Autopilot — Installation Manual

Kanardia d.o.o.

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Contact Information

Publisher and producer:
Kanardia d.o.o.
Lopata 24a
SI-3000
Slovenia

Tel: +386 40 190 951
Email: info@kanardia.eu

A lot of useful and recent information can be also found on the Internet. See `http://www.kanardia.eu` for more details.

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Revision History

The following table shows the revision history of this document.

Revision	Date	Description
1.0	Aug 2015	Initial release.
1.1	Maj 2016	Tuning notes were added.
1.2	Jul 2016	Tuning table expanded.
2.0	Feb 2020	Complete Manual rework.
2.1	Nov 2020	Updated for changes in software version 3.8, Amigo and Nesis/Aetos windows.
2.2	Jan 2021	Updated for changes in software version 3.9.

Contents

1   Introduction

First of all, we would like to thank you for purchasing our product.

This chapter describes the basic principle on which autopilot operates. After reading it, you will be familiar with basic knowledge you will need to properly install and tune the autopilot.

CAUTION: The autopilot is not TSO approved as a flight instrument.

1.1   Designations

A few icons appear on the side of the manual, which have special meanings:

This icon denotes information that needs to be taken with special attention.

This icon denotes background information about the subject.

This icon denotes a tip.

In the text, `Shall` & `Should` appear frequently.

`Shall` . . . the use of this term indicates a requirement!

`Should` . . . the use of this term indicates a characteristics that is not required, but it is highly recommended.

1.2   Intended Use

The autopilot is designed to help a pilot in stable, controllable flight conditions during cruising. If such conditions are met, the autopilot can be engaged to take some relief from the pilot, who can perhaps focus a bit more on ATC communication or to do some navigation task. Nevertheless, it is still pilot's responsibility to monitor the autopilot and airplane behavior all the time.

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1.3   Operation Limitations

Always respect the following limitations.

- The autopilot shall be only used in VFR (Visual Flying Rules) conditions.

- Information from the Aircraft Operating Handbook always supersedes information given in this manual.

- The autopilot is designed to be used only in cruising conditions. It will not work at low and high speeds. It can't fly approaches and departures and it can't do takeoffs and landings.

- The autopilot shall not be used in turbulence.

- Do not use the autopilot with flaps extended.

- In any case of abnormal activity, the autopilot must be deactivated and the pilot must take over the commands immediately. Never wait for autopilot to deactivate itself automatically.

- Autopilot does not use any information from Magu (magnetic compass).

1.4   Minimal Configuration

Most modern light airplanes can be controlled during a stable flight by controlling elevator and aileron only. An autopilot function can be achieved using the following minimum configuration:

- Two servo motors that are mechanically connected with the airplane command system. One motor controls elevator and the other controls aileron.

- An AD-AHRS-GPS device which consists of many sensors and provides crucial information required by the autopilot system (airspeed, rate of climb, pitch, roll, position, direction, altitude, etc.) Such device is inside one of our PDF instruments, for example, Nesis PFD, Aetos PFD, Horis PFD or Emsis PFD.

- A display unit takes pilot inputs like required altitude and direction. It is also used to enter configuration parameters required to properly setup the autopilot system.

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- A servo motor controller. It monitors the pilot instructions and information obtained from the sensors and controls the servo motor accordingly.

- A communication system that connects all devices and allow information exchange in real time.

In Kanardia autopilot case, there are two different solutions for an autopilot minimal system.

1.4.1   Nesis/Aetos Based Minimal System

When Nesis or Aetos is used as a base, the following minimal equipment is required for a fully functional autopilot:

- Two SERU servo motors. SERU consists of a servo motor and an integrated controlling unit, which serves as a motor driver. One SERU controls elevator and the other controls aileron.

- Nesis III (or Aetos) PFD. The display has integrated AD-AHRS-GPS device, which provides all sensor data. The display has several buttons and a knob that allow pilot control over the system. In addition, touch screen can be also used on Nesis III.

- Simple RJ45 cables (a.k.a. Ethernet cables) are needed to connect them together. The devices are communicating using the CAN bus system, which is integral part of almost all Kanardia devices.

In this combination Amigo is optional, but recomended nevertheless.

1.4.2   Horis/Emsis Based Minimal System

When Horis or Emsis is used as a base, the following minimal equipment is required for a functional autopilot:

- Two SERU servo motors. SERU consists of a servo motor and an integrated controlling unit, which serves as a motor driver. One SERU controls elevator and the other controls aileron.

- Horis 80/57 (or Emsis 80/3.5") PFD unit with integrated AD-AHRS-GPS device, which provides all sensor data.

- Amigo display, which acts as a command panel for the autopilot.

- Simple RJ45 cables (a.k.a. Ethernet cables) are needed to connect them together. The devices are communicating using the CAN bus system, which is integral part of almost all Kanardia devices.

In this combination, Amigo is essential.

1.5 Principle of Operation

When autopilot is active, pilot selects requested altitude, direction and rate of climb or descend. AD-AHRS-GPS device provides current values for almost all flight parameters. Controller units compare the requested values with actual values and give appropriate commands to the servo motors. The PID controller principle is used together with the cascade control system.

The autopilot drives two separate controls: aileron and elevator. In general these two controls are independent, though minor dependency may exists.

Each control has two control loops[1]. Elevator control has pitch loop and vertical speed loop. The two loops are regulated by cascade. This means that requested altitude sets wanted vertical speed and the vertical speed loop sets wanted pitch. The pitch loop then controls the elevator by minimizing the difference between requested and actual pitch. Aileron works in a similar way. Requested direction sets the required roll angle and the roll loop controls the aileron trying to minimize the difference between requested and actual roll angle.

This means that autopilot has four loops: *pitch* and *vertical speed* loops are used for elevator, while *heading* and *roll* loops are used for aileron. All these loops must be properly tuned to achieve requested autopilot operation. Various experimental values in the form of tuning parameters are provided at the end of the document. These values represent good starting point for first autopilot tests.

2 Mechanical Installation

This section provides information about the installation of autopilot servo motors (the SERU device) into an airplane. It contains important rules which

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[1] The control loop is basic term from control theory. In simple terms – the control loop tries to move the actuator in such a way that difference between WANTED and ACTUAL value becomes minimal.

must be obeyed to have a working and safe autopilot system. The installation information in this section is extremely important and must be clearly understood by the installer.

Improper servo installation or failure to observe and diagnose installation problems prior to flight can result in extremely serious consequences, including loss of ability to control the aircraft. If there are any questions on the part of the installer it is mandatory to resolve these questions prior to flight of the aircraft.

> CAUTION: Improper installation could result in lost aircraft controls, injury or death!

2.1   Servo Motor

The servo motor must be installed in a fixed position. It must be attached with all four mounting screws. The motor mount should be provided by aircraft manufacturer and has to be adapted to specific airplane model. The motor should be oriented parallel with longer edge regarding control rod connected to the servo arm. The servo schematics is given in Figure 1. It defines three important elements:

① Safety pin,

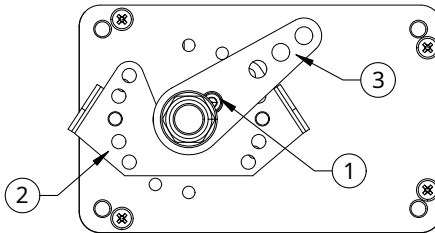② Arm movement limiter,

③ Arm.

Figure 1: Safety pin, limiter and arm.

2.2   Servo Arm

Servo arm has multiple holes for mounting control rod, Figure 2. Choose the hole which maximize the arm rotation. The hole center radius are 28, 34 and 40 mm from the rotation center. Assuming ideal arm rotation of -60°to +60°with neutral position at 0°, this allows for 48.5, 58.9 and 69.3 mm of ideal command rod travel respectively. In practice, command rod travel will be shorter. Namely, ideal mounting position is usually not ideal and full arm rotation is seldom achievable. Some experimentation is required.
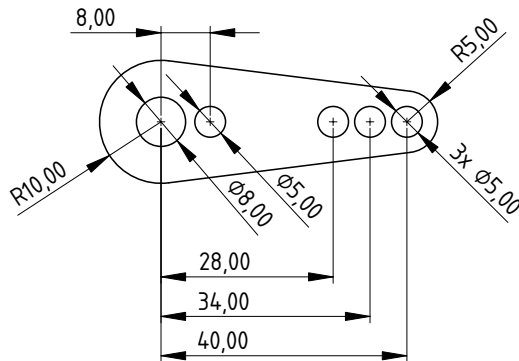
Figure 2: Position of holes.

