Adaptive Autopilots for Steering of Large Tankers

Källström, Claes; Eriksson, J.; Åström, Karl Johan; Sten, L.; Thorell, N. E.

1977

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):
Källström, C., Eriksson, J., Åström, K. J., Sten, L., & Thorell, N. E. (1977). *Adaptive Autopilots for Steering of Large Tankers*. (Research Reports TFRT-3145). Department of Automatic Control, Lund Institute of Technology (LTH).

Total number of authors:
5

CODEN: LUTFD2/(TFRT-3145)/1-066/(1977)

Adaptive Autopilots for Steering of Large Tankers

C G Källström
K J Åström
N E Thorell
J Eriksson
L Sten

KOCKUMS
Kockums Automation AB

Dokumentutgivare
Lund Institute of Technology
Handläggare Department of Automatic Control

Dokumentnamn
REPORT

Dokumentbeteckning
LUTFD2/(TFRT-3145)/1-66/(1977)

Utgivningsdatum
July 1977

Ärendebeteckning
STU 73 41 87
STU 74 41 27

Författare
C.G. Källström, K.J. Åström
N.E. Thorell, J. Eriksson and L. Sten

Dokumenttitel och undertitel

Adaptive Autopilots for Steering of Large Tankers

Referat (sammandrag)

The design of two adaptive autopilots is discussed. The simple adaptive autopilot contains velocity scheduling, a self-tuning regulator for steady state course keeping and a turning regulator. The more advanced autopilot is similar to the simple autopilot but it also contains a Kalman filter. The self-tuner of both autopilots is based on recursive least squares identification and minimum variance control. Computer simulations and full-scale experiments on three different tankers are presented. The different autopilot functions are shown to be working excellently under different load, speed, and weather conditions. The economic benefits by using the adaptive autopilots instead of conventional PID regulators are also estimated. It is concluded that the adaptive autopilots are indeed feasible.

Referat skrivet av
authors

Förslag till ytterligare nyckelord
Ship steering, ship manoeuvring, ship control, adaptive control

Klassifikationssystem och -klass(er)

Indextermer (ange källa)
Control simulation, ship manoeuvring (Thesaurus of Engineering and Scientific Terms, Engineers Joint Council, N.Y., USA

Omfång
66 pages

Övriga bibliografiska uppgifter

Språk
English

Sekretessuppgifter

ISSN

ISBN

Dokumentet kan erhållas från
Department of Automatic Control
Lund Institute of Technology
P.O. Box 725, S-220 07 LUND 7, Sweden

Mottagarens uppgifter

Pris

DOKUMENTDATABLAD enligt SIS 62 10 12

Blankett LU 11:25 1976–07

ADAPTIVE AUTOPILOTS FOR STEERING OF LARGE TANKERS

by

C G Källström and K J Åström

Lund Institute of Technology
Department of Automatic Control

and

N E Thorell, J Eriksson, and L Sten

Kockums Automation AB

Issued 7707
No MB 34

ABSTRACT

The design of two adaptive autopilots is discussed. The simple adaptive autopilot contains velocity scheduling, a self-tuning regulator for steady state course keeping and a turning regulator. The more advanced autopilot is similar to the simple autopilot but it also contains a Kalman filter. The self-tuner of both autopilots is based on recursive least squares identification and minimum variance control. Computer simulations and full-scale experiments on three different tankers are presented. The different autopilot functions are shown to be working excellently under different load, speed, and weather conditions. The economic benefits by using the adaptive autopilots instead of conventional PID regulators are also estimated. It is concluded that the adaptive autopilots are indeed feasible.

TABLE OF CONTENTS

1. INTRODUCTION

Background

The requirements on ship steering are increasing due to requirements of safety and economics. The autopilots commonly used today consist of simple PID controllers. The measured heading signal is compared with the desired heading and the error is used as the controller input. The output of the controller is fed to the rudder servo. Special techniques like limiting of the heading error or two mode operation, i.e. one mode for steady state course keeping and another for turning, are used to avoid saturation for large changes of the desired heading. Some autopilots are also using a rate gyro to obtain a good derivative feedback. An autopilot must be properly adjusted in order to obtain a good performance. Adjustments are required to compensate for wind, waves, current, speed, trim, draught, and water depth. The adjustments are tedious and time consuming. In practice the controller is often used with a fixed setting only. It is a common experience that the autopilots do not work well in bad weather or when the speed is decreased. It has also been the experience that autopilots may have difficulties when making large manoeuvres. The reason is partly that the autopilot is not properly tuned and partly that the PID algorithm is too simple to handle the requirements. The practical consequence is that the autopilot is frequently switched off and that manual steering is used in situations where automatic control is needed most.

Adaptive Control Methods for Ship Steering

Some of the disadvantages of conventional autopilots can be avoided by using an adaptive autopilot. Such a pilot can adjust its parameters to compensate for changes in the environment. Because the parameters of the controller are tuned automatically it is also possible to use control for the purpose of minimizing a specific loss function. Two different autopilots have been explored. The dependence of the ship velocity is handled by gain scheduling in both cases. The ship speed is thus measured or computed from the propeller rate of revolution and the feedback gains are changed accordingly. Adaptation is used to compensate for variations in the other factors. The simple system uses only heading measurements but the more complicated system may also exploit measurements of yaw rate, sway velocity and rudder angle. The more complicated system has a Kalman filter. This uses the information from all sensors to obtain a reliable and smooth estimate of the heading, the yaw rate and the sway velocity. Both systems have been found to function well under a wide set of operating conditions. For the simple system it was found empirically that for steering of tankers the inclusion of a rate gyro added very little to the performance if a good gyrocompass was used. This is contrary to the experience gained from conventional fixed gain autopilots. The explanation is that the control law used is more complex than in ordinary autopilots and that this can be accepted because the tuning is automatic. The benefits of using a rate gyro will thus depend on the quality of the gyrocompass.

The more complicated system which includes the Kalman filter has better performance than the simple system, even if the heading angle is the only measurement signal available. The Kalman filter was found to function very well. It allows for compensation of drift and biases in the different sensors. It also has the potential to give a very reliable system because sensor failures can be detected by comparing the sensor signal against the estimates of the Kalman filter. The more complicated system is particularly advantageous in cases where the autopilot is part of a larger system with collision warning, path prediction etc. Empirical comparisons show

The benefits from tuning a PD autopilot have been estimated in Åström (1977) using a simple model. The analysis shows that the benefits will depend on many factors, among others the disturbance level and the loading condition. Table 1.1 shows the loss functions for constant gain PD autopilots and optimally tuned PD autopilots under different loading and sea conditions. The range of sea conditions in Table 1.1 corresponds to a factor 10 in wind speed. With this range the minimal value of the loss function may change by a factor of about 8, if both stable and unstable loading conditions are considered. The practical difficulties of evaluating the performance of an autopilot are clearly seen from Table 1.1. Consider for example a tanker in a stable loading condition. It follows from the table that the loss function can change with a factor of 5 depending on the sea conditions.

