting, and after operations when you have stopped the engine. This will help you to quickly discover abnormalities, or if something is about to happen.

Look especially carefully for oil, fuel and coolant leakages, loose bolts, worn or poorly tensioned drive belts, loose cable connections, damaged electrical cables and hoses. This inspection only takes a few minutes and can prevent serious malfunctions and expensive repairs.

In this section, introductory to the maintenance tasks description, the manufacturer recommends carrying out a general visual check of the engine before starting it, which obviously would be performed by the crew on board.

- ***Oil Level, Check***

The oil level must be within the marked range on the dipstick and should be checked daily.

The descripted technique for checking the level of the engine oil consists of introducing a dipstick to visualize the oil amount in the system. It is important to notice that, even though the oil should be changed every 500 hours or 12 months, according to the Service Protocol, the oil level must be checked every day.

- ***Engine Oil, Filling***

Top up the oil through the filler opening in the ventilation cover. Make sure the correct level is attained but wait a few minutes to allow the oil to run into the oil sump.

The procedure for filling the oil container that is explained on the manual is to do it by hand, with the need of human operation.

- ***Checking the coolant level***

Avoid opening the filler cap for engine coolant system (freshwater cooled engines) when the engine is still hot. Steam or hot coolant can spray out as system pressure is lost.

When engine is cold the coolant level must be visible at the lower edge of the filler neck on the expansion tank.

The recommended procedure for checking the coolant level is also by doing a visual inspection.

- ***Filling coolant***

When topping up, use the same coolant mixture as already in the system. Fill the freshwater system (HT) with coolant to the correct level through the filler opening in the expansion tank. Fill slowly so that evacuated air is able to pass the filler opening.

The operation required to fill the coolant tank is the same as with the oil, so it would require the presence of a person to do it by hand.

5. RESULTS AND DISCUSSION

5.1. Introduction

Once the required human interaction with the engine has been identified, the next step is to map potential sensors that could be installed in the engine or in the engine room as a solution to the lack of human presence on board.

Thus, in this chapter, various sensors and systems are proposed as alternatives to be implemented in the engine, first focusing on the ones that substitute the time-based maintenance tasks performed by the crew, and then those responsible of the condition monitoring of the motor. The goal is to explain what kind of sensors and equipment could be useful, what should they detect and how could the data obtained be treated.

5.2. Sensors and equipment for Time-Based Maintenance

5.2.1. Remote starting system

As seen previously, the engine is put into operation and stopped by using a key, which requires a person manipulating it. As an alternative, this key-based system must be replaced by a remote starting system, which allows controlling the start-up and stop of the engine from the on-shore control center.

This way, the engineers in this control center can manage and distribute the load between the gensets so that none of them gets to the 500 hours of work before the vessel comes back for refueling and maintenance.

5.2.2. Remote alarm display

Similarly, in order to replace the existing warning display on the engine, the alarms should be connected to the data transmission system (which is not the subject of this thesis), so that the alarms can be tested remotely, as well as allowing the warnings to be received from the shore control center.

5.2.3. Oil and coolant level sensor

The method for checking the oil level is by using a dipstick, and to check the coolant level a visual inspection is needed. Both of these actions require the intervention of a human being.

The proposed solution is to install oil and coolant level sensors on the engine. In the case of the coolant level sensor, it appears as an optional extra offered by Volvo Penta (Product bulletin D7A TA Genset, 2022), that would activate a warning when the coolant level gets below the critical point. For the oil level sensor, an external solution is required. However, this isn't a problem as there are many reliable options in the market. They usually work using an electrical resistance method, so that the less of the sensor is covered by the oil, the bigger the change in the resistance value. A more modern option would be the use of ultrasonic sensors with a piezoelectric transducer that sends pulses into the oil to get back echoes (Oil sensors explained, 2022).

As there is no need of keeping continuous track of the oil and coolant level from onshore, the data could be sent from the vessel every day or every couple of hours. However, it could be interesting to collect more continuous data and store it to be analyzed when the boat goes back for refueling, so the oil and coolant consumption can be analyzed and that the behavior trends of the engine depending on the conditions can be predicted.

