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DOCUMENT TITLE
AUTOMATIC FLIGHT CONTROL SYSTEMS (CASA ATPL)

CHAPTER 2 – AUTOPILOTS

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INTRODUCTION

Autopilots are designed to maintain the aircraft in the attitude, heading and altitude that is present when the autopilot is turned on or "engaged". This means that once engaged, the autopilot system will detect a deviation from the engaged setting and operate the flight controls automatically to correct the deviation and return the aircraft back to the engaged setting.

The most basic operating principle of an autopilot is to provide Stability Augmentation.

An autopilot is always "live" as long as electrical power is available and is shadowing the aircraft's behaviour so that when the autopilot is "engaged" a smooth transition to automatic flight occurs. A single autopilot may be classified as one of three types:

- Single axis;
- Two axis; and
- Three axis.

Single Axis

This type provides control about the longitudinal axis only, with automatic control of ailerons and is often referred to as a wing leveller. It is typically used in light aircraft only.

Two Axis

In a two axis autopilot control is provided about the longitudinal and lateral axes by ailerons and elevators respectively. These systems are capable of holding a heading and a preset cruising altitude. Commonly used for light medium and older large aircraft approved for IFR flight.

Three Axis

This type is common to all large modern transport aircraft and can provide full control and stability about all three axes, longitudinal, lateral and vertical. This type of autopilot is required for full autoland capability.

Typically, aircraft that have swept wings and operate at higher altitudes are also fitted with a yaw damper system. Yaw dampers provide stabilization about the vertical axis and turn co-ordination in normal flight.

Note that because of the yaw damper system a three axis autopilot does not use the yaw axis in normal flight. However, when an autoland is being conducted the autopilot's yaw axis becomes active to control the rudder and nose wheel steering.

STABILITY AUGMENTATION

Each axis of the autopilot ensures the aircraft attitude about that axis is accurately maintained by using a group of components which form a control and feedback circuit known as the **INNER LOOP**. Refer to Figure 2-1.

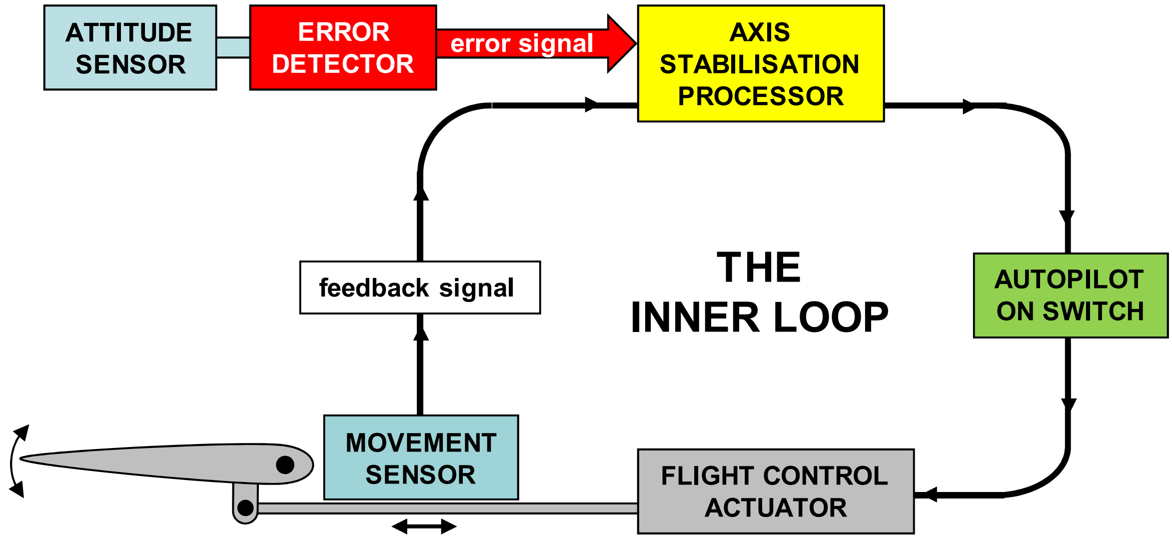

Figure 2-1 The Inner Loop

The process begins with an aerodynamic disturbance causing the aircraft to change attitude.

An attitude sensor, typically a gyroscope, senses a change in attitude which is measured by an error detector.

The error detector translates the attitude change into an electrical signal and sends it to the stabilisation processor.

The processor amplifies the signal and creates a command to move the control surface a certain amount at a certain rate based on the error signal.

The process so far is occuring continuously anytime power is applied to the aircraft so that when the autopilot is turned ON (engaged) the process can continue immediately.

As the control surface moves its travel is measured by a sensor which generates a feedback signal to the processor.

The processor contains a comparator unit which compares the feedback signal with the error signal and when the error signal is cancelled the processor commands the control actuator to return the surface to neutral.

The individual components of the inner loop are made up of the following components:

- Attitude sensor;
- Error detector;
- Stabilisation processor;
- Engagement control;
- Flight control actuator; and
- Movement sensor.

Attitude Sensor

The attitude sensor is essentially a gyro which moves from its stable condition.

In light aircraft the gyro will typically be a **VERTICAL GYRO** for **PITCH** and **ROLL** movement and a **RATE GYRO** for **YAW**. These gyros are primarily fitted for the operation of the flight instruments; however, they can be used to generate error signals for the autopilot.

In larger modern aircraft movement is detected by electronic or laser gyros and accelerometers which are integrated into Inertial Navigation Systems (INS) or Inertial Reference Systems (IRS).

<u>Attitude sensing is achieved by comparing aircraft attitude to a gyroscopic reference.</u>

Error Detector

A type of transducer which converts the physical gyro displacement into an electrical signal.

