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Exploring digital ecosystems: field insights from a powertrain monitoring perspective

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ABSTRACT

Digitalization is commonly agreed as the enabler for developing future technologies and the key for meeting the most ambitious targets across the industry. Whereas the role and importance of novel digitalized approaches is out of question, the reality of establishing such new concepts in the field is rather challenging as there is still a lack of standards in the relevant digital ecosystems.

In this paper, the focus lies on implementing a digitalized powertrain monitoring on marine vessels and large power plants with the focus on data exchange and the new opportunities offered by the resulting data models. The considered monitoring system can be seen as a role model of wide-spread devices with stand-alone purposes or - at most - with limited numbers of relations to superior systems such as e.g., an alarm management system.

For such established systems, operators are continuously confronted with the demand of increased connectivity requirements nowadays. An answer to the frequently arising question of operators, why nearly all devices are striving for an internet connection or other system integration actions, is sketched by various case studies for the discussed powertrain monitoring system. Beyond the standard processing of sensor signals for vibration and torque analyses, these case studies reveal the capabilities of enlarged datasets from the perspective of powertrain components and the monitoring thereof as well as the operational benefits originating from collecting and sharing this kind of vibration data with other systems.

Based on field experiences, the major obstacles for integrating a new component into a digital ecosystem are highlighted. As examples, these challenges arise from antiquated infrastructures, new demands on technical skills of crew members or technical staff on-site to missing standards for data exchange. For the latter issue, newly developed concepts for data exchange are finally analyzed for their capabilities of eliminating the gap of standardization from the perspective of the presented powertrain monitoring system.

1 INTRODUCTION

Digitalization is increasingly recognized as the key enabler for the development of future technologies. By leveraging digital tools, data exchange and interconnected systems, new opportunities for innovation, efficiency and growth are emerging.

Monitoring systems play a crucial role in this transformation, offering the ability to collect, analyze and exchange data. These capabilities allow for improved decision-making, enhanced performance evaluation and the creation of smarter, more adaptive systems. As the demand for digitalized solutions grows, the role of monitoring systems becomes even more critical in driving forward new, innovative applications across various industries.

This paper focuses on the perspective of a powertrain monitoring system that has long served as a stand-alone system onboard many vessels but is now evolving to an interconnected component within a broader digital ecosystem. The shift to a connected system offers significant opportunities for further innovation and efficiency and is enabling new functionalities that were not possible with the isolated system. A case study in Section 3 is used to illustrate this new potential for the presented powertrain monitoring system.

To integrate this monitoring system effectively into a larger digital ecosystem, specific requirements must be met. Reliable internet connection and data exchange are essential, as well as ensuring compatibility with existing systems through e.g. standardized communication protocols and by applying appropriate cybersecurity countermeasures. This integration process presents challenges for the design and architecture of such systems, particularly in achieving seamless interoperability between diverse technologies onboard and onshore which are discussed in Section 4 in detail.

2 POWERTRAIN MONITORING SYSTEM

2.1 Basic functionality

Torsional vibrations are an inherent part of internal combustion engines, caused by the cyclical fluctuations in rotational speed. These fluctuations result from the forces of piston motion and combustion within the cylinders, see e.g. [1]. The resulting vibrations, which act on the crankshaft and other drivetrain components, must be carefully managed to prevent damage to the powertrain.

To control torsional vibrations, systems are often equipped with torsional vibration counter-measures, such as torsional vibration dampers at the free end of the crankshaft or by high-damping, flexible couplings as part of the propulsion system. These components are specifically designed to tune and dampen the system's vibrations and to protect essential components of the drivetrain such that safe operation is ensured.

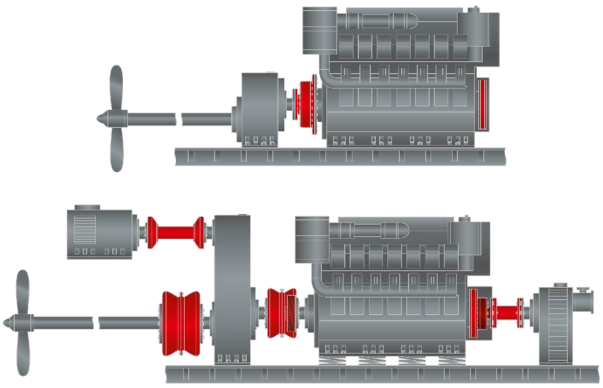

Figure 1 Two examples of marine propulsion system configurations (top: conventional, bottom: hybrid) with a sample of powertrain components highlighted in red that can be monitored with the powertrain monitoring system.

