Chapter 9

Automatic steering

9.1 Introduction

It has already been implied that a modern merchant vessel must be cost-effective in order to survive the ever-increasing pressure of a financially orientated industry. A good automatic pilot, often called an Autohelm, although a registered trade name, can improve the profit margin of a vessel in two ways. First, it enables a reduction to be made in the number of ships' personnel, and second, a considerable saving in fuel can be achieved if the vessel makes good its course with little deviation. This chapter, dealing with the principles of automatic pilots, enables the reader to understand fully the electronic systems and the entire operator control functions.

Early autopilots were installed in the wheelhouse from where they remotely operated the vessel's helm via a direct drive system as shown in Figure 9.1. This figure gives an excellent indication of system first principles.

Although efficient, the main drawback with the system was the reliance upon a hydraulic telemotor system, which required pressurized tubing between the transmitter, on the ship's bridge, and the receiver unit in the engine room. Any hydraulic system can develop leaks that at best will cause the system to be sluggish, and at worst cause it to fail. To overcome inherent inefficiencies in hydraulic transmission systems, they have been replaced with electrical transmitters, and mechanical course translating systems have been replaced with computer technology.

9.2 Automatic steering principles

Whatever type of system is fitted to a ship, the basic principles of operation remain the same. Before considering the electronic aspects of an automatic steering system it is worthwhile considering some of the problems faced by an automatic steering device.

In its simplest form an autopilot compares the course-to-steer data, as set by the helmsman, with the vessel's actual course data derived from a gyro or magnetic repeating compass, and applies rudder correction to compensate for any error detected between the two input signals. Since the vessel's steering characteristics will vary under a variety of conditions, additional facilities must be provided to alter the action of the autopilot parameters in a similar way that a helmsman would alter his actions under the same prevailing conditions.

For a vessel to hold a course as accurately as possible, the helm must be provided with data regarding the vessel's movement relative to the course to steer line. 'Feedback' signals provide this data consisting of three sets of parameters.

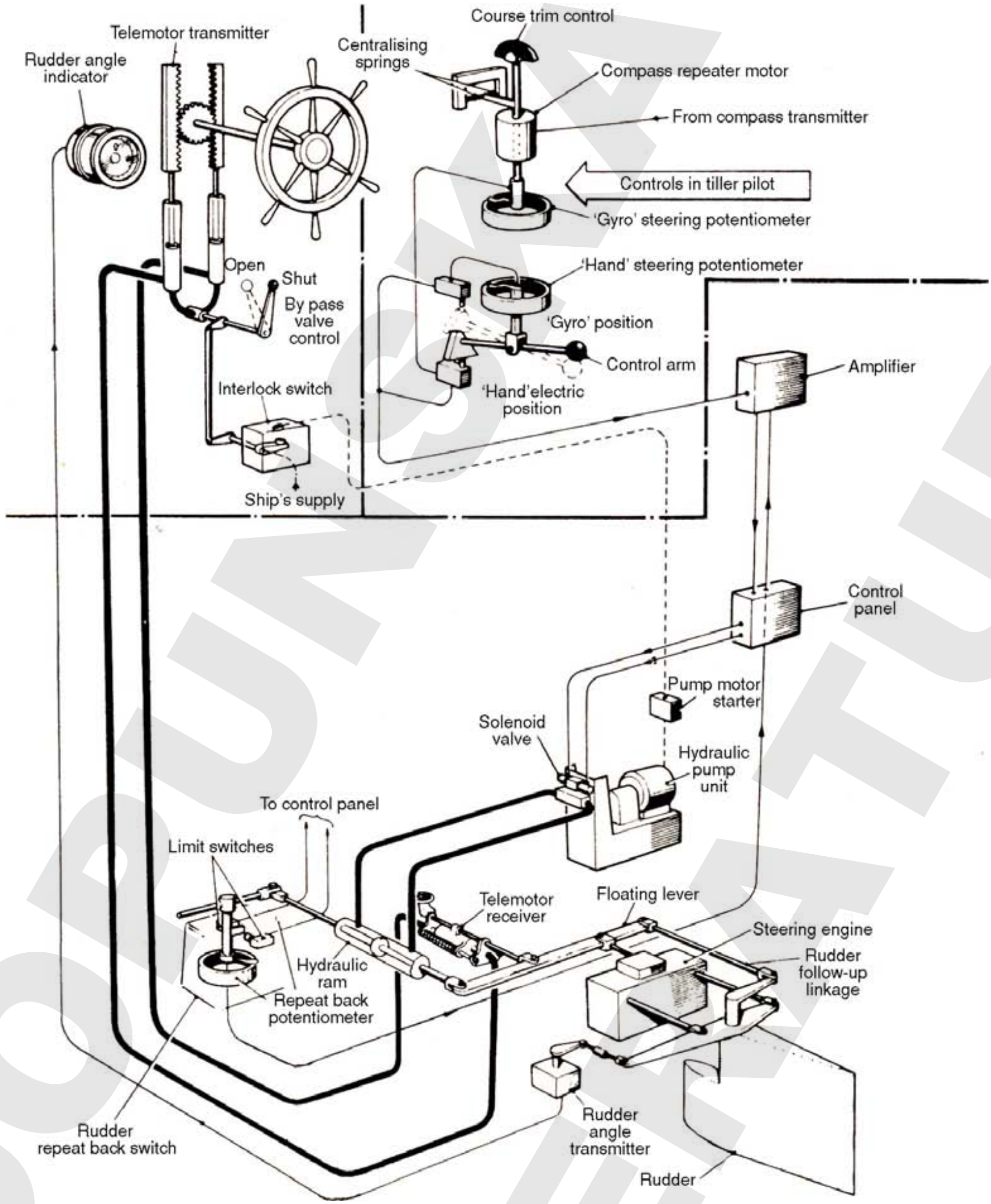

Figure 9.1 An early electro-mechanical autopilot system using telemotors. (Reproduced courtesy of Sperry Ltd.)

- Position data: information providing positional error from the course line.
- Rate data: rate of change of course data.
- Accumulative error data: data regarding the cumulative build-up of error.

Three main control functions acting under the influence of one or more of the data inputs listed above are: proportional control, derivative control and integral control.

9.2.1 Proportional control

This electronic control signal causes the rudder to move by an amount proportional to the positional error deviated from the course line. The effect on steering, when only proportional control is applied, is to cause the vessel to oscillate either side of the required course, as shown in Figure 9.2. The vessel would eventually reach its destination although the erratic course steered would give rise to an increase in fuel expended on the voyage. Efficiency would be downgraded and rudder component wear would be unacceptable.

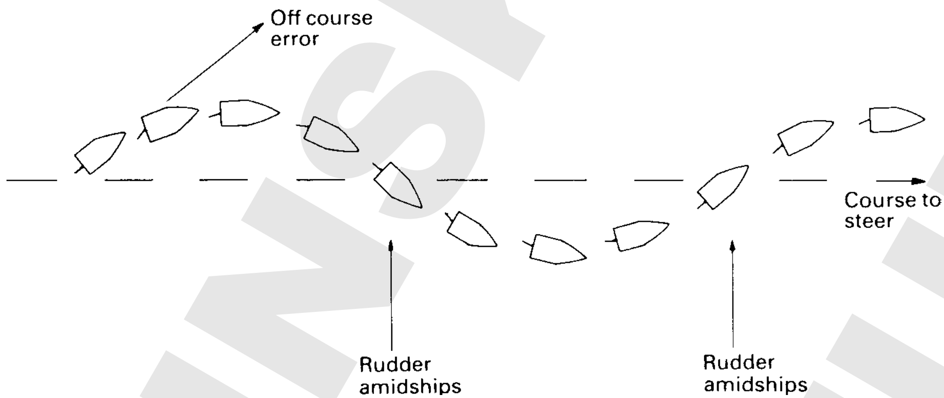

Figure 9.2 The effect of applying proportional control only. The vessel oscillates about the course to steer.

At the instant an error is detected, full rudder is applied, bringing the vessel to starboard and back towards its course (Figure 9.2). As the vessel returns, the error is reduced and autopilot control is gradually removed. Unfortunately the rudder will be amidships as the vessel approaches its course causing an overshoot resulting in a southerly error. Corrective data is now applied causing a port turn to bring the vessel back onto course. This action again causes an overshoot, producing corrective data to initiate a starboard turn in an attempt to bring the vessel back to its original course. It is not practical to calculate the actual distance of the vessel from the course line at any instant. Therefore, the method of achieving proportional control is by using a signal proportional to the rudder angle as a feedback signal.

9.2.2 Derivative control

With this form of control, the rudder is shifted by an amount proportional to the 'rate-of-change' of the vessel's deviation from its course. Derivative control is achieved by electronically differentiating the actual error signal. Its effect on the vessel's course is shown in Figure 9.3.