Stabilisation Processor

This component may also be called the Signal Processor and each axis of the autopilot has one which receives the error signal, amplifies it and creates a command to move the appropriate control surface to correct the error signal received. It must also monitor the feedback to ensure that the required control is moving and the desired effect is being achieved. The computations that take place vary from very simple in an altitude hold situation to very complex in a full multi-mode AFCS. Examples of complex computations are:

- <u>Limiting</u> the amount of parameter change e.g. limiting pitch rate to a specific limit;
- <u>Shaping</u> the computer output so that the required flight path is achieved; and
- <u>Programming</u> using individual processes to cause the aircraft to perform defined manoeuvres.

Modern processors allow the error signal to be modified to cater for the appropriate level of response of soft or firm damping. The processor is always active whenever power is applied to the aircraft and ready to take control smoothly when the autopilot is engaged.

Engagement Control

Each individual autopilot has a switch to engage the autopilot to the flight controls. The engagement switch is always located on the control panel for the autopilot. Certain conditions must be present for successful engagement. These conditions are usually such things as:

- AC and DC power available;
- Flight control computers available;
- Gyros, INS or IRS functioning;
- Yaw dampers on;
- Automatic pitch trim available;
- Air data computer available;
- Hydraulic system press sufficient; and
- Manual flight controls in neutral.

These conditions are monitored by **INTERLOCKS** and when all interlocks are enabled the autopilot can be engaged. At any time any interlock opens due to malfunction the autopilot will disengage automatically.

Only one autopilot is engaged for climb, cruise and descent. All autopilots are engaged for autolanding. Autopilots may be engaged and disengaged by a number of methods. Refer to Figure 2-2.

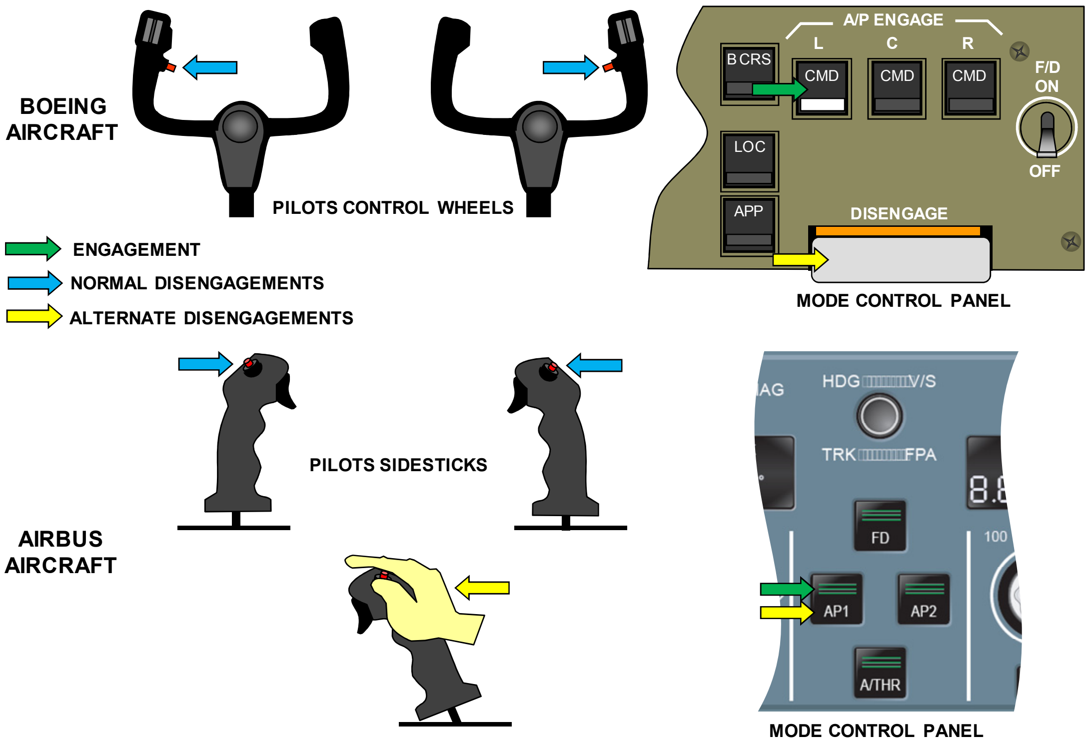

Figure 2-2 Autopilot Engagement and Disengagement

To disengage autopilots several methods are available. The normal method is by switches located on the flying controls so the pilot is able to take immediate manual control of the aircraft. Refer to Figure 2-2.

Alternate methods are provided but these are considered to be NON-normal methods. Refer to Figure 2-2.

Additionally the autopilot may disengage itself for malfunctions or other reasons such as loss of hydraulic system pressure or failed components.

When a normal disengagement occurs the pilot is warned by an alert, typically a wailer on Boeing aircraft and a sound called the “cavalry charge” on Airbus aircraft. A second push of the disengage button cancels the alert.

A NON-normal method is intended as a back-up if the normal method fails to disengage the autopilot. An autopilot runaway malfunction must be controlled quickly.

When a non-normal method or a malfunction disengagement occurs a different warning is annunciated to the pilot.

Servo Mechanism

When an autopilot is fitted to an aircraft with unpowered flying controls a slipping clutch servo motor is used to connect and move the flight controls when the autopilot is engaged. Refer to Figure 2-3.