Operating condition	Loading	Sea condition	Optimal	AP1	AP2	AP3
1	Stable	1	1	1	1.9	4.3
2	Stable	3	2.3	4.5	2.5	4.4
3	Stable	5	4.9	40	8.0	5.3
4	Marginally stable	1	1.9	2.4	2.7	5.0
5	Marginally stable	3	3.4	10.8	3.4	5.1
6	Marginally stable	5	6.1	94.7	11.2	6.3
7	Unstable	1	3.7	∞	4.4	6.2
8	Unstable	3	5.1	∞	5.7	6.3
9	Unstable	5	7.6	∞	18.6	7.6

Table 1.1 - Normalized loss functions for optimally tuned PD autopilots under different operating conditions and for three constant gain PD autopilots, AP1, AP2, and AP3.

and in bad weather conditions. Usually the gains are also larger in full load condition compared to ballast condition. When the more complicated adaptive autopilot, which includes a Kalman filter, is compared to the simple adaptive autopilot, a decrease in fuel consumption of approximately 0.5 % is obtained. The final evaluation of the benefits of the adaptive autopilots can, of course, only be done after extensive filed tests based on long time operation on many ships. Accepting Schilling's estimate of a 1-2 % reduction in fuel consumption when going from a "normally" tuned PID controller to an optimally tuned PID controller it appears reasonable to estimate that the autopilots discussed here may give an additional gain of 1 % which brings the total saving up to 2-3 %.

Organization of the Report

The report is organized as follows. The design of the adaptive autopilots is discussed in Section 2. This section covers the Kalman filter, the self-tuning regulator and the regulator used for turning. Simulations were used extensively in the project. This is discussed in Section 3. Experiments on different tankers were a major activity of the project. Over 130 tests were performed. They are summarized in Section 4. Some autopilots have also been used in normal operation after the tests were finished. The autopilot designed for the Sea Swift has for example been in use since October, 1974. The major conclusions to be drawn from the project are given in Section 5. It is found that adaptive ship steering has substantial advantages and that the chosen design concepts are sound. The experiences gained during the project are a sufficient basis for the engineering design of commercial systems.

mainly in the number of measurements used. The simple adaptive autopilot KADPIL 1 (Kockums ADaptive autoPILot 1) is shown in the schematic diagram in Fig. 2.1. The simple autopilot uses measurements of forward speed, or propeller rate of revolution, and heading.

A schematic diagram of the more advanced autopilot KADPIL 2 is shown in Fig. 2.2. It is similar to the simple autopilot but it also contains a Kalman filter. This implies that it may use more measurements than KADPIL 1 namely yaw rate, rudder angle, fore and aft sway velocities. The autopilot can function with the same measurements as KADPIL 1 but the additional measurements will improve the performance of the regulator. This design concept also offers interesting possibilities for sensor diagnosis. Because of the redundant measurements the advanced autopilot can stand some instrument failures and/or malfunctions. The Kalman filter will also provide smoothed values of heading, yaw rate, sway velocities, rudder angle, rudder bias and sensor biases. This information is useful not only for the autopilot functions but also for other functions like navigation and collision warning.

The autopilots KADPIL 1 and KADPIL 2 were the two main alternatives that were investigated in detail. Several other configurations were also considered. The effect of adding a yaw rate measurement in the simple autopilot was e.g. investigated. Detailed descriptions of the autopilots KADPIL 1 and KADPIL 2 are presented in Källström (1976e).

Velocity Scheduling

The influence of speed variations on ship dynamics is well-known. To obtain a performance of the autopilot that is invariant with the ship velocity the parameters of the Kalman filter, the self-tuner and the turning regulator are changed using the ship speed. This function is called velocity scheduling. It is included in both autopilots. The self-tuner will, of course, adapt to variations in velocity. The response to velocity variations by scheduling is, however, much quicker than that obtained by adaptation. The velocity variations are therefore compensated by gain scheduling both in the self-tuner and in the turning regulator.

The speed dependence of the ship dynamics can easily be determined analytically. The general characteristics are that the controller and filter parameters should be increased with decreasing speed. If true time invariance is desired the controller gains should be inversely proportional to the square of the speed, i.e. $G_V(t) = (V_0/V(t))^2$, where G_V is the gain schedule and the design speed V_0 usually is chosen equal to the service speed. If invariance in the path of the ship is the goal then the gains should be inversely proportional to the ship velocity, i.e. $G_V(t) = V_0 / V(t)$. To avoid very large rudder motions at low speed the gains are limited. The gain schedules G_V are shown in Fig. 2.3.

A more detailed discussion of the gain scheduling is given when discussing the other functions of the autopilots. The speed signal to be used for the scheduling can be taken from the speed log. It is also possible to use the fact that the steady state velocity is a function of the propeller rate of revolution. This is preferable when the speed measurements are unreliable.

to the yaw rate estimate are given not only by the measured yaw rate but also by heading angle, rudder angle, and sway velocities. By processing all the measurements, it is sometimes possible to detect sensor failures and to compensate for rudder and sensor biases. See e.g. Willsky et al (1974). The resulting system is also comparatively insensitive to sensor failures. It can be shown that the system is completely observable from the heading signal. This means that it is possible to obtain all estimates as long as the heading signal is functioning. However, the estimates will, of course, not be as accurate as when all measurements are available. The concept offers a nice way to obtain a system with graceful degradation.

With the Kalman filter it is also possible to separate the tasks of filtering and control. This means for example that it is not necessary to readjust the feedback gains when a sensor signal is lost.

The design of a Kalman filter is straightforward. See e.g. Åström (1970). The design requires a mathematical model of the ship and its disturbances. The particular model used in this case is given in Appendix A. It includes a model of the ship steering dynamics and the rudder servo. Biases in the measurements of sway velocities, yaw rate, and rudder angle are also included as well as models for disturbances in terms of stochastic processes. The parameter values used in the mathematical model for a specific ship can be calculated from ship construction data or estimated from tests with scale models. Process identification techniques based on data from full-scale experiments is another method, which also gives models for the disturbances, see Åström, Källström, Norrbin, and Byström (1975) and Åström and Källström (1976).

Normalization of the model using the length of the ship as the length unit and the time unit as the time it takes

Self-Tuning Regulator for Steady State Course Keeping

The problem of steady state course keeping is the following. If the course is not kept constant there will be a retarding force due to cross-coupling between yaw rate and sway velocity. There is also a retarding force due to the increased drag caused by the increased drift angle as well as a distance loss due to the course deviation. The latter effect is, however, smaller than the effect of the yaw rate-sway velocity coupling.