Servo arm should not be removed or replaced without Kanardia advise. The removal of servo arm includes removal of safety pin. Please contact Kanardia before replacing safety pin for latest instructions.
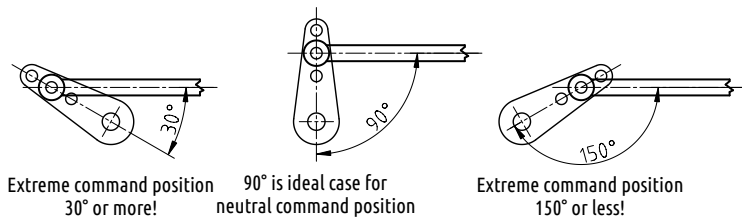
Figure 3: Main servo dimensions.

Figure 3 illustrates valid relative positions between command rod and servo arm. When command is in neutral position, the angle between rod and arm shall be 90° or at least very close to this ideal case. When command is in

its extreme position the angle between the command rod and the arm must never be more than 150° or less then 30°.

Under no circumstances the servo arm is allowed to come into position called *over center* – the position at which the primary aircraft control would lock up and will result in a fatal crash. A mechanical stop must be applied to prevent this to happening. Mechanical stops must limit the arm movement at least 30° before the over center situation.

2.3   Servo Arm Limiter

To protect against control lock up, a mechanical arm limiter is supplied with servo. The limiter is drilled so that it can be mounted at different angles as required (18° intervals).

The limiter must not prevent aircraft command movements. Always make sure that the controls can have their full travel and they never reach the servo limiter.

2.4   Servo Arm Safety Pin

Safety pin is a safety mechanism which prevents blocking of the aircraft command system for the case of blocked servo motor. If servo blocks the command system, pilot must apply high force on the command stick. This force will break the pin and release the servo from command system. Once the pin is broken, the autopilot system is not operational until the pin is replaced.

If safety pin is broken or it gets slack the whole autopilot system must be checked. Only after the cause of the problem was found and corrected, safety pin can be replaced with a new pin. Always use original safety pin.

The safety pin is made from high grade steel (metric grade 12.9) and it is intentionally weaken to break at specific torque applied on servo arm. The pin should sustain 10 Nm occasional torque without any pin damage. This is slightly above the max torque of 6 Nm provided by the servo motor (or 3 Nm of the smaller servo). The nominal break torque is estimated at 14.3 Nm, the plastic deformation torque is estimated at 12.9 Nm (permanent damage in the pin).

The airplane command system must be capable to withstand the forces in the command system required to break the safety pin.

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3 Electrical Installation

Servo motor has two electrical connections. The first one provides power for the electrical motor and the second one connects controlling device with the CAN bus. (The controlling device is hidden inside the servo motor).

3.1 Electrical Power

The autopilot servo motor must be connected to a 12 V DC standard aircraft power source. It is also possible to use 24 V DC power. The maximum current consumption for one servo motor is 1.5 A (at 12 V). Always protect servos with an automatic/replaceable fuse and a switch. The fuse protects against over-current and the switch allows quick disconnect by taking power from the motor. Figure 4 shows typical connection.
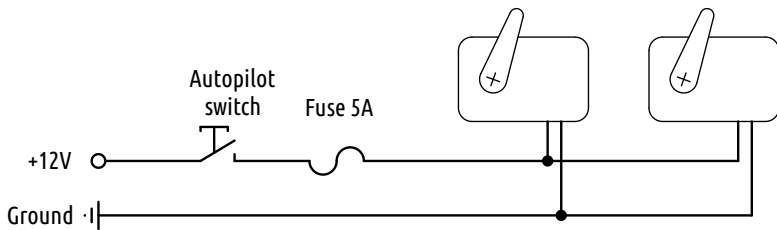
Figure 4: Typical connection of servo motor electrical power.

The *autopilot switch* must be easily accessible by the pilot. The pilot must be able to reach it in any moment.

3.2 CAN Bus

Servo motor must also be connected to the CAN bus. The controller module is built in the servo housing. The controller exchanges the information over the CAN bus. In addition, CAN bus is also used to power the controller. This means that controller works even when servo motors are without power.

Figure 5 shows CAN bus connections for the minimal autopilot configuration. In reality more devices can be connected to the CAN bus. The CAN bus goes trough Nesis or Aetos, where it is internally connected to AD-AHRS-GPS module. On the servo side, T junction is needed and a short connection is made from T to the servo controller.

Figure 5: Typical CAN bus connection for Nesis/Aetos based minimal autopilot configuration.

Please note that CAN bus must be terminated with a 120 Ohm terminator on both ends of the main line. Terminators are not shown on Figure 5.

3.3   External Push Button

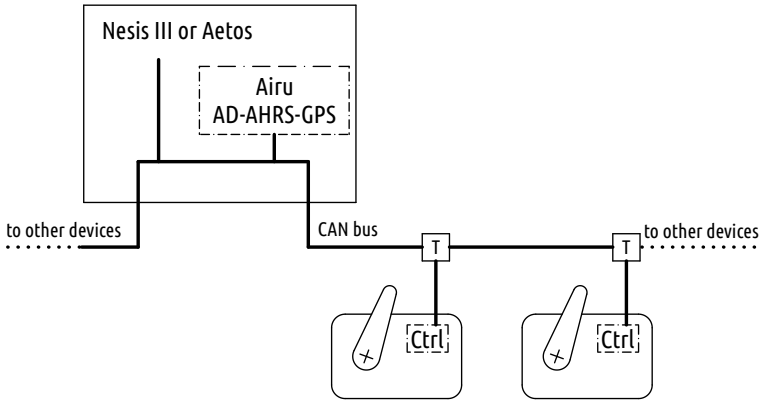It is advisable to install an external push button, which allows for quick autopilot disconnect and level commands. The push button shall be installed on the command stick, where it is easily accessed by pilot. Two wires from the push button must be connected to the Nesis/Aetos service port or to Amigo auxiliary port. The connection details are given in the Nesis/Aetos installation or in Amigo manual, see the *External Push Button* section.

3.3.1   Autopilot Quick Disconnect

Nesis/Aetos must be then configured to react on the push button event. When the button is pushed, the autopilot disconnect command is sent via CAN bus to both servo controllers, which will cut power of both servo motors.

In the case of Amigo, no configuration is necessary.

3.3.2   Autopilot Level

The same button can be used also used for the autopilot level command. This command will activate Track Hold mode for aileron and Altitude Hold mode

for elevator.

In the case of Nesis/Aetos, this function must be configured. In the case of Amigo, it is activated by a long press on the external button. No configuration is necessary.

3.4 Joyu Command Stick

Alternatively, Joyu command stick can be also used. Joyu has multiple programmable buttons and one or more of its buttons can be assigned to operate the autopilot.

Short press on the button should be used for autopilot disconnect and long press for the autopilot level function.

Please see the Joyu manual for more details.

4 Configuration

For the autopilot to operate properly, controllers inside the servo motors must be configured. Once the configuration is complete, the whole system must be also tuned. In general, tuning is needed for every airplane. In most cases airplanes of the same type may use the same autopilot configuration if autopilot mechanical installation is identical.

Any accidental change of any of parameters in this section and subsections may result of autopilot being inoperative.

4.1 Overview

These configuration and tuning can be done either with Nesis/Aetos or with Amigo. This section includes several figures. Each figure illustrates Nesis/Aetos solution on the left and Amigo solution in the right.

If you have both Nesis/Aetos and Amigo, do not use the Autopilot configuration or tuning on both instruments at the same time. Use either Nesis/Aetos or Amigo.

Next steps reveal typical workflow:

1. Configure both servos. Each servo has several parameters that must be set properly. Its function (what it moves – ailerons or elevator) and movement direction are two examples.

2. Ground test is performed. It tells weather servos are moving commands (elevator and ailerons) in correct directions.

3. Autopilot operation limits are set. They define an envelope of values, which must be met for AP to operate. This is a very important safety feature.

4. Autopilot controller parameters are set. Most of them can be set on the ground, but some must be adjusted during flight tests.