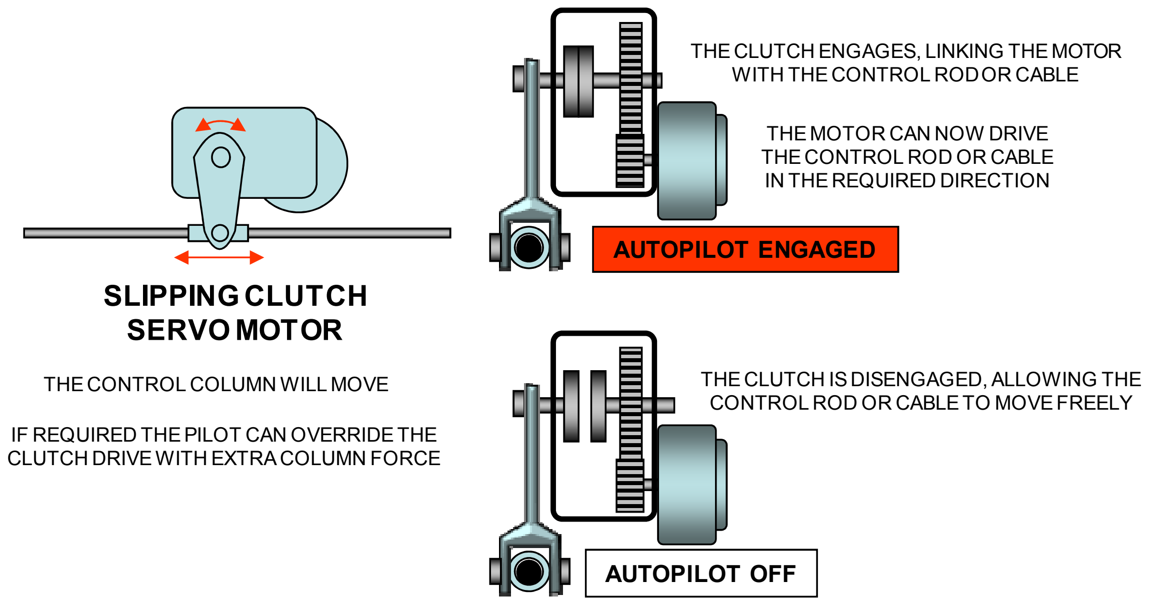

Figure 2-3 Slipping Clutch Servo Motor

Servo Motors can be connected to manual flight control systems in two ways;

Series-connected, which move the control surface without moving the pilots associated control, and

Parallel-connected, which move both the control surface and the pilots associated control.

When an autopilot is fitted to an aircraft with powered traditional flight controls a hydraulic transfer valve mounted on the flight control actuator begins operating when the autopilot is engaged. Refer to Figure 2-4.

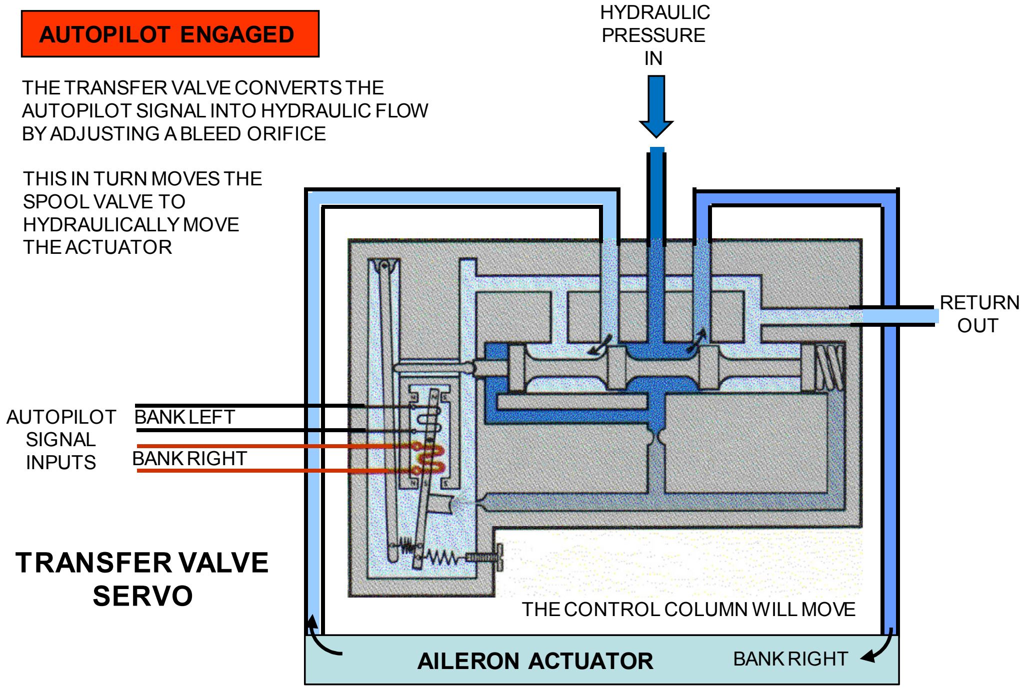

Figure 2-4 Transfer Valve Servo

When an autopilot is fitted to an aircraft with fly by wire flight controls autopilot inputs are sent directly to the flight control computers. Refer to Figure 2-5.

