Optimal Pitch, Speed and Fuel Control at Sea

Thomas Hellström
Associate Professor, Department of Computing Science, Umeå University, Sweden., thomash@cs.umu.se

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ABSTRACT

This paper discusses algorithms for fuel saving control for large vessels. The fuel saving is achieved by optimizing control at three levels: low level propeller and main engine control, dynamic speed control to avoid peeks in the fuel consumption and finally route planning for optimal speed profiles compensated for varying depth and weather conditions. The control problems involve classical control functions as well as numerical optimization.

INTRODUCTION

The fuel costs are the second largest item (after salaries) on a big vessel's budget. The fuel consumption for a large ferry ranges between 1,000 and 5,000 liters per hour. This means that the ship consumes more oil per hour than a one-family house does for one whole year's heating (in northern Sweden). The annual fuel budget for a ferry running 20 hours per day is in the order of millions of dollars. Even small reductions of a few percent o. the fuel consumption means considerable annual savings.

This paper discusses the experiences of a challenging research and development project for fuel saving and top-level control of a ship's performance. More information can be found in [3] and [4]. The developed system is operated from the central unit placed on the bridge (see Figure 1). The operator, normally the ship's First officer or Captain, inputs the required values for speed, arrival times, and complete route plans from the keyboard. The main engines (10-40,000 horsepower) and propellers are then automatically adjusted, to reach and maintain the required speed at the lowest fuel consumption. Fuel saving is typically 5-10%, corresponding to at least 1 cubic meter of heavy fuel oil per day. The saving is achieved by optimizing control at

three levels:

1. Pitch optimization. The pitch angle of the blades on a controllable propeller acts as a kind of gear box, and effect the ship's speed together with the main engine's revolutions (rpm). The optimal combination of pitch/rpm depends on a number of external and time-varying conditions, and therefore must be subjected to dynamic optimization to be optimal.
2. Dynamic control of speed to avoid sudden peaks in fuel consumption caused by low water depth, or unanticipated changes of the weather conditions.
3. Route planning. The fuel consumption for a ship depends not only on speed, but also on water depth and weather conditions.

The optimal speed distribution along the route can be computed in advance, if a weather forecast is available. The described hardware and software have been implemented as part of the Seapacer system which has been installed on around 20 ferries across northern Europe. This paper discusses the underlying principles and the

Fig. 1. The central unit placed on the bridge of the vessel. The left screen is used for real-time control tasks such as speed settings while the right screen is used for long term voyage analysis and follow-up.

experiences of the research and development of the system. Section 2 describes the design and basic operation. The three levels of optimizing control described above are covered in more detail in Sections 3, 4 and 5. Section 6 discusses general experiences and difficulties encountered during the project.

THE DESIGN OF THE CONTROL SYSTEM

The basic layout of the system is shown in Figure 2. The central unit takes over control from the manoeuvering handles of the main engine's speed (revolutions per second) and of the propeller pitch. The most important components are shown in the figure.

From the user's perspective, the system is a tool for high-level control of the vessel's speed and fuel consumption. The main functionality can be described as a number of control systems aiming at obtaining and keeping set values for speed, fuel consumption or arrival time. More information about the functionality of the system can be found in the User's Guide: *Seapacer Optimizing System Mark II* [3].

The system interfaces with a large number of sensors and sub-systems on the vessel. The most important inputs are ship's speed over ground, fuel consumption, propeller revs and GPS navigator. Many of the signals are highly noisy and also give off completely incorrect signals from time to time. This has to be handled in a stable manner by the software by filtering and outlier detection. Sensor fusion is also utilized for the estimation of bottom track speed. The primary source for speed is the Doppler log, which measures the echoes of ultrasound pulses against the bottom. This

normally works well, but can sometimes give off incorrect values due to false echoes or too large water depth. A differential GPS navigator provides an alternative speed source. In older systems, this signal is often updated too slowly or too much delayed to be useful as input in the actual control system. However, the GPS speed is useful as a backup for the speed log, if and when the speed log fails. Likewise, the speed log is used as complement to the navigator. The navigator sometimes loses the signal from the satellites. The speed log is then, in combination with the last estimate of the ship's course, used for dead reckoning to update the estimate of the ship's position. Tha main unit is integrated into the vessel's existing control system for main engine revs and propeller pitch control.