5. Autopilot is tuned, which is the most difficult part. This can be performed only in flight. Several controller values must be determined.

First three steps shall be set on the ground. Most of the fourth step can be also set on the ground, but may be necessary to change some of parameters during the flight test. Final step can be only done in flight.

Section 7 reveals the workflow for airplanes where autopilot parameters are already known.

4.2 Autopilot Settings

Please refer also to the Nesis/Aetos or Amigo manual.

In Nesis/Aetos, the settings are accessible from `Service options` page in the display. Special password (provided with the instrument) must be entered to access the Service options page. The password can be also found under the `Info` icon.

In Amigo, press and hold the ALT knob and then select the `Autopilot` from the menu.

Figure 6 shows the main autopilot settings menu. Nesis/Aetos version is on the left and the Amigo version is on the right. This pattern repeats throughout this section.

The menu items follow the logic from the workflow:

`Servo config` is used to configure servo motors. Section 4.2.1 reveals the details.

`Ground test` is used to make sure that servos are correctly moving the controls. See section 4.2.2.

`Limits` is used to define valid operation envelope of the autopilot, section 4.2.3.
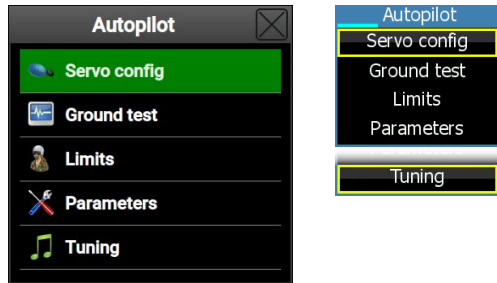
Figure 6: Main autopilot settings menu.

Parameters is used to define various controller parameters, section 4.2.4.

Tuning is an in-flight operation used to setup PID terms of the controller loops for the elevator and aileron. See section 5.5.

4.2.1 Servo Configuration

When setting up an autopilot, configuring the servos is the first step. Two servos are required: one for elevator and the other for ailerons. A servo can perform either role. Each servo has its own serial number.

During the mechanical installation, write down the serial number of the servo which was connected to aileron and the serial number of the servo used for elevator.

Select the servo to configure. A selection example is shown on Figure 7.

Figure 7: An example of servo selection based on serial number.

Once serial number is selected a window with servo details opens, Figure 8.

The servo configuration window defines following parameters:

Function must match the servo mechanical connection. If servo with given serial number is connected to the aileron, then the function must also
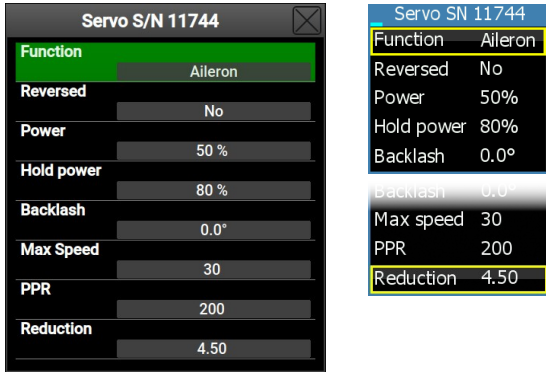
Figure 8: An example of servo settings window.

be `Aileron`. Change the function if necessary. You can choose between `Aileron` or `Elevator`.

`Reversed` has values `No` or `Yes`. Choosing correct value is a guessing game. Start with `No` and if ground test, described in section 4.2.2 fails, change it to `Yes` and vice versa.

`Power` defines how much power (=torque) shall be used by servo when moving its arm. 100% means total servo capacity. Try to avoid using more than 90% due to possible servo overheating. This also depends where and how servo is installed. In long term, try to find the lowest value, which still provides enough torque.

`Holding power` defines how much power is used when motor is not moving. This value depends on the power value above. If it is set to 50% this means that motor will use 50% of the torque set with the power parameter. For example, if power is set to 70% and holding power is set to 50%, the motor will use 35% of maximal power (torque) at standstill.

`Backlash` defines the amount of command system *free* travel, which is a combination of free play and elastic command resistance. It is given in degrees of servo arm movement. In ideal circumstances this shall be zero, but this is seldom the case.

`Max speed` is the maximal speed of servo arm movement in degrees per second. This value is usually set between 10 and 30 deg/s.

PPR   tells how many pulses are needed for one rotation of internal stepper
        motor (always 200 for current servos). This is servo motor characteris-
        tics and shall not be changed.

Reduction is the gearbox reduction factor between the arm and stepper mo-
        tor. (This factor is 4.57 for recent servos. But factors between 4 and
        5 are also in use.) This is servo motor characteristics and shall not be
        changed.

In general, PPR, Reduction and Max speed shall not be changed and original
values shall be kept. Change them only if Kanardia support team approves
the changes.

4.2.2   Ground Test

The ground test is used to check correct servo motor movement. Figure 9
illustrates available options.
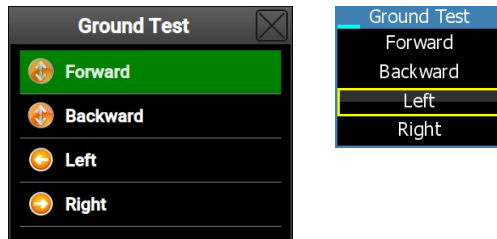
Figure 9: Ground test movement options.

Forward shall move the command stick slightly forward (nose down). Make
         sure that command stick is not fully forward before this command is
         issued.

Backward shall move the command stick slightly backward.

Left   shall move command stick slightly to the left.

Right   shall move command stick slightly to the right.

You can issue the same command several times in the row.

In many cases the weight of elevator control pulls stick forward on the ground.
Servo is probably not strong enough to overcome this weight. In this case, hold

the stick gently in the neutral position and execute the `Forward/Backward` commands. You will feel servo movement in your hand.

If a movement appears in wrong direction, go back to the `Servo Config` and toggle the `Reversed` option.

If servo moves a wrong command, go back to the `Servo Config` and modifiy the `Function`. Check both servos.

Do not start tuning until you are 100% sure that ground test works correctly.

4.2.3   Operation Limits

Autopilot is allowed to operate only when the airplane is within operating limits of approved autopilot use.

The limits shall be defined by the airplane producer. These autopilot limits are much, much stricter than airplane capabilities. The limits are set around stable, coordinated flight at the economy cruise speed.

As soon as any parameter goes out of the limits, autopilot will be disconnected.

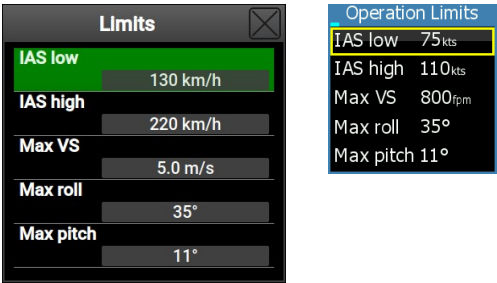Figure 10: An example of autopilot operation limits.

The following limits must be set:

`IAS low` ... set this slightly below the economy cruising speed. This shall be significantly more that the stall speed. In fact, this should be set above VFE.

`IAS high` ... set this slightly above the economy cruising speed. This shall be significantly less than VNE.

`Max VS` ... set maximal allowed rate of climb or descent.

`Max roll` . . . maximal allowed roll for autopilot operation. Set this to 35° or less.

`Max pitch` . . . maximal allowed pitch for autopilot operation. Set this to 12° or less.

⚠️ All limits must be checked with a flight test after the tuning has been completed. The limits must be set conservatively. Make any adjustments with great care.

⚠️ Flying with the autopilot at a slow speeds is not allowed. It would be extremely dangerous. The dynamic characteristics of the airplane at low speed can be completely different from the characteristics at cruising speed.

⚠️ Flying with the autopilot at high speeds is not allowed. It would be extremely dangerous. The dynamic characteristics of the airplane at high speed can be completely different from the characteristics at cruising speed.

