New Artificial Intelligence Technology Improving Fuel Efficiency and Reducing CO_2 Emissions of Ships through Use of Operational Big Data

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Fuel cost and CO_2 emissions in operating ships are major challenges for the maritime industry. A large marine transport company spends more than 2.6 billion U.S. dollars on fuel every year. In order to reduce fuel consumption as well as CO_2 emissions from ships, it is crucial to be able to accurately calculate the impact of winds and waves on ship speed and fuel efficiency. Normally, existing ship performance estimation technologies rely on experiments with model ships in tanks of water, or on physics model simulations. However, they do not take into account the complicated interactions of winds, waves, and sea currents that influence the state of ships at real sea waters, resulting in large margins of error. Against this background, Fujitsu Laboratories has developed a technology to visualize ship performance. In addition to weather and sea conditions including winds, waves, and sea currents during actual ship operation, it collects engine log data and ship operation data such as location and ship speed, and posts it to the cloud, and then analyzes these data using high-dimensional statistical analysis that we developed. Applying this technology to a university-owned test ship and some merchant ships resulted in highly accurate estimation of ship speed and fuel consumption for each of the ships, with error of 5% or less. We also evaluated this technology through simulation and verified that it can improve fuel efficiency significantly. This paper describes this technology to predict ship performance in real sea waters, which is key to reducing ship fuel consumption, with some examples of system configurations.

1. Introduction

The impact of ship operations on the environment and the economics and safety of ship operations are major issues in the maritime industry (shipbuilding, shipping, etc.). In 2012, annual CO_2 emissions from ship operations reached approximately 900 million tons, which represents about 3% of worldwide CO_2 emissions. Against this background, CO_2 emissions regulations applicable to newly built ships were introduced as part of the 2013 revision of a convention by the International Maritime Organization (IMO), a specialized agency of the United Nations. Given that annual fuel expenses of shipping companies can reach several hundred billion yen, reduction of these expenses is a major theme. Further, increasingly the collection, accumulation, and analysis of ship operation data in stormy weather are being sought for the design of safer and more economical ships and for safer ship operations in stormy weather.

An accurate grasp of the fuel efficiency of ships for specific weather and sea conditions would allow determination of the most fuel-efficient route, such as traveling the shortest route or taking a roundabout route to avoid waves and winds. However, existing ship performance estimation technologies that rely on experiments with model ships in water tanks or on physics model simulations do not take into account the complicated interactions of winds, waves, and sea currents that influence the state of ships at real sea waters, resulting in large margins of error compared with performance in real sea water.

To solve this problem, Fujitsu Laboratories developed a technology based on high-dimensional statistical analysis which allows the visualization of ship performance without using physics models. Application of this technology was found to result in highly accurate visualization of ship performance by using ship operation data, engine data logs, and other ship-related information collected in the cloud. This advance allows the creation of various services, including the selection of fuel-efficient routes, the creation of guidelines for the design of fuel-efficient ships, and comparison of ship performance before and after ship maintenance.

This paper introduces the maritime industry's efforts to reduce fuel consumption, Fujitsu Laboratories' proprietary high-dimensional statistical analysis technology for realizing fuel economy improvement, configurations of the system using this technology, and the results of demonstration experiments.

2. Efforts to reduce fuel consumption in maritime industry

The maritime industry is focused on developing energy-saving technologies for ships.[1] Various technologies have been developed, from structural improvements such as in engine combustion efficiency, propeller efficiency, and hull resistance, to development of merchant ships using alternative energy sources such as sunlight and wind power, paints that improve fuel economy, and technology that reduces the friction resistance between the ship's bottom and the seawater through the discharge of air bubbles along the ship's bottom.