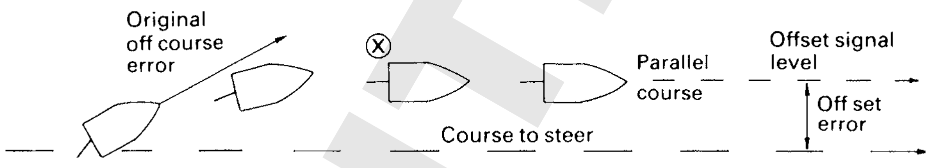

Figure 9.3 The effect of applying derivative control only.

Any initial change of course error is sensed causing a corrective starboard rudder command to be applied. The rate-of-change decreases with the result that automatic rudder control decreases and, at point X, the rudder returns to the midships position. The vessel is now making good a course parallel to the required heading and will continue to do so until the autopilot is again caused to operate by external forces acting on the vessel.

An ideal combination of both proportional and derivative control produces a more satisfactory return to course, as shown in Figure 9.4.

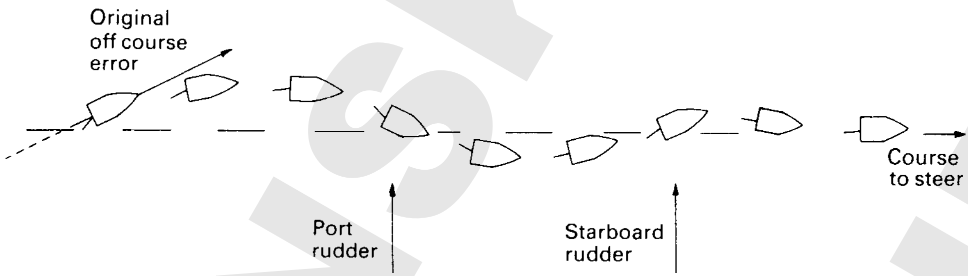

Figure 9.4 Applying a combination of proportional and derivative control brings the vessel back on track.

The initial change of course causes the rudder to be controlled by a combined signal from both proportional and derivative signals. As the vessel undergoes a starboard turn (caused by proportional control only) there is a change of sign of the rate of change data causing some counter rudder to be applied. When the vessel crosses its original course, the rudder is to port, at some angle, bringing the vessel back to port. The course followed by the vessel is therefore a damped oscillation. The extent of counter rudder control applied is made variable to allow for different vessel characteristics. Correct setting of the counter rudder control should cause the vessel to make good its original course. Counter rudder data must always be applied in conjunction with the output of the manual 'rudder' potentiometer, which varies the amount of rudder control applied per degree of heading error.

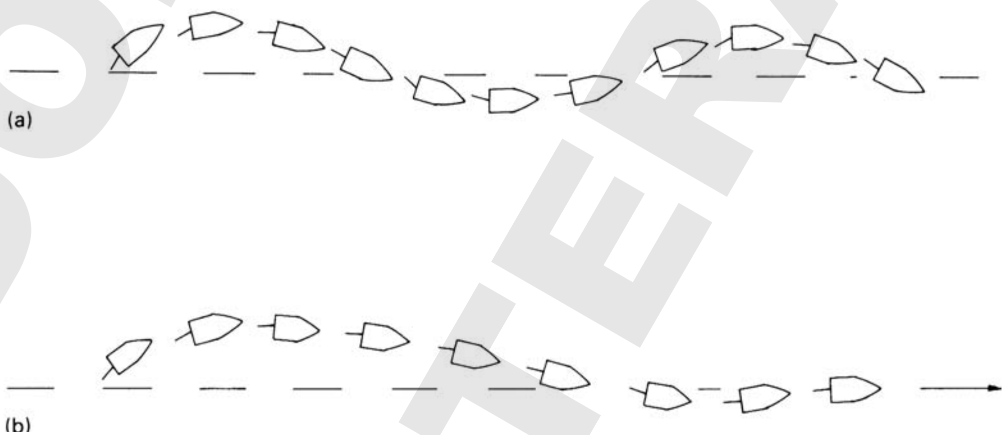

Figure 9.5 (a) If 'counter rudder' and 'rudder' controls are set too high, severe oscillations are produced before the equipment settles.(b) If 'counter rudder' and 'rudder' controls are set too low, there will be little overshoot and a sluggish return to the course.

Figures 9.5(a) and (b) show the effect on vessel steering when the counter rudder and rudder controls are set too high and too low, respectively.

9.2.3 Integral control

Data for integral control is derived by electronically integrating the heading error. The action of this data offsets the effect of a vessel being moved continuously off course. Data signals are produced by continuously sensing the heading error over a period of time and applying an appropriate degree of permanent helm.

In addition to proportional control, derivative control and integral control, autopilots normally have the yaw, trim, draft, rudder limit, and weather controls, which will be dealt with in more detail later in this chapter.

9.3 A basic autopilot system

The simplest form of autopilot is that shown in Figure 9.6. An output from a gyro or magnetic repeating compass is coupled to a differential amplifier along with a signal derived from a manual course-setting control. If no difference exists between the two signals, no output will be produced by the amplifier and no movement of the rudder occurs. When a difference is detected between the two sources of data, an output error signal, proportional in magnitude to the size of the difference, is applied to the heading error amplifier. Output of this amplifier is coupled to the rudder actuator circuit, which causes the rudder to move in the direction determined by the sign of the output voltage. The error signal between compass and selected course inputs produces an output voltage from the differential amplifier that is proportional to the off-course error. This type of control, therefore, is termed 'proportional' control. As has previously been shown, the use of proportional control only, causes the vessel to oscillate either side of its intended course due to inertia producing overshooting.

With a Proportional, Integral and Derivative steering control system, the oscillation is minimized by modifying the error signal (ψ) produced as the difference between the selected heading and the

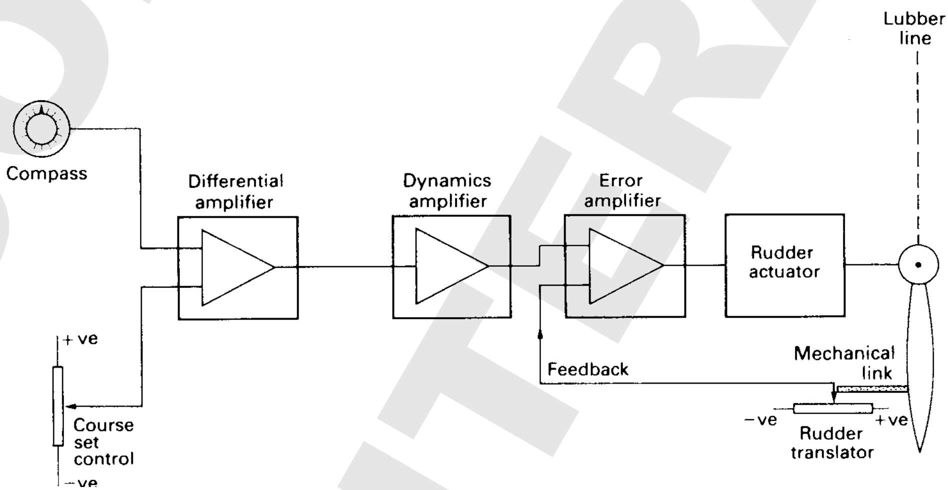

Figure 9.6 A simple autopilot system.

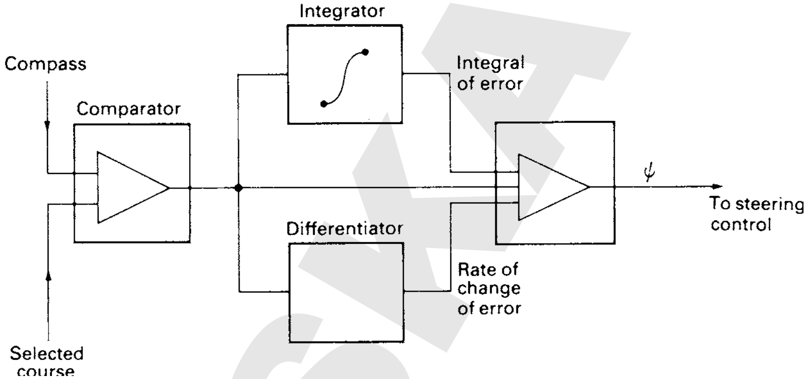

Figure 9.7 Error signal summing circuit.

compass heading. Figure 9.7 shows that a three-input summing-amplifier is used, called a dynamics amplifier, to produce a resultant output signal equal to the sum of one or more of the input signals.

The demanded rudder error signal (ψ) is inspected by both the differentiator and the integrator. The differentiator determines the rate of change of heading as the vessel returns to the selected course. This sensed rate of change, as a voltage, is compared with a fixed electrical time constant and, if necessary, a counter rudder signal is produced. The magnitude of this signal slows the rate of change of course and thus damps the off-course oscillation. Obviously the time constant of the differentiation circuit is critical if oscillations are to be fully damped. Time constant parameters depend upon the design characteristics of the vessel and are normally calculated and set when the vessel undergoes initial trials. In addition, a 'counter rudder' control is fitted in order that the magnitude of the counter rudder signal may be varied to suit prevailing conditions.