5.2.4. Oil and coolant injection systems

Once the level-checking problem is addressed, the next step is to implement a system to refill the oil and coolant tanks without the needs of human interaction with the engine. To do so, the proposed idea is to install oil and coolant tanks with an electrically controlled valves that would open when the system receives a low oil/coolant level warning, and the shore control center sends the order. There is no need of using a pump because the injection does not have to be pressurized, as the usual method is refilling by hand.

5.3. Sensors and equipment for Condition Monitoring

5.3.1. Vibration analysis

The vibration analysis is probably the most powerful tool when it comes to condition monitoring of rotatory machines. For this reason, it is a very interesting option for this project, as the data collection doesn't require in-situ measurements, so all the process can be carried out remotely.

The D7A-B-TA, like all kinds of diesel engines, is made up of numerous rotatory components and each one of them generates vibrations with different frequencies. To assess this problem, it would be interesting to place different sensors in distinct location, so this way it would be easier to separate the different vibration signals. Consequently, the processing of the data would be less complicated, and it would be easier to locate an eventual unusual data that could be useful to predict a failure.

All vibration measurements are acquired using a transducer that produces an analog electrical signal proportional to the instantaneous vibratory acceleration, velocity, or displacement. Then, to obtain the vibration magnitudes, the output voltage is multiplied by a calibration factor.

Once the data is acquired and digitalized, the next step is to filter it. This step is necessary because, as commented before, the vibration measurements obtained from the sensors are formed by various overlapping signals, each of them with a different frequency. This generates a very noise signal, so the use of low pass, high pass, and bandpass filters can be really useful to get rid of this useless information.

Next, in order to analyze the obtained signals, there are two possibilities: a time domain analysis or a frequency domain analysis. In the time-domain analysis area, various techniques can be used for our application, such as wave forms, beating, modulation, and envelope analysis. Regarding the frequency domain analysis, there are also different techniques available: Fourier transform, amplitude modulation, logarithmic plots, or zoom analysis. (IS 13373-2, 2005)

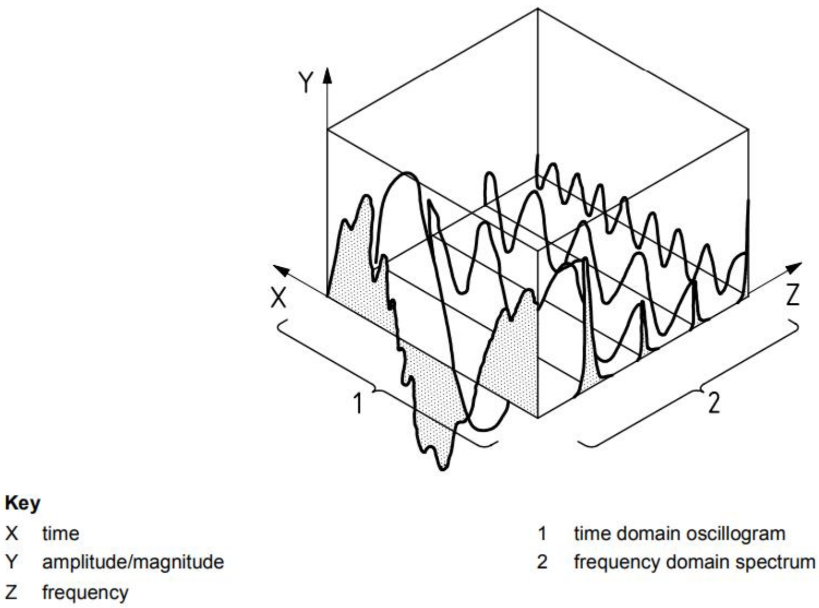

Figure 8: Time and frequency domains (IS 13373-2: 2005.)

The vibration analysis process, from the data acquisition, to the noise reduction and the subsequent analysis and predictions, is a really complex technique that should be developed in full depth. Even though this is not the purpose of this thesis, the vibration monitoring should be one of the main focuses of the potential future works on this unmanned vessel project.