4.2.4   Controller Parameters

This window defines various parameters that are required for optimal operation. Some of these values can be only determined during flight test. Figure 11 illustrates an example.
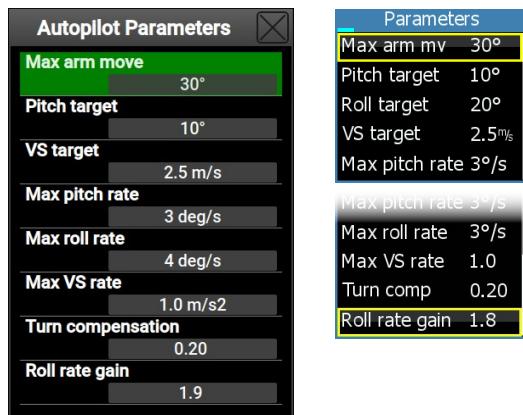

Figure 11: An example of autopilot parameters.

`Max arm mv` defines maximal servo arm movement and is used to detect servo slip condition. When autopilot is engaged, servo remembers its arm position and treats this as a zero angle. During operation servo monitors

virtual relative angle regarding the zero angle. If this virtual relative angle exceeds the `Max arm mv` value, the system reports a *Motor slip error*. Namely, servo does not measure angle directly, but it is counting steps from *zero* position. If motor is slipping (servo torque is too small) these counts will accumulate to a number (virtual angle) large enough to trigger the error. Due to slips, the arm did not move that much in reality.

`Pitch target` this is the maximal pitch angle that controller will require for a climb or a descent. This angle shall be smaller than max pitch from the limits, section 4.2.3.

`Roll target` is the maximal roll that can autopilot require in order to change direction. This angle shall be smaller than max roll from the limits, section 4.2.3.

`VS target` is the target vertical speed, when change in the elevation is required. This speed shall be smaller than max vertical speed from the limits, section 4.2.3.

`Max pitch rate` tells how quickly pitch reference can change. Controller loops are calculated several times per second and they change their *desired* pitch all the time. If the outer loop – vertical speed control loop asks for a quick change in pitch, the controller will limit the speed of change to the value entered here. The airplane will therefore make a smooth transition.

`Max roll rate` tells how quickly roll reference can change. Same as above, but now for the roll angle. If the outer loop – heading control loop asks for a quick change in roll, the controller will limit the speed of change to the value entered here. The airplane will therefore make a smooth transition.

`Max VS rate` is the rate of change of the target vertical speed (it has dimension of acceleration). Similar as above, but now for vertical speed.

`Turn comp` defines amount of elevator compensation that is required when airplane is executing a turn. Pitch will be slightly increased during the turn. The increase grows with the roll angle.

`Roll rate gain` Value 0.9 is special and it means that Roll rate gain mode is disabled.

4.2.5 Tuning

Tuning is a in-flight operation. This operation is quite complex and is based on *trial and error*. Here only window description is given. Please refer to the section 5.5 for details about the tuning procedure.

conducted on a clear, VFR day. Before commencing the flight test, ensure that you have adequate altitude, enough fuel, clear weather, no traffic, no obstructions in the flight path, great visibility, no airspace conflicts, etc.

When the `Tuning` option is selected from the Autopilot menu, a window illustrated on Figure 12 appears. Select one of four autopilot control loops to tune.
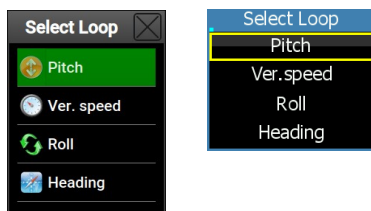
Figure 12: Selection of an autopilot control loop.

Once loop was selected, a tune window appears. This window allows changing the PID controller parameters and observing the response at the same time. Figure 13 illustrates the example.

Figure 13: An example of roll loop tuning window.

The `Ref.` represents the loop target value. The target value is changed and airplane response is observed in the chart. The target is drawn in magenta color and the response is in yellow.

`P`, `I` and `D` terms are controller terms. The controller tries to reduce an error between a target (magenta) value and an actual value (yellow). Error is a difference between target and actual value.

`P term` defines controller's proportional (gain) part.

`I term` defines controller's integral (cumulative) part.
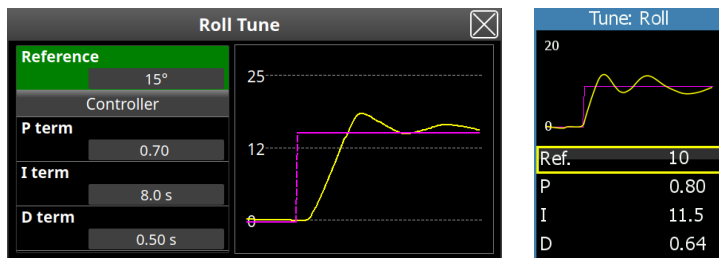
`D term` defines controller's derivative (rate of change) part.

5 Tuning

Each autopilot must be taught how to fly a plane. This is done during tuning procedure. The following section provides you with a necessary knowledge how to properly tune the aircraft autopilot.

The tuning of the autopilot is based on trial and error method. The operator has to gain knowledge and experience. It will take time and it is possible that more than one flight is needed to complete this task properly.

5.1 Controller

The controller is a system which monitors the process and calculate the required output of the actuator to keep the process variable within a set range. Autopilot actuators are motors which moves aircraft control surfaces and process is aircraft which is monitored with multiple different sensors.

5.1.1 PID controller

The Kanardia autopilot is using standard `PID` controllers. A `PID` controller is control loop mechanism employing feedback of controlling parameter. A `PID` controller continuously calculates an error value as the difference between a desired reference and a measured process variable (roll, pitch, VS and heading). It applies a correction based on proportional, integral, and derivative terms (denoted `P`, `I`, and `D` respectively). During tuning the operator is searching for optimal terms inside each loop: roll, pitch, vertical speed and heading.

`P term` a.k.a *gain* defines controller's proportional part. For example, if error is large and positive, the controller output will be also proportionately large and positive.

Unfortunately the P term is bad in removing small errors and here `I-term` comes into play.

`I term` is the integration time of the controller. It tells how fast the controller is trying to eliminate the steady-state error. The more error persists, the larger will be its time integral and consequently, the larger will be integral contribution.

`D term` is an estimate of the future trend of the error. It is based on the rate of error change. The more rapid the error change, the greater the controlling or dampening effect.

Typical block representation of the controller with feedback is shown on figure 14. The input to `PID` controller is the difference between reference and measured process value. Output of the controller must control the process to reduce the difference. Controller performance depends heavily on the accuracy of the sensed process variable and the precision of the actuator.
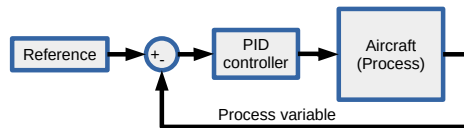
Figure 14: Typical PID controller block diagram.

If you are interested in PID controller, a good start may be the Wikipedia article, `https://en.wikipedia.org/wiki/PID_controller`.

5.2   Step Change and Response

Controller tuning is an iterative process. The operator triggers a step change of the reference value for each loop observing the aircraft response. Based on the aircraft response the terms of the controller are modified to get optimal ones. Analysis of response needs few technical terms which are explained with a figure 15:

1. Reference step change.

2. Overshoot.

3. Steady-state error - remaining error.

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Figure 15: Step response of closed loop system.

4. Response time - 90% of reference step.

5. Oscillations.

5.3   Cascade Controller
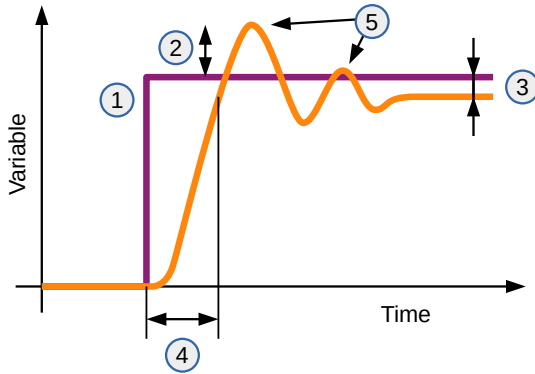
The main problem of the aircraft control is the fact that the aircraft is a complex process. We have to control at least elevator and ailerons. For each one we are using a cascade control system.

A cascade control involves the use of two controllers. The output of the first controller provides the reference for the second controller.