Permanent disturbances of the course due to design parameters of the vessel must also be corrected. These long-term errors, typically the shape of the hull or the effect of the screw action of a single propeller driving the ship to starboard, may be compensated for by the use of an integrator. The integral term thus produced is inserted into the control loop offsetting the rudder. This permits proportional corrections to be applied about the mean offset course (the parallel course shown in Figure 9.3). The offset signal amplitude causes a permanent offset-error angle of the rudder. The output of the dynamics amplifier is now the total modified error signal (ψ) which is regulated by the 'rudder' control to determine the amount of rudder correction per degree of heading error to be applied.

An overall simplified diagram of an autopilot is shown in Figure 9.8.

The rudder error amplifier is provided with variable sensitivity from the 'weather' control, which in effect varies the gain of the amplifier by varying the feedback portion of the gain-determining components. In this way the magnitude of the heading error signal required, before the output from this amplifier causes the rudder to operate, may be varied. Using this control a delay in rudder operation may be imposed if weather conditions cause the vessel to yaw due to a heavy swell aft of the beam.

Under certain conditions, mainly draft and trim of the vessel, a degree of permanent rudder may be required. The 'permanent helm' control provides an input to the rudder error amplifier that may be positive or negative depending on whether the rudder needs to be to starboard or to port. Since the effect of rudder movement does not influence the setting of this control, the rudder will remain

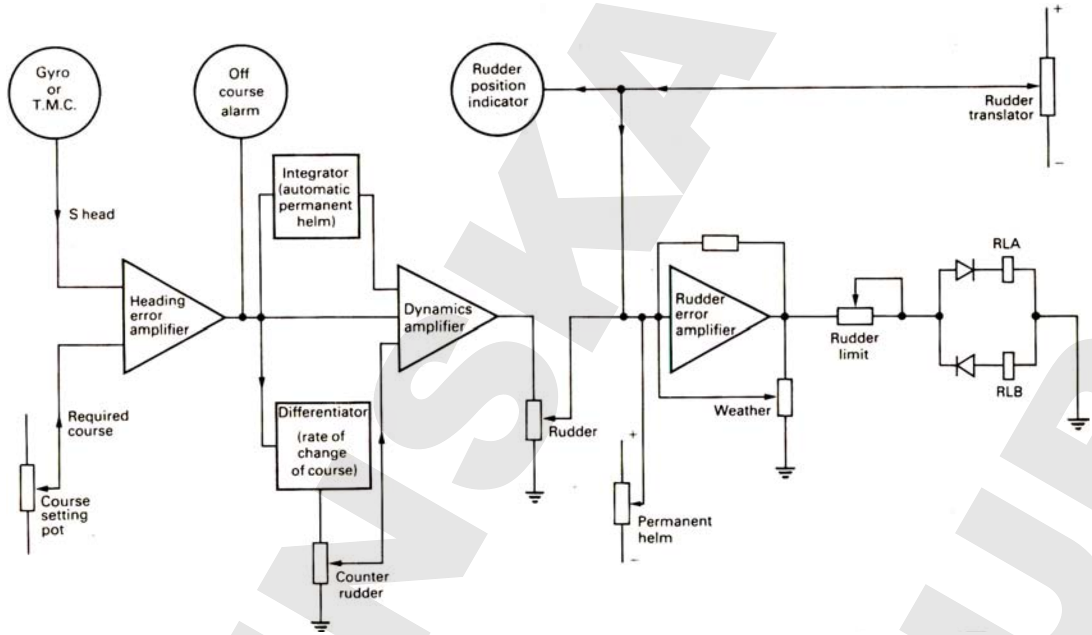

Figure 9.8 A simplified diagram of an autopilot system.

permanently in the position set by the control (assuming no other control signals are produced). Permanent helm will also be applied automatically by sensing the build-up of heading error in the integrator circuit.

In the system described control relays RLA and RLB are used to switch power to the steering gear contactors, which in turn supply power of the correct amplitude and polarity to the prime rudder mover. As the rudder moves, a mechanical linkage drives the slider of a potentiometer to produce the rudder feedback signal. Output from this ‘rudder translator’ potentiometer is normally used to indicate the instantaneous rudder angle. Excursions of the rudder may be limited by the manually operated ‘rudder limit’ control which fixes the maximum amount by which the rudder may move from the midships position.

An off-course alarm circuit senses the error signal at the output of the heading error amplifier and causes an audible alarm to be sounded when a signal amplitude outside pre-determined limits is detected. A manual off-course limit control (not shown) is provided to enable an operator to select the point at which the alarm will sound.

9.4 Manual operator controls

9.4.1 Permanent helm

This control is intended for use when the vessel is being driven unilaterally off-course by a crosswind. Its function is to apply sufficient permanent rudder angle to offset the drift caused by the wind, thus holding the vessel on the required heading. Permanent helm is also applied automatically when the steering system is in the automatic mode of operation.

Automatic application of permanent helm makes no use of the permanent helm control. The degree of rudder offset required for course holding is now electronically computed and applied automatically.

Since the computing process involves the charging of a capacitor, the required degree of permanent helm is built-up gradually over a period of minutes. This period may be changed by altering the charging time of the capacitor.

9.4.2 Rudder

Rudder limit control sets a finite limit on the rudder angle obtained irrespective of the angle commanded by the automatic control circuitry. Obviously if the rudder was permitted to exceed design parameters severe damage may be caused.

The rudder potentiometer enables the ship's steering characteristics to be modified in accordance with the changing requirements caused by loading and speed factors. This control determines the absolute degree of rudder command obtained for every degree of steady-rate heading error. For example, if this control is set to '2', the rudder will move through 2° for every degree of heading error.

The counter rudder control determines the degree of opposite helm to be applied if it is demanded by the control circuit. The control permits daily adjustments to be made as dictated by loading conditions.

9.4.3 Weather

The effect of weather and sea conditions can be effectively counteracted by the use of this control. The circuits controlled by this switch progressively desensitize the control amplifier, which in turn causes an increase in the deadband width. The control also imposes an increasing time delay on the rudder command signal in order that the ship will recover naturally when under the influence of repetitive yaw. This means that the steering gear is not subjected to continual port/starboard commands. Thus the higher the setting of the weather control, the wider will be the deadband. This increases the amplitude of yaw that can be tolerated before the steering gear is enabled.

9.4.4 Non-follow-up mode (NFU)

The rudder is manually controlled by means of two position port/starboard lever switches. These switches energize the directional valves on the hydraulic power unit directly, thus removing the rudder feedback control. In this mode the normal autopilot control with repeat back is by-passed and the rudder is said to be under 'open loop' control. There is no feedback from the rudder to close the loop. The helmsman closes the loop by observing the rudder angle indicator and operating the NFU control as appropriate.

9.4.5 Follow-up mode (FU)

In this mode the FU tiller control voltage is applied to the error amplifier (Figure 9.9) along with the rudder feedback voltage. Rudder action is now under the influence of a single closed loop control.

9.5 Deadband

Deadband is the manually set bandwidth in which the rudder prime movers do not operate. If the deadband is set too wide, the vessel's course is hardly affected by rudder commands. With the control set narrow, the vessel is subjected to almost continuous rudder action causing excessive drag.

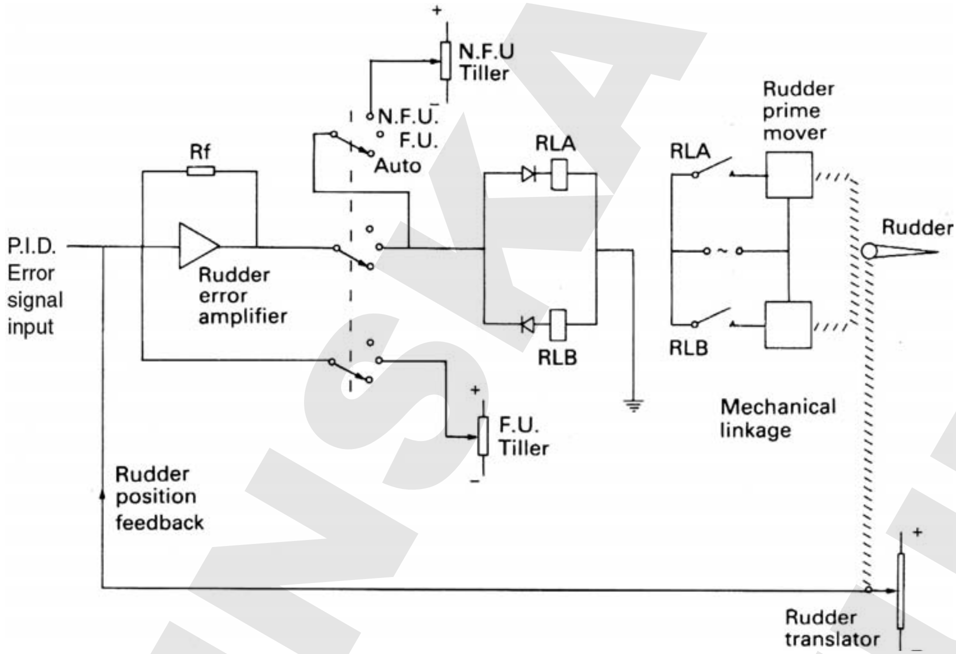

Figure 9.9 FU and NFU control of tiller operation. (Reproduced courtesy of Racal Marine Controls.)