PITCH OPTIMIZATION

The pitch angle of the blades on a controllable propeller acts as a gearbox, and controls the ship's speed along with the main engine's revolutions (rpm). The optimal combination of pitch/rpm depends on a number of external conditions, and therefore must be subjected to dynamic optimization to be optimal. The system minimizes the consumption of fuel by maintaining an optimal ratio between the propeller's pitch and the speed of rotation. The optimization aims at minimizing the fuel consumption, measured as consumed oil per nautical mile, for a given set speed s_{set}. The directly measurable entities are water track speed s_{wt} (nautical miles per hour) and fuel consumption c (liters per hour). Both s_{wt} and c are functions of the pitch p and main engine revs r. Hence, the pitch optimizer tries to solve

$$(r_{opt}, p_{opt}) = \arg\min \frac{c(r, p)}{s_{wt}(r, p)} \tag{1}$$

with the constraint

$$s_{wt}(r, p) = s_{set} \tag{2}$$

where s_{set} is the set speed for the vessel. s_{set} is given explicitly by the operator. The optimization problem has to be solved in real-time with both c and s_{wt} being extremely noisy. Furthermore, the time constants involved in the processes generating c and s_{set} are large. This means that a change in r or p not immediately causes a measurable change in neither c nor s_{wt}. By the time c and s_{wt} respond, the process may very well have a new characteristic, i.e. the optimal values (r_{opt}, p_{opt}) may have changed. Altogether the optimization problem is indeed very hard. The implemented solution uses an algorithm that first controls r and p such that constraint (2) is fulfilled. In the next stage, r and p are moved in one direction until a local min value for $c(r, p)$
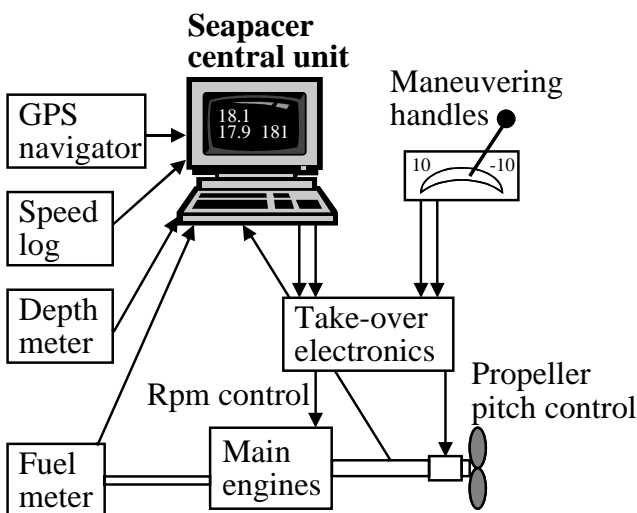

Fig. 2. Block diagram of a basic system. The central unit takes over control from the maneuvering handles and controls the main engine speed and propeller pitch.

$\div s_{wt}(r, p)$ along this direction has been detected. The step sizes for r and p are set so the reduction in engines revs r is approximately balanced by the change in pitch p. In this way the constraint (2) is approximately fulfilled during the search operation. If necessary, r is finally adjusted so the constraint is not violated. The system then waits, either a predefined period of time, or until a detection algorithm signals that a new search may be fruitful. The search direction is now reversed. The algorithm works well, but needs steady and fast responding fuel signals to be meaningful. This is seldom the case with ordinary fuel meters installed on the ship for ordinary purposes.

DYNAMIC CONTROL

The system's basic functions are a set of controllers for speed, fuel consumption liters/hour, fuel consumption liters/nautical mile, and shaft power. These controllers may be used as such by issuing set points from the keyboard. The controllers are ordinary PID controllers, which control a linearized version of the physical entity to be controlled. For example, to control the speed s of the vessel, a model f for the static dependency between r, issued rpm (main engines revs), and s, is utilized. The relation is given by $r = f(s)$ where the function f is approximated from sampled data and linear interpolation. Different functions have to be used for different numbers of engaged main engines. The speed controller acts on the f entity:

$$r = k_p E + k_i \int E dt + k_d \frac{dE}{dt} \qquad (3)$$

with the control error E defined as

$$E = f(s_{set}) - f(s_{act}) \qquad (4)$$

where s_{set} is the commanded set speed, and s_{act} is the ship's actual speed. In practice, the derivative part is not used, i.e.: $k_d = 0$ in most cases.

The control of the main engines has to be done in a gentle way to avoid unnecessary rapid thermal changes. Of course, this can be adhered to in the tuning of the PID controllers, but other functions have also been added. It is possible to limit the speed, by which the controllers are allowed to change the main engine revs. This causes the main engines to operate more smoothly than when run manually.