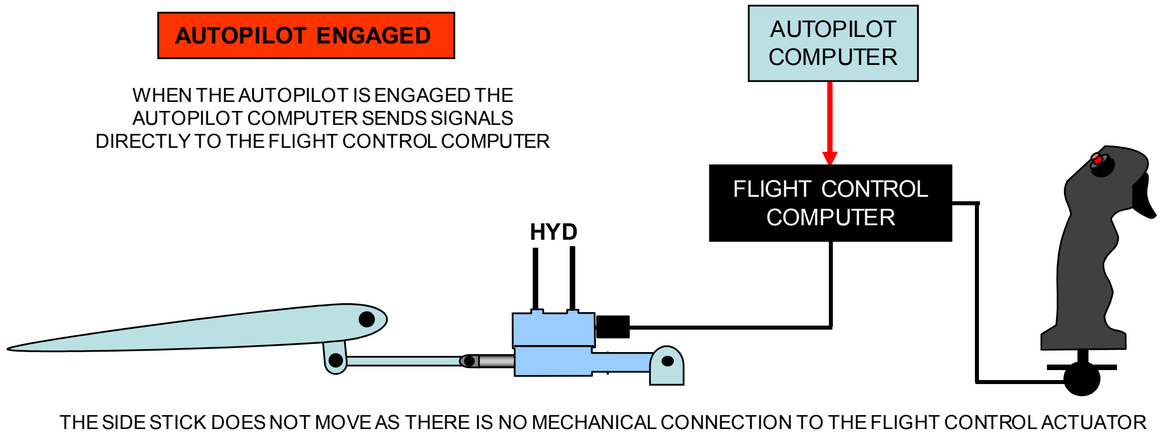

Figure 2-5 Electronic input to Flight Control Computer

Feedback Mechanism

The feedback signal that completes the loop is normally generated by a transducer. A transducer is a general term relating to a device that will convert physical movement into an electrical signal. The transducer is usually mounted at the actuator but may be located anywhere between the actuator and the control surface as long as it is measuring movement of the control surface. The transducer provides both amount and rate of control surface movement. Refer to Figure 2-6.

Figure 2-6 Transducer

Structure Protections

To avoid structural overload caused by sudden or excessive operation of the autopilot, sometimes called a hardover the linkages between the actuators and the flight control surfaces include **TORQUE LIMITERS** which absorb and dampen excessive movement. Refer to Figure 2-7.

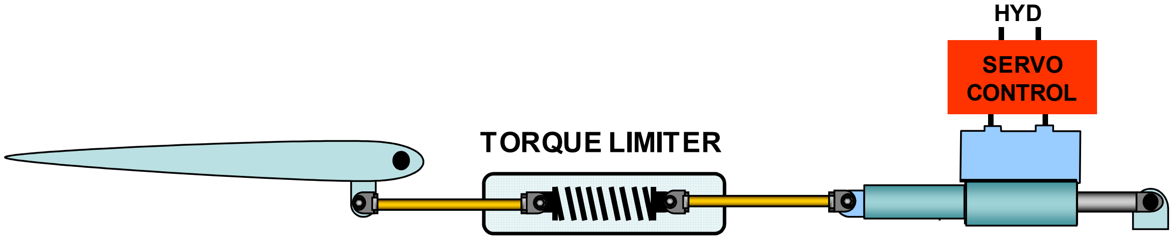

Figure 2-7 Torque Limiter

General Rules Regarding Autopilots

Whilst there are many types of autopilots some general rules that apply are as follows:

- Trim the aircraft before engaging the autopilot;
- When disengaging an autopilot the controls should be held firmly to avoid unintended manoeuvres; and
- All autopilots can be overridden if required by extra control column force.

MANOEUVRE CONTROL

The most basic and the primary function of the autopilot is stability augmentation which is achieved by the "inner loop" previously discussed.

To manoeuvre the aircraft to new headings or altitudes without disengaging the autopilot additional controls are added. These controls allow the manual operation of the pitch and roll axes individually allowing the other to remain automatic. Refer to Figure 2-8.

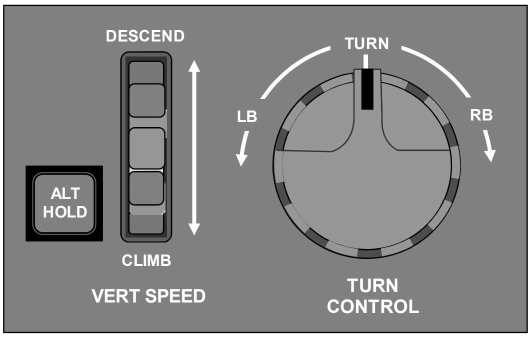

Figure 2-8 Pilot Inputs for Manoeuvre Control

To maintain (hold) altitudes barometric altitude is added as an input. These external inputs of pilot selections and barometric altitude are referred to as the **OUTER LOOP**. Outer loop inputs basically provide new error signals for the "inner loop" to correct. Refer to Figure 2-9.

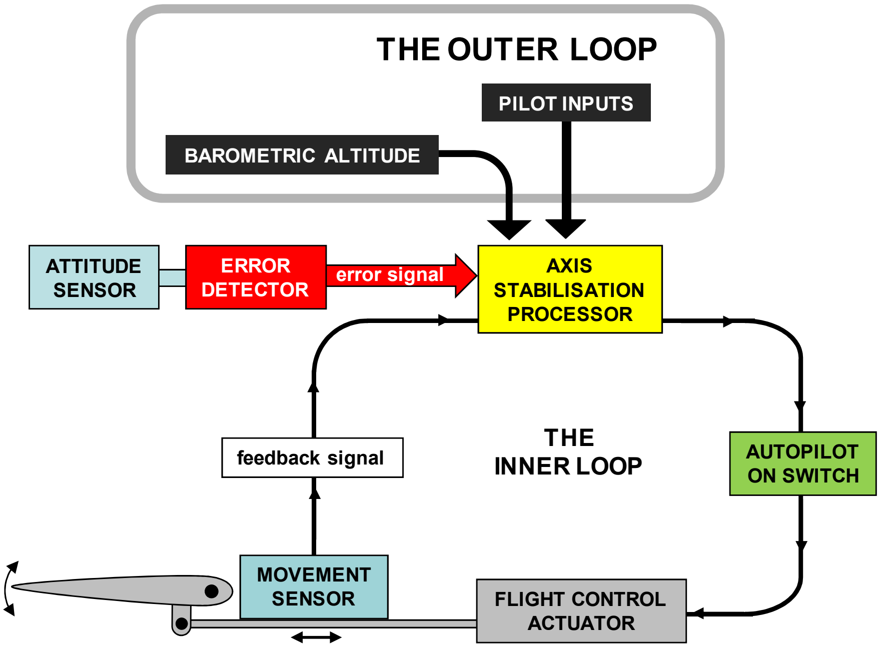

Figure 2-9 The Outer Loop

On complex automatic flight control systems many more outer loop control inputs are provided, increasing the capability of the autopilot to automatically control and navigate the aircraft vertical and laterally in the most efficient manner, with a minimum of pilot intervention.