9.5.1 Overshoot

For optimum course-keeping performance it is imperative that an autopilot operates with as narrow a deadband as possible. All steering systems suffer a degree of inherent overshoot. The effect of this overshoot on the stability of the rudder positioning system can be graphically represented as shown in Figure 9.10.

Two scales are plotted on the vertical axis, the first shows the rudder angle in degrees with respect to the midships position and the second, the voltage corresponding to that angle produced by the rudder translator.

It is assumed that a starboard rudder command is applied to the autopilot at time $t = 0$ s, and as a result the starboard rudder controller pulls in to cause the rudder to move to starboard. Since the mechanical linkage of most autopilot systems take a finite time to develop full stroke, the rudder does not reach its terminal velocity until $t = 2$ s. At time $t = 9$ s, the position feedback signal (*Vp*) crosses the release threshold of the starboard relay. Prime power is now removed from the steering gear pump. Because of inherent overshoot, caused by inertia, the rudder will continue to move to starboard as shown by the solid line. If the overshoot is of sufficient magnitude, it will cause the position feedback signal to cross the operating threshold of the port relay ($t = 12.5$s), and thus set the rudder moving towards the midships position. When, at $t = 15.25$s, *Vp* crosses the release threshold of the port relay, power is again removed from the steering gear. Overshoot now carries the *Vp* signal back through the operating threshold of the starboard relay and the rudder once again moves to starboard. The control system is now described as unstable and the rudder is caused to oscillate or hunt.

The dotted curve in Figure 9.10 illustrates the operational characteristics of a stable system. Here, overshoot does not cause the port relay to be activated and thus the rudder arrives at the commanded position in one continuous movement.

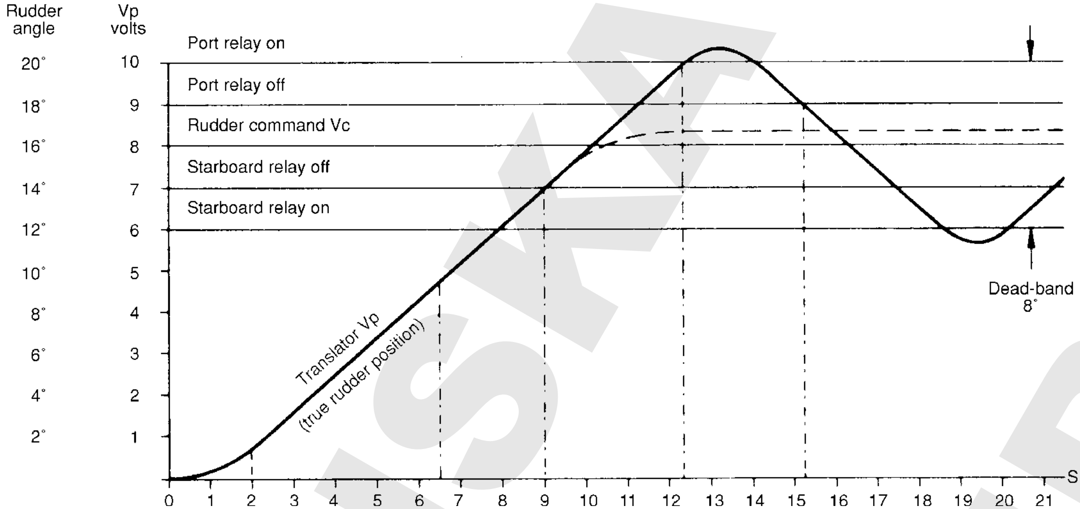

Figure 9.10 Effect of overshoot on control system stability. (Reproduced courtesy of Racal Marine Controls.)

One method of stabilizing an unstable system is to decrease the sensitivity of the rudder amplifier. This solution is not satisfactory because it has the effect of increasing the distances between the ‘operate and release’ thresholds of the steering relays thus producing a wider deadband and a degradation of the steering performance and efficiency.

A better solution is to remove power from the steering gear at some determinate time before *Vp* crosses the release threshold of the starboard relay. The extent of this pre-determined release time must be dependent upon individual steering gear overshoot characteristics. In Figure 9.10, if power was removed from the steering gear at $t = 6.5$ s (a time advance of 2.5 s), the inherent overshoot would not carry *Vp* through the operating threshold of the port relay and rudder movement will follow the dotted line illustrating a stable system. This principle is an outline of a system known as phantom rudder.

9.6 Phantom rudder

Dependent upon the setting of the ‘phantom rudder speed’ control, a determinate d.c. voltage is applied to an integrator input resistance with the result that the circuit starts to generate the positive going ramp voltage *Vp* defined by the solid line in Figure 9.11.

It should be noted that the polarity of the integrator output is the reverse of that of the translator output *Vt*, hence the provision of separate voltage scales on the y-axis of the graph. It is arranged so that the slope of *Vp* and *Vt* are equal. On the assumption that the steering gear takes 1 s to run up to speed, the phantom output establishes a lead of approximately 0.75 V (1.5°) during this period. At time $t = 2.4$ s, the phantom output, functioning as a position feedback signal, arrives at the release threshold of the starboard relay, one contact of which removes the input from the integrator causing the output to halt at +3 V. It is arranged that at this time a second input is applied to the phantom rudder circuit integrator, which now produces a negative going ramp. The slope of this ramp is made to be gradual by limiting the amplitude of the signal applied to the integrator.

At time $t = 3$ s, the phantom (*Vp*) and translator (*Vt*) outputs will be equal and of opposite polarity causing the output from the integrator (*Vp*) to stop increasing. This condition is not stable because as

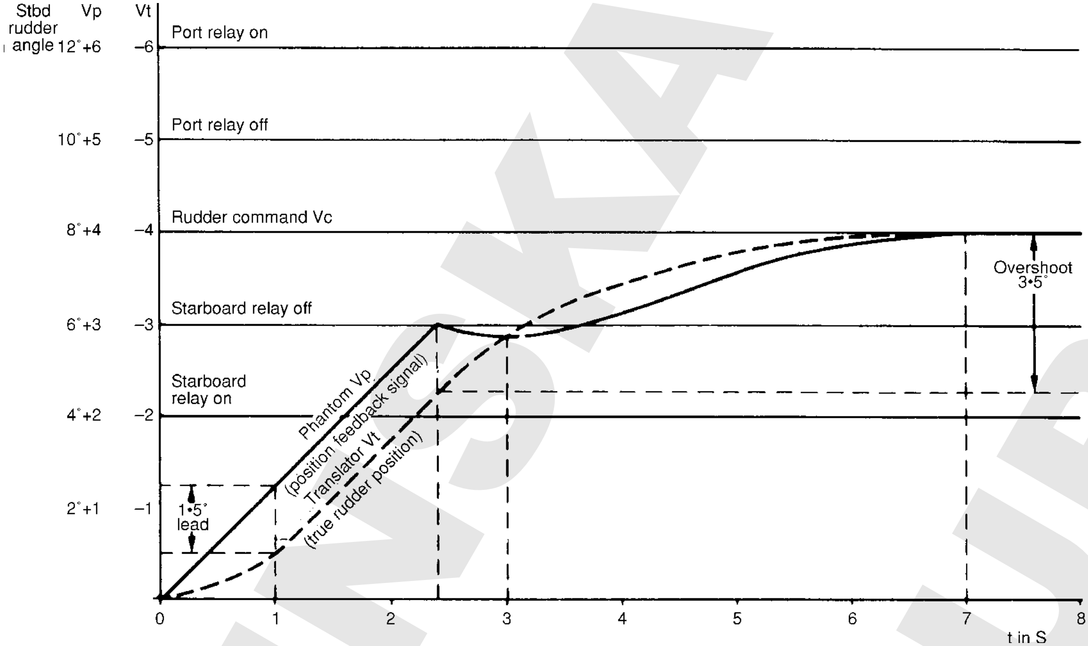

Figure 9.11 Operational principle of a phantom rudder. (Reproduced courtesy of Racal Marine Controls.)

Vt is carried progressively more negative by rudder overshoot, the integrator generates a positive going ramp with a low incline. Output from the integrator will now continue to rise, and the slope will gradually decrease as the positive potential of *Vp* approaches parity with the negative potential of *Vt*. Ultimately at $t = 7$ s, *Vp* will be equal to *Vt*. Since no input is now applied to the integrator, its output *Vp* will be held at the attained level, and the hypothetical position of the phantom rudder will be the same as that of the true rudder.

In the foregoing example, the lead of the phantom rudder on the true rudder was obtained purely as a result of the slow take-off of the steering gear. In practice, it is desirable that the phantom rudder speed output be set 20% higher than that of the true rudder. Since, with this arrangement, the phantom rudder output will continue to increase its lead on the translator output so long as the steering gear is energized, some means has to be provided to limit the lead that the phantom output is permitted to build up. This function is performed by the 'steering gear overshoot', effectively limiting the rise time of the integrator causing *Vp* to level off in stages as illustrated in Figure 9.12.