An additional control function allows the user to enter a fuel consumption limit (liters per nautical mile). This is treated as a constraint in the control algorithm, and has a higher priority than the set speed, which is the actual control entity. In the same manner, a lower and a higher power constraint was entered. The fuel limit

and upper power limit serve as safeguards against temporary and unanticipated increases in the load, caused by changing weather conditions, or low water depth below the keel. The lower power limit is necessary to ensure acceptable working conditions for the main engines. In the control system, the constraints are handled as penalties by modifying the control error E to reflect the violated constraint, for example, excessive fuel consumption. The modification is done by a model function g that relates the constraint entity to the control entity (normally the speed). In speed mode with a fuel consumption limit, a function $s = g(c)$ is used. c denotes the fuel consumption and s denotes the speed that approximately corresponds to c. Like the function f in the previous section, the function g is approximated from sampled data and linearly interpolated. Assuming a set fuel consumption limit c_{max} and a sampled fuel consumption c_{act}, the control error E is now computed as

$$E = \begin{cases} f(g(c_{act})) - f(g(c_{max})) : \text{if } c_{act} > c_{max} \\ f(s_{set}) - f(s_{act}) \qquad : \text{otherwise} . \end{cases} \qquad (5)$$

In practice, the sharp switch point in the definition of E is smoothed so the penalty starts to work already before the limit is violated. The effect of the modified control error is that too high a fuel consumption (i.e.: $c_{act} > c_{max}$) makes the controller act as if the speed is too high, even if $s_{set} > s_{act}$. Since expressions (4) and (5) only compute differences of the functions f and g, the absolute values for these models are not critical. The purpose of using them is to linearize the control entities so the apparent process for the PID controller is more linear and easier to control.

The main objective for the crew of a ferry is normally to keep the set arrival times. For this purpose, a function that dynamically designates the set speed of the speed controller, is implemented as a separate running mode. The user enters the arrival time and distance to the goal. The vessel now runs at the lowest speed possible, while still arriving in time. The speed necessary to travel the distance is updated continuously. No updating takes place for the five last minutes ahead of estimated arrival time or when less than 0.5 NM remain of the stated distance. The distance is computed by integrating the log signal (speed relative to ground). A similar run mode works by using a given geographical location (waypoint), instead of a certain distance to travel. In this way the system is more tolerant for deviations from the originally intended routes than in the previously described mode. A more complete handling of entire routes is implemented and is described in more detail in Section 5.

The fuel and power limits serve as safeguards against temporary increases in the load. The result of

such an increase, e.g. caused by shallow waters, is a slowing down of the vessel to reduce the fuel consumption or power below the set upper limit. This can be a very useful function as such, provided the settings of the limits are done carefully. However, too hard limits prohibit the system from keeping the arrival times, while too loose limits are without effect. To eliminate the need for manual choice of limits, a dynamic computation of suitable values has been developed. It works by slowly lowering the upper limit until the limit almost becomes active, i.e. when the actual fuel consumption, or the main engine power necessary to maintain the speed, almost reaches the dynamically set upper limit. In this way a sudden increase in load causes the limit to be violated and the system to lower the speed. However, after a pre-defined delay time, the dynamically set limit is slowly adapted upwards, to allow the vessel to run at the necessary speed in the long run. The result of the dynamic set points for fuel and power limits is that of evening out the power over the entire route. This results in lower total fuel consumption.

ROUTE PLANNING

The route planning of a ship with varying speed in different parts of the route is designed to keep the set arrival time, while reducing the total fuel consumption. The presented system automatically optimizes the speed distribution between the route legs. Legs with different depths and/or weather conditions then run at different speeds to minimize the total fuel consumption. Following are some of the most important factors that affect the fuel consumption of a ship: ship-specific parameters, number of engaged main engines, the ship speed relative to the ground, water currents, water depth under the keel, the ship's draft, wind and waves. Route planning consists of varying the ship's speed in different parts of a route. Since the external conditions (wind, current, and depth) vary, it is evident that fuel consumption cannot be maintained at a minimum, if a constant speed is kept throughout the route. Therefore, we get a minimization problem that has to be solved numerically: we have to find the speed distribution that minimizes the total fuel consumption within the constraint of keeping the scheduled arrival time. Route planning of some kind or another is done on all ships. Most often the "calculation" consists of manual estimates, based on previous experience from the same route. The developed system contains functions for automatic route planning. Wind, current, and water depth can be input by the operator before departure or during the voyage. The system then automatically calculates a speed profile that minimizes the total fuel consumption. Based on the computed speed profile, the computer regulates the ship's speed

by controlling the main engines and the propellers. The arrival time is kept without unnecessary margins. Following is a description of the basic route planning system.