Typical inputs of a modern system include INS/IRS, Air Data Computers, Flight Management Computers, programmed mode selections and manual inputs. Navigational aids are also entered via the outer loop control and this is often called “autopilot coupling”. Refer to Figure 2-10.

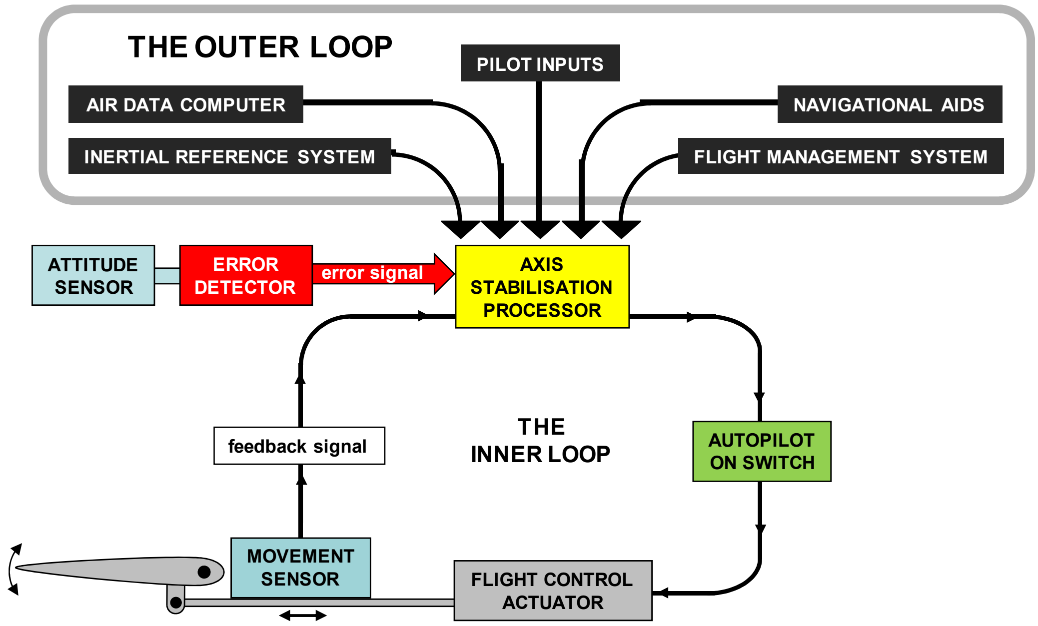

Figure 2-10 Outer Loop Inputs

AUTOPILOT CONFIGURATIONS

Generally speaking there a three levels of autopilot configuration depending on aircraft size and intended capability.

Light Aircraft

Some small aircraft may be fitted with a single autopilot with control about the roll axis only providing lateral stabilisation. The inner control loop receives its input from a gyro sensitive to movement about the aircraft’s longitudinal (roll) axis and whose rate of precession is therefore proportional to rate of roll. The system servo motors will activate the ailerons to correct roll and maintain wings level flight. Outer loop inputs are possible with this type such as change of heading by pilot input and maintenance of track from a radio navigational source. In this configuration the autopilot is referred to as the autopilot.

Medium Transport Aircraft

These aircraft are typically fitted with a single autopilot with control about the roll and pitch axis. Such a system will automatically maintain straight and level flight and usually with the capability to track navigational aids and hold and maintain a selected altitude via the outer loops. Older aircraft such as this were typically limited to climb cruise and descent autopilot use only; however, modern aircraft such as the Dash-8 can perform autolands as well. Depending on the autopilot type and capability in this configuration the autopilot may be called just the autopilot or an automatic flight control system.

Large Transport Aircraft

All large modern transport aircraft are fitted with more than one autopilot for redundancy, specifically for autoland capability. Each autopilot is a three axis autopilot. Each autopilot has an inner and outer loop for each axis. The outer loops are typically coupled to a Flight Management System (FMS).

The Flight Management System can automatically control the autopilot operation to navigate the aircraft in all phases of flight except for take-off in the most economical way if desired.

The Flight Management System receives information from multiple sources including Air Data Computers (ADC), Inertial Reference Systems (IRS) and radio altimeters. It controls the operation of the Flight Directors (FD) for the pilot guidance and Autothrottle (A/T) Systems for thrust control.

This combination of flight management system, autopilots, flight directors and autothrottle is referred to as an automatic flight control system.

This system operates in MODES, some of which are automatic and some selectable. The modes may be relevant only to the autopilot(s), flight directors or autothrottle or may include all.

AUTOPILOT MODES OF OPERATION

Single autopilots in light aircraft and Automatic Flight Control Systems on large aircraft depend on data inputs to operate. In light aircraft limited data can be obtained from instrument gyros and compasses. In some medium and all large aircraft a Central Air Data Computer (CADC) will provide all of the information required for fully automatic operation of the autopilots, flight directors and autothrottle.

The data inputs are “coupled” to the automatic flight controls system to achieve three basic conditions of **HOLD**, **LOCK** and **CAPTURE.**

<u>The data provided by the CADC is sometimes referred to as “manometric” data.</u>

Depending on the type of aircraft and autopilot/AFCS configuration the typical data inputs to the inner and outer loops are as listed below. These inputs translate into the MODE of operation.

Altitude Select, Capture and Hold

A manually selected pressure altitude is fed to the inner loop which compares it to a signal provided by a static pressure capsule in the air data computer via the outer loop. The pitch control inner loop will continuously adjust the elevators to maintain the signals in agreement. This is referred to as a **PITCH** mode and is common to medium and large aircraft. In climbs and descents this mode can be programmed to capture the selected pressure altitude. Some light aircraft may be fitted with this mode.