9.7 The adaptive autopilot

Autopilot systems so far described have operated under various command functions, the origins of which have been small signals produced by feedback loops. The rudder command-loop signals have been further modified by the proportional, integral and derivative terms to form the nucleus of the PID autopilot systems. The adjustment of operator controls on the PID autopilot requires considerable expertise if the system is to operate efficiently. It is not feasible to continually reset

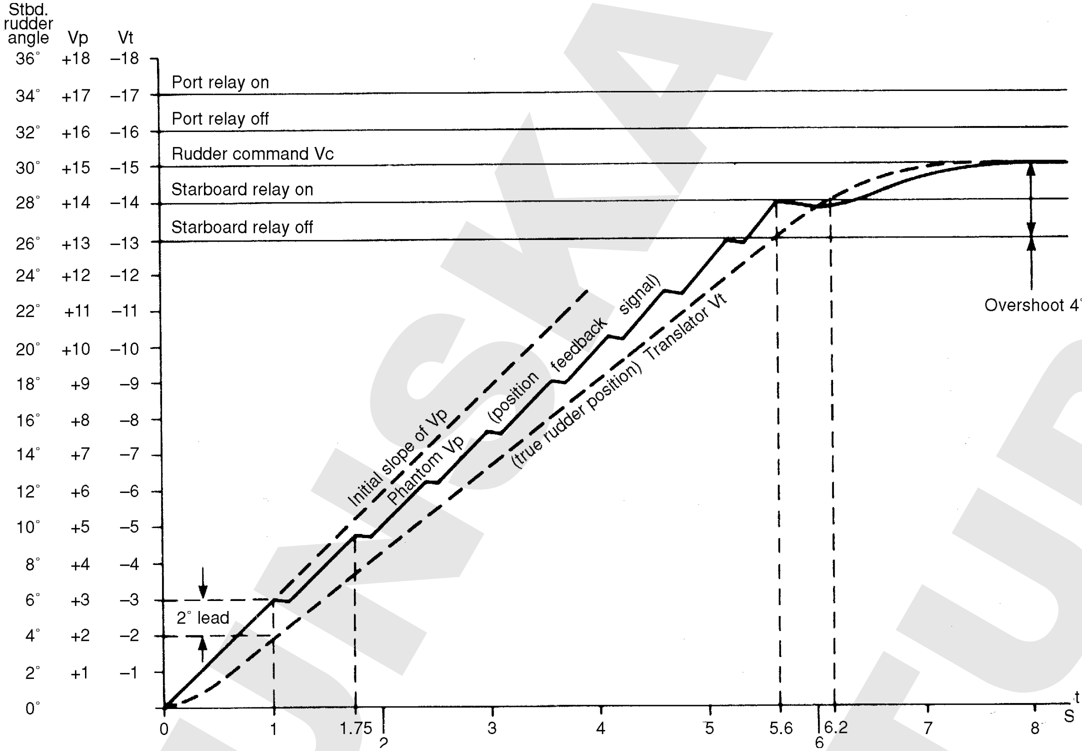

Figure 9.12 Characteristics of a practical application of phantom rudder. (Reproduced courtesy of Racal Marine Controls.)

the potentiometers during constantly varying weather conditions; thus the system cannot be absolutely efficient.

The PID autopilot was developed in an effort to enable a vessel to follow a course as accurately as possible by reducing drag caused by excessive rudder angles whilst limiting rudder excursions to a low level in order to minimize wear on the steering gear. Considerable research has been undertaken into the effects of the ship's natural yaw action in relation to the course to be steered, and it has been found that a straight course is not necessarily the most economical and that the ship's natural yaw action should not be smoothed out.

Operating parameters for modern adaptive autopilots (AAPs) have been developed by a number of notable design engineers over the past three decades. Probably the most influential of these is N. H. Norrbin who, in the early 1970s, derived a performance index relating to added resistance due to imperfect steering control. This he produced in the measurable term of 'the square of the average heading error'. Most modern AAP controllers use this index as the fundamental control term. In addition to the fact that a straight course is not the most economical course it was decided that steering control should always be optimized with respect to the prevailing environmental conditions and a low bandwidth should be used to minimize losses. There are, therefore, two main factors that affect the steering control.

- The complex characteristics of the vessel. Handling parameters will be different for each vessel, even of the same type, and will change with the loading factor.

- Environmental influences, namely wind and tide which will be constantly shifting and introducing instantaneous variable course errors.

As has been standard practice for many years, ship handing characteristics can be programmed into a standard autopilot system and their effects counteracted. However, environmental effects are a different matter. They can, to some extent, be counteracted by the helmsman. But to nullify their effects totally would require the skills of an extraordinary person, one with the ability to instantaneously predict all ship and environmental effects before applying corrective rudder. Such a helmsman would be a treasure indeed. It is more logical to replace the helmsman with a computer that is able to react more quickly to the constantly changing parameters that are input from various sensors.

The AAP is, in its simplest form, a good quality autopilot system with the addition of a digital control system (microcomputer) producing the final rudder command signal. Contained in the microcomputer are data relating to the dynamics of a 'virtual ship' which may be analysed in order that rudder commands for the actual ship can be predicted. Obviously the dynamics of this 'virtual ship' are critical to the AAP operation and in practice will be accurately set for the vessel on which the AAP is fitted.

9.7.1 The 'virtual ship' principle

Most adaptive autopilot equipment is designed around the 'virtual ship' principle, a computer-generated model vessel, and the following criteria.

- The ship's operating envelope, including the vessel's speed, load factor and external environmental conditions.
- Precise dynamics of the vessel that relate directly to its steering control.
- The dynamics of the ship's steering system.
- The dynamics of the gyrocompass.
- The dynamics of the seaway.

It is then necessary to define the principal modes of operation that require specific performance criteria. The most used of these modes is open sea course keeping where optimized steering can lead to potentially large savings in fuel oil.

9.7.2 Open sea course keeping

Fuel consumption, which is of major importance for the economic operation of a vessel, is affected by a number of factors, such as engine performance, trim, and the condition of the hull below the waterline. These factors are, however, predictable and counteractive data is easily obtained and input to the AAP. It is essential that the central processor is able to distinguish between ship/engine loss parameters and rudder movements, and apply corrective rudder only when course keeping is affected by environmental conditions and not by the natural yaw of the vessel. Various mathematical formulae have been developed to analyse the AAP integral term to optimize rudder performance. Thus the AAP system automatically minimizes propulsion losses and is termed an adaptive control system. The term adaptive is used because the mathematical parameters of the model ship have been 'adapted' to match those of the actual vessel.

The performance criterion, when reduced to a form suitable for online evaluation on board ship, may be represented as

$$J = (\lambda\psi^2 + \delta^2)dt$$

where ψ = ship's heading error,
δ = rudder angle, and
λ = weighting factor derived from analytical expressions of drag forces due to steering.

Obviously the adaptive autopilot must be able to detect that a course change has been commanded. This is the function of the course changing control circuitry.

9.7.3 The course changing controller

When changing course it is standard practice to consider three phases of the manoeuvre:

- the start of the turn
- the period of steady turn
- the end of the turn.

The measure of rudder applied determines the rate-of-turn and also the peak roll-angle. In practice therefore the maximum roll-angle is determined by the maximum permissible rudder limit. Proportional and rate gains can be obtained for each vessel and its loaded condition as a function of speed. In an AAP, gains are chosen based on the optimized results of the virtual ship during a controlled turn. The primary concern of the AAP whilst manoeuvring in confined waters must be safety.

9.7.4 Confined waters mode

When manoeuvring in confined waters, it is essential that cross-track error be minimized. Since the central processor cannot determine cross-track data, an alternative mathematical concept is used. Balancing the heading error against the rudder rate derives cross-track data.

$$J = (\lambda\psi^2_e + \delta^2)dt$$

The main difference between the open sea course keeping controller and the confined waters controller is that the gain of the latter is varied only as a function of the ship's speed.

9.8 An adaptive digital steering control system

Sperry Marine Inc., now part of the Litton Marine Systems group, is a traditional manufacturer of compass and control equipment, and their ADG 3000VT Adaptive Digital Gyropilot® Steering Control system is a good example of an up-to-date autopilot using many of the principles described in this chapter (see Figures 9.13 and 9.14).

At the heart of the autopilot is a sophisticated microcomputer and electronic circuitry providing control signal outputs to the steering gear pump controllers. The microelectronic circuitry is programmed (calibration/configuration CALCON) at installation to set controller gains and time

Figure 9.13 The Sperry Adaptive Digital Gyropilot" Steering Control Console. (Reproduced courtesy Litton Marine Systems.)

constants specific to the ship's design affecting heading keeping and manoeuvring. Inputs of speed and heading data are provided from a speed log and a gyrocompass for automatic operation, and manual control is from the primary helm unit, primary NFU controller or remote FFU controllers. Rudder angle information feedback data is interfaced with the main electronics unit. System control is from the main control panel, although a serial I/O data line enables automatic course order entry from an integrated bridge unit, such as the Sperry Marine Inc's Voyage Management System VMS.