A technology called "weather routing" that improves fuel efficiency by optimizing route selection has also been developed and put to practical use.[2] Weather routing is a technology designed to calculate optimum routes while taking into consideration weather and sea condition forecasts and their anticipated impact on ship speed and fuel consumption, factoring in constraints such as arrival date and time, in order to optimize parameters such as navigation time, fuel consumption, damage to hull or cargo, and passenger comfort, either singly or combined. Weather routing has a long history. At the beginning of the eighteenth century, it was already being used to shorten the duration of sea voyages by exploiting ocean currents. In 1957, R. W. James from the U.S. Navy demonstrated a method of determining optimum routes through the use of isochronous curves, and weather routing services were soon launched by private sector companies.

The visualization of ship performance in real sea waters greatly contributes to the improvement of weather routing performance. Traditionally, prediction of ship performance in real sea waters was based on physics models of hulls, waves, and winds. Efforts were made to improve prediction accuracy by building physics models, analyzing data collected from tank experiments and operation at real sea waters, and correcting physics model parameters. However, physics models do not necessarily meet all hull, weather and sea conditions, and there are cases where the model fits or does not fit depending on the conditions.

3. Fujitsu Laboratories' proprietary high-dimensional statistical analysis technology

Fujitsu Laboratories thought better weather routing performance could be achieved through application of both its proprietary big data analysis technology and artificial intelligence (AI) technology. By applying our own AI technology, "Human Centric AI Zinrai," to big data analysis of ship operation, we succeeded in developing a technology to estimate ship performance in real sea waters with a margin of error of 5% or less, an extremely high level of accuracy.

Abandoning conventional physics models, Fujitsu Laboratories' proprietary high-dimensional statistical analysis technology is employed to determine the actual impact of winds and waves on a ship based on the large amount of ship operation data and engine log data collected by the ship. The data used consists of weather and sea sensing data such as winds, waves, and ocean currents recorded during actual ship operation, the ship's engine log data, and ship speed and location data. High-dimensional data integrating all the above data are analyzed and learned, and ship performance is then estimated under weather and sea conditions for which actual measurement data has not yet been obtained.

The features of the present technology are as follows.

1) Analysis based on actual ship operation data without physics models

The above-mentioned high-dimensional statistical analysis technology was applied and simultaneous analysis of various influences such as weather and sea conditions was successfully carried out using the measurement data obtained from ship operation. This made it possible to estimate ship performance taking into account the complicated interactions of winds, waves, sea currents, and the like, based on the raw data obtained in real sea waters, not data from water tank experiments.

2) Automatic grouping of actual measurement data and learning level adjustment

As shown in **Figure 1 (a)**, in a conventional physics model, the estimation accuracy cannot be improved because the physics phenomena are represented by a model that simplifies, for example, by classifying wind strength as either uniformly "weak" or "strong." By contrast, as shown in **Figure 1 (b)**, the present technology automatically groups high-dimensional data integrating various measured data by similarity, such as weather and sea conditions, allowing learning and estimation according to each group. As a result, suppression of estimation errors due to averaging over the whole range was achieved.

4. System configurations and modes of operation

The incorporation of this technology into FUJITSU Intelligent Society Solution SPATIOWL, a cloud service that utilizes location information, to create a system for providing various ship-related services, is being considered (**Figure 2**). Data, including that from voyage data recorders (VDR) on ships, and other data such as the fuel consumption data included in engine log data, is aggregated in SPATIOWL.

Figure 2 shows an example in which AI and a weather routing simulator are mounted on SPATIOWL. AI allows the visualization of ship performance based on weather and sea conditions through the aforementioned proprietary high-dimensional statistical analysis technology of Fujitsu Laboratories. Such visualization is used to set the WR parameters. By using the highly