Airspeed/ Mach Select and Hold

Airspeed is controlled by sensing dynamic pressure. A manually selected airspeed is fed to the pitch control inner loop which is compared by the loop controller to a signal provided by a transducer in the air data computer. At high altitudes the addition of altitude within the air data computer provides a Mach signal for speed control.

In level cruise situations the engine thrust maintains the selected speed via autothottle or manual control but in certain situations involving climb or descent a biasing signal may be applied to the pitch control inner loop to maintain airspeed by pitch control. This would occur in climb with a constant climb thrust set or descent with idle thrust. This mode is referred to as a **PITCH** mode. This pitch control of airspeed is not the same pitch mode as the following Vertical Speed Mode.

Vertical Speed Select and Hold

During climb or descent a constant rate may be required and this can be automatically maintained by input data from the CADC. A reference vertical speed is inserted by the pilot and the CADC compares rate of change of altitude from static pressure sensing with the rate of change of altitude demanded by the pilot. This biases the pitch control loop to maintain a constant rate of change. This mode is referred to as a **PITCH** mode. Obviously thrust must be controlled for vertical speed in climb or descent and this is done by autothrottle or manual control.

Vertical Navigation

In modern aircraft fitted with Flight Management Systems it is possible to compute a climb or descent profile or “path” to satisfy various requirements. These requirements can include maximum rate climbs, maximum speed climbs, optimum profiles in climb or descent whilst automatically satisfying waypoint altitude restrictions. In most situations this <u>single mode</u> can replace the use of the previously described pitch modes. Typically abbreviated as **VNAV** it is a **PITCH** mode. Obviously thrust must be controlled for vertical navigation and this is done in conjunction with the autothrottle system.

Heading Select and Hold

This involves the automatic maintenance of flight on a selected magnetic heading set by the pilot or the flight management system. Heading relates to the roll axis outer loop and is referred to as a **ROLL** mode. Heading reference is from the aircraft’s compass system or in large aircraft the INS/IRS. This mode is common to light, medium and large aircraft.

VOR Capture and Tracking

VOR receiver outputs may also be coupled to the autopilot roll control. In association with steering commands and heading data this will automatically control the lateral flight path in relation to fixed locations on the ground. To avoid the errors which would occur within the VOR’s cone of confusion, an automatic cut-off is activated on entering the cone. Whilst in the cone, the roll control responds only to heading input data. This is referred to as a **ROLL** mode.

Lateral Navigation

In modern aircraft fitted with Flight Management Systems a planned route may be entered, enabling the autopilot to capture and track the route automatically. In most situations this single mode can replace the use of the previously described roll modes. The aircraft position sensing is typically provided by inertial systems, GPS or a multi-sensor system. Typically abbreviated as **LNAV** it is a **ROLL** mode.

Instrument Landing System Capture and Tracking

Localizer only or localizer and glidepath information from the aircraft's ILS receiver comprises the outer loop inputs this aspect of automatic flight. The localizer is intercepted, captured and tracked first, followed by interception and capture of the glideslope from below the glideslope beam. It is possible to on some systems to manually force capture of the glideslope beam from above but this is not normal operation.

When conducting an ILS approach for a transition to a manual landing only one autopilot is required, but when conducting an autoland all autopilots must be engaged. This will involve the **ROLL** modes for the localizer, **PITCH** modes for the glideslope and **YAW** modes for decrabbing and centreline rollout of all autopilots. Most large transport aircraft are fitted with this capability.

Autoland Operation

During approach when the localizer and glideslope modes are armed the radio altimeters begin signal inputs to the autopilots. At approximately 1500 feet with localizer and glideslope beams captured the remaining autopilots are engaged which is the beginning of the autoland sequence. All three autopilots are available to control the aircraft and the **YAW** modes of each autopilot are active. There are two sub-modes that occur within the autoland sequence which are **FLARE,** which is a **PITCH** mode and **ROLLOUT**, which is a **ROLL** mode. These sub-modes are only available during a multi-autopilot autoland sequence. The autoland sequence is discussed in greater detail in Chapter 5.

Go-Around Operation

Fully automatic go-around is normally performed with multi-autopilot operation from the autoland sequence, but a single autopilot go-around can also be made. Go-around mode is armed and ready for use from the point when glideslope is captured until just after touchdown. A go-around will involve the **ROLL** and **PITCH** modes of the autopilot(s). Go-around operation is discussed in greater detail in Chapter 5.

AUTOPILOT CONTROL

Depending on the aircraft's autopilot or automatic flight control configuration many of the modes described previously are selected manually by the pilot or automatically by the flight management computer. As autopilot systems have developed over time the methods of control have varied to suit the intended capability of the aircraft.

In light aircraft the typical autopilot is a single axis type referred to as a "wing leveller" and will have a single engage/disengage control. In most cases however inputs from the directional gyro or compass system allow the autopilot to maintain a set heading.

If fitted with a two axis autopilot, altitude hold and vertical speed will also have controls. These manual controls allow the pilot to control the autopilot whilst it remains engaged rather than disengaging the autopilot. This type of autopilot when fitted to older large transport aircraft could be coupled to navigational aids to follow VOR radials or localizer tracks. Refer to Figure 2-11.