Failures of these components typically evolve to critical damages to the protected components such as crankshafts or other propulsion shafts as an effect of unacceptable high stresses within these components. For this reason, one of the main purposes of powertrain monitoring systems is to monitor the performance of vibration countermeasure components by indicating whenever critical load levels are achieved.

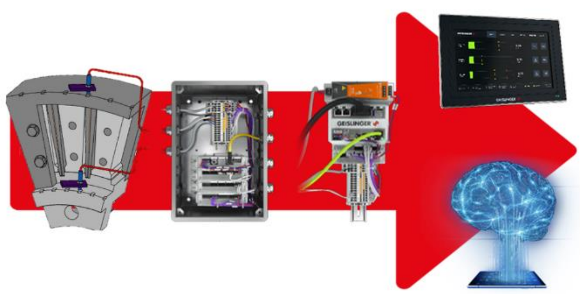

Figure 2. Components of a powertrain monitoring system. From left to right: Torsional vibration damper with sensors, Junction box for collecting sensor signals, System Unit for processing of sensor signals and data communication, onsite operating panel (right-top) and illustration of data-driven-digital solutions (right-bottom).

A component overview of such a powertrain monitoring system is illustrated in Figure 2. It consists of digital sensors (proximity switch sensors) that are mounted against rotating components with gear patterns. For the analysis of torsional vibrations, the passing times of the flanks are considered and transferred to angular deflection or twist signals. Using the Fourier transform, these results are mapped to the frequency domain, enabling spectral analysis, particularly in relation to relevant engine orders, see [2, 3].

Monitoring is usually performed by comparing measured vibration amplitudes within specific frequency ranges to threshold levels. Alarms and warnings are triggered by the monitoring system whenever normal operation conditions are exceeded. Due to the highly accurate analysis by means of a torsional vibration calculation (TVC), those critical thresholds can be derived from simulation results and parameter variations therein, [2].

Other sensor signals, used for indicating further critical incidents such as pressures or temperatures, can be seen as well-established extensions of the base torsional vibration monitoring functionality and are widely used in the field.

2.2 Beyond the stand-alone solution

The system is designed as a stand-alone solution, relying on a fixed set of sensor input signals that are typically dedicated to its own monitoring function. These sensors are often exclusive to the system and included as part of its standard configuration. As a result, expanding or upgrading the sensor set is a complex and costly task. Moreover, the system does not share sensor signals with other systems, leading to inefficiencies. It may end up using separate, own sensors that are already installed for other systems, or conversely, other systems may require sensors that this system uses, creating unnecessary redundancies for both cases.

Torsional vibration analysis and determining normal vibration conditions are complicated tasks because they are influenced by many factors that change over time and vary across different operation conditions. Monitoring systems that only use standard data often cannot detect or interpret small changes in vibrations, see e.g. [4], as factors like engine power, engine tuning, weather, and other conditions have a strong impact on the powertrain's vibration behavior as it is illustrated in Figure 3.

Figure 3 Illustration of factors that are strongly correlated with torsional vibrations of marine propulsion systems, [4].

An efficient way to overcome these difficulties is combining the powertrain monitoring system with other systems and enforcing data exchange between the different sources. On the one hand side, efficiency is achieved by avoiding sensor duplicates onboard or on-site. On the other side, the overall system can offer deeper insights into the system's dynamics or into diagnostics by identifying root causes for vibration issues.

Besides the on-site data exchange options, there is also the option to use common data processing within a centralized cloud infrastructure. This allows developing further and easily adaptable data-driven solutions, historic data storage and cloud-to-cloud data exchange possibilities. This interconnected online approach not only enhances the accuracy of diagnostics and simulations but also reduces costs by leveraging existing data on high-performance, centralized infrastructures in a fast way.

The discussed powertrain monitoring system can provide both data exchange options as it supports on-site data exchange with various supported physical interfaces and communication protocols as well as an online data-push via internet connection.

3 CASE STUDY

In this section a case study is performed to illustrate the potential of highly connected systems in large engine frameworks from a powertrain monitoring's perspective. This case study is an investigation moving beyond the static monitoring purposes of the powertrain components that is enabled by the combination of operational and vibration data.