The example of cascade PID controller for an elevator is shown on figure 16. Note that there are two feedback loops and two controllers. Inner controller is controlling pitch of the aircraft and outer is controlling its vertical speed.
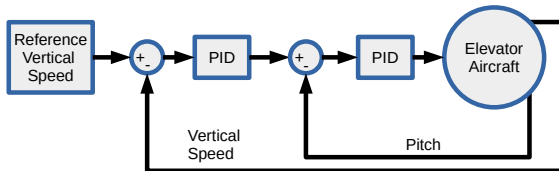

Figure 16: Elevator cascade PID controller block diagram.

The important fact of this system is that outer loop response depends on the performance of the inner control loop. This means that inner control must be

tuned first and the response of the inside loop must be good enough.

5.4 Controller Problems

The PID controller is very robust but sometimes the tuning does not provide any usable results. There are two major problems which influence the control loop behavior: mechanical backlash and motor slip.

5.4.1 Backlash

is lost motion between the servo motor and the control surface. It has a negative impact on control loop performance. Mainly it results in constant and stable oscillation of aircraft around a problematic axis.

In this case it is best if the backlash in commands is removed. This needs some study where and why the backlash is present. However sometimes this is not doable without serious redesigning the autopilot mechanical linkage. Also it is possible that there is elastic backlash present.

In those cases we provided software backlash compensation. This means that on each servo motor reversal of the direction the motor moves for pre-specified angle. This angle is specified in the servo config dialogue specified in section 4.2.1.

5.4.2 Slip

When the momentum on the motor arm is too large the motor will slip. Slipping motor is unable to control the aircraft. Resolve slip issues on either axis before proceeding, either by increasing motor torque, changing hole on control arm or switching to a larger servo. If the motor is slipping there are no software options.

You can notice the slipping as a sudden small jump of the stick. The most common behavior of the aircraft with one of the servos slipping is that aircraft suddenly starts a turn and is unable to correct it.

5.5 Tuning Procedure

The tuning of the autopilot requires a ground preparation and a flight testing.

5.5.1   On-Ground

Before first flight the operator shall enter appropriate initial values for the autopilot, as described in section 7. The `P-term` of control loops shall be slightly smaller than `P-term` for similar aircraft. `I-term` shall be set to 30.0s and `D-term` to 0.0. Also the motor test shall be done.

AD-AHRS unit inside Horis, Emsis, Aetos or Nesis used for autopilot control must be leveled. When in level flight at desired cruising speed it shall show zero bank and pitch angles.

5.5.2   In-Flight

The flight test should be conducted on a calm, VFR day. Before commencing the in-flight tuning, ensure that you are at the safe altitude, you have enough fuel, clear weather, no traffic, no obstructions in the flight path, good visibility, no airspace conflicts, etc.

It is highly recommended that you bring someone along on the autopilot test flight. At many points the pilot's attention will be divided between documentation, tuning autopilot, and maintaining situational awareness. An extra pair of eyes looking out is very helpful.

5.6   Tuning Rules

The operator should follow following rules during in-flight tuning and testing the autopilot:

- Make notes during flight.

- Change only one parameter or term at once.

- Make small changes of parameters ot terms.

- Test every parameter change multiple times.

- Always tune `P-term` first, next `I-term` , last `D-term` .

- Keep `D-term` small - max. 1/10th of a `I-term` .

- `I-term` of inner loop shall be smaller than `I-term` of outer loop.

6   In-Flight Tuning

Kanardia autopilot system uses two-axis control: elevator and aileron. The tuning of autopilot is divided into two independent tasks. The operator shall tune the elevator control first and then move to aileron control tuning.

Please note that during the tuning of the elevator the pilot is responsible to maintain roll angle of the aircraft and take care for direction as well. When tuning ailerons the autopilot will already keep control over elevator. Therefore it is a bit more difficult to tune the elevator.
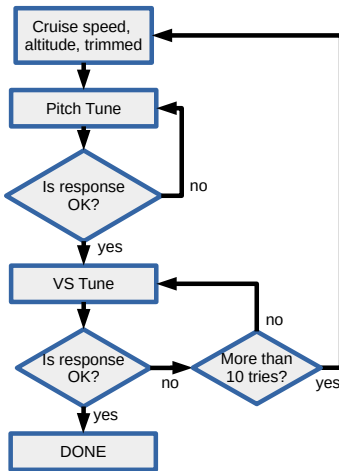
6.1   Elevator

Figure 17: Elevator tune.

Elevator control consist of two cascaded control loops: pitch and vertical speed. The operator shall tune the pitch loop first. Without properly operating pitch loop the VS loop is impossible to tune.

During in-flight tuning the elevator will be controlled by the autopilot servo. The pilot shall maintain aircraft leveled with ailerons during the elevator tuning but it shall not move the elevator control.

When tuning the VS loop there is a chance that operator can not get any meaningful response. If this happens operator shall disengage autopilot and re-trim aircraft and then proceed with a tuning. The usual cause of VS loop malfunction is the bad pitch loop performance. The operator should re-tune the pitch loop before proceeding. It is also possible that one of fundamental controller problems is present. Please see section 5.4 and resolve the issues first.

6.1.1   Pitch tuning

When reaching target altitude and cruising speed make sure the aircraft is trimmed properly for a level flight. The operator shall enter the Tune dialog for pitch loop as shown in figure 13. By default the autopilot servo motor is in disengaged state. The autopilot engages every time the operator selects new *Reference* value and disengages every time the operator changes any of the P-, I- or D- term.

We provided a real tuning procedure example on figure 18. We choose 0.45 for initial `P-term` . Then we gradually increased the `P-term` by 0.2 until we reach satisfactory response. There should be small overshoot present and the servo motor should quickly react to the pitch reference change. Before every step change set reference to 0° and wait for the aircraft to stabilize. Follow provided flow charts for tuning each controller term.

P-term   shall be tuned following flow chart shown in figure 6.1.1. Start with low `P-term` and then gradually increasing it, until you reach satisfactory response.

1. Set 0 degrees reference angle.

2. Steady state - Wait enough time for controller to stabilize. Around 10 seconds usually is enough.

3. Step change - Change reference angle by 3-5 degrees. This depends on aircraft. In our example we choose 4 degrees.

4. Observe - Wait 10-15 seconds.

5. P-term - Depending on the aircraft response we have to modify the `P-term` . Please see example tuning on figure 18 for example responses and appropriate actions.

6. Repeat - Go back to step 1.
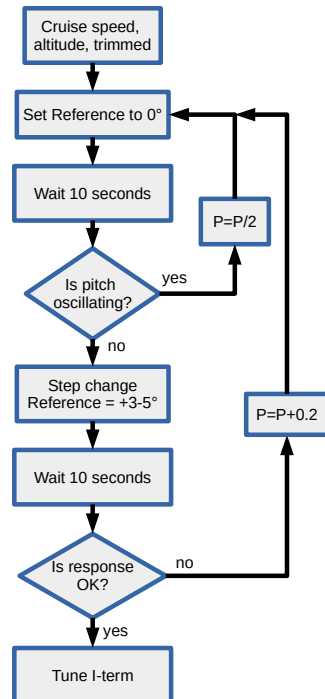
I-term shall be set to start value. Tune it following flow chart shown in figure 6.1.1. Start with high `I-term` and then gradually decrease it, until you reach satisfactory response.

I-term will add some oscillations, do not worry about this for now. The `D-term` should damp it enough. If you get too much overshoot or too much oscillations it is possible that you have basic control loop problems as described in 5.4.
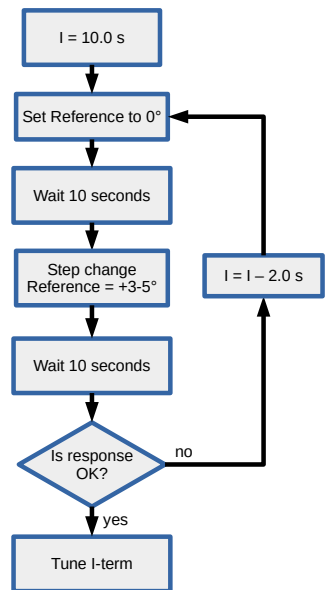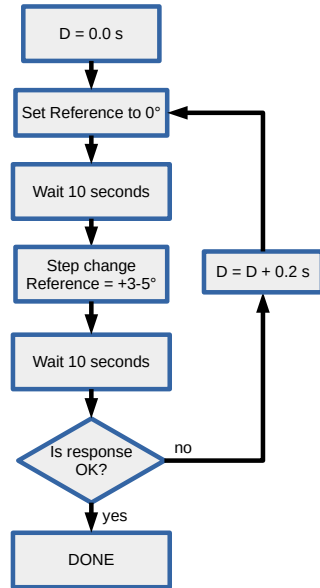
1. Set 0 degrees reference angle.