The course deviations can be decreased by compensating rudder motions. The rudder motions will, however, also generate retarding forces. The objective of the course keeping regulator is to balance these effects so that the sum of the retarding forces is as small as possible and to keep the requested course in average. It is intuitively clear that the best compromise will depend on many factors: water depth, trim, draught, ship speed, forces from wind and waves. To get the best result it is therefore necessary to make readjustments of the trade-offs when the operating conditions change. This is the major motivation for using an adaptive autopilot in steady state course keeping. It was shown by Koyama (1967) and Norrbin (1972) that the average increase in drag due to yawing and rudder motions can be approximately described by

$$\frac{\Delta R}{R} = k[\bar{\psi}^2 + \lambda\bar{\delta}^2] \tag{2.2}$$

where R is the drag and $\bar{\psi}$ and $\bar{\delta}$ denote the average heading error and rudder angle amplitude, respectively. The parameters k and λ will depend on the ship and its operating conditions. Norrbin (1972) gives the following numerical values for a typical tanker

$$k = 0.014 \ \text{deg}^{-2} \qquad \lambda = 1/12$$

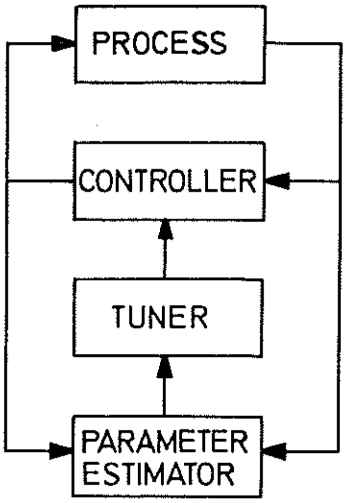


Fig. 2.4 - Block diagram of the adaptive regulator.

It requires a code of over 2 k words on a typical minicomputer with floating point arithmetic in hardware. It was therefore attempted to use a simpler version of a self-tuner which can be implemented using shorter code. Although 2 k words is not very large it was decided to try the simpler algorithms first.

If the control problem is sampled it can be shown that minimization of the loss function (2.3) is approximately equivalent to minimize the predicted value of the heading, i.e.

$$J_1 = \sum_{t=1}^{N} [\hat{\psi}(t+k+1|t) - \psi_{ref}]^2 \qquad (2.4)$$

where a longer prediction interval corresponds to a heavier weighting on the control variable.

The self-tuning regulator which minimizes (2.4) is considerably easier to implement than the one that minimizes

The parameter estimation is done using exponential forgetting to discount past data. It is advantageous to use the gain scheduling $G_V = (V_0/V)^2$ because this will make the parameters almost invariant with forward speed and the tuning is then simplified. The self-tuner then only has to adapt to changes in weather, sea and loading conditions. Experiments have been performed with a self--tuner without gain scheduling to compensate for velocity variations, and then it was found that the self-tuner was quite capable also to adapt to speed changes. The parameter estimates were, of course, changed significantly when the speed was changed, and this is sometimes a drawback when the regulator is implemented. The scale factor b_0 and the parameters k, n_a, n_b, the sampling interval and the forgetting factor can be chosen from a priori knowledge of the ship and disturbance dynamics. The sampling interval and the parameter k are the crucial parameters.

The minimum variance regulator associated with (2.5) is

$$\begin{aligned} u(t) &= \frac{1}{b_0}\Big(a_1\, y(t) + \ldots + a_{n_a}\, y(t-n_a+1)\Big) - \\ &\quad - b_1\, u(t-1) - \ldots - b_{n_b}\, u(t-n_b) - \\ &\quad - \frac{1}{b_0}\Big(c_1\, w_1(t) + c_2\, w_2(t)\Big) \end{aligned} \tag{2.6}$$

An integrator is introduced in the regulator by the use of $\nabla\delta_c(t)$ instead of $\delta_c(t)$. This will assure that the requested heading ψ_{ref} is kept in average.

A slight modification can be introduced by

$$\overline{\nabla\delta_c(t)} = \frac{b_0^2}{b_0^2 + q\, G_V^2(t)}\, \nabla\delta_c(t)$$

The major concern when turning is to keep a tight control of the motion of the ship, possibly at the expense of rudder motion. This is true at least for tankers. Several possibilities of designing a turning regulator were explored.

The ordinary course keeping regulator can handle small changes in reference heading. For larger changes in heading the dynamics of the ship may change considerably. For a large turn there may also be a substantial change in the rudder bias due to a reorientation of the ship relative to wind and waves.

The steady state relation between rate of turn and rudder angle for an unstable ship is shown in Fig. 2.5 which clearly exhibits the nonlinear properties of a large tanker. The figure gives a quantitative information about the changes in rate of turn that can be handled by the course keeping regulator. The figure also indicates the necessity of taking the nonlinear characteristics into account when designing the turning regulator.

Let us use Fig. 2.5 to discuss what happens in a typical turn. Starting at A the turn is initiated and the yaw rate increases, until the desired yaw rate is achieved at B. The desired yaw rate is then maintained until the ship has turned almost the desired angle. The turning is then interrupted. It is thus natural to consider three phases in the turning. It is clear from Fig. 2.5 that the nonlinear characteristics of a ship are important both when the turn is initiated and interrupted.

Different approaches to design the turning regulator were explored. The conclusion obtained after substantial analysis and simulation was that the turning regulator could be handled by fixed gain regulators provided that the different phases are considered separately. It was also

Phase 1 - Initialization

The turn is initialized using a proportional rate feedback. The following control law is used:

$$\delta_c(t) = G_V(t)\,\mathrm{sat}\Big(k_4(\hat{r}(t) - r_{ref}),\ \bar{c}_1|r_{ref}|\Big) + \bar{\delta}_c$$

where

$$\mathrm{sat}(x,y) = \begin{cases} x \quad \text{if} \quad |x| \le y \\ y\ \mathrm{sgn}(x) \quad \text{otherwise} \end{cases}$$

The first factor is the gain schedule. The saturation function is necessary to make sure that the rudder deflection is reasonable even if the commands are large.

Phase 2 - Control of Steady State Rate of Turn

This phase is simply a rate controller designed to maintain a constant yaw rate. The control law used is

$$\delta_c(t) = G_V(t)\Big(k_5(\hat{r}(t) - r_{ref}) + k_6 T_s \sum_{n=0}^{t-1} (\hat{r}(n) - r_{ref})\Big) + \bar{\delta}_c$$

where T_s is the sampling interval.

Phase 3 - Stopping the Turn

It is essentially a dead beat control problem to stop the turn. The following control law is used:

$$\delta_c(t) = G_V(t)\ \mathrm{sat}\Big(k_7(\hat{\psi}(t) - \psi_{ref}) + k_8\hat{r}(t),\ \bar{c}_3|r_{ref}|\Big)$$

This control law is essentially a PD algorithm. It is effective in halting the rate of turn. With reasonable

Källström (1976 b and c). Determination of the parameters of the regulator is discussed. The reports also include extensive simulations based on the SSPA model of a 355 000 tdw tanker, described in Dyne and Trägårdh (1975).