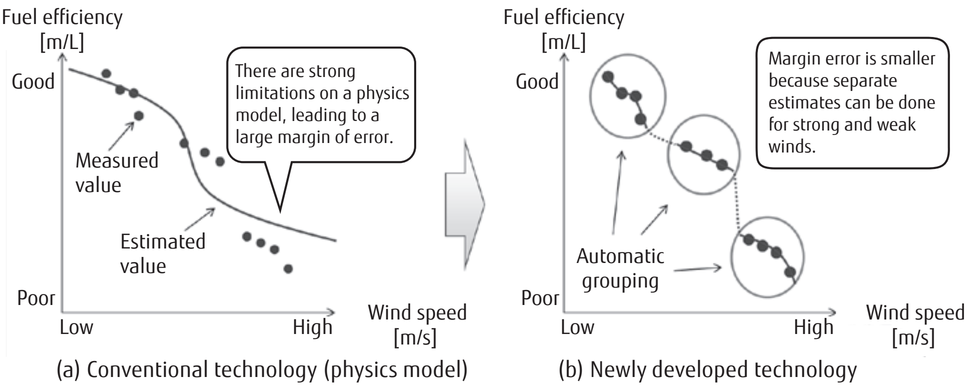
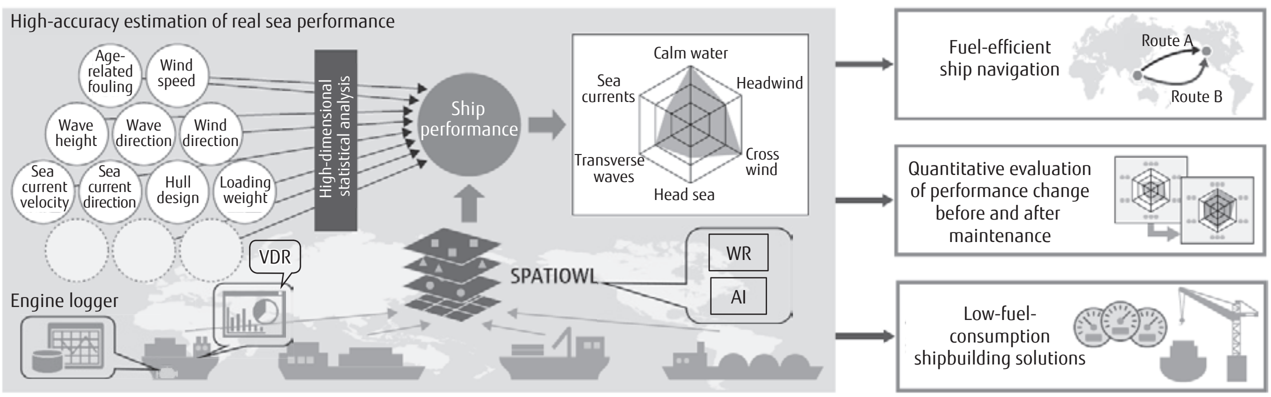


Figure 1
Differences between conventional technology and newly developed technology.



WR: Weather routing simulator

Figure 2
Examples of incorporation of developed technology into SPATIOWL.

accurate real sea water performance estimation results for the target ship, it is possible to determine optimum routes better than ever before, allowing ship navigation with low fuel consumption. Further, by allowing accurate ship performance visualization, this technology makes comparison of ship performance before and after maintenance possible, as well as prediction of ship performance during ship building and feedback of findings to design.

5. Collaborative research and demonstration experiment

In developing this technology, we collaborated with Tokyo University of Marine Science and Technology (TUMSAT). The data were collected off the coast of Tateyama, Chiba Prefecture, using a test ship owned by TUMSAT. The ship was navigated several times off the coast of Tateyama in a course forming rectangular patterns, collecting various types of data including ship speed and fuel consumption data in real sea waters under the influence of weather conditions, with winds and waves coming from various directions. The acquired data consisted of the following ten items.

- Bow direction
- Speed through water (STW)
- True wind direction
- True wind speed
- Rudder angle
- Controllable pitch propeller (CPP) blade angle
- Shaft revolutions
- Shaft power
- Main engine revolutions
- Fuel consumption

In this experiment, ship performance was estimated using the data obtained from the measurement of the above items. As the developed method does not require a physics model, if items other than the above, such as wave direction, wave height, tidal current direction, and tidal current velocity, are measured, they can simply be added for analysis. Generally, the accuracy of performance estimation improves as the number of items used increases.