Manual steering and input commands are under the control of the helmsman whereas automatic steering can be performed from three different automatic steering modes.

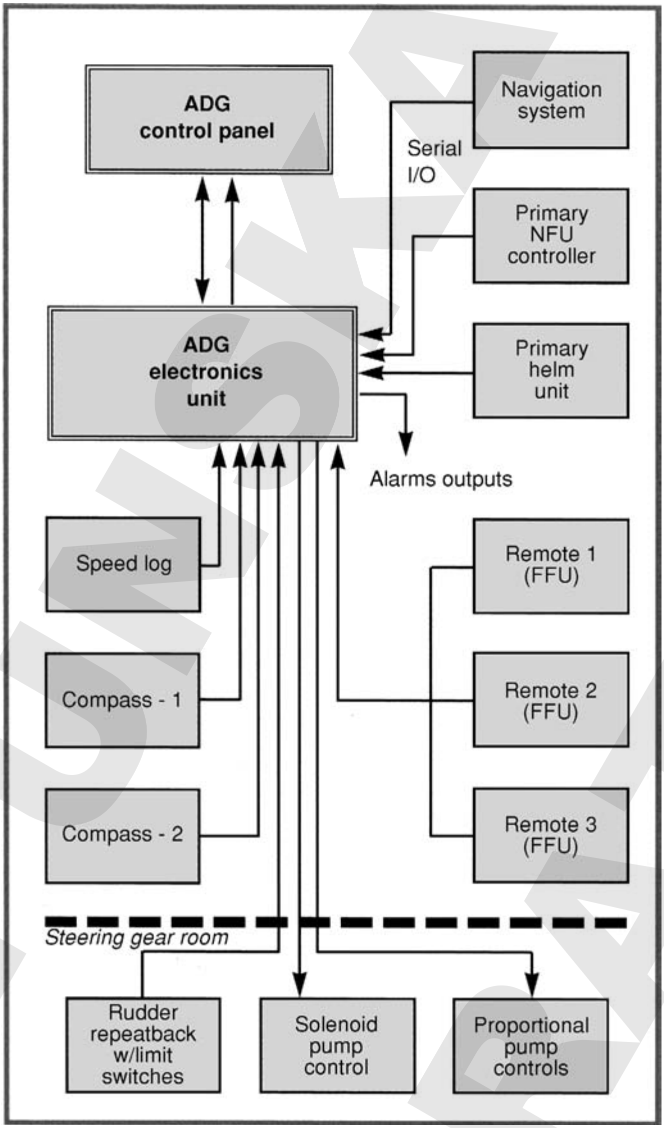

Figure 9.14 Sperry ADG 3000VT autopilot bridge configuration. (Reproduced courtesy of Litton Marine Systems).

- AUTO mode. The primary mode, used for automatic heading keeping with data input from a gyrocompass and the helmsman's Order setting.
- NAV mode. An optional steering mode performing automatic heading keeping using inputs from an external management system to steer the vessel to pre-determined waypoints. Only available if installed by Calcon during installation.
- TRACK mode. An optional steering mode using inputs from an external navigator, which is corrected for cross-track error by the autopilot to steer the ship to a waypoint over a designated ground track.

9.8.1 Operation

As previously stated, the autopilot can be operated in one of three modes; Auto, Nav and Track mode. This section considers the autopilot when using the Auto mode with interfaced data from a gyrocompass and a helmsman inputting data via the keypad.

Referring to Figure 9.15, the number 1 is the Status selector switch and numbers 2–6 are the indicators. In this case Auto will be selected. Number 7 is the Adap/Man display and number 20 is the control. An ‘A’ is displayed indicating that adaptive (automatic) gain selection has been chosen by the helmsman to compensate for sea conditions. If a fixed gain setting is selected, the display shows a number 1–7, with the highest number indicating the lowest gain and therefore the lowest number providing tighter heading keeping. This choice will depend upon sea conditions. In this case Adaptive has been selected permitting the autopilot to determine automatically the gain, based upon heading error and rudder activity.

The number 8 (displaying 15 in the diagram) is the rudder set-limit display, set by the helmsman with switch 17. This may be set to any value between 1° and the ship’s maximum permitted rudder angle. It is the ‘effective’ rudder limit based on ‘weather helm’ and may differ from the true rudder angle. The indicator 18 lights to show that the rudder order output is equal to the selected rudder limit.

Display number 9 (showing 014) is the rate order display. This is set by control 15, which selects the turn rate to be followed during turn manoeuvres.

Display number 10 is the status and control display showing autopilot information. Menu scroll buttons, 11 and 12, and switch 13 select different display data. As an example, the display is currently showing Turn Radius Order data but it may be switched to one of many other functions affecting the operation of the autopilot and not immediately obvious on the control panel display. These include deadband, turn radius, speed selection, load selection, and rudder order bias amongst other functions.

Number 22 indicates the vessel’s heading display derived from the master compass input data. The display numbered 40 shows the current heading order (in 1/10th of a degree) and display number 38 displays the heading order entered via the control knob 37 or from the pre-set values, controls 34 and 35.

Indicator number 24 warns of an off-course situation, indicator 27 warns of a malfunction in the system, and indicator number 28 warns of errors or failure of the compass input data.

After a successful power-up, during which the autpilot performs a self-diagnostic function, the following sequence enables automatic operation.

- Adjust the autopilot controls to the desired settings.
- Verify that the steering control system is selecting the autopilot.
- Press the Status switch to select Auto.
- Rotate the Order knob until the required heading-to-steer appears in the Order display.

9.8.2 System description

The heart of the autopilot is the central processing unit holding a processor, various I/O ports and buffers, and ROM/RAM memory. A block diagram of the overall system is given in Figure 9.16.

Rudder commands are output to U6, a dual channel 12-bit digital-to-analogue converter (DAC) on the Analogue Digital Serial board (ADS), giving an analogue output in the range ±5 V to the rudder servo-amplifier. Ultimately this circuitry provides a dual proportional rudder order (RO) analogue

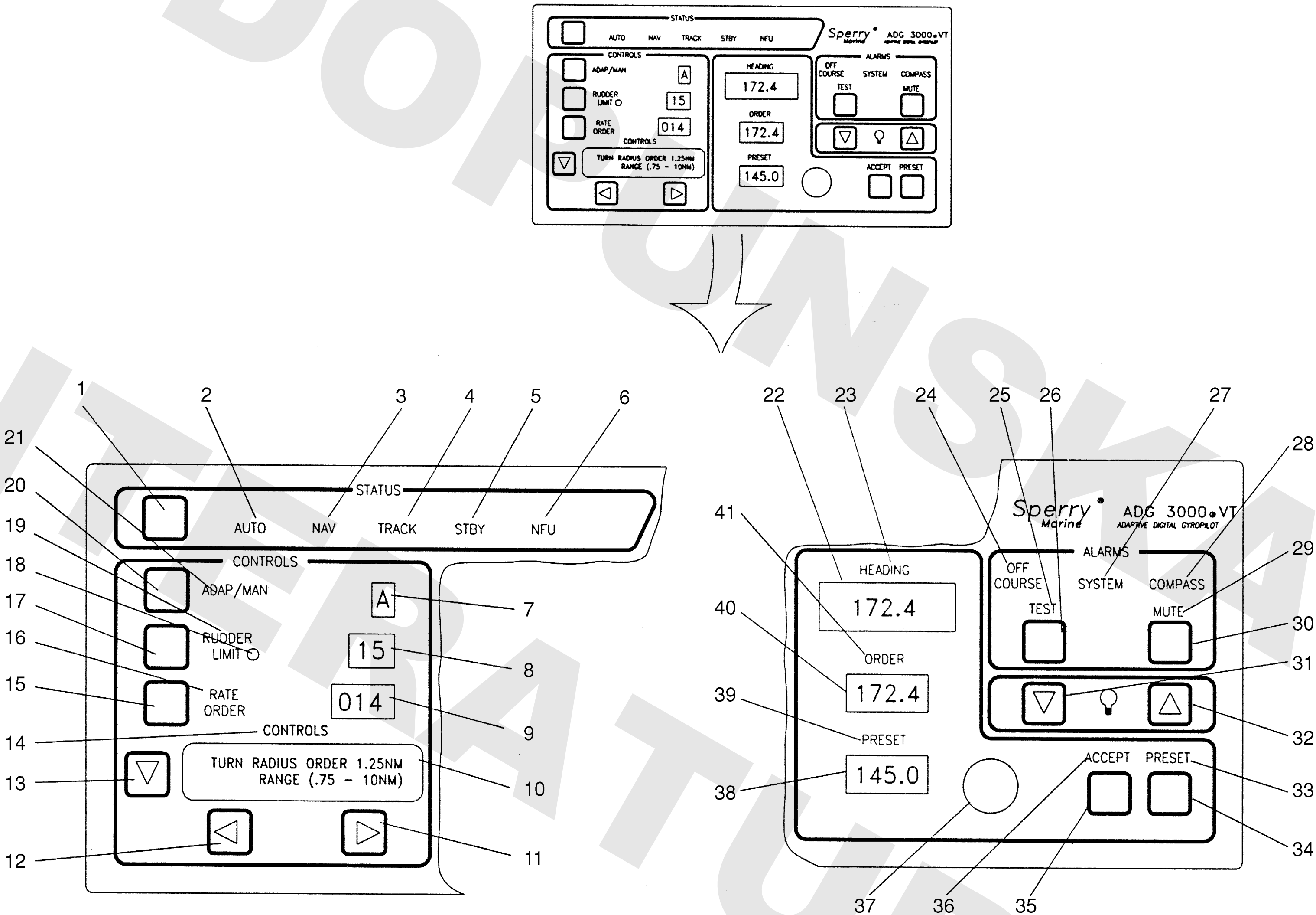

Figure 9.15 Display unit. (Reproduced courtesy Litton Marine Systems.)