	0	1	2	3	4
0		$\Delta\psi_{ref} > \psi_2$			$\psi_1 < \Delta\psi_{ref} \le \psi_2$
1			$r_{ref} \geq 0$ and $\hat{r}(t) - r_{ref} > -\varepsilon_1$ or $r_{ref} < 0$ and $\hat{r}(t) - r_{ref} < \varepsilon_1$ or (time in phase 1) > T_1	$r_{ref} \geq 0$ and $-\bar{c}_2\sqrt{\frac{V_0}{V(t)}}\ \hat{r}(t) < \hat{\psi}(t) - \psi_{ref}$ or $r_{ref} < 0$ and $-\bar{c}_2\sqrt{\frac{V_0}{V(t)}}\ \hat{r}(t) > \hat{\psi}(t) - \psi_{ref}$	
2				$r_{ref} \geq 0$ and $-\bar{c}_2\sqrt{\frac{V_0}{V(t)}}\ \hat{r}(t) < \hat{\psi}(t) - \psi_{ref}$ or $r_{ref} < 0$ and $-\bar{c}_2\sqrt{\frac{V_0}{V(t)}}\ \hat{r}(t) > \hat{\psi}(t) - \psi_{ref}$	
3					$\lvert\hat{r}(t)\rvert < \varepsilon_2$ or $r_{ref} \geq 0$ and $\hat{\psi}(t) - \psi_{ref} > -\varepsilon_3$ or $r_{ref} < 0$ and $\hat{\psi}(t) - \psi_{ref} < \varepsilon_3$ or (time in phase 3) > T_3
4	(time in phase 4) > T_4				

Table 2.1 - Switching conditions between the different control modes of the turning regulator. Steady state course keeping is denoted phase 0 and the requested heading change is denoted $\Delta\psi_{ref}$. The entry (0,1) shows e.g. the condition to terminate phase 0 and to initiate phase 1.

$$V_\ell = \frac{1}{T}\int_0^T \left[\left(\psi(t) - \psi_{ref}\right)^2 + \lambda\delta^2(t) \right] dt \tag{3.2}$$

was used to compare the steering quality of different autopilots. The value of the weighting factor λ was always equal to 1/12. The approximate relation (cf. (2.2))

$$\frac{\Delta R}{R} \approx 0.014\ \Delta V_\ell \tag{3.3}$$

was used to relate the change of loss ΔV_ℓ between two simulations to the change of drag ΔR.

Simulations of a 255 000 tdw Tanker

Preliminary simulations of straight course keeping of a 255 000 tdw tanker at the speed of 16 knots are presented in Aspernäs and Foisack (1975). Several versions of KADPIL 1 were tested under different load and weather conditions and compared to a well-tuned PID regulator. Further simulations are discussed in Källström (1976a), where also a self-tuning regulator based on least squares identification and linear quadratic control was investigated. The performance of this regulator, which contains substantial calculations because it is necessary to solve a Riccati equation, was not as good as the performance of KADPIL 1. This was explained by the biased parameter estimates obtained, since the disturbances were coloured. Comparisons between KADPIL 1 and a well-tuned PID regulator are given in Table 3.1. Notice that non-filtered measurements were used by the PID regulator. The same steering quality was obtained when the ship was ballasted, but a reduction of fuel consumption of approximately 0.3 % was achieved when the fully loaded ship was controlled by KADPIL 1 instead of the PID regulator. The dynamics of the ship is faster in ballast condition

A reduction of fuel consumption of approximately 0.6 % was achieved when KADPIL 2 was used instead of KADPIL 1 in full load condition, when the wind speed was about 6-8 m/s (moderate breeze). The gain was as much as 1.4 % at the wind speed 17-20 m/s (fresh gale). Larger savings were found when the ship was ballasted, but these simulations were questionable since the parameters of KADPIL 1 and KADPIL 2 were not tuned for the ballast condition case before the simulations started.

Simulations of a 355 000 tdw Tanker

Simulations of straight course keeping of a 355 000 tdw tanker of Kockums' design at three different speeds, viz. 15.8, 10 and 4 knots, are presented in Källström (1976c). The mathematical model used is described in Dyne and Trägårdh (1975). Different structures of the adaptive autopilots KADPIL 1 and KADPIL 2 were tested in full load condition as well as in ballast condition and comparative simulations with a well-tuned PID regulator were also performed. Either the Kalman filter estimates or the non-filtered measurements were used by the PID regulator. A wind speed of about 11-14 m/s (strong breeze) was simulated.

It was concluded that the performance of the Kalman filter was very good in full load condition as well as in ballast condition, when the speed was 15.8 and 10 knots. An example is shown in Fig. 3.1. Notice that the bias of the yaw rate measurements was estimated correctly after about 15 min and that the difference between the true yaw rate and the estimated yaw rate is very small, although the yaw rate measurements are very noisy. The quality of the filter estimates was decreased, although quite acceptable, when the speed was 4 knots. A difficulty is that the limited rudder deflection rate has not been considered in the Kalman filter. This means rather poor estimates of the rudder angle when large rudder changes are requested, which is the case quite often when the speed is extremely low. Measurements of sway velocity, yaw rate, heading and rudder angle were usually fed into the Kalman filter. It was, however, explored that good state estimates were obtained even if the only measurement signal used was the heading angle.

Some of the straight course keeping simulations are summarized in Table 3.2. An example is shown in Fig. 3.1. A reduction of fuel consumption of approximately 0.3 % was achieved at the speed of 15.8 knots, when Kalman filter estimates were used by the PID regulator instead of non-filtered measurements. The saving was approximately 0.9 % at the speed 10 knots. The gain when KADPIL 2 was used instead of KADPIL 1 at the speed of 15.8 knots was also approximately 0.3 %, but a somewhat greater gain than 0.9 % was obtained when the speed was 10 knots. It is also concluded from Table 3.2 that a reduction of fuel consumption of approximately 0.3 % was achieved in full load condition when KADPIL 2 was used instead of the PID regulator including Kalman filter. Notice, however, that it was hardly no difference when the ship was ballasted. Finally, if KADPIL 2 was used instead of the PID regulator using non-filtered measurements, a saving of approximately 0.9 % was obtained in full load condition. When the ship was ballasted, the gain was only 0.1 % at the speed of 15.8 knots but as much as 1.1 % at the speed 10 knots. The loss function values of Table 3.2 are larger when the speed is 10 knots compared to the speed 15.8 knots. This depends on the fact that the dynamics of the ship is becoming slower when the speed is decreased. A ship at the speed of 15.8 knots is consequently easier to control than at the speed of 10 knots. Table 3.3 shows simulations of straight course keeping at the speed of 4 knots. The mean value of $(\psi-\psi_{ref})^2$ was computed instead of the loss