The example of the powertrain monitoring system can be seen as a role model of other systems' approaches and motivates the tendency of more and more devices onboard a vessel demanding for internet access due to the additional capabilities.

3.1 Goal

The hypothesis to be investigated is if torsional vibration data can be used for additional digital services besides the analysis of single powertrain components. To determine if torsional vibration data can provide deeper insights into e.g. the operational condition of the monitored powertrain, a case study on the feasibility and effectiveness of combing vibration-related monitoring data with engine, operating and contextual data is designed based on data-driven approaches.

The case study examines training data models with vibration data combined with other sources (such as engine or operational data), allowing the prediction of contextual target data points using vibration data alone. Such models could be used to ensure backup strategies in case of sensor failures, identifying drift in signals or even be considered as the basis for reducing the number of sensors onboard by data models.

3.2 Data selection

3.2.1 Data sources

The study leverages data from a fleet of container vessels, each with a capacity of 14000 TEU and powered by 12-cylinder 2-stroke engines with MCR of 45500kW at 93rpm. All engines are equipped with a torsional vibration damper (TVD) and a powertrain monitoring system for monitoring the vibration amplitudes at the TVD.

The powertrain monitoring system provides a set of torsional vibration data per engine revolution, such as rotational speed or vibration amplitudes resolved in up to 24 engine orders, see e.g. [2, 3]. This data is transferred via cloud-push and stored in a timeseries database.

The vessels employ an advanced information system providing data for an online fleet performance optimization and monitoring platform. The data of the platform is used as additional data set that is combined with the vibration data for this case study. This external system delivers operational data based on two major key data sources:

- Report data: Aggregated data provided at set intervals, such as noon reports. These reports include sensor readings and manual input of the crew covering the operational conditions of a certain timespan. The temporal resolution of these reports is relatively low, and data quality is qualitatively varying as human input and interpretation is required, which limits their utility for detailed analyses.

- Sensor data: High-resolution data recorded automatically in 15-minutes intervals, focusing on key parameters as power, fuel consumption and other operational data.

3.2.2 Data preparation

A data preparation process is crucial for ensuring reliable and accurate analysis. The basic tasks of the data preparation are summarized in Figure 4.

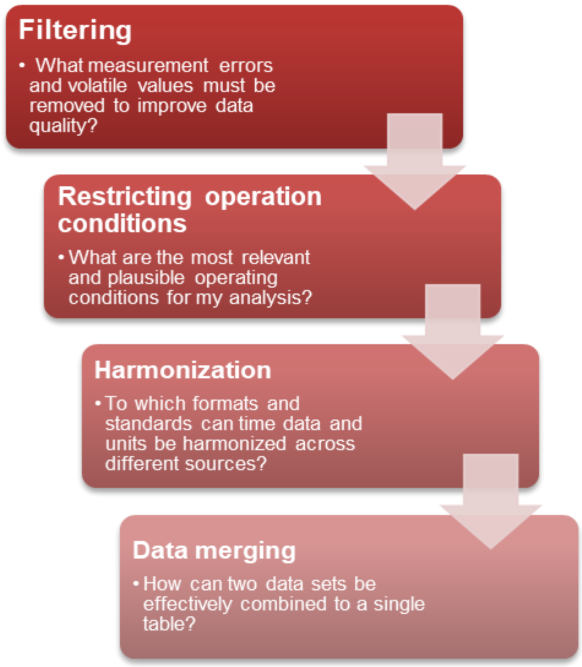

Figure 4 A summary of the data preparation process from a general point of view.

For combining the vibration data sets with the additional external data sources, the described processing steps look as follows:

- Filtering: Data is filtered to remove unreliable or volatile values, such as apparent measurement errors, improving overall data quality. As an example, fast transient dynamic changes could lead to numerical instabilities in the outcome of the vibration analysis which are identified by values exceeding physically possible thresholds.

- Restriction of operational conditions: To ensure reliable steady-state results, the analysis focused solely on data from the steady “At Sea” operating state, representing normal sailing conditions. Data form anchoring, port operations or maneuvering was excluded due to the variability and limited relevance of such conditions to steady-state torsional vibration analysis.

- Harmonization: Time information from various resources is standardized using the ISO 8601 format, [5], which simplifies interpretation and ensures consistency. Since all data is already stored in UTC, there is no possibility for wrong time zone assignments. Units across the different datasets are aligned to ensure consistency and prevent errors in analysis.