The dependency of fuel consumption upon speed, wind, and water depth is essential for the route planning and optimization. Analytical models are rare and are not general enough to be used for all sorts of ships. Therefore, data is sampled at different running conditions, and gathered in tables. These tables serve as models for the optimization and route planning. Values in-between points are estimated by a 1- or 2-dimensional linear interpolation. In this way the following three functions are defined:

- Speed Model $F(x_w)$ represents the fuel consumption (liters/hour) for different speeds through water x_w.
- Depth Model $D(x, d)$. In limiting water depths the ship's speed decreases due to the increased water resistance. In very shallow waters (typically a few meters below the keel), the so-called "squat effect" pulls the ship downwards, thereby reducing its speed further. The function $D(x, d)$ represents the fuel consumption increase (%) for different water depths d and speeds x.
- Wind Model $W(w, w_d)$. Represents the fuel consumption increase caused by wind. The parameter w_d is the wind direction (degrees). w is the Beaufort degree (0-10).

1. Route Optimization

The route is divided into n parts, each having a constant depth, wind, and current conditions. n is typically between 2 and 40. Each part is denoted "route leg" or just "leg". For each leg i, the following data is available: Length s_i (nautical miles), Longitudinal current component $c_{l,i}$, (unit: knots) parallel to the ship's direction, Transversal current component $c_{t,i}$, (unit: knots) perpendicular to the ship's direction, Wind strength w_i (Beaufort), Relative wind direction $w_{d,i}$. (0.-360) Water depth d_i (meters) below keel, minimum allowed bottom track speed $xmin_i$ (knots) and finally maximum allowed bottom track speed $xmax_i$ (knots). For the route as a whole, the total travel time T (unit: hours) is provided. The ship's speed relative to the ground (also called bottom track speed) is given in knots. The speed relative to the ground, x_i, is related to the speed through water, $x_{w,i}$ (also called water track speed) and the current components $c_{t,i}$ and $c_{l,i}$ according to:

$$x_{w,i} = \sqrt{c_{t,i}^2 + (x_i - c_{l,i})^2} \ . \tag{6}$$

In other words, the water track speed $x_{w,i}$ is the vector difference between the bottom track speed and current vector. The fuel consumption (liters) on leg i is denoted C_i and is a function of speed over ground x_i and the properties of leg i; the length s_i, the current $(c_{l,i}, c_{t,i})$, the wind strength w_i, the wind direction $w_{d,i}$, and the water depth d_i:

$$C_i = \frac{s_i}{x_i} F(x_{w,i}) (1 + D(x_i, d_i)/100) (1 + W(w_i, w_{d,i})/100 \tag{7}$$

where the factor $\frac{s_i}{x_i}$ is the time (hours) that the ship is on route leg i. For the optimization algorithm it is practical to express the fuel consumption as a function of the bottom track speed x. We therefore define the fuel consumption (liters) on leg i for x knots bottom track speed as

$$C(x, i) = \frac{s_i}{x_i} F(x_w) (1 + D(x, d_i)/100) (1 + W(w_i, w_{d,i})/100 \tag{8}$$

where

$$x_w = \sqrt{c_{t,i}^2 + (x_i - c_{l,i})^2}. \tag{9}$$

The vector $\mathbf{x}$ is defined as $(x_1, x_2, ..., x_n)$, i.e. the unknown bottom track speeds on the n legs. The total fuel consumption for a voyage is given by:

$$\Phi(x) = \sum_{i=1}^{n} C(x_i, i). \tag{10}$$

The objective of the optimization is to find the speed vector $\mathbf{x}$ that minimizes $\Phi(\mathbf{x})$. As constraints in the optimization of $\Phi(\mathbf{x})$ we have:

$$\sum_{i=1}^{n} \frac{s_i}{x_i} = T, \tag{11}$$

namely, the ship has to arrive on time, and

$$xmin_i \le x_i \le xmax_i, \forall i. \tag{12}$$

The constraints (12) can be used to define speed limits on parts of the route, and also to set the available speed register for the ship. $\Phi(\mathbf{x})$ should now be minimized with respect to $\mathbf{x}$ under the above mentioned constraints.