2. Steady state - Wait enough time for controller to stabilize. Around 10 seconds usually is enough.

3. Step change - Change reference angle by 3-5 degrees. This depends on aircraft. In our example we choose 4 degrees.

4. Observe the response - Wait approx. 10-15 seconds.

5. Modify the `I-term` according on the aircraft response. Please see example tuning on figure 18 for example responses and appropriate actions. If you would like to decrease the response time `I-term` should be decreased.

6. Repeat - Go back to step 1.

D-term start value shall be set to 0.1s. Then it should be gradually increased, until you reach satisfactory response. The maximum `D-term` should not exceed 1/5th of a controller `I-term` . To tune `D-term` of the pitch control loop follow flow chart shown in figure 6.1.1.

1. Set 0 degrees reference angle.

2. Steady state - Wait enough time for controller to stabilize. Around 10 seconds usually is enough.

3. Step change - Change reference angle by 3-5 degrees. This depends on aircraft. In our example we choose 4 degrees.

4. Observe - Wait approx. 10-15 seconds.

5. D-term - Depending on the aircraft response we have to modify the `D-term` . Please see example tuning on figure 18 for example responses and appropriate actions. If you would like to increase damping you should increase the value of `D-term` .

6. Repeat - Go back to step 1.

```
D = 0.0 s
   ↓
Set Reference to 0°  ←───────┐
   ↓                          │
Wait 10 seconds               │
   ↓                          │
Step change          D = D + 0.2 s
Reference = +3-5°             ↑
   ↓                          │
Wait 10 seconds               │
   ↓                   no      │
Is response ─────────────────┘
OK?
   ↓ yes
DONE
```

**Testing**   After successful tuning of pitch loop the operator shall test the pitch loop with different reference angles. The aircraft response shall be with small overshoot and without oscillations.

Be aware that setting excessive reference pitch angle values will cause that aircraft will pitch up or down quickly. Depending on the aerodynamics of the aircraft the airspeed can change quickly. Keep the aircraft within safe limits.
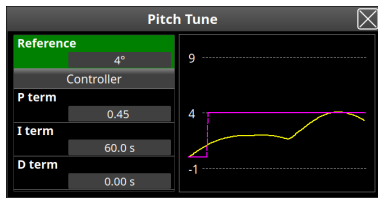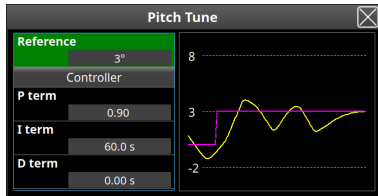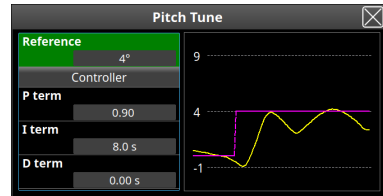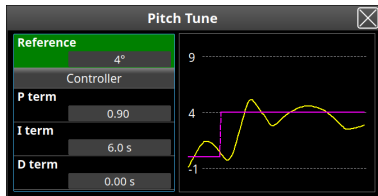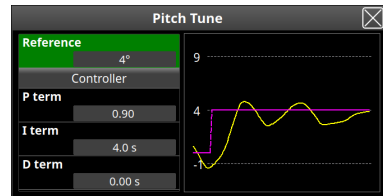
(a) P too low.
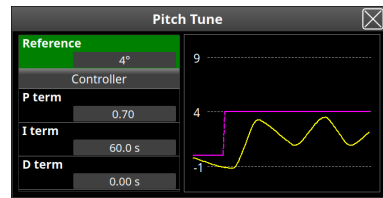
(b) P still too low.
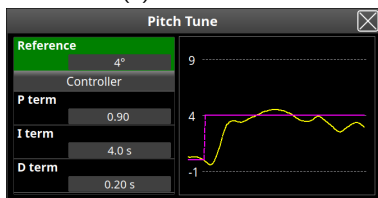

(c) P ok - Small overshoot.
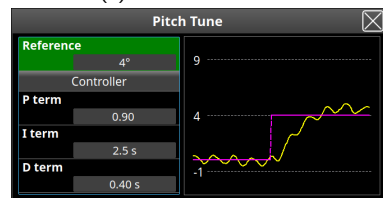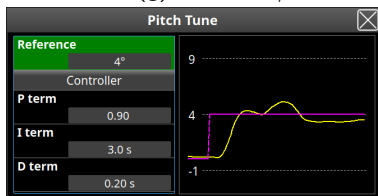

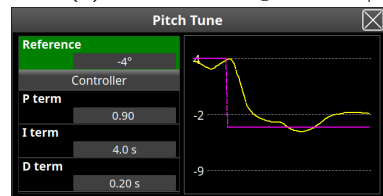(d) Start I for pitch is 8s.

(e) Lower I - better.

(f) Lower I - even better.

(g) Add D=I/20.

(h) D-term too big ... D=D/2.

(i) Decrease I slightly - DONE.

(j) Test also in minus

Figure 18: Example of pitch tuning process.

6.1.2 Vertical speed tune

In software version 3.9 we have implemented new autopilot control system for vertical speed. The tests on multiple aircrafts have shown that the vertical speed control is much better with new system than with PID controller. The new system does not use PID control therefore no tuning is necessary. We call it *compensated* because it automatically compensates the changes of aircraft angle of attack.

However the autopilot will use old control system if the autopilot was tunned with older software. After upgrade to version 3.9 no change in autopilot behaviour is expected.

If you are using software version 3.8 or older please see version 2.1 of this manual.

Switching between old and new control is possible. This is done through Vertical Speed Tuning dialog. To use new control system the user must select maximum value for D-term. When maximum value is selected the dialog will show value *Compensated*. Now the system will use new control system and other two values - P-term and I term are ignored.

6.2 Aileron tune

With properly operating elevator autopilot it is much easier to tune the remaining aileron axis. For aileron axis we have to tune two control loops: roll and heading.

6.2.1 Roll tune

There are two major operating modes for roll loop. The operator can select between modes by setting the roll rate gain parameter. If it is set to "Disabled" the roll loop is controlling the roll angle directly with the `PID` controller. If the roll rate gain parameter is set to any other value the roll controller will operate in roll-rate mode.

The older tuning method with disabled roll rate gain is not recommended for new installations. In this manual we will describe only the tuning with the roll rate controller.

Roll rate gain   tells controller the factor to calculate the desired roll rate from the roll angle error. If this parameter is set to 1.0 this means that autopilot will try to correct the error of 5° with an roll rate of 5°/s. For start it should be set to 1.0. This value is fine for most installations.

P-term   With Roll rate gain parameter set to 1.0 we are now tuning the roll rate and not the roll angle. For this you will notice dashed lines in tuning dialog which marks the selected Maximum Roll Rate parameter. Before first tuning we should set this parameter to the default safe value of 5°/s.

We start tuning with a low value for `P-term` . On our example on Figure 19 we started with `P-term` of 0.5. Note that `I-term` is set to a bit lower starting value of 10.0s. The `P-term` is then gradually increased to obtain fast enough response without oscillations.

I-term   When tuning the `I-term` the starting value should be around 10-12s. After setting the `P-term` we can try to decrease `I-term` to improve response, but we should never get to a response with oscillations. If this happens the `I-term` shall be increased by at least 2.0s.

D-term   shall be always set to 0 in roll-rate-gain mode.

6.2.2   Heading tune

If the roll control loop is operating properly the tuning of the heading loop is usually simple. However the operator must check that response of the aircraft is good enough under operating all conditions. The starting values for `P-term` shall be 1.0 and `I-term` 25.0s. The step angle for testing the controller response should be 10° larger than selected *Target Roll Angle.*

P-term   should be set to 1.0 as a starting point. After step change it should be increased if the response of the aircraft heading is too slow. The usual `P-term` values range from 1.0 to 1.8.