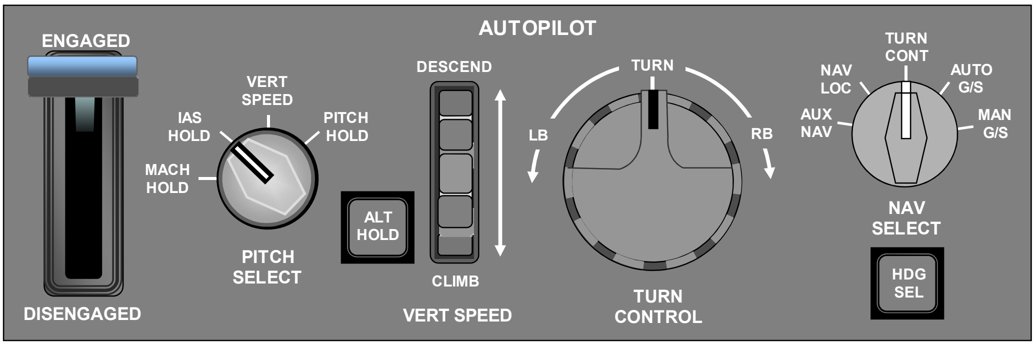

Figure 2-11 Older type of autopilot controls

Medium and large aircraft can be roughly divided into four methods of autopilot control as follows;

Manual and Command Controls

Typically found on older large aircraft these autopilots had a two position (MANUAL or COMMAND engagement switch. When selected to Manual the autopilot is engaged but the aircraft may be steered manually using a turn controller or pitched manually using a pitch wheel. When selected to Command the autopilot may be coupled to radio aids for lateral navigation, air data computers for altitude captures and localiser and glideslope beams for ILS approaches. Aircraft fitted with two or three of these types of autopilot along with a flight director and autothrottle system could begin to descend to lower and lower decision heights and conduct autolands. The B747 Classic is an example aircraft.

Control Wheel Steering (CWS)

Also typically found on older large aircraft but still in use on some modern aircraft, Control Wheel Steering operates on the principle that when the pilot physically moves the control wheel in roll or pitch the autopilot disengages that axis until the pilot force is relaxed at which time it reengages at the new attitude. Pressure sensitive switches are located within the control wheel to trigger this action. CWS can still be part of a modern Automatic Flight Control System. Control wheel steering is used on the B737-800 AFCS. Refer to Figure 2-12.

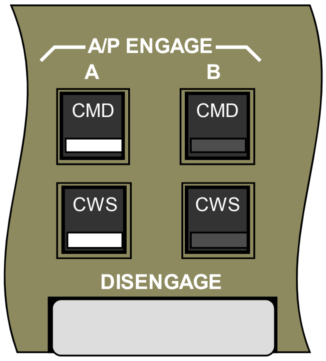

Figure 2-12 Control Wheel Steering Control

Touch Wheel Steering (TWS)

Similar to Control Wheel Steering is Touch Wheel Steering which uses the same principle but the pilot has to touch (push and hold) a button on the control wheel to disengage the axis as he adjusts the aircraft to the new attitude. Releasing the button reengages the autopilot axis.

Another name for this system is **Tactile Control Steering (TCS)**.These systems are fitted to some medium size aircraft such as the Embraer 145 (TWS) and De Havilland Dash 8 (TCS). Refer to Figure 2-13.

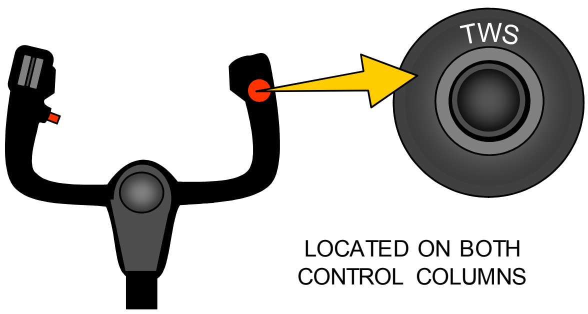

Figure 2-13 Touch Wheel Steering Control

A Modern Automatic Flight Control System

Modern large aircraft are all fitted with Flight Management Systems and Automatic Flight Control Systems. Many of the modes are controlled by the FMS for the most efficient operation and automatic navigation. Some modes have to be selected at certain points on the flight profile and some modes may be selected at any time for manual steering or pitch control. The AFDS used in the B767 is an example of this type of system and we will focus on this aircraft in this textbook.

AUTOPILOT MODES AND STATUS

Modes

The autopilot operates in PITCH, ROLL and YAW modes. Some modes are selectable and some operate automatically.

Some modes may be ARMED for automatic engagement or ARMED for pilot engagement. When a mode is ARMED it is ready to engage and when a mode is ENGAGED it is active and controlling the aircraft.

<u>Only one pitch mode can be engaged at a time and only one roll mode can be engaged at a time, however, a pitch or roll mode may be engaged with another pitch or roll mode armed simultaneously</u>.

Mode Status

In older analog aircraft the operating mode status was observed on small discrete annunciators or simply by observing the selected switches. Typically the autopilot engage switch was of such a design that it was easy to see if it was engaged and in command of the aircraft.

With the introduction of the electronic instruments the autopilot status and the autopilot mode status is displayed at the top of the EADI or Primary Flight Display (PFD). The standardised colours used for <u>modern mode status</u> display are **WHITE** for ARMED and **GREEN** for ENGAGED. Refer to Figure 2-14.