(1) Start Value Algorithms

As start value for $\mathbf{x}$, three methods have been considered:
1. Assign an equal speed to all legs; namely, $x_i = \sum_{j=1}^{n} \frac{s_j}{T}$,

$\forall i$. This method hardly needs any calculations, but

on the other hand does not take current, wind or water depth into account.
2. Compute one value x_w for the speed through water, same for all legs, that makes the ship arrive on time (i.e. $\mathbf{x}$ fulfills constraint (11) above). This means that legs with a counter current are run at a lower speed (through water) than legs with the current along. I.e.: Compute a value x_w that solves

$$\sum_{i=1}^{n} \frac{s_i}{x_i} = T \tag{13}$$

$$x_w = \sqrt{c_{t,i}^2 + (x_i - c_{l,i})^2}, \forall i. \tag{14}$$

Expression 14 assigns values to all bottom track speeds x_i in such a way, that the water track speed becomes equal in all legs. If constraint (12) above out rules the necessary bottom track speed for a leg, assign the relevant end point in the constraint to x_i. This method gives an $\mathbf{x}$ vector that compensates for the current, but not for the water depth d or the wind w.
3. Compute a fuel consumption λ (liters/hour) that, if used on all legs on the route, makes the ship arrive on time (fulfills constraint (11) above). This means that legs with a counter current are run at a lower speed over ground than legs, in which the ship runs with the current. It also means that legs with a heavy load due to shallow waters and/or wind are run more slowly than other legs. The algorithm involves solving two nested equations:

• Find the fuel consumption λ (liters/hour) that solves:

$$\sum_{i=1}^{n} \frac{s_i}{y_i(\lambda)} = T \tag{15}$$

where $y_i(\lambda)$ is the bottom track speed achieved on leg i if the fuel consumption is λ liters/hour. I.e.: Each $y_i(\lambda)$, $\forall_i$ has to satisfy

$$• C(y_i(\lambda), i) \cdot \frac{y_i(\lambda)}{s_i} = \lambda \tag{16}$$

where C is given by equation (8).

Equation (15) is solved by the secant method. Each term in the sum requires solving equation (16) for a particular value on λ. This is also done by the secant method. If constraint (12) above out rules the computed bottom track speed for a leg i, the relevant end point in the constraint to x_i is assigned to $y_i(\lambda)$.

Start value algorithm 3 gives an $\mathbf{x}$ vector most often very close to the optimum for $\Phi(\mathbf{x})$, and can actually be used to compute the speeds on the different legs on the ship's route. Further attempts to improve the reached optimum can be found in [1], where a number of optimization routines are applied to the problem. The tables with models are approximated with continous

functions so the derivatives can be computed analytically. Both quasi-Newton and conjugated gradient methods are applied together with a variant of Fletcher's line searching algorithm [2] and also with a golden section search algorithm. The combination of quasi-Newton and Fletcher's line searching gives best results, but a general conclusion is that start value algorithm 3 most often gives a good enough solution vector, and definitely much faster. Therefore, the route planning module uses this algorithm to compute optimal bottom track speed values for each leg in the route plan.

2. Using the Optimized Route

The input to the optimization consists of positions for the legs in the route. The following data is also given for each leg:

• **CURRENT** - Strength c and absolute direction c_{dir} of current. Unit: knots.
• **WIND** - Strength w and absolute direction w_{dir} of wind. Unit: Beaufort.
• **DEPTH** - Mean water depth below the keel. Unit: meters.

c_{dir} and w_{dir} are absolute values, and are entered as any of the following abbreviations: N, S,W, E, NE, NW, NNW, NNE, SE, SW, SSE, SSW, ENE, ESE, WNW, WSW. The relative directions are computed automatically by the system, depending on the ship's actual course at each moment. Additional inputs are the ship's mean draft and required departure/arrival times. The route optimizer computes the bottom track speeds x_i, $\forall i$, that minimize the total fuel consumption for the voyage. The arrival time is always kept as requested. The route plan shown in Table 1 has been computed with algorithm 3 described above. The set values x for speed are

Table 1. Optimized route plan for the route Gothenburg-Kiel. The x values are optimized speed (bottom track) values compensated for the varying depth values and weather conditions on the 31 legs. The x values are used as set values for the speed control along the route.