I-term   is used to improve the time needed to eliminate steady-state error. The `I-term` should be set in between 15.0s and 25.0s. Decreasing the `I-term` will decrease the time needed to establish new heading. At the same time it is possible that low enough `I-term` will cause the overshoot of the reference

(a) P way too low.

(b) P still too low.

(c) P still too low.

(d) P is now just enough.

(e) Start value for I.

(f) Lower I - oscilations - go-back.

(g) Test into other direction.
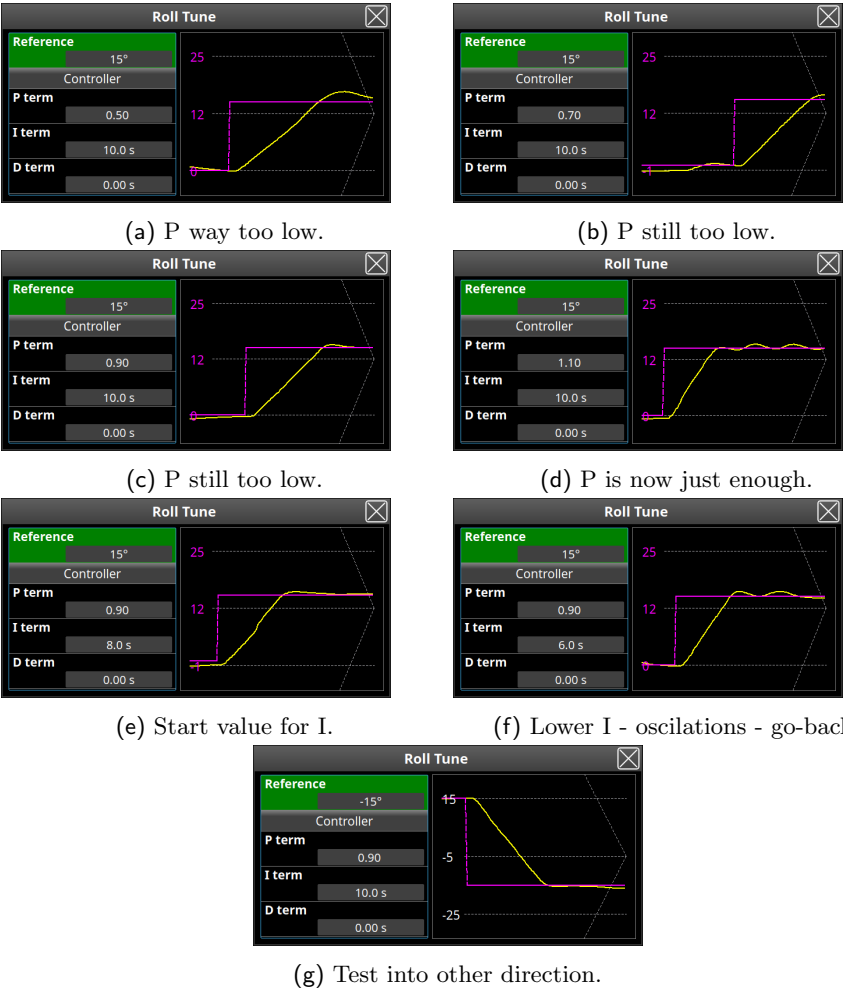
Figure 19: Example of roll rate tuning process.

heading. This is usually undesired behaviour. In this case we should increase the I-term .

Test for overshoot shall be done also for small changes of reference heading. Try to test with small step change of 5°. If there is too much overshoot increase the I-term .

D-term   shall remain set 0.0
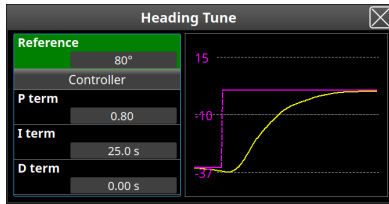
(a) P way too low.
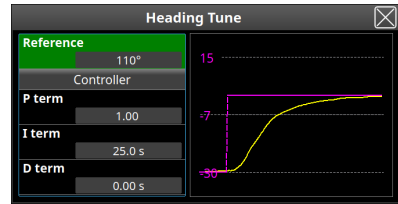
(b) P still too low.
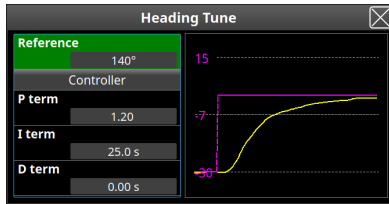
(c) P still too low.
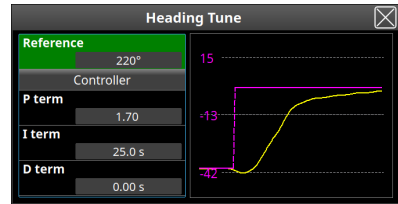
(d) P is now just enough.
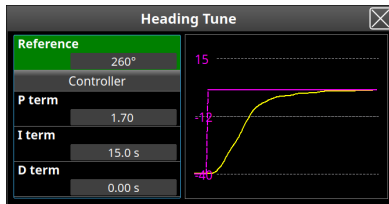
(e) Start value for I.
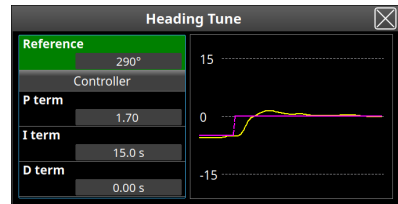
(f) Test small angle.

Figure 20: Example of heading tuning process.

6.3   Fine tuning

There are some parameters that should be adjusted after the basic tuning is done. This parameters will improve autopilot performance.

6.3.1   Roll feed forward

This parameter sets how much the elevator control is pulled or pushed during the turn. When initiating the turn observe the pitch of the aircraft. If it dives when initiating turn and climbs when finishing it you have to increase Roll

feed forward parameter. For most ultra-light aircraft's it should be around 0.2 and 0.3.

For start it should be set to 0.1. Now with autopilot in level mode change autopilot heading. If the aircraft still dives when initiating turn you should increase the this parameter by 0.1 and re test. Repeat this two steps until you find a value which is applicable for your aircraft.

6.3.2   Motor power

If the stick is very hard to overcome the torque of the motor the torque of the appropriate axis should be lowered. This will reduce the current consumption of the motor and it will reduce the motor heating. Also the pilot will be able to override the autopilot with more appropriate force.

7   Quick Configuration

This is a quick reminder of Nesis/Aetos commands inputs required to configure the autopilot system for a know airplane.

7.1   Configure Servos

Define which servo is used for elevator and which for aileron. Write down their serial numbers.

Now configure the motor as *elevator* or as *aileron*. Other values are:

- Reversed - select `Yes` or `No` depending on the results of the *Direction Test*.

- Power: 80%

- Holding power: 80%

- Backlash: 0

- Max speed: 10°/s

- PPR : 200

- Ratio: 4.5

7.2   Direction Test

Options ⇒Service Mode ⇒Autopilot ⇒Test.

Press move forward, backward, left, right. The yoke/stick should move in the correct direction. If the movement is opposite, change the `Reversed` parameter in Servo Configuration.

7.3   Operating Limits

Options ⇒Service Mode ⇒Autopilot ⇒Limits.

- Minimum IAS: 140 km/h

- Maximum IAS: 200 km/h

- Maximum vario: 6 m/s

- Maximum Roll: 30°

- Maximum Pitch: 12°

Values shown above are given for example only – use appropriate limits for your airplane. If the aircraft exceeds this limits the autopilot will disengage immediately and the reason will be shown on the display.

7.4   Tuning

Enter values from tables given in section B.
Options ⇒Service Mode ⇒Autopilot ⇒Tune and then:

- Pitch ⇒Manual tune,

- Vario ⇒Manual Tune,

- Roll ⇒Manual Tune,

- Heading ⇒Manual Tune

Please fill the report from appendinx A once the installation and tuning is complete and send the form to Kanardia. The form is needed for future references and maintenance purposes.

8   Safety Measures

Autopilot system is not terrain or traffic aware and it will not make any avoidance action or issue any terrain warning!

The autopilot is directly linked with aircraft commands thus it presents high risk if something fails or goes wrong. Kanardia autopilot is using following safety measures in order to reduce this risk to a minimum.

- Automatic disable when aircraft is outside safe operating limits.
- Multiple Manual disable options.
- Servo power switch immediately cuts the power of servo motors.
- Motor override – the servo motor can be safely overridden, but the commands are jerky.
- Safety pin will break if the motor or gears inside are mechanically blocked.
- Mechanical limiter limits the movement of the motor lever preventing mechanical lock-up.