- Data merging: Once harmonized, data from different sources is combined using a shared element – time data. This step ensures that torsional vibration data is accurately linked with relevant context data. If time information cannot be linked easily due to synchronisation issues, it is also possible to link two data sets based on operational data such as e.g. engine rpm.

3.3 Model building

Once the data has been prepared, it is available as a table containing all relevant vibration data and context data from external sources. The next step is to design a suitable statistical or machine learning model. The aim is to be able to determine various context data such as performance parameters, torque or even weather conditions from the torsional vibration data.

A widely used tool for processing such data is XGBoost, see e.g. [6]. This program library uses ensembles of decision trees with which efficient data-driven models can be created. Simpler algorithms are not suitable due to the complex, non-linear relationships in the considered data.

The tool offers many advantages, such as high scalability and performance as well as being easily adaptable to different use cases. It automates many processes that have to be implemented with other tools and methods. It should be noted that the selected tool can only be used efficiently with structured data which is guaranteed by the data selection and preparation from Section 3.2.

3.4 Results

The objective of supervised learning is to accurately map the relationships between model parameters and target variables. To achieve this, the available data is split into two portions: the larger portion (typically 80%) is used for training the model, while the smaller portion (20%) is used to evaluate how well the model captures these relationships. This approach serves as a reliable measure since the model should be able to generalize effectively, meaning it should make accurate predictions on data it has not seen during training. Furthermore, the model must be usable after training phase to support data-driven services.

The comparison of predicted and real data for engine fuel consumption, indicated by fuel flow measured by onboard flow meters, is shown in Figure 5. The real data is displayed on the horizontal axis, while the predicted data is on the vertical axis. Each dot represents a prediction alongside a corresponding measured value. Similarly, Figure 6 illustrates the same results for the shaft torque measured by a shaft torquemeter. As observed, except for a few outliers, the mapping is highly accurate for both target parameters: engine fuel flow as indicator for fuel consumption and shaft torque.

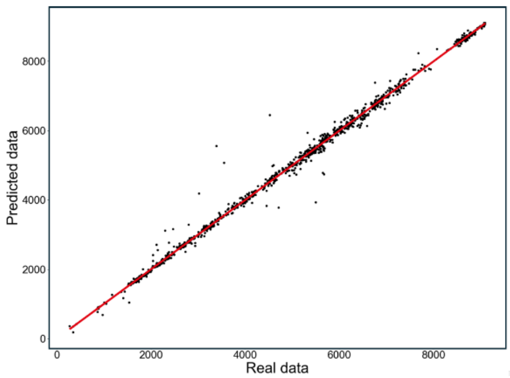

Figure 5 Comparison of predicted and real data for fuel flow [kg/h]

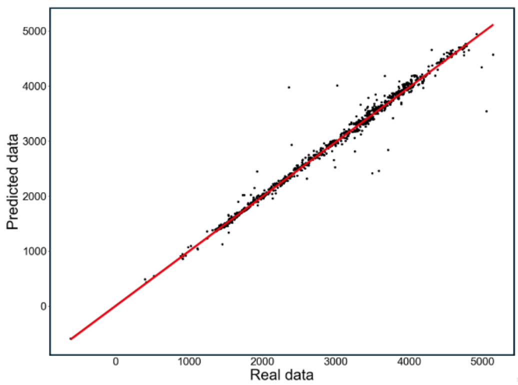

Figure 6 Comparison of predicted and real data for shaft torque [kNm]

The performance of a model for wind speed can be seen in Figure 7. The correlation is not as accurate as for fuel consumption or shaft torque, which can be seen by the stronger deviations from the ideal red line. However, the fact that the tendency is recognizable here as well by a data model only relying on vibration data was not to be expected from the beginning.

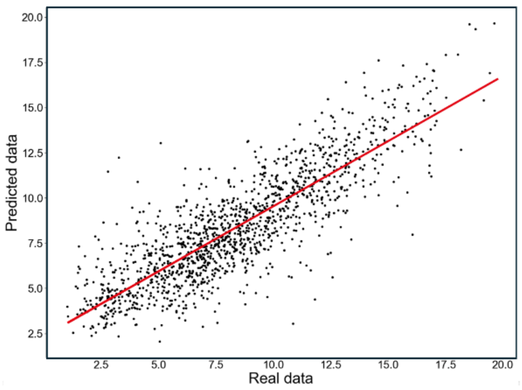

Figure 7 Comparison of predicted and real data for wind speed [m/s]

An interesting aspect to examine is when deviations occur between predictions and real data. This was investigated by assessing individual trips. Noticeable patterns can be observed, as illustrated in an example in Figure 8. Two distinct clusters are evident: one occurring in the region of South India (yellow), which can be attributed after further analysis to poor weather conditions, and another near Sumatra (red), caused by measurement errors of the onboard shaft torque meter.

