Adaptive Autopilots for Steering of Large Tankers

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1977

[Link to publication](#)

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Dokumenttitel och undertitel
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Referat (sammandrag)
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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

ADAPTIVE AUTOPILOTS FOR STEERING

OF LARGE TANKERS

by

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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
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simulations and full-scale experiments on three
different tankers are presented. The different auto-
pilot 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 auto-
pilots are indeed feasible.

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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 depen-
dence 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 esti-
mated 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 condi-
tion. 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 diffi-
culties 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 condi-
tions 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 measure-
ments 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 infor-
mation 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 auto-
pilots 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 auto-
pilots. The self-tuner will, of course, adapt to varia-
tions 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 auto-
pilots. 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 com-
paratively 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 para-
meter 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 identifi-
cation techniques based on data from full-scale experi-
ments 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

$$k = 0.014 \quad \text{deg}^{-2} \qquad \lambda = 1/12$$
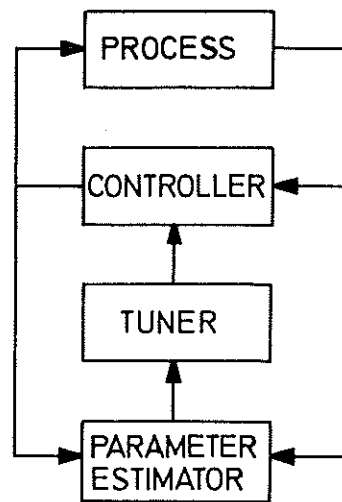
Fig. 2.4 - Block diagram of
            the adaptive regulator.

It requires a code of over 2 k words on a typical mini-
computer 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 consi-
derably 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

$$
u(t) = \frac{1}{b_0} \left(a_1 \, y(t) + \ldots + a_{n_a} \, y(t - n_a + 1) \right) -
$$

$$
- b_1 \, u(t-1) - \ldots - b_{n_b} \, u(t - n_b) -
$$

$$
- \frac{1}{b_0} \left(c_1 \, w_1(t) + c_2 \, w_2(t) \right) \tag{2.6}
$$

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 inter- rupted. 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:

$$\delta_c(t) = G_V(t) \, \text{sat}\left(k_4 \left(\hat{r}(t) - r_{ref}\right), \overline{c}_1 |r_{ref}|\right) + \overline{\delta}_c$$

where

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

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

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

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:

$$\delta_c(t) = G_V(t) \, \text{sat}\left(k_7\left(\hat{\psi}(t) - \psi_{ref}\right) + k_8\hat{r}(t), \overline{c}_3 |r_{ref}|\right)$$

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.	·	$\Delta\psi_{ref} > \psi_2$			$\psi_1 < \Delta\psi_{ref} \leq \psi_2$
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 $-\bar{c}_2\sqrt{\dfrac{v_0}{v(t)}}\,\hat{r}(t) < \hat{\psi}(t) - \psi_{ref}$ or $r_{ref} < 0$ and $-\bar{c}_2\sqrt{\dfrac{v_0}{v(t)}}\,\hat{r}(t) > \hat{\psi}(t) - \psi_{ref}$	
2				$r_{ref} \geq 0$ and $-\bar{c}_2\sqrt{\dfrac{v_0}{v(t)}}\,\hat{r}(t) < \hat{\psi}(t) - \psi_{ref}$ or $r_{ref} < 0$ and $-\bar{c}_2\sqrt{\dfrac{v_0}{v(t)}}\,\hat{r}(t) > \hat{\psi}(t) - \psi_{ref}$	
3					$|\hat{r}(t)| < \varepsilon_2$ 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.

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

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))

$$\frac{\Delta R}{R} \approx 0.014 \; \Delta V_\ell \qquad (3.3)$$

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 simu-
lations are discussed in Källström (1976a), where also a
self-tuning regulator based on least squares identification
and linear quadratic control was investigated. The perform-
ance of this regulator, which contains substantial calcu-
lations 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 simu-
lations 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 simu-
lated.