The data was measured and accumulated at one-second intervals during ship operation. For the evaluation, one day's worth of data, corresponding to one operation period of the test ship, was used. The total number of measured data was 77,435. Among these, 9,574 of data excluding data recorded at low speeds with STW of 5 knots or less were used for evaluation.

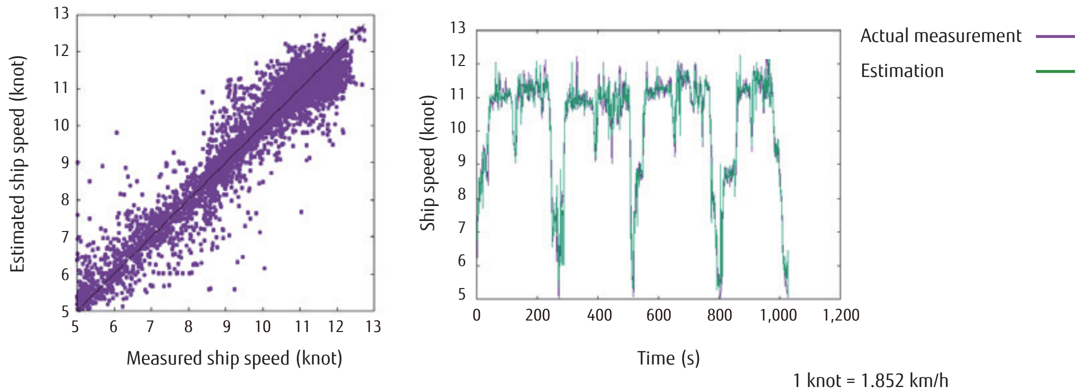
In this evaluation, the acquired data was divided into data to be used for learning and data to be used for estimation, and the ship performance was visualized using only the learning data. With regard to STW, the relationships between STW and the nine other items in the above list were visualized. Likewise, with regard to fuel consumption, the relationships between fuel consumption and the nine other items in the above list were visualized.

Whether fuel cost and ship speed can be accurately estimated from the ship performance thus visualized was verified using the test data for estimation. The results are shown in **Figure 3**. **Figure 3 (a)** is an estimate of ship speed. The horizontal axis of the left-side graph indicates the actually measured ship speed, and its vertical axis indicates the estimated ship speed. The closer the plotted points are along the diagonal line, the closer the measured values are to the estimated values. The right-side graph shows the measured values and estimated values of ship speed arranged in chronological order. The more the graphs of the measured values and the estimated values overlap, the higher the accuracy of the estimation. **Figure 3 (b)** shows the estimated fuel consumption in a similar manner. From the above results, it was found that the STW and fuel consumption can be accurately estimated without using physics models.

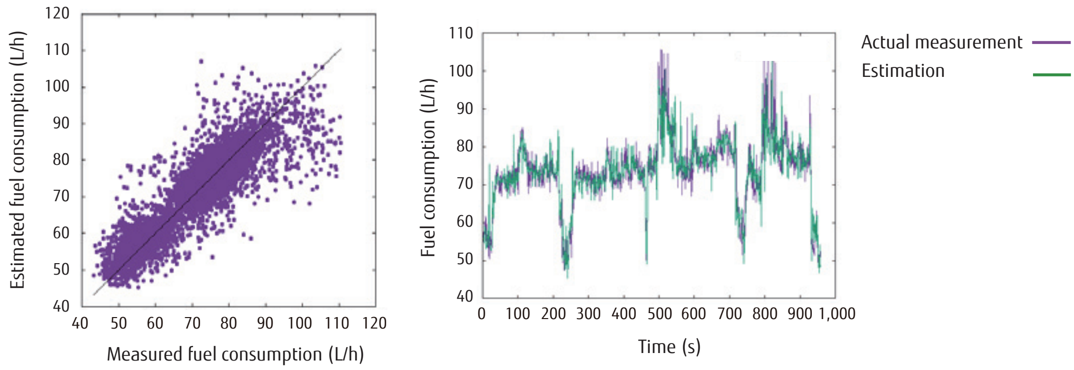
Table 1 lists the results of evaluation of estimation

Table 1
Evaluation results of ship performance estimation.