5.3.2. Oil Condition Monitoring

Oil is an essential element of the engine, as it does not only lubricate the components of the system, but also seals the combustion chamber, refrigerates the moving parts and transfer contaminants. The oil level is not the only parameters that needs to be controlled, as the quality of the oil flowing through the system is as important as its quantity.

The usual method to check the state of the oil is to periodically collect samples and send them to a laboratory to be analyzed. This is not possible on our case, as the vessel will almost always be sailing unmanned, so the delay of this process is not suitable for this project. The solution is then to implement a real-time condition monitoring system for checking the oil state.

The oil contamination and degradation are mainly indicated by its oxidation. As oil goes through heat and pressure cycles, interaction with oxygen, moisture and other contaminants, the antioxidants are depleted resulting in oxidation. The oxidation of the oil leads to an increase in the Total Acid Number (TAN) and a decrease in the Total Base Number (TBN). The viscosity also increases because of the oxidation which could lead to deposit formation. Thus, if this process is not monitored it could lead to corrosion on vital engine parts that would cause a loss in the efficiency, obstruction of the filters, engine reliability problems and even a catastrophic failure. The oil viscosity and condition could also be affected by different contaminants such as soot, fuel, coolant, water, dirt and engine wear elements. (Cummings Filtration Inc., 2020) This degradation process is schematically represented in *Figure 8.*

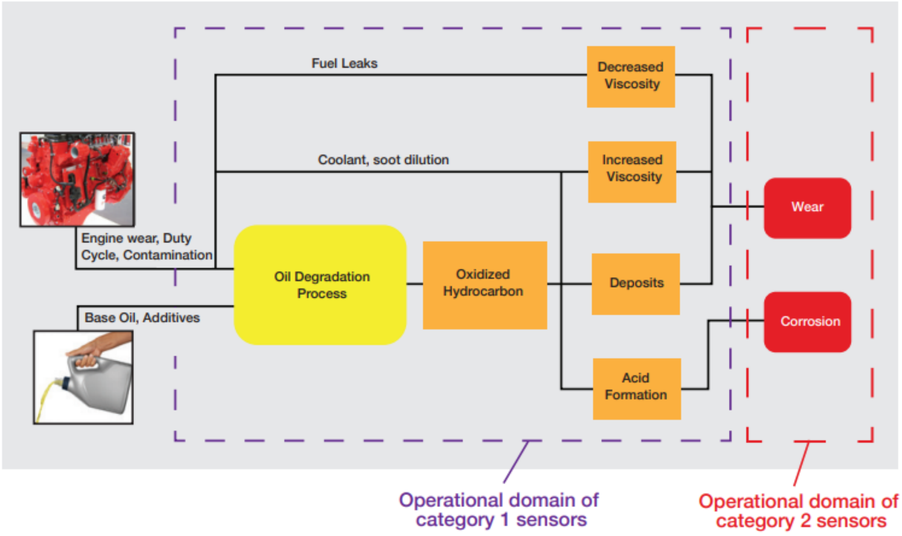

Figure 9: Flow diagram of a typical oil degradation process (Cummings Filtration Inc., 2020)

As seen in the diagram, there are two different sensor categories attending to their operational domain. The sensors in the category 1 are response technologies that show change of chemical degradation (oxidation, TBN, viscosity) of the oil or contamination of the lubricant. The implementation of these sensors could be really useful to detect signs of oil degradation on its early phases, so preventive and predictive tasks can be performed. The category 2 sensors are wear metal sensors that catch and identify wear particles, which can contribute noticing severe failure if the oil degradation goes past the operational domain of category 1 sensors. Some failures happen without previous signs on the category 1 sensors, due to the engine age, metallurgical properties of the components and others, so the implementation of these sensors would be really useful to prevent this kind of failure. (Cummings Filtration Inc., 2020).

Other sensors, such as temperature or pressure, could also be really useful for the monitoring of the oil condition. These parameters can not only predict failure caused by the degradation of the oil health, but can also indicate developing failure causes in other components of the engine, such as overheating of the bearings and abnormal situations in the combustion process, or oil leakages that cause a pressure drop.