3.5 Interpretation of results

Machine learning models, as demonstrated in this study, reveal strong correlations between torsional vibrations and engine operating conditions, which can be effectively modeled. It is shown that it is possible to link complex thermodynamic processes responsible for fuel consumption and shaft torque to vibration data. Overall, the quality of the data models' predictions is much better than anticipated.

A potential use case for this case study is the ability to supplement physical sensors onboard with data models based on vibration data. This approach could provide a valuable sensor backup, enhancing the reliability and flexibility of monitoring systems.

One further key take-away is the limited transferability of models across the fleet. Despite the ships being almost identical in design, applying a model developed for one vessel to another sister vessel leads to large prediction errors due to subtle differences that are incorporated into the vessel's data models after the training phase.

4 DIGITAL ECOSYSTEMS

Together with the opportunities provided by digitalized monitoring approaches, also the complexity and requirements of the integration tasks for such monitoring systems are increasing. This section examines the design and

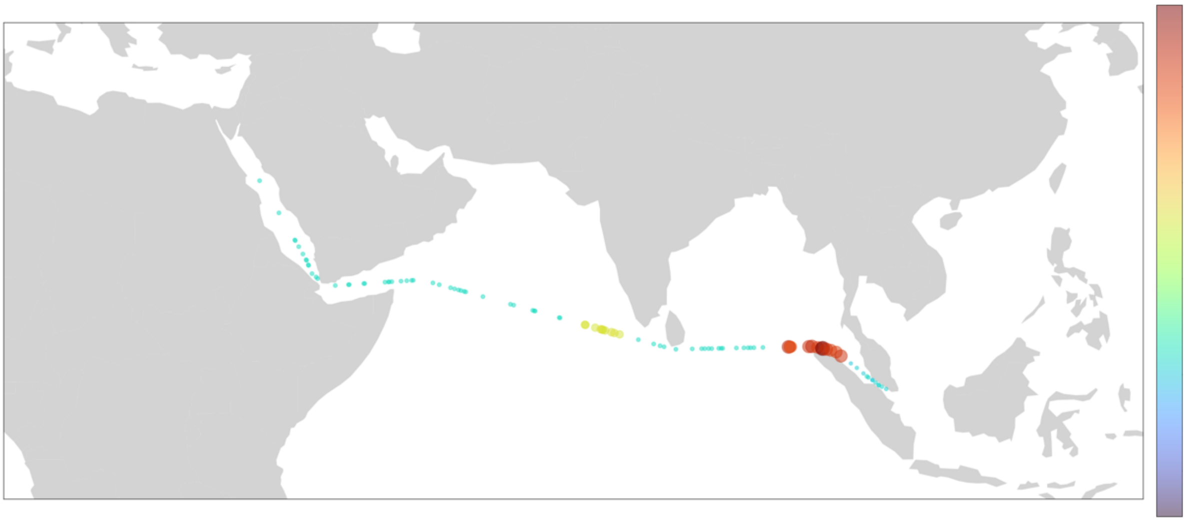

Figure 8 Evaluation of a single trip, where the color code refers to deviations between predicted and onboard measured shaft torque. Large deviations from the model's prediction are marked in yellow to red.

development of a monitoring system that can be integrated into both existing and newly built marine installations. It addresses how digital ecosystems influence the system architecture and design of such a monitoring system, as outlined in Section 2.

4.1 System requirements

As a starting point, requirements of the monitoring system are collected and their implications on the design of the system are illustrated. The strategy for this - from the perspective of the powertrain monitoring system - is based on guidance on how to implement a monitoring system in hybrid marine applications described in [7]. Special emphasis is placed on the illustration of additional issues and tasks arising for highly connected systems.