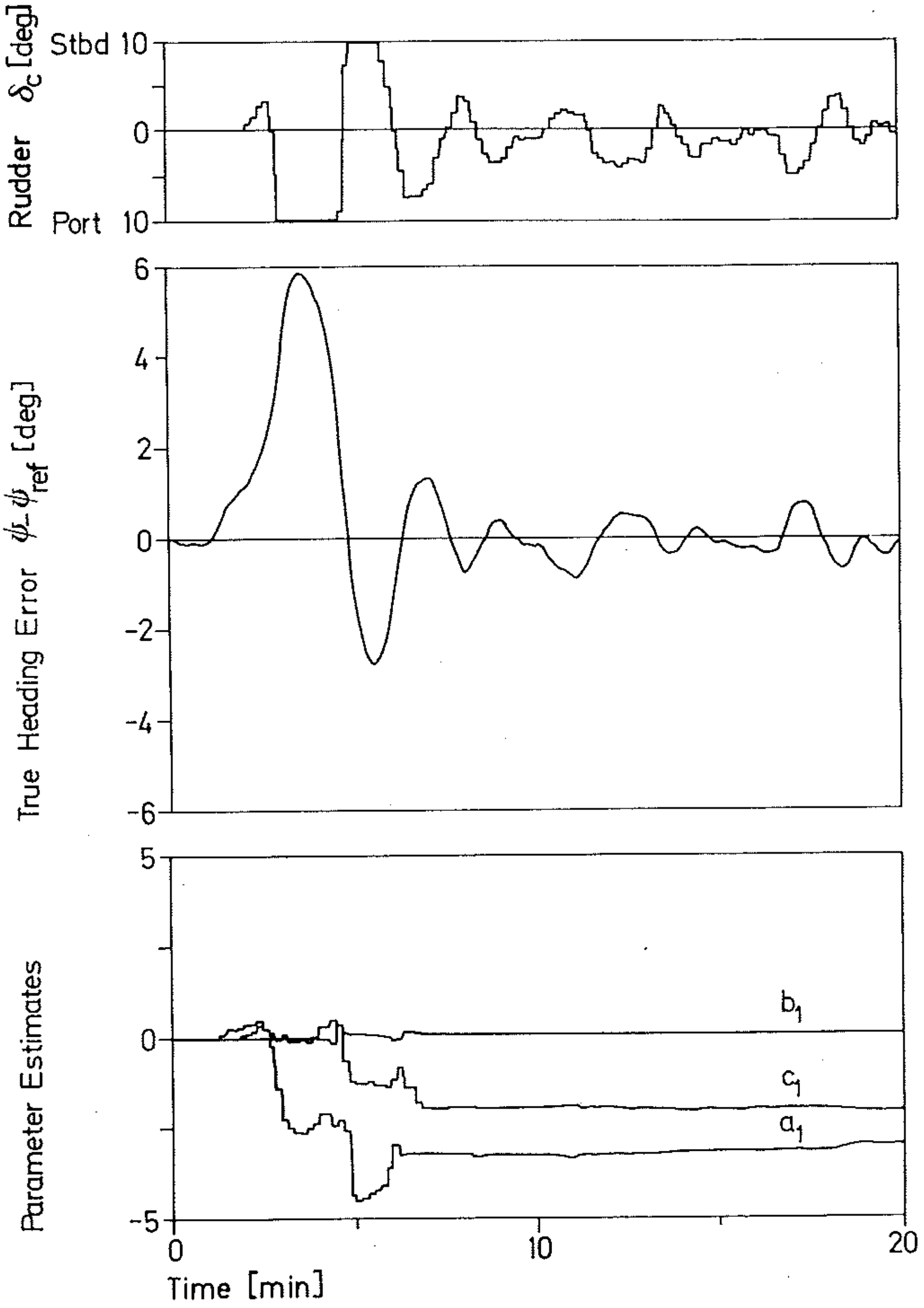


Fig. 3.2 - Simulation of straight course keeping of a fully loaded 355 000 tdw tanker at the speed of 15.8 knots, when the adaptive autopilot KADPIL 2 was used. The initial values of all parameters of the self-tuning regulator were zero. Estimates of only 3 parameters are shown. A wind of about 11-14 m/s (strong breeze) was blowing on the starboard beam. The rudder limit was 10 deg. It is, of course, suitable to provide good initial parameter estimates instead of the values zero to avoid large, initial course errors.

Summary

The simulations have shown that it is possible to design a Kalman filter which generates excellent state estimates for different load, speed, and weather conditions during straight course keeping as well during turning. The performance was good even if the only measurement signal used by the Kalman filter was the heading angle.

The autopilot KADPIL 2 was superior to both KADPIL 1 and a well-tuned PID regulator, with respect to the fuel consumption in steady state course keeping. A reduction of fuel consumption of 0.3 - 0.9 % was achieved in full load condition when KADPIL 2 was compared to a well-tuned PID regulator. The corresponding gains were 0 - 0.3 % when KADPIL 1 was compared to a well-tuned PID regulator. The low values were obtained when Kalman filter estimates were used by the PID regulator and the large values were obtained when the non-filtered measurements were used directly. The gains were lower in ballast condition. A Kalman filter improves the steering performance of both a self-tuning regulator and a PID regulator. A reduction in fuel consumption of 0.3 - 0.6 % was obtained in both ballast and full load condition when filtered values were used. Significantly larger gains were achieved at low speeds and in bad weather conditions.

The performance of the turning regulator was very good in different load, speed and weather conditions. It is, however, important to have a smooth yaw rate estimate to avoid large rudder deflections.

It has been possible to check the validity of some of the simulation results by comparisons to the full-scale experiments described in Section 4. A quite acceptable consistency was then obtained. However, the performance of a well-tuned PID regulator seems to be slightly overestimated using simulations. The gains with the adaptive autopilots are thus larger in the experiments than in the simulations.

	Sea Scout	Sea Swift	Sea Stratus	Σ
Deadweight [ton]	255 000	255 000	355 000	
Load condition	Ballasted	Fully loaded	Ballasted	
Variation of forward speed [knots]	15-17	4-18	12-16	
Variation of wind speed [m/s]	0-9	0-24	0-15	
Number of experiments				
with KADPIL 1	6	61	2	69
with KADPIL 2	1	0	43	44
with PID	1	5	7	13
for off-line identification	3	4	4	11
Total number of experiments	11	70	56	137
Total experimental time [h]	16	57	33	106

Table 4.1 - Summary of recorded experiments. Notice that a few experiments for off-line identification of the steering dynamics were performed on each tanker. Four experiments on the Sea Swift were in fact carried out in ballast condition.

The Sea Scout Experiments

Preliminary experiments of straight course keeping and turning on the Sea Scout in ballast condition are presented in Källström (1974). Both KADPIL 1 and KADPIL 2 were tested, but the Kalman filter, the self-tuner and the turning regulator were all early versions and they differed rather much from the description given in Section 2. The velocity scheduling was e.g. not yet introduced. The major

Ship speed [knots]	Wind speed [m/s]	KADPIL 1	PID using filtered yaw rate
18	4-8	0.3	0.4
17	4-8	$\left\{ \begin{array}{c} 0.5 \\ 0.6 \end{array} \right\}$	0.7
5	17-24	3.7	5.6

Table 4.2 - Loss function values V_ℓ from experiments of straight course keeping on the Sea Swift (255 000 tdw) in full load condition. The wind was blowing on the port beam or on the bow.

a well-tuned PID regulator (cf (3.3)). The gain was as much as 2.7 % at low speed and bad weather conditions. Using the evaluation procedure suggested by Schilling (1976), where mean values of speed and propeller rate of revolution are compared, the corresponding gains are 1.5 % and 11.7 % resp. The bad consistency between the two evaluation methods is a good illustration of the difficult task to compare steering performances. Fig. 4.2 shows the excellent performance of KADPIL 1 in bad weather conditions. It was very difficult to adjust the parameters of the PID regulator to obtain the fairly good performance shown in Fig. 4.2. According to the captain of the ship, a conventional autopilot usually had to be switched off and replaced by manual control in such a bad weather. No velocity scheduling was introduced in KADPIL 1, so the self-tuner had to compensate for velocity variations. The parameter estimates $a_1 = -11.4$ and $b_1 = 0.9$ were e.g. obtained at the speed of 17 knots (Fig. 4.1), while the values $a_1 = -22.7$ and $b_1 = 0.1$ were found at the speed of 5 knots and bad weather conditions (Fig. 4.2).

