CONFIGURATION OF UAV AUTOPILOTS' DYNAMICS USING A 3 DOF AIRCRAFT MOTION SIMULATOR

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Abstract

The paper presents the role of Autopilots in Unmanned Aerial Vehicles (UAVs) and the process of their configuration before flying can occur. The common autopilot architecture, emphasising the control module, is given shortly and the functionality of the commercially available UAV autopilot "Micropilot MP2028", used for initial flights of the first Slovenian UAV "Karantanija", is summarised in a table. Furthermore, the development of the 3 degrees-of-freedom aircraft motion simulator is presented.. The motion simulator was developed and used as a test bench in attempt to tailor autopilot's flight dynamics to "Karantanija" UAV even before the actual first unmanned flight. The author presents the evolution of the motion simulator which was first used in open-loop configuration and later adapted for Hardware-in-the-Loop simulations using actual autopilot hardware. Once completed, the equipment was used to evaluate UAV's (autopilots) capability to carry-out the required mission in case of various sensor failures in different stages of flight. The paper also presents the anticipated behaviour of the aircraft following an engine failure in two different autopilot altitude handling modes, based on the experiment with the 3 degrees-of-freedom motion platform. Benefits, future possibilities of use and further development of the aircraft motion simulator are discussed in the conclusion.

Keywords: UAV, Autopilot configuration, Aircraft Motion Simulator

Presenting Author's biography

Tine Tomažič graduated from grammar school "Veno Pilon" in Ajdovščina in 2002 with highest honors. He is presently a 5th year student in pursue of degree in Automation at University of Ljubljana's Faculty of Electrical Engineering. He published several conference papers and received a student competition award at AIG'07 conference in Maribor, Slovenia. Besides college engagements, Tine is a qualified flight instructor and test pilot for Slovenia's largest light aircraft producer.

1   General

UAVs range from small tactical bird-sized flying machines with only minimal sensors to fully armed strategic aircraft capable of operating from the other side of the World. At the moment UAVs seem to be the most attractive military and law-enforcement flying machines due to lower maintenance costs, lower operational costs, and smaller risk to human personnel. What is more, UAVs have recently proliferated in non-military operations, which include forest fire supervision (Hungary), whale hunting oversight (Western Europe, Japan), pirate ship attack prevention (Indonesia, Australia), road traffic surveillance and traffic-jam reporting (U.S.A.), and more.

The very concept of UAV requires very advanced autopilot systems. Amongst other features UAV systems require that in the event of a lost remote control signal the vehicle autonomously returns to home base. Early age UAVs were called drones because of their limited autonomous capabilities. They were piloted directly by a human operator, who used camera imagery and data feeds from basic flight instruments to judge the progress of the flight. Later UAVs incorporated basic autopilot functions such as pitch-hold mode to ease the workload off the drone operators by automatically stabilizing the UAV. Further development yielded autopilot devices, which were able to carry out stabilized flight as well as basic manoeuvres, although the flights were still commanded by a human operator in real-time.

Modern UAVs autopilots, like their manned-aviation counterparts, generally divide a flight into several phases, such as take-off, climb, level flight, descent, approach/landing and various emergency situation recoveries. Each of these flight phases present their own set of challenges, which autopilots must cope with. But a modern UAV autopilot is not just a system, used to steer the aircraft in a stabilized manner – it is an advanced navigational package which typically incorporates a Control Module, Flight Management System, Continuous double-way Telemetry Data Link and the capability of