	MAPE (%)				Calculation time (s)
	Average	Standard deviation	Max.	Min.	
STW (knot)	2.8	0.0001	3.0	2.6	11
Fuel consumption (L/h)	4.4	0.0002	4.8	4.3	11



(a) Estimation accuracy of ship speed



(b) Estimation accuracy of fuel consumption

Figure 3
Verification of estimation accuracy of developed technology.

error using 10-fold cross validation. Ten-fold cross validation is a validation method that repeats verification a total of ten times, by dividing the entire data into ten blocks, selecting and learning nine out of these ten blocks, and using the data of the remaining block for evaluating the estimation error, in order to evaluate estimation error in all blocks.

As the error index, mean absolute percentage error (MAPE) obtained by the following equation was used.

$$MAPE = \frac{1}{T}\sum_{t=1}^{T}\frac{|f(x_t)-y_t|}{|y_t|}$$

where T is the number of samples of evaluation data, t is the ordinal number among all T samples, x_t is the input data used for estimation of the t-th sample, $f(x_t)$ is the estimated value of the STW or fuel consumption relative to x_t, and y_t is the measured value of the STW or fuel consumption of the t-th sample.

The mean absolute percentage error with respect to the estimation of the STW was 2.8%, and the mean absolute percentage error with respect to the estimation of the fuel consumption was 4.4%, showing that the proposed technology is capable of high accuracy estimation in both cases with an error of 5% or less. Generally, although this depends also on the nature of the data and the required accuracy, 3,000 or more data were found in this experiment to be the number of samples required to estimate both STW and fuel consumption with an error of 5% or less.

As shown in Table 1, the calculation time required for learning is just 11 seconds for both STW and fuel consumption, a level that qualifies as high-speed learning. The computer used was a PC with an Intel Xeon Processor E3-1275 v2 (3.50 GHz, 64 bits), 32 GB of RAM, and running Windows 8.1 Pro.

The proposed technology was also applied to merchant ships actually carrying cargoes to verify its accuracy. From the merchant ships' operation data and engine log data, the ships' speed and fuel efficiency were visualized, and the ships' speed and fuel consumption on actual routes were estimated. As a result, similarly to the verification described above, it was found that both speed and fuel consumption can be estimated with an error of 5% or less.

Based on the above results, use of this technology allows prediction of ship speed and fuel consumption with high precision on routes to be traveled. Thus, the proposed technology is considered to be more suitable for optimum route selection than traditional weather routing algorithms that use physics models.

The results of the demonstration experiment off Tateyama were incorporated into the weather routing simulation of TUMSAT, and the fuel consumption reduction effect of this technology was evaluated. With respect to the North Pacific routes from Tokyo to Los Angeles, it was confirmed that when navigating optimum routes based on ship performance visualized by this technology, fuel consumption can be reduced by about 5% compared with navigation of the shortest route, and significant reductions in fuel cost and CO_2 emissions can be achieved as a result.

6. Conclusion

This paper introduced the utilization of Fujitsu Laboratories' proprietary AI technology to estimate and visualize ship performance in real sea waters with a high degree of accuracy and, through application of the results to weather routing simulation, the possibility of greatly improving fuel economy.

We plan to further improve the estimation accuracy of this technology through collaborative research with Tokyo University of Marine Science and Technology in the future. We plan also to demonstrate the application of this technology to various types of ships and routes, and aim to offer it as a service of FUJITSU Intelligent Society Solution SPATIOWL in the course of FY2017.

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