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
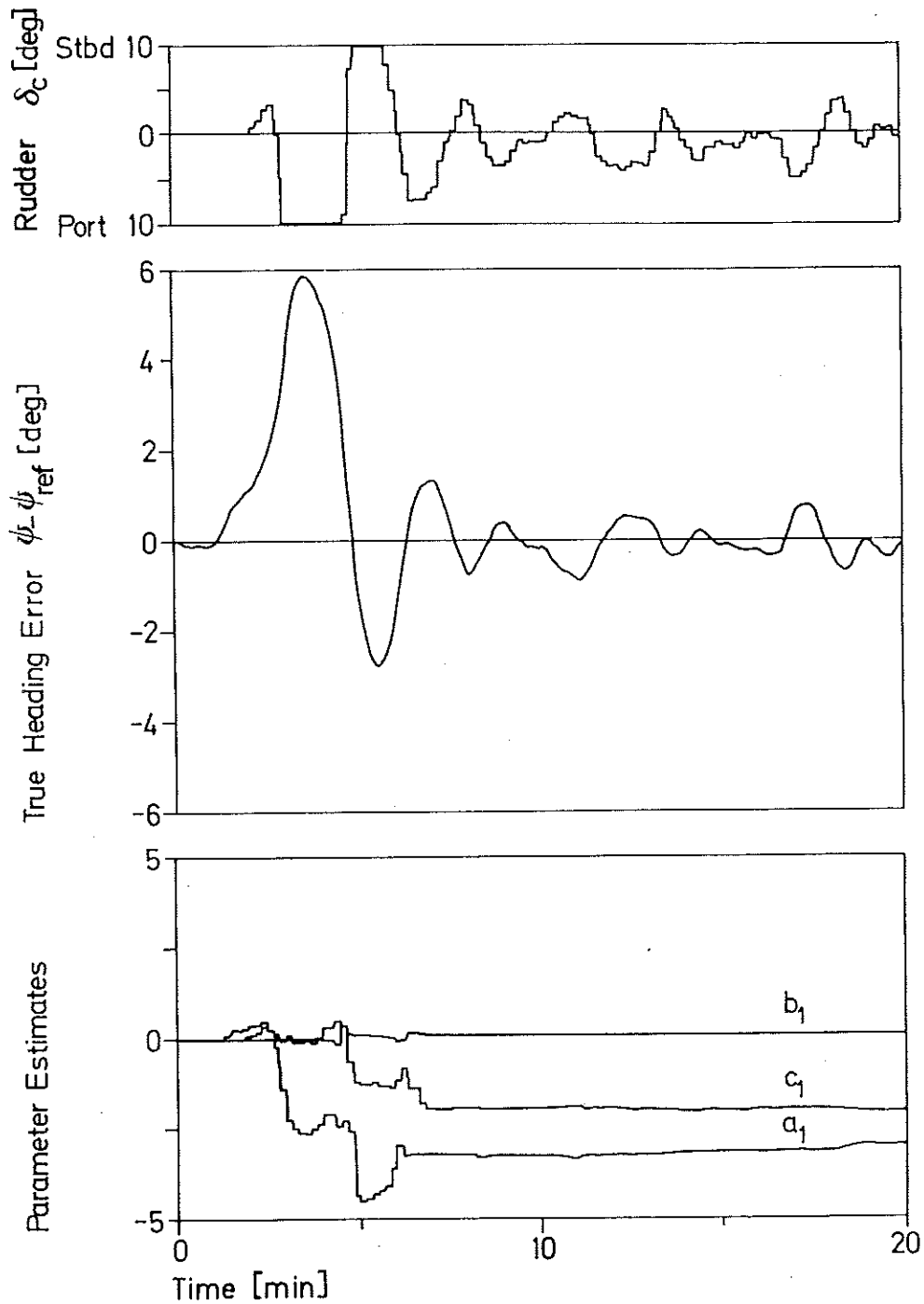value of $(\psi - \psi_{ref})^2$ was computed instead of the loss