SEAPACER PC VOYAGE CONDITIONS SET UP
MS Emmaräng
Voyage conditions 1
Route number 1: Göteborg - Kiel
Mean draft: 6.3 meters

leg		Name	c	c_{dir}	w	w_{dir}	Depth	ME	x	x_w
1	at	KAJ GÖTEBORG	0.0	N	3.0	SW	8	1	7.00	7.00
2	at	Göteborgsgrund	0.0	S	3.0	SW	10	3	13.00	13.00
3	at	Brandnäs	0.0	S	3.0	SW	22	4	17.81	17.81
4	at	Trubaduren	0.0	N	3.0	SW	40	4	19.13	19.13
5	at	Vanguardsgrund	0.0	N	3.0	SW	45	4	19.13	19.13
6	at	No. 4	0.0	N	3.0	SW	30	4	18.63	18.63
7	at	Anholt Knob	0.0	N	3.0	SW	30	4	18.49	18.49
8	at	No. 7	0.0	N	3.0	SW	15	4	17.32	17.32
9	at	No. 11	0.0	N	3.0	SW	18	4	17.52	17.52
10	at	SNR	1.0	N	3.0	SW	22	4	17.08	17.94
11	at	No. 15	1.0	N	3.0	SW	16	4	16.75	17.54
12	at	No. 20	1.0	N	3.0	SW	20	4	16.97	17.96
13	at	No. 23	1.0	N	3.0	SW	22	4	17.15	18.09
14	at	No. 25	1.0	N	3.0	SW	16	4	17.17	18.00
15	at	No. 26	1.0	N	3.0	SW	24	4	17.24	18.24
16	at	No. 28	1.0	N	3.0	SW	30	4	18.16	19.08
17	at	Vengeance grund	1.0	N	3.0	SW	30	4	17.72	18.72
18	at	Ägersö	1.0	N	3.0	SW	20	4	16.96	17.80
19	at	No. 2	1.0	N	3.0	SW	20	4	16.97	17.96
20	at	No. 3	1.0	N	3.0	SW	20	4	17.01	17.95
21	at	DW 51	1.0	N	3.0	SW	20	4	17.18	17.76
22	at	DW 53	1.0	N	3.0	SW	20	4	16.89	17.82
23	at	DW 55	1.0	N	3.0	SW	30	4	17.72	18.72
24	at	DW 57	1.0	N	3.0	SW	18	4	16.77	17.69
25	at	DW 59	1.0	N	3.0	SW	18	4	16.86	17.83
26	at	DW 61	1.0	W	3.0	SW	14	4	17.88	17.10
27	at	KO 2	1.0	W	3.0	SW	10	4	17.54	16.65
28	at	Kieler Förde	1.0	W	3.0	SW	10	4	17.20	16.76
29	at	Fartbojen	1.0	W	3.0	SW	10	3	11.00	10.77
30	at	Friedrichsort	1.0	W	3.0	SW	8	1	8.00	7.50
31	at	Kiel 11 Reede	1.0	W	3.0	SW	7	1	7.00	6.72
32	at	Scwedenkai								
33	at	End of route plan								

Optimization data:
Mean: 3078 l/h Total: 40320 litres Total dist: 234.6 nm Total time: 14:00
Successful optimization

automatically executed as set speed commands by the central unit. The speed control is combined with the dynamic limits for fuel consumption (see Section 4). In this way the engines are controlled in a smooth and economical way throughout the route. The route is automatically re-optimized every 10 minutes or when new current or wind values are entered.

CONCLUSION

The propulsion of ships offers many interesting and challenging control and optimization problems. The control problems are characterized by large time constants and noisy sensor signals. For reasons of robustness and generality, simple and intuitive solutions are often to be preferred. Furthermore, the noisy and time-dependent nature of the problem makes the search for global and exact optima pointless, and even sub-optimal, if it involves a slower system with a higher risk for volatile behavior.

We have successfully implemented a number of control systems that aim at lowering the fuel consumption by optimizing control. The systems have worked particularly well for vessels with a wide speed-control range. This gives room for intelligent route planning, which really makes a difference for the total fuel consumption. The pitch optimization has worked best for older ships, where the initial rpm/pitch combinations are far from optimal. Newer ships have partly recognized the importance of having correct rpm and pitch at varying running conditions, and allow less room for a separate optimizer such as the presented system.

The general trend in bridge equipment has, for a number of years, been integrated systems, where the same manufacturer delivers integrated equipment for many bridge functions. Along this trend, some radar manufacturers are offering primitive route planning functions and speed control functions as options in their systems. Also, advanced electronic sea chart systems are likely to include more and more route planning options in the future.

ACKNOWLEDGMENTS

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