A low-pressure warning sensor is already equipped in the engine, and optionally Volvo offers a pressure gauge to keep a continuous track of the oil pressure (Product bulletin, 2022). The temperature sensor, as well as all the degradation sensors commented above, would have to be installed externally.

5.3.3. Temperature sensors

Additionally to the already presented oil temperature sensors, it would also be interesting to install temperature sensors in other parts and components of the engine.

One possibility is to install a sensor to control the coolant temperature. The goal would be to notice any abnormally high temperatures that could indicate that an overheating is occurring in come part of the engine that is refrigerated by the coolant. This way, the developing fault could be addressed before it happens.

A good option would also be to install sensors at the inlet and outlet of the turbocharger. This part of the motor is one of the most problematic ones, so checking that the air temperature change when passing through the component can be an interesting way of identifying an incorrect functioning of the turbocharger, so that measures can be taken before the failure occurs.

The data treatment for all of these sensors could be such that only unexpected data is sent to the shore control center. The continuous evolution of the temperature could be stored in the vessel to be analyzed when it is back onshore. This way, the company could save bandwidth capacity in the remote communications.

5.3.4. Flow sensors and power delivery

With the implementation of air and fuel flow sensors, the expected delivered power could be calculated. Later, by comparing this result with the expected theoretical power, some conclusions could be drawn. If the real delivered power is substantially less than the expected, it can be a symptom that something is going wrong, and the engine performance has decreased. This can serve as a prewarning to take a look at the other sensors and equipment to locate the fault more precisely.

5.3.5. Infrared thermography

Even though some temperature sensors have been proposed, the temperature lots of components of the engine would still be uncontrolled. The use of infrared thermography (IRT) could be a great solution to this problem, as it can provide thermal images of more general parts of the engine, the data of which would be impossible to obtain without this technology.

It is important to point that with infrared thermography the temperature of the components is not obtained directly, but with the infrared energy coming from the target. There are various IRT techniques used in the industry, but the most suitable for this project is Comparative thermography. It can be used to provide the best available data, as ideal thermal measurements are usually too difficult to obtain.

Comparative thermography can be quantitative or qualitative. For this application the better option is to implement quantitative comparative thermography. This technique is really effective for evaluating the condition of the engine by determining approximate temperatures. As commented before, IRT does not measure temperatures directly, but the infrared radiation. This is dependent on the emissivity, reflectivity, and transmissivity of the components, which are usually difficult to estimate precisely. For this reason, the use of comparative quantitative thermography is useful in this case. Instead of determining the exact temperatures in the engine, with comparative measurements we could identify a thermal deficiency by comparing the temperatures obtained using a consistent emissivity value for those surfaces with similar emissivity, for example, across the surface of a certain component. The temperature differential between similar surfaces can then be measured numerically. (ISO 18434-1, 2008) Then, we could obtain the compare the approximate temperature values with the expected ones in a normal operation situation.

This way, we would not obtain exact temperature measurements of the temperature of the engine components. But instead, we could compare these temperature differentials and identify abnormal values that could indicate the overheating of a certain part of the motor.

5.3.6. Smell detectors

As suggested by the uSEA engineer, there is the need to replace the human interaction with the engine and this includes the five senses of the human being. Focusing on the smell, the solution would be the implementation of devices that substitute this interaction: the electrochemical noses.

An electrochemical nose, also known as e-nose or micro nose, is an artificial olfaction device with an array of chemical gas sensors, a sampling system, and a system with a pattern-classification algorithm used for analysis of gases, vapor, or odors. The chemical sensors in these devices have a sensitive layer that translates a chemical interaction into a unique signal patter, which is interpreted by pattern recognition/classification algorithms (Mathas, 2011).

This way, when any particle is on the sensor's surface, the change on its resistance is measured and the particle can be identified. For the application in this project, the implementation of these devices would be really interesting, because they could detect smells that indicate fuel or coolant gases, as well as poorly evacuated exhaust gases. Therefore, this be a leakage prewarning, as a minor leak that would not be noticeable yet by the other sensors, would be detected by the e-nose, so the shore control center team can start looking at the other sensors to locate the fault before it causes a major accident.