The officers of the Sea Swift have the possibility to select between the adaptive autopilot KADPIL 1 and the conventional PID regulator since October, 1974. They have usually preferred to use KADPIL 1, which, of course, is a very pleasant hint.

The Sea Stratus Experiments

The final tests of the adaptive autopilots KADPIL 1 and KADPIL 2 were carried out on the Sea Stratus in ballast condition. A detailed description of the experiments is given in Källström (1976d).

The performance of the Kalman filter was very good in the different speed and wind conditions during straight course keeping as well as during turning. Fig. 4.3 shows a comparison between yaw rate measurements, estimates obtained by numerical differentiation of the heading, and Kalman filter estimates. Notice that the data were recorded every second. Fig. 4.3 shows that the yaw rate estimates obtained from the Kalman filter are excellent and that numerical differentiation of the heading is better than the yaw rate measurements. The excellent yaw rate estimates obtained from the Kalman filter during a turn are shown in Fig. 4.4.

Usually all measurement signals, i.e. the sway velocity of bow, the yaw rate, the heading and rudder angle, were used by the Kalman filter. However, the performance when the only measurement signal used was the heading angle was approximately of the same quality as the performance when all measurement signals were used. One experiment showed that it was possible to obtain an acceptable course keeping during at least 15 min after the heading measurement signal was discarded by the Kalman filter, when the three other measurement signals were used. The initial performance

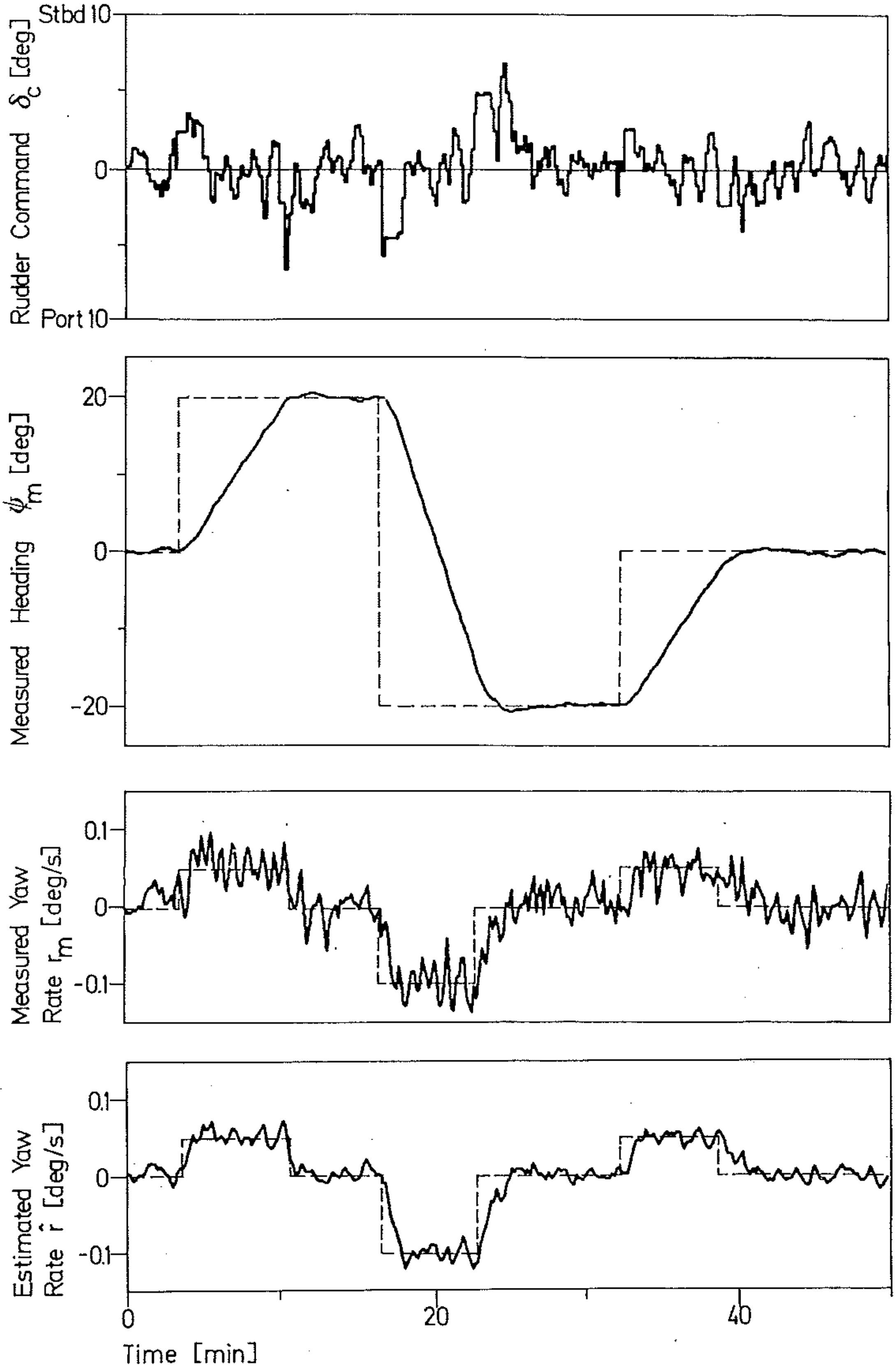
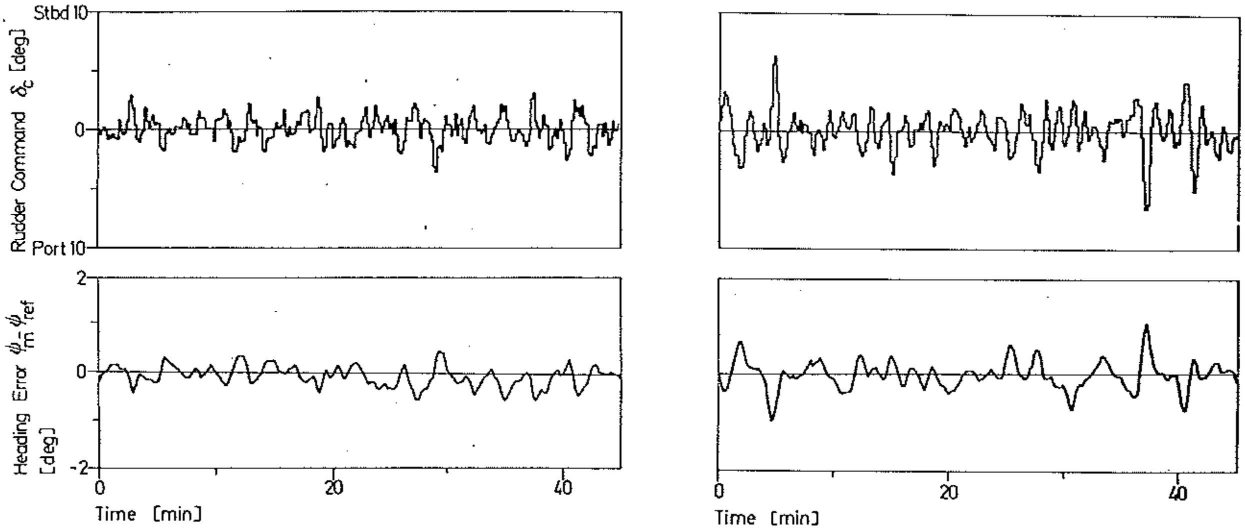


Fig. 4.4 - Turning experiment on the Sea Stratus (355 000 tdw) in ballast condition and at the speed of 13 knots. A wind of about 7 m/s (moderate breeze) was blowing on the bow.