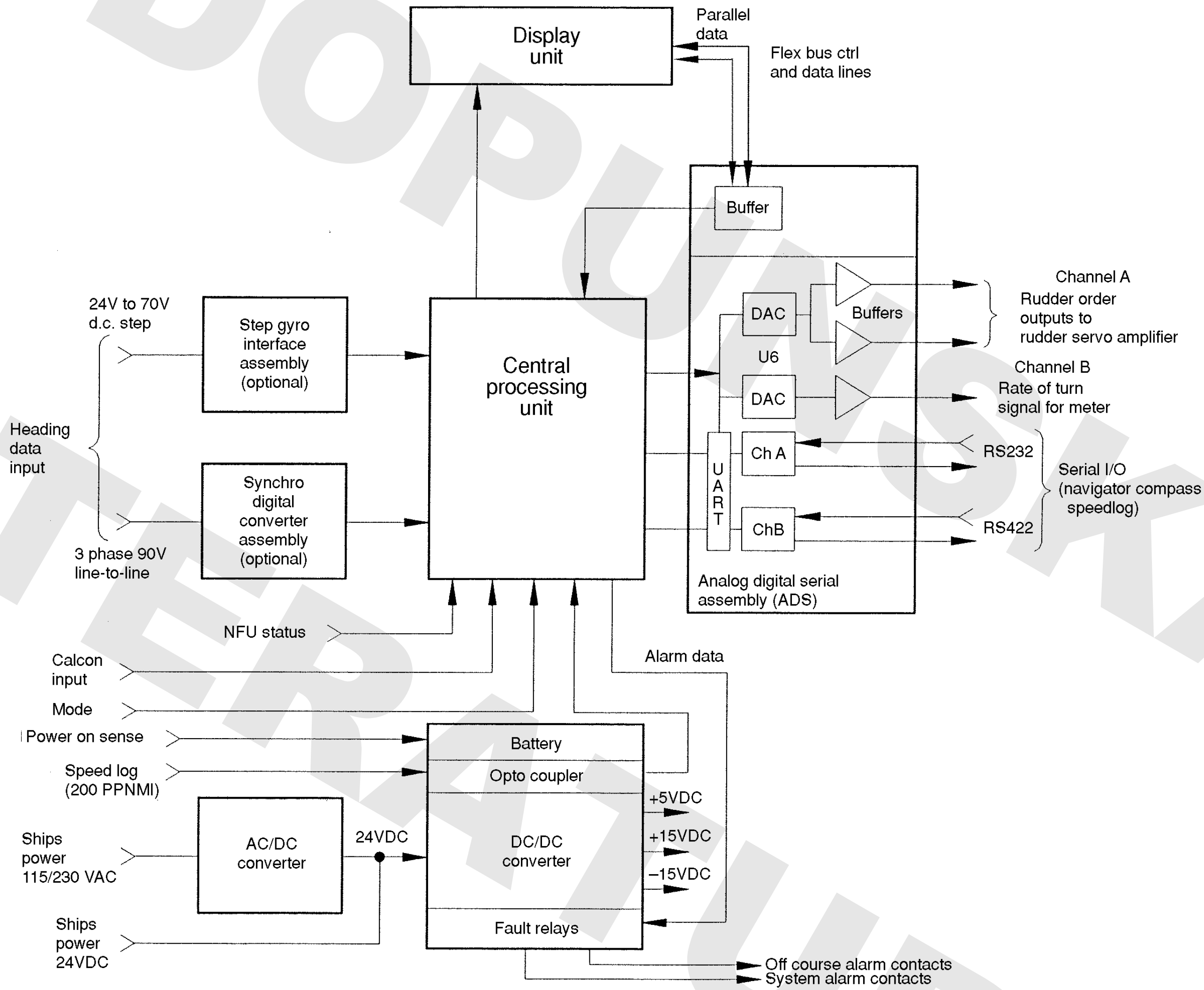

Figure 9.16 Overall system block diagram. (Reproduced courtesy of Litton Marine Systems.)

voltage capable of driving rudder servo-amplifiers. The output voltage is in the range –11.25 to +11.25 V, corresponding to 45° left and right rudder orders, or 0.25 V/°. The output of DAC-A is routed through an analogue switch that prevents any output at power-up and thus produces 0 V to the rudder servo-amplifier. This ensures there are no rudder commands until the central processor is ready. The output of DAC-B is gated to provide rate-of-turn signals.

The ADS circuitry also communicates with the display unit via an 8-bit bi-directional parallel data bus interface (flex bus). This is the main command path between the CPU and the display unit. The ADS board also has two serial I/O channels to communicate with an electronic navigator, compass or speed log equipment: channel A is configured to be an RS-232 interface and channel B an RS-422 line. Speed information may be input on the RS-422 interface line in the NMEA 0183 format or via the power board optocoupler in 200 pulses per nautical mile (200 PPNMI). See Table 9.1.

Table 9.1 Interface signals. (Reproduced courtesy of Litton Marine Systems)

Inputs	
Speed log input	
Pulsed	200 pulse/nautical mile (PPNMI) format (contact closure)
Serial	RS-232 (channel A or C) or RS-422 (channel B) communications in NMEA 0183 format, $VBW, $VHW
Navigator (vessel management system) input	Serial data for heading order, rate order, and cross track error information in RS-232 or RS-422 communication on channel A, B or C. in NMEA format $APB, $HSC, $HTR, $HTC or $XTE.
Compass	
Step data	Positive or negative step data (24 or 70 V)
Synchro	1X, 90X or 360X
Data	$HDT (on channels A, B or C)
Serial data	
Mode switch sense contacts	External switched opened or closed to inform autopilot to change from Standby mode to an automatic mode
NFU sense contacts	External contacts to indicate when the NFU controller is active
Power failure circuits	Closed contacts on external power switch to activate power failure alarm
Outputs	
Interface to external rudder servo control amplifiers	Bipolar analogue voltage proportional to the rudder order. ± 11.25 V (maximum limit) equal to ± 45° or rudder
Rate of turn interface	Bipolar analogue voltage proportional to a turn rate indicator. ± 4.5 V (max) equal to ±90° turn/min. Resolution equal to 0.5°/min.

Gyrocompass input data is coupled via either a synchro digital converter assembly (SDC) or a step gyro interface assembly to the CPU board. Both boards have the same function, i.e. to convert the azimuth data from a gyrocompass to a suitable data input for the CPU. The SDC board accepts a synchro azimuth input as three-phase 90 V line-to-line signal to a resolver circuit. A built-in test (BITE) circuit detects any errors or failure in the azimuth data at this point. Output from the resolver is a 16-bit data line to the CPU.

All the external operator command functions are requested through the display unit. The CPU scans the X select lines of an X–Y matrix and monitors each of the Y lines sequentially searching for a keypad command. When a switch is pressed the X select gets transferred to a particular Y line and the command is initiated.

9.8.3 NMEA 0183 interface format

Communication with other shipboard navigation equipment is via the RS-232 and RS-422 ports. Message format and field definitions are outlined below using the speed serial interface as an example. The heading, heading order, and speed messages follow the NMEA 0183 format with extensions for status and tenths resolution.

Incoming messages are required to begin with the string, $ttsss, where: tt = (upper case characters) talker identifier; and sss = (upper case characters) sentence identifier. Incoming messages may omit the ‘*cc’ checksum field.

Table 9.2 Sperry ADG 3000 VT Autopilot NMEA 0183 input message styles. (Reproduced courtesy of Litton Marine Systems)

(a) Input message styles

Sentence	*Data*	*Expected rate (Hz)*	*Time delta without message before alarm(s)*
HDT	Heading, true	8	1
VBW	Velocity, bottom and water	1	4
HSC	Heading order command	$\frac{1}{2}$	15
HTC	Heading of course to next waypoint	$\frac{1}{2}$	15
HTR	True rate order	$\frac{1}{2}$	15
XTE	Cross track error	$\frac{1}{2}$	15
APB	Alternate order command and cross track error	$\frac{1}{2}$	15
VHW	Alternate water speed	1	4

(b) Output message style

Sentence	*Data*	*Output rate (Hz)*
FLT	Faults	1
HSC	Heading to steer	1
HTC	Heading to waypoint	1
ROR	Autopilot rudder order	1
STA	Autpilot status and commands	1
STB	Autopilot controls	1
VHW	Heading and water speed	1

Serial speed interface

If the autopilot is configured for serial speed input, the CPU reads fore/aft speed data from the configured channel. In an automatic mode, the CPU expects one message per second. If it does not receive at least one message within 4 s, the system alarm is set and the autopilot defaults to the last known speed input.