The purpose of the powertrain monitoring system can be summarized as follows:

- The system must be able to operate with no additional input signals beyond those included in the delivery scope (i.e., it is working as a stand-alone system). The minimum sensor configuration includes a single digital sensor mounted against a rotating component.
- The main task is to provide indications of the condition of the powertrain. More specifically, in case of critical or abnormal conditions, the system provides warnings and alarms to local staff (independently of the considered digital ecosystem as a stand-alone system) as well as fast feedback to superior systems (like e.g. alarm management systems).
- Furthermore, the system provides tailor-made data for detailed system analysis for experts in the field of torsional vibration analysis, especially with focus on the performance evaluation of torsional vibration dampers and flexible couplings.
- Beyond the onboard tasks, a target is to establish a cloud-based monitoring application that provides insights on the condition of the powertrains and their key components with trend and predictive analyses with the aim to develop and integrate new data-driven services. The beneficiaries of such services are intended to be either onboard (e.g. chief engineers) or onshore (e.g. fleet managers or superintendents).
- Based on the development of new services and demands the system must be able to expand the functionality and input data set of the monitoring for establishing new monitoring products based on value added data.

In accordance with the requirements, a digital ecosystem of powertrain monitoring is shown in Figure 9.

The step from a stand-alone system towards an interconnected approach with other systems raises new challenges and demands that are described in subsequent sections in more detail.

4.1.1 Compatibility with digital ecosystems

There are different design decisions that must be made at an early stage of the development process of a monitoring system in terms of being compatible with the ecosystem on-site. The decision about which hardware components and which physical interfaces are selected is important whenever the system needs to be prepared for a specific level of data exchange.

As the requirements also include a variability of monitoring functionalities and input signals

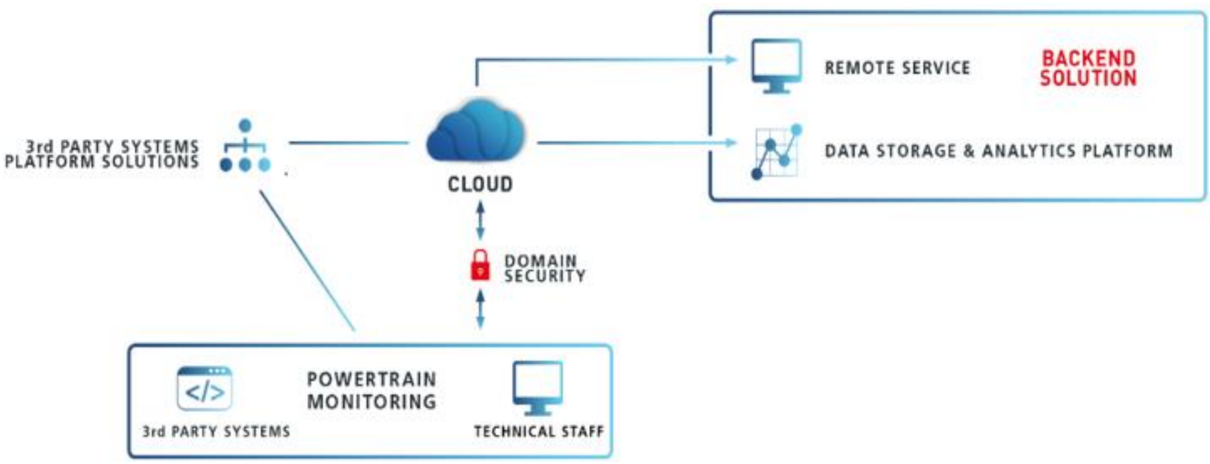

Figure 9 Digital ecosystem of the powertrain monitoring system [8].

together with the uncertainty of upcoming necessary cybersecurity countermeasures, a continuous development process must be made possible by the software design. Consequently, a product is not only limited to the state of delivery but might be subject to changes by updates during its entire lifetime. An admissible update distribution strategy is therefore mandatory to not only maintain the monitoring purpose itself, but also to guarantee compatibility with the digital environment.

4.1.2 Data and information transfer

Modern systems must support data sharing and cloud-based analytics to handle the growing complexity of newly demanded monitoring applications as well as proving highest demands on cybersecurity and operational safety.

There are three major data exchange options that need to be considered during the design phase of the powertrain monitoring system:

4.1.2.1 On-site/onboard monitoring – To fulfill the local requirements, the monitoring systems need to be able to locally communicate with other parties by using various interfaces. All those interfaces and data exchange strategies must be designed to meet the requirements of the receiver in terms of security, latencies, bandwidth, communication interruption handling and data quality, see [7].