Ship speed [knots]	Wind speed [m/s]	KADPIL 2	KADPIL 1	PID using Kalman filter estimates	PID using non-filtered measurements
13	4-9	0.1 0.2 0.2	0.2	0.2	0.8
13	3-7	0.1 0.1	0.3	0.1	1.7
12	11	0.1	-	0.3	-
12	11	0.4	-	0.5	-
14	3	0.3	-	-	0.5

Table 4.3 - Loss function values V_ℓ from experiments of straight course keeping on the Sea Stratus (355 000 tdw) in ballast condition. The wind was blowing on the bow or on the port beam.



KADPIL 2

PID

Fig. 4.5 - Results from two experiments of straight course keeping on the Sea Stratus (355 000 tdw). The ship was ballasted and the speed was 12 knots. A wind of about 11 m/s (strong breeze) was blowing on the bow. The autopilots KADPIL 2 and a well-tuned PID using filtered headings and yaw rates from a Kalman filter were used. The values of the loss function V_ℓ are 0.1 and 0.3 respectively. Under the conditions of the experiments the fuel consumption is thus 0.3 % lower with the adaptive autopilot.

5. CONCLUSIONS

The purpose of the project was to explore the feasibility of using adaptive techniques for ship steering. Several alternatives were analysed, simulated and tested. Trade-offs between realistic problem formulations and autopilot complexity were investigated. The considerations resulted in two alternatives which differ mainly in the measurements used.

The simple adaptive autopilot uses measurements of forward speed, or propeller rate of revolution, and heading. It contains velocity scheduling, a self-tuning regulator for steady state course keeping and a turning regulator. The self-tuner is based on recursive least squares identification and minimum variance control. The more advanced autopilot is similar to the simple autopilot but it also contains a Kalman filter. This implies that more measurement signals may be used, namely rudder angle, yaw rate, and sway velocities. Because of the redundant measurements, the advanced autopilot can also stand instrument failures and/or malfunctions. Interesting possibilities for sensor diagnosis are also obtained. The Kalman filter will provide smoothed values of heading, yaw rate, sway velocities, rudder angle, rudder bias and sensor biases. It was concluded that it is worth-while to include a Kalman filter in all autopilots for ship steering.

Straightforward FORTRAN implementations of the adaptive autopilots required 2800 and 4600 memory cells on the computer PDP-15 for the simple autopilot and the more advanced autopilot, respectively. Execution times for one step of the algorithms on the PDP-15 were typically 0.02 s for the simple autopilot and 0.06 s for the more advanced one. The execution time for one step of the Kalman filtering was 0.02 s. Typical sampling intervals are 1 s for the Kalman filter and 10-20 s for the autopilot. The computational requirements are thus reasonable.

consumption based on the quadratic loss functions were as high as 2.7 % in bad sea conditions.

The benefits of using the more advanced adaptive autopilot instead of the simple adaptive autopilot were also explored. Gains of approximately 0.5 % in reduced fuel consumption were observed. The same gain was obtained even if the more advanced autopilot was using exactly the same measurement signals as the simple autopilot.

Experiments by Schilling (1976) indicated that reductions of fuel consumption of 1 - 2 % were achieved on a tanker, when an optimally tuned PID regulator was used instead of a PID regulator tuned by the officer in charge. The gain will of course depend very much on operating conditions and on how well the PID regulator was adjusted. Notice, however, that the regulators discussed in this report will give additional gains over well-tuned PID regulators.

Much experimental work is naturally required before it can firmly be established how much the fuel consumption will be reduced due to improved steering. Based on the results of this report and Schilling's experiment it is, however, not unreasonable to guess that a fuel reduction, or an increased speed, of the order of one or a few percent may be achieved in normal operation. The economic benefits obtained for a 355 000 tdw tanker of Kockums' design are estimated in Appendix C for two different economic situations, provided that the adaptive autopilot increases the speed by 1 %. In a good economic situation, corresponding to World Scale 100, a net gain of $292 000 per year is obtained due to an increased transport capacity. When only a part of the transport capacity of the ship is used, as in a bad economic situation, then the benefits of the adaptive control are obtained as a reduced fuel consumption. A net gain of $24 000 per year is estimated in this case, if it is assumed that the bunker oil price is $87 per ton.

6. ACKNOWLEDGEMENTS

This work has been supported by the Swedish Board for Technical Development under contracts 73 41 87 and 74 41 27.

The authors would like to express their gratitude to the Salén Shipping Companies for their positive attitude to this type of research and their willingness to allow experiments to be performed with their ships and their equipment. We are particularly grateful to captain S Jansson and the captains of the test ships, Mr S Nilsson, Mr L Sjöberg, and Mr B Svensson, and their crews.

The manuscript has been expertly typed by Mrs G Christensen and Mrs E Dagnegård. The figures are drawn by Miss B-M Carlsson and Mrs H Balogh.

Åström, K J, and Källström, C G (1976): "Identification of Ship Steering Dynamics", Automatica 12, 9-22.

* Åström, K J (1977): "Why Use Adaptive Techniques for Steering Large Tankers?", Department of Automatic Control, Lund Institute of Technology, Lund, Sweden, CODEN: LUTFD2/(TFRT-3144)/1-35/(1977).

Dyne, G, and Trägårdh, P (1975): "Simuleringsmodell för 350 000 tdw tanker i fullast- och ballastkonditioner på djupt vatten", Report 2075-1, The Swedish State Shipbuilding Experimental Tank, Gothenburg, Sweden.

Elmqvist, H (1975): "SIMNON- An Interactive Simulation Program for Nonlinear Systems, User's Manual", TFRT-3091, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Emel'yanov, S V (1967): "Automatic Control Systems of Variable Structure", Moscow, Nauka.

Henschke, W (1957): "Schiffbautechnisches Handbuch", Bd I (2nd edition), Berlin.

Highfill, III, J H, and Spurgin, W T (1975): "Improvement in Steering Control for Merchant Ships", Report NMRC-KP-138, National Maritime Research Centre, Kings Point, New York.

* Källström, C (1974): "The Sea Scout Experiments, October 1973", TFRT-7063, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

* Källström, C (1975): "The Sea Swift Experiments, October 1974", TFRT-7078, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

* Källström, C (1976a): "Simulation of Adaptive Ship Steering with Penalty on the Rudder Motion", TFRT-3133, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Schilling, A C (1976): "Economics of Autopilot Steering Using an IBM System /7 Computer", Proc 2nd IFAC/IFIP Symp on Ship Operation Automation, Washington DC.

Willsky, A S, Deyst, J J, and Crawford, B S (1974): "Adaptive Filtering and Self-Test Methods for Failure Detection and Compensation", JACC.