If water speed is supplied but marked invalid, the processor uses it for steering; if water speed is unavailable, the processor uses bottom speed. In either case, a system alarm is set for misformatted messages. If speed is constantly less than 1 knot, the processor sets a system fault and uses the normal service speed instead. The processor reports speed system faults only in automatic steering modes.

The NMEA 0183 input speed message format is:

$ttVBW,sww.w,sx.xx,a,syy.y,szz.z,a*cc<cr><lf>

where	tt	=	talker ID;
	s	=	negative for aft/port speeds, omitted for fore/starboard speeds;
	ww.w	=	alongship water speed in knots;
	xx.x	=	athwartship water speed in knots;
	yy.y	=	alongship bottom speed in knot;
	zz.z	=	athwartship bottom speed in knots;
	a	=	status sign: A, if valid speed data is available; V, if not;
	cc	=	ASCII hex 8-bit XOR characters after '$' through the letter before the '*';
	<cr><lf>	=	carriage return and line feed end-of-sentence markers.

Examples are:

$ttVBW,20.0,,A,,,V = Valid water speed with trailing zeroes omitted.

$ttVBW,,,V,18.2,,A = Bottom speed.

9.8.4 Troubleshooting

The system possesses an extensive fault identification system that enables system malfunctions to be isolated to a circuit board or major subassembly level. Extensive use is made of the system's BITE function to identify types of malfunctions by means of pre-programmed diagnostics. It is also possible for an operator to diagnose certain types of faults that are undetectable by the processor-dependent BITE functions.

If a System or Compass alarm occurs, the operator presses and holds the Mute switch for 4 s or longer. During this time, the CPU will search for a malfunction and, if it is one of the listed faults in Table 9.3, it will display error information and a code corresponding to that condition. For instance, if there is an error in the input data from a speed log, the autopilot display may show Speed Log Error 40 Enter Manual Speed. Referring to the fault code and corrective action chart, part of which is reproduced as Table 9.3, it is possible to locate and/or replace a faulty assembly.

The fault logic diagram, shown in Figure 9.17, shows the procedure to be followed if no fault code is present on the control unit display.

Table 9.3 Sperry ADG 3000 VT fault codes and corrective action chart. (Reproduced courtesy of Litton Marine Systems)

Fault message (20 spaces per line)		*Description*	*Corrective action*
(DEVICE B) LOST (See Above)	14	Loss of receiver interrupts for 15 s (when NMEA 0183 device installed on RS-422 port (Channel B))	a. Check source. b. Check wire connection. c. Replace ADS Assembly. d. Replace CPU Assembly.
(DEVICE B) ERROR (See Above)	15	Framing error; invalid message bit format (on RS-422)	a. Check serial channel wire protocol of source. b. Replace ADS Assembly.
(DEVICE B) ERROR (See Above)	16	Overrun error (on RS-422)	a. Check serial channel wire protocol of source. b. Replace ADS Assembly.
(DEVICE B) ERROR (See Above)	17	Loss of transmitter interrupts for 1 s after character sent (on RS-422)	Replace ADS Assembly.
(DEVICE C) ERROR (See Above)	18	Overrun error; input too fast (on RS-232)	a. Check serial channel wire protocol of source. b. Replace ADS Assembly.
CALCON I/O ERROR Frame/Overrun/Noise	18	Framing, overrun, or noise error (if CALCON connected)	a. Check CALCOM cable connection. b. Try running CALCON from a different PC. c. Replace CPU Assembly.
(DEVICE C) ERROR (See Above)	19	Loss of transmitter interrupts for 1 s after character sent (on RS232)	Replace ADS Assembly.
CALCON I/O ERROR Loss of interrupts	19	Loss of transmitter interrupts for 1 second after character sent	a. Check CALCON cable connection. b. Try running CALCON from a different PC. c. Replace CPU Assembly.
SPEED LOG ERROR Enter Manual Speed	40	No VBW/VHW message received for 4 s	a. Check source. b. Check wire connection. c. Replace ADS Assembly. d. Replace CPU Assembly.
SPEED LOG ERROR Enter Manual Speed	41	Invalid format in VBW/VHW sentence	a. Check message string output by the source. b. Check connection. c. Replace ADS Assembly. d. Replace CPU Assembly.
SPEED LOG ERROR Enter Manual Speed	42	Data out of range 1 … XX kts per CALCOM (low speed detected in AUTO/NAV/TRACK modes; others detected always)	a. Check speed log source (log data strings from source). b. Check wire connection speed log. c. Replace DC/DC Assembly. d. Replace CPU Assembly for pulse log.
SPEED LOG ERROR Enter Manual Speed	43	Speed data null or marked invalid	Check speed log source (log data strings from source).
RADIUS DISABLED Log Speed Required	44	Speed setting changed to a manual entry while in RADIUS control	Operator misuse.

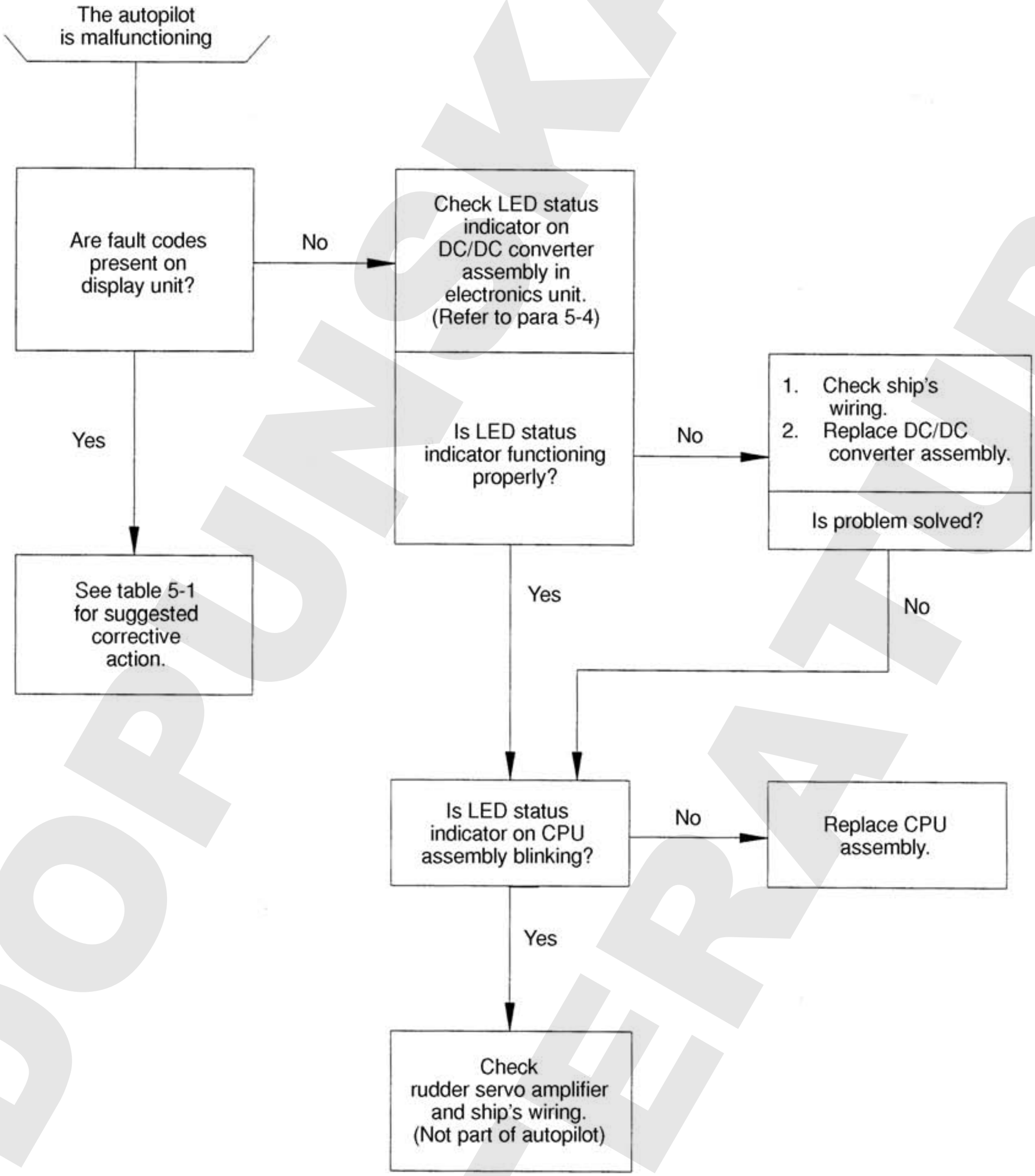

Figure 9.17 Sperry ADG 3000 VT fault logic diagram. (Reproduced courtesy of Litton Marine Systems.)