5.3.7. Engine room cameras

As the previous case, visual inspections are quite frequent in a manned vessel, so to substitute the human sense of sight it would be a good idea to install cameras on the engine room.

But as a continuous video transmission would take a lot of the available bandwidth, it would be interesting to only transmit one picture every hour. The images could be compared to a reference one of a normal operation situation, so that if any change happens, the shore control center receives a warning. In the case of one of these warning, or any other reason, it would be useful that the SCC can receive more detailed and continuous pictures from the camera, like a high-resolution photo every second.

5.3.8. Coolant Leak Detector UV Dye

Finally, UV dyes can be added to the coolant without affecting the engine performance. With the installation of UV lights in the engine room, this could be a really useful technique for detecting the location of a leakage in the cooling system. This system would have to be installed together with the cameras commented in the previous point, so that the SCC can get a picture of the potential coolant leakage.

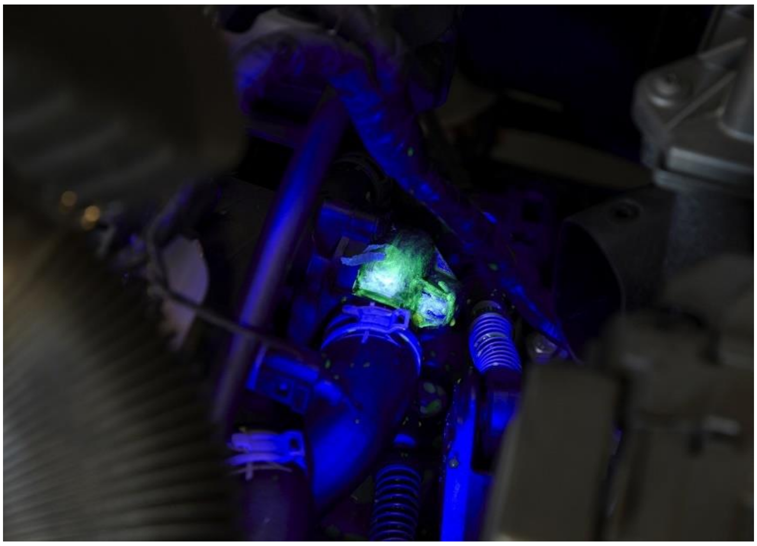

Figure 10: Example of the use of UV dye in a car engine (Coolant System Leak Detection Dye, 2022)

6. CONCLUSIONS

Thanks to the advances in the control technologies and big data, the marine industry is moving towards a future where autonomous vessels and intelligent boats can operate safely. However, after the literature survey of this thesis, I have acknowledged that the sector is not yet that advanced, and the development of autonomous ships is still at its early stages.

Nevertheless, the project presented by uSEA is pushing these limits and has an enormous potential to change the standards in the marine industry. Even though the human interaction with the engine has been identified in numerous parts of the operating and maintenance processes, the alternatives proposed in this thesis could ensure the safe functioning of the motor.

This thesis provides only a survey on the state of condition monitoring in the marine engine nowadays, and some initial steps on this uSEA project. Nevertheless, the proposed maintenance system can be fully developed to be finally implemented in the diesel engine, so that the company can ensure the safety on the operations of the unmanned vessels.

Many challenges will arise in the future, as uSEA moves forward with the project, but with the work carried out in this thesis it can be ensured that the maintenance of the engine can without the intervention of a human being is feasible.

7. SUGGESTIONS FOR FUTURE WORK

As commented before, this thesis only serves as an initial step in the development of the maintenance system for this project. Consequently, there is a lot of future work that can be done on the basis of this project.

All the sensors and techniques proposed for the condition monitoring of the engine have to be fully developed to be implemented. The forthcoming work can focus on the selection of the specific sensors that the different companies offer. Also, on the particular location of the sensors inside of the engine, as well as in the engine room. In addition, an essential part of the condition monitoring process, that is not covered in this thesis, is the data analysis, which will enable the company to identify abnormal situations on the engine and to prevent the failure. Also, the data transmission topic can be developed more in depth with the purpose of proposing the most suitable technology for this project.

To sum up, all the proposals that result from this thesis must be developed, so that the potential of the uSEA project can be fully exploited.

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