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 experi-
ments described in Section 4. A quite acceptable consi-
stency 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	$\left\{ \begin{matrix} 0.5 \\ 0.6 \end{matrix} \right\}$	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 auto-pilot 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 com-
parison 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
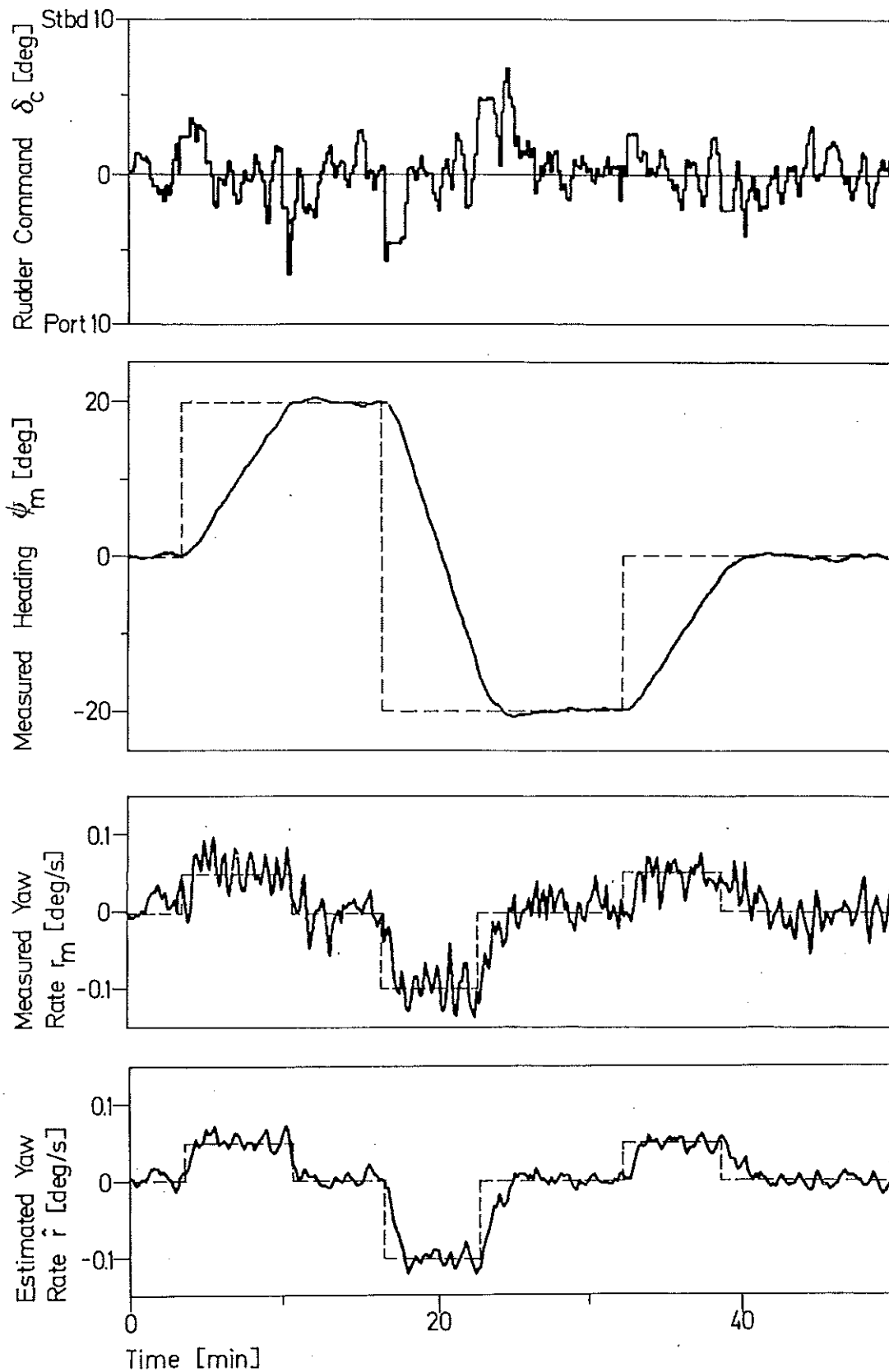other measurement signals were used. The initial performance

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	$\left\{\begin{array}{l}0.1\\0.2\\0.2\end{array}\right\}$	0.2	0.2	0.8
13	3-7	$\left\{\begin{array}{l}0.1\\0.1\end{array}\right\}$	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.
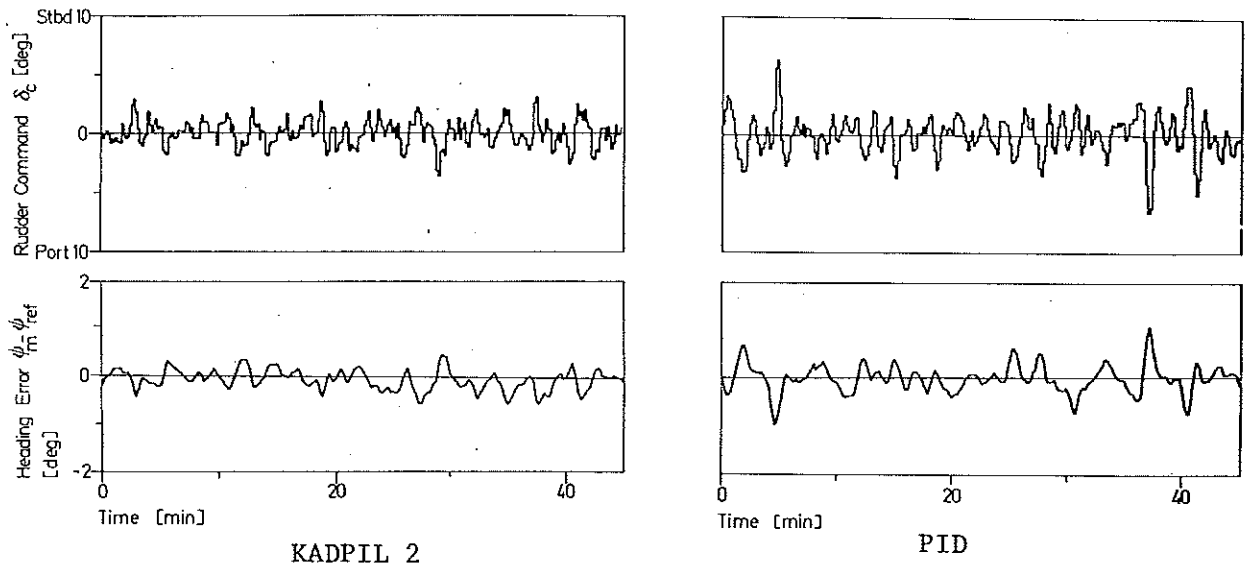