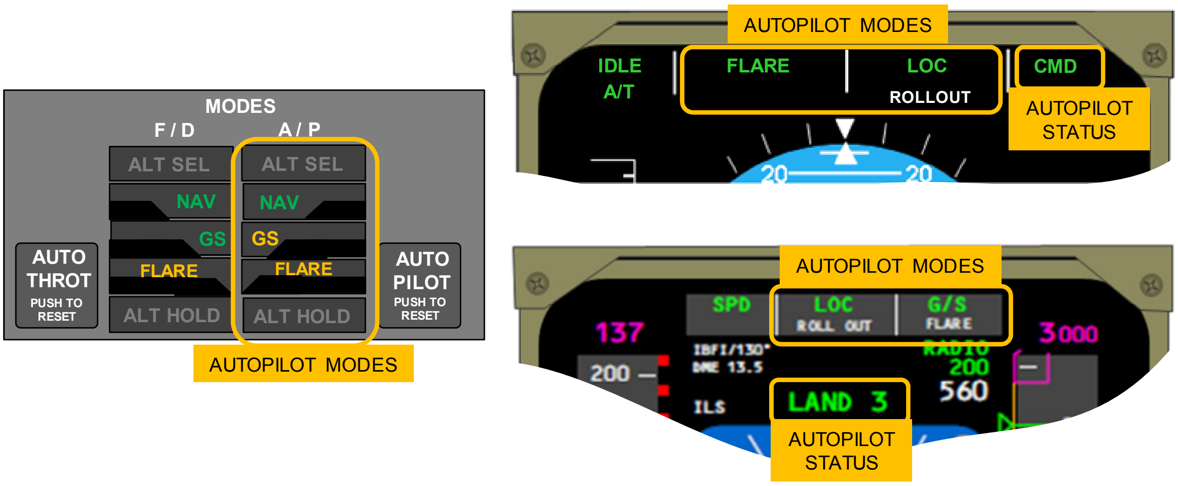

Figure 2-14 Autopilot Status Displays

Typically on a modern system the autopilot modes that may be **ARMED or ENGAGED** by the pilot with switches on the Mode Control Panel (MCP) are:

- Localizer (LOC) a roll mode;
- Approach (APP) - ARMS or ENGAGES localizer and glideslope, pitch/roll modes;
- Vertical Navigation (VNAV) a pitch mode; and
- Lateral Navigation (LNAV) a roll mode.

Modes that are ARMED or ENGAGED automatically are:

- Altitude Capture (ALT CAP) a pitch mode;
- Glideslope (G/S) – ARMED by Approach selection, a pitch mode;
- Flare (FLARE), a pitch mode; and
- Rollout (ROLLOUT) a roll mode.

Some modes can only be **ENGAGED** by the pilot with switches on the Mode Control Panel (MCP). They are:

- Heading select (HDG SEL) a roll mode;
- Heading Hold (HDG HOLD) a roll mode;
- Vertical Speed (V/S) a pitch mode; and
- Altitude Hold (ALT HLD) a pitch mode.

Refer to Figure 2-15.

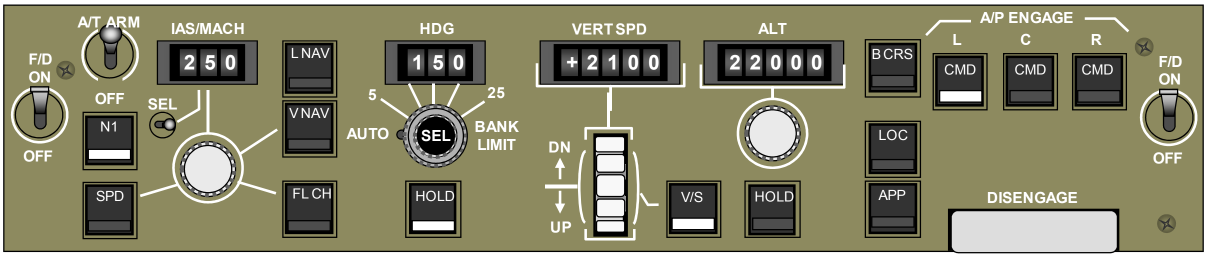

Figure 2-15 Modern Mode Control Panel

One last autopilot mode is Go-around (G/A); pitch/roll modes, which are typically **ARMED** automatically and if required, **ENGAGED** by the pilot using switches remotely located at the thrust levers.

Other selections that can be made from this panel include autothrottle modes which will be discussed in Chapter 4 Autothrottle

AUTOPILOT REDUNDANCY

Aircraft that are capable of autoland must have multiple autopilots for redundancy during this critical phase of flight. Some aircraft such as the B767 and B747-400 have three independent autopilots whilst others have only two such as the B777 and Airbus.

The typical operation of an aircraft with multiple autopilots is as follows:

- Only ONE autopilot is engaged for normal autoflight except for autolanding when ALL are engaged.
- The ONE autopilot that is engaged is on the same side as the pilot flying; LH when the Captain is flying the sector and RH when the F/O is flying.
- The Centre autopilot, if fitted, is an alternate is case the others have failed.
- At the beginning of an autoland sequence the remaining autopilots are engaged for redundancy during the autoland operation.

Some single autopilots are designed to have multiple sub-autopilots within its component structure, thus providing an alternate method of redundancy.

A single 3 axis autopilot is called a SIMPLEX autopilot and some aircraft are fitted with three simplex autopilots for full autoland capability. This may be referred to as a “multiplex’ configuration.

Some autopilots are designed with 2 fully independent LANES for each axis thus doubling the redundancy in a single autopilot. This is called a DUPLEX autopilot which provides full autoland capability with only two autopilots. This may also be referred to as a “multiplex” configuration.

The term **CHANNEL** is often used in relation to autopilots and it can be interpreted in two ways. Some manufacturers call each axis of the autopilot a channel therefore a single three axis (simplex) autopilot is said to be a “three channel” autopilot. Other manufacturers refer to the individual autopilot as a channel of the AFCS so a B767 can be said to have a three channel automatic flight control system

Autopilot redundancy is also usually supported hydraulically and electrically. Refer to Figure 2-16.

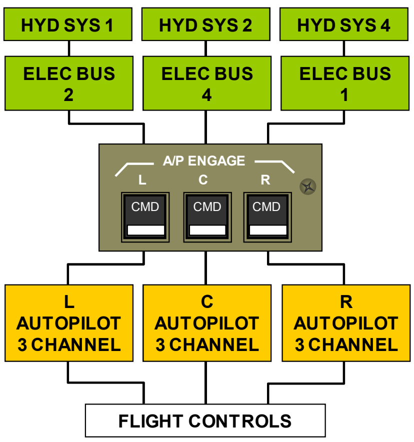

Figure 2-16 Hydraulic and Electrical Redundancy

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