4.1.2.2 Vessel to cloud data transfer – From the perspective of the powertrain monitoring system, there are essentially two ways for the data transfer to the cloud infrastructure. First, direct cloud-push from the device itself and second, by a local data exchange to a local device (e.g. data logger) and centralized transfer to a backend solution.

For the direct cloud-push option, the internet connection and rights for data transfer must be supplied by onboard facilities for the considered powertrain monitoring system. A separate internet module or comparable options are in terms of efficiency not admissible as such modules would generate unwanted redundancies and system complexity and thus lead to avoidable costs.

In the case of temporarily missing or disrupted internet connection a local data storage must be kept avoiding losing significant amounts of data. However, this backfall option is only capable of recovering a certain amount of data or time and needs to be selected based on risk assessments or on available field experience.

For external data exchange, typically third-party data storage and platforms receive onboard data through a single device that is locally collecting data. Thus, for this kind of option it is often required to maintain both - local interfaces for onboard communication between the involved devices and for automated exchange between backend solutions - which raises the efforts significantly.

4.1.2.3 Cloud-to-cloud transfer & backend design – As an integral part of the design of the powertrain monitoring system, there is also the requirement to define an admissible architecture of the backend solution. The development of the onboard hardware is closely linked to the design of the cloud infrastructure as the data exchange and processing of generated data in the cloud is a basic requirement. Therefore, the entire development process of hardware, diagnosis software on-site and onshore needs to be coupled accordingly.

Based on the expected population increase of the system after market entry, a strategy for scalability of the cloud system needs to be defined to guarantee a smooth transition from the ramp-up phase starting with low data traffic to an increasing number of devices connected to the backend solution.

Already at a rather early stage of development, strategic decisions concerning data processing and sharing strategies in the backend need to be addressed. This concerns among other issues, e.g., how long the data should be accessible, how to manage the different user roles for data access and the corresponding APIs or how the data should be visualized and compressed for the optimal user experience.

4.2 Limitations

This section explores the limitations observed in digital ecosystems, particularly in the integration of powertrain monitoring systems into existing infrastructures. It is based on insights gained from market and customer feedback, as well as field experiences collected between February 2021 and December 2024. These real-world findings highlight various challenges and constraints that emerged during the implementation phase, providing a clearer understanding of the gaps between system requirements and practical application and missing standards in the industry.

4.2.1 Increasing technical requirements and missing standards

In addition to the overall complexity of designing a digital ecosystem for new-built systems, the aspect of retrofitting digital solutions is of particular interest for existing powertrains. For vessels that are already in service for a long time, the IT infrastructures onboard might look completely different depending on the efforts taken by the operator on the digitalization of the ship. This ranges from well-suited and in terms of cybersecurity well-protected IT infrastructures to antiquated hardware or insufficient availability of internet access. From the view of system integration, this leads to the situation that a wide range of varying boundary conditions must be considered for integrating a new component, such as a new monitoring system, to the existing digital ecosystem.

In addition, the technical requirements and requests for crew members are rapidly changing. This might be solved by intense training of the crew and technical staff, implementation of new positions within involved stakeholders or by outsourcing to third party service providers. In any case, there are new substantial stakeholders to be considered when it comes to a modification of the digital ecosystem onboard.

In highly connected frameworks, data exchange is crucial for meeting the requirements in terms of digital solutions. As for IT infrastructures, also data sharing is subject to a variety of different physical interfaces and communication protocols due to a lack of wide-spread industry standards. This missing standardization results in high efforts to set up data exchange strategies with different partners, which makes it besides legally and commercially demanding also to a technical challenge.

A major concern with data exchange is that errors and faulty connections are often identified at a late stage, typically after the implementation and installation phases, making it difficult to apply quick fixes. This requires careful attention and pre-testing, as such issues can lead to significant project delays and require extra effort to resolve even minor problems for globally operating installations.

For many applications data exchange has become mandatory as IT departments often require minimizing the number of devices used to transfer data from the vessel to onshore locations. This approach aims to reduce the number of potential vulnerabilities associated with multiple outbound communication channels. As a result, on-site data exchange between different systems is unavoidable in many cases, requiring local system integration in a first step to ensure efficient and secure data flow to a cloud infrastructure.