KADPIL 2   PID

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 situa-
tions, 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

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, Depart-
    ment 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 perpen- diculars [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
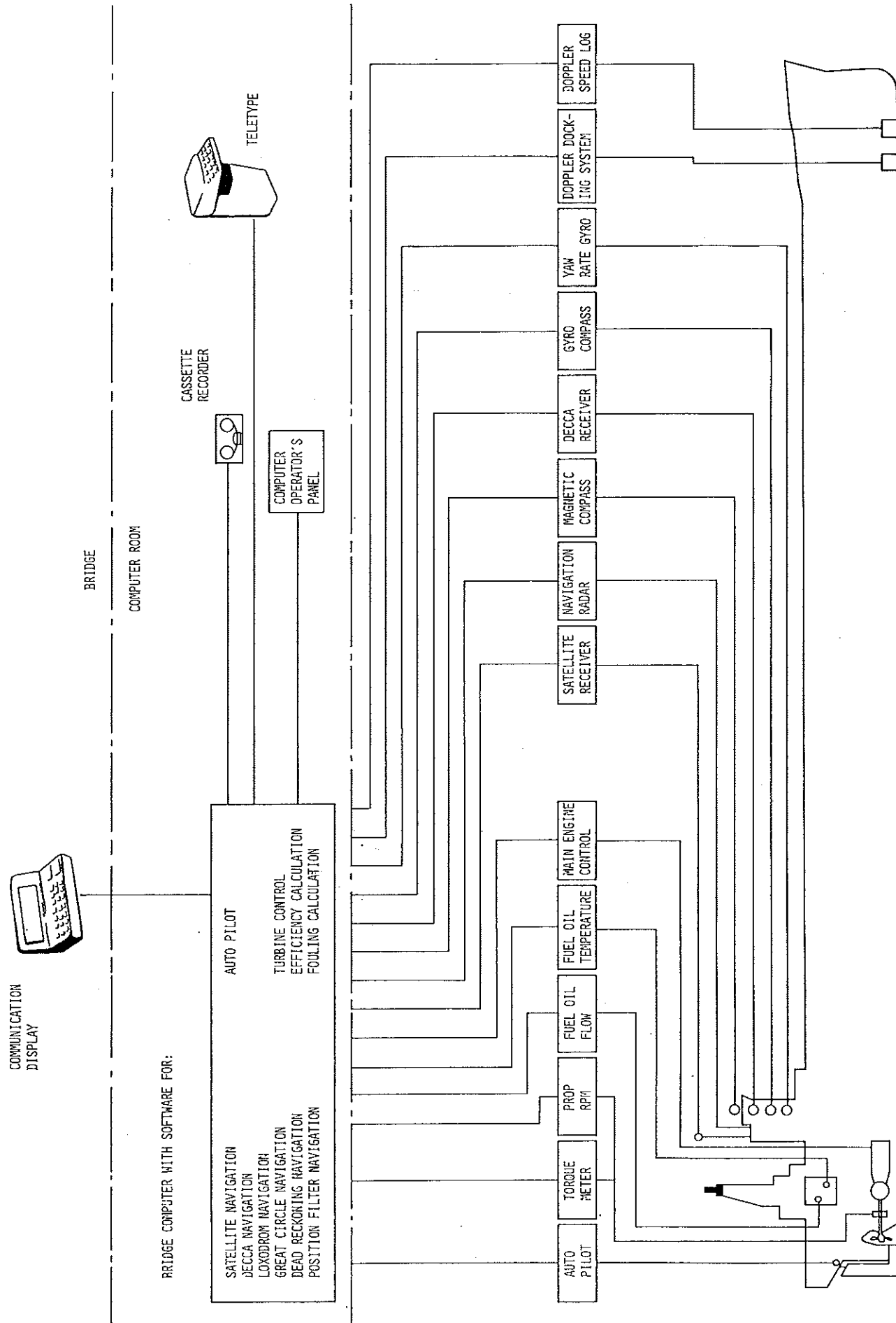of the system are given in Fig. B.2.

Fig. B.2 - Main functions of Kockum's 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