Wittenmark, B (1973): "A Self-tuning Regulator", TFRT-3054, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

APPENDIX A - KALMAN FILTER MODEL

The design of the Kalman filter is based on the following standard model

$$\begin{cases} dx = Axdt + Budt + dw \\ y(t_k) = Cx(t_k) + e(t_k), \qquad k = 0, 1, 2, \ldots \end{cases}$$

where

$u = \delta_c$ rudder command

$x_1 = v$ sway velocity at midship

$x_2 = r$ yaw rate

$x_3 = \psi$ heading angle

$x_4 = \delta - \delta_0$ deviation of rudder angle from bias

$x_5 = \delta_0$ rudder bias due to disturbances

$x_6 = d_{v_1}$ bias in fore sway velocity

$x_7 = d_{v_2}$ bias in aft sway velocity

$x_8 = d_r$ bias in yaw rate measurement

$x_9 = d_\delta$ bias in rudder angle measurement

$y_1 = \delta_m$ measured rudder angle

$y_2 = v_1$ measured fore sway velocity

$y_3 = v_2$ measured aft sway velocity

$y_4 = r_m$ measured yaw rate

$y_5 = \psi_m$ measured heading angle

and the disturbances are denoted w and e.

The matrices A, B and C are given by

APPENDIX B - CHARACTERISTICS OF TEST SHIPS

The experiments were performed on three tankers, all built for the Salén Shipping Companies in Stockholm by Kockums Shipyard in Malmö. The characteristics of the ships are given below:

	T/T Sea Scout T/T Sea Swift	T/T Sea Stratus
Dedweight [ton]	255 400	356 400
Length over all [m]	340.5	362.5
Length between perpendiculars [m]	329.2	350.0
Beam [m]	51.8	60.0
Mean draught [m]	20.06	22.33
Main engine power [shp]	32 000	40 000
Trial speed at full draught [knots]	15.7	15.5

The ships have an Integrated Navigation System - Kockums Bridge System type 530 or type 546. The two Integrated Navigation Systems are in principal of the same design.

The hardware is given in Fig. B.1 and the main functions of the system are given in Fig. B.2.

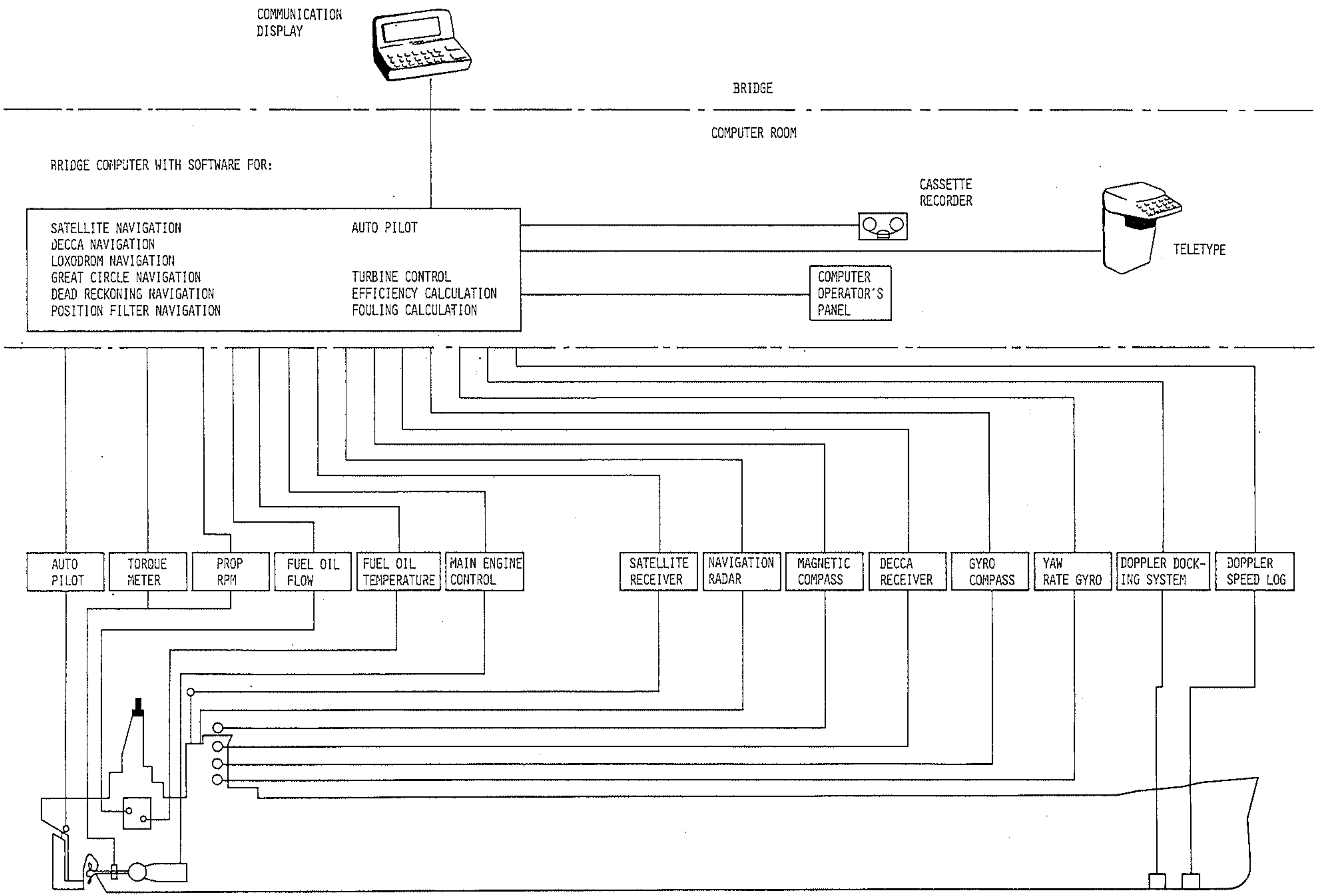


Fig. B.2 - Main functions of Kockums Bridge System.

APPENDIX C - ESTIMATED ECONOMIC BENEFITS BY USING ADAPTIVE CONTROL

The economic benefits obtained for a 355 000 tdw tanker of Kockums' design are estimated in this appendix, provided that an adaptive autopilot increases the speed by 1 % compared to a conventional autopilot. The route Persian Gulf - Europe, a distance of 11 200 nm, is considered and it is assumed that a load of 348 685 tons is transported during each trip. Two different economic situations are analysed.

In the first case a good economic situation, corresponding to World Scale 100, is assumed. The economic benefit is obtained as an increased transport capacity, which is shown by the following table, where the harbour stay is assumed to be 40 h each time and the ship is assumed to be sailing 350 days per year:

	With conventional control	With adaptive control
Service speed at full draught [knots]	15.200	15.352
Service speed at 40 % draught [knots]	16.900	17.069
Number of round trips per year	5.677	5.731
Transported cargo per year [ton]	1 979 606	1 998 322
Increased transport capacity per year [ton]		18 716
Increased income per year at World Scale 100 [$]		301 000
Reduction due to increased harbour charges per year [$]		7 000
Reduction due to increased maintenance costs per year [$]		2 000
Net gain per year at World Scale 100 [$]		292 000