4.2.2 Digital ecosystems and user platform variety

With increasing number of digitalized components and digital services, users are often confronted with multiple user platforms that are time consuming to be handled all at once. Instead of a multi-platform environment, it is requested to have all services in as few platforms as possible to maintain a centralized view on the services and tasks.

It is state-of-the-art that leading market participants can provide multiple applications out of their product portfolio in a single platform. However, it is still rather difficult from various perspectives (legal, commercial as well as technical) to set up a collaborative platform approach where different service providers can easily contribute to.

The greatest benefit of a common platform is that it allows each participating provider to contribute its specific field expertise, while simultaneously reducing the number of user platforms. This streamlines the user experience, ensuring seamless access to various services without the complexity of managing multiple platforms.

4.2.3 Digital services and data accessibility

Data-driven solutions typically demand for a continuous data exchange as basis for the provided services. In reverse, without a continuous data transfer the services cannot be provided in the same quality and quantity.

A commonly discussed issue in marine digitalization, internet availability e.g. on high sea routes, tends to become less critical due to newly accessible internet providers for remote destinations. On this branch of the technology development, demand for internet connectivity without major geographical restrictions can be fulfilled.

However, although the technical solutions for connectivity are constantly improving, flawless data availability still cannot be granted. One of the major impacts is the increasing complexity of IT infrastructures and cybersecurity measures that might prohibit the data transfer due wrong configurations, changed cybersecurity guidelines or by misunderstandings between an onshore IT office, the crew onboard and further involved stakeholders.

In the absence of data, services and data models that rely on a continuous data flow may become outdated or inaccurate, potentially resulting in the failure to provide the requested service under worst-case conditions.

4.2.4 Reporting and KPIs

Torsional vibration data is commonly agreed as expert data requiring a certain level of training and knowledge of specialized simulation models (TVC) that are not accessible to standard users of the monitoring system. The multidimensional structure and the non-linear dependence on complex thermodynamic processes such as e.g. the combustion process typically prohibits an easy rule-based evaluation of the data. For this reason, it is important to reduce the complexity of the data for reporting. The main challenge is to bring all the domain knowledge to the data evaluation within the backend system and provide sufficiently reduced and condensed information with reports or KPIs. The overall goal is to support the operational tasks of the user with the provided documents and KPIs which need to be understandable and usable also for non-vibration experts.

4.2.5 Explainability of purely data-driven approaches

A major obstacle for purely data-driven services is connected to the explainability of the used data models. In contrast to physical or simulation-based approaches, the conclusion why a specific outcome is derived from a data model is not always available or comprehensible. It is therefore important to focus not only on the outcome for such applications, but also on the explanation why a data model provided them.

4.2.6 Training data and new events

A further key issue with data models is their behavior when extrapolating beyond the trained ranges. In such cases, the model may still generate predictions, even when the input values are far outside the data it was trained on. This can lead to highly unreliable results, as the model is unable to accurately capture the underlying patterns or relationships in these unfamiliar regions. This can significantly compromise the accuracy and trustworthiness of its predictions and might require a re-training of the data models with the training data capturing these new events.

5 CONCLUSIONS

In this paper, the integration of a powertrain monitoring into state-of-the-art digital ecosystems is discussed. Motivated by a case study that revealed the significant potential of vibration data for advanced powertrain monitoring and data-driven decision-making, the focus lies on providing insights into how such a system can be integrated into new-built or existing systems from various point of views – ranging from discussions of used hardware, software and cloud infrastructures towards various kinds of challenges based on field experiences.

Although being only a small part of the digital ecosystem it shows the great potential, but also the big challenges of digitalization within the marine context. It is addressed that overcoming challenges in data exchange and related issues remains a major hurdle. As for instance presented in [9], there are increasingly many efforts for a seamless data exchange across different systems which is crucial for enhancing operational efficiency or for achieving a higher level of autonomous shipping. However, a key question persists: who will provide the necessary infrastructure and implementations to enable effective and secure data flow? The answer is not yet clear and without a unified solution, widespread adoption remains uncertain.

Moreover, the shift to digitalization in the marine industry goes beyond technical challenges. It also involves significant commercial and legal complexities, including the development of new business models, the need for standardization, ensuring cybersecurity, and adapting regulatory requirements. Achieving a fully integrated digital ecosystem will require collaborative efforts from stakeholders across different industry sectors to address these multifaceted challenges.

6 ABBREVIATIONS

TVC: Torsional Vibration Calculation

TVD: Torsional Vibration Damper

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