The servomotors are designed to be over-driven with external force from command stick with no damage.

8.1   Automatic Disable

The Autopilot will disengage automatically and immediately when any of the following values is out of the range:

- minimum autopilot IAS,
- maximum autopilot IAS,
- maximum autopilot vertical speed,
- maximum autopilot roll angle,
- maximum autopilot pitch angle.

These values must be configured correctly and they depend on the type and performance of the aircraft. See section 4.2.3 for limit details.

8.2   Manual Disable

The following ways may be used to disable autopilot system manually:

1. Select the *Disable* option from the autopilot menu of Nesis/Aetos.

2. On Nesis/Aetos, press the *User* button when the autopilot menu is active (double click on user button).

3. On Nesis/Aetos, make a long press on the *User* button – the long press function must be properly configured.

4. When an external push button is installed on a command stick, press the button to disable the autopilot. Nesis/Aetos or Amigo must be properly configured.

5. When *Joyu* is connected to the CAN bus and its buttons are properly configured, press (or long press) the corresponding button on Joyu.

6. When *Amigo* is connected to the CAN bus, press the top knob to disconnect aileron servo and bottom knob to disconnect the elevator servo.

7. On Nesis only, make a long touch on autopilot status window.

8.3   Electrical Disable

The autopilot motors are disconnected as soon as power supply is removed. Therefore it is essential that the power to the servo motors can be cut with removable fuse or with a separate switch. See section 3.1 for more details.

8.4   Mechanical Disable

The servo motor torque is small enough that it can be overridden by higher force in the command stick even when servo is operating with 100% torque. However, the commands feel jerky and precise steering is a bit challenging.

Safety pin is the inserted between the servo arm and the servo motor shaft. In the very unlikely case of blocked motor or blocked gears, pilot can use force on the command stick, which will break the pin and release servo motor shaft from the command system.

A   Autopilot Installation And Tuning Form

Date		Airplane/Type	
Customer		Registration	
Performed by		Signature	

Servo motor settings

Setting	Elevator	Aileron	Setting	Elevator	Aileron
Model			Reversed		
Lever			Power		
Lever hole			Hold pwr		
PPR			Backlash		
Reduction			Top speed		

Operating limits

Max IAS		Max roll	
Min IAS		Max pitch	
Max VS		-	

Configuration parameters

Max arm mv		Max pitch rate	
Pitch target		Max roll rate	
Roll target		Max VS rate	
VS target		Turn comp	
-		Roll rate gain	

Tuning parameters

Parameter	Pitch	Vario	Roll	Heading
P-term				
I-term				
D-term				

B   Parameters For Known Airplanes

Tables in this section list the tuning parameters for autopilots we have installed in different airplanes. If your installation is identical, then these values should give you a very reasonable autopilot behavior.

However, when the hardware installation is a bit different (usually, it is) or if different servo arm was used or a different hole in the servo arm, etc, then these values may not be completely suitable and re-tuning is necessary.

Some loops given below are using special values. RFF means Roll Feed Forward, VS is Vertical Speed, RRG means Roll Rate Gain.

B.1   Ekolot Topaz

Table 1: Topaz configuration parameters

Max arm mv	40°	Max pitch rate	10°/s
Pitch target	12°	Max roll rate	3°/s
Roll target	20°	Max VS rate	1.5m/s^2
VS target	3m/s	Turn comp	0.0
-	-	Roll rate gain	Disabled

Table 2: Topaz PID values

Parameter	Pitch	VS	Roll	Heading
P-term	1.0	0.018	0.8	0.75
I-term	14.0	19.0	10	28
D-term	0.16	0.16	0.02	0.3

B.2   Pipistrel Sinus

Table 3: Sinus configuration parameters

Max arm mv	40°		Max pitch rate	5°/s
Pitch target	12°		Max roll rate	3°/s
Roll target	20°		Max VS rate	1.5m/s^2
VS target	3m/s		Turn comp	0.0
-	-		Roll rate gain	disabled

Table 4: Sinus PID values

Parameter	Pitch	VS	Roll	Heading
P-term	0.5	0.02	0.5	1.0
I-term	7.0	12.0	8.0	25
D-term	0.16	0.2	0.02	0.2

B.3   Aeropilot Legend 540

Table 5: Legend 540 configuration parameters

Max arm mv	40°		Max pitch rate	5°/s
Pitch target	10°		Max roll rate	3°/s
Roll target	20°		Max VS rate	1.0m/s^2
VS target	3m/s		Turn comp	0.2
-	-		Roll rate gain	disabled

Table 6: Legend 540 PID values

Parameter	Pitch	VS	Roll	Heading
P-term	0.65	0.017	0.9	0.6
I-term	4.0	15.0	6	26
D-term	0.2	0.32	0.16	0.2

B.4   Evector Eurostar EV97

Table 7: EV97 configuration parameters

Max arm mv	40°	Max pitch rate	2°/s
Pitch target	12°	Max roll rate	5°/s
Roll target	20°	Max VS rate	$1.5m/s^2$
VS target	3m/s	Turn comp	0.3
-	-	Roll rate gain	disabled

Table 8: EV97 PID values

Parameter	Pitch	VS	Roll	Heading
P-term	0.4	0.025	0.7	0.9
I-term	7.0	12.0	8	26
D-term	0.0	0.2	0.2	0.2

B.5   Aerospool Dynamic WT9

Table 9: WT9 configuration parameters

Max arm mv	30°	Max pitch rate	2°/s
Pitch target	10°	Max roll rate	3°/s
Roll target	20°	Max VS rate	$1.0m/s^2$
VS target	2.5m/s	Turn comp	0.2
-	-	Roll rate gain	1.0

Table 10: WT9 PID values

Parameter	Pitch	VS	Roll	Heading
P-term	1.2	0.024	0.6	1.5
I-term	6.5	15.0	4.5	26
D-term	0.5	0.3	0.4	0.14

B.6   Roko Aviation

Table 11: NG6 configuration parameters

Max arm mv	30°	Max pitch rate	3°/s
Pitch target	10°	Max roll rate	3°/s
Roll target	20°	Max VS rate	1.0m/s^2
VS target	2.5m/s	Turn comp	0.2
-	-	Roll rate gain	disabled

Table 12: NG6 PID values

Parameter	Pitch	VS	Roll	Heading
P-term	1.2	0.017	0.6	0.6
I-term	6.5	15.0	4.5	26
D-term	0.52	0.32	0.4	0.2

B.7   Aeroprakt

Table 13: A22 & A32 configuration parameters

Max arm mv	30°	Max pitch rate	2°/s
Pitch target	10°	Max roll rate	3°/s
Roll target	20°	Max VS rate	1.0m/s^2
VS target	2.5m/s	Turn comp	0.2
-	-	Roll rate gain	1.0

Table 14: A22 & A32 PID values

Parameter	Pitch	VS	Roll	Heading
P-term	1.9	0.020	0.45	0.45
I-term	5.0	20.0	5.0	22
D-term	0.2	0.2	0.16	0.3

B.8   Direct Fly

Table 15: TG configuration parameters

Max arm mv	30°	Max pitch rate	2°/s
Pitch target	10°	Max roll rate	3°/s
Roll target	15°	Max VS rate	1.0m/s^2
VS target	2.5m/s	Turn comp	0.2
-	-	Roll rate gain	1.0

Table 16: TG PID values

Parameter	Pitch	VS	Roll	Heading
P-term	1.0	0.014	1.0	0.8
I-term	5.0	12.0	3.0	26.0
D-term	0.26	2.0 (Comp)	0.0	0.0

B.9   Comco Ikarus

Table 17: C-42C configuration parameters

Max arm mv	30°	Max pitch rate	2°/s
Pitch target	10°	Max roll rate	3°/s
Roll target	15°	Max VS rate	1.0m/s^2
VS target	2.5m/s	Turn comp	0.2
-	-	Roll rate gain	1.0

Table 18: C-42C PID values

Parameter	Pitch	VS	Roll	Heading
P-term	1.1	0.016	0.85	0.5
I-term	3.0	8.0	6.0	26.0
D-term	0.2	0.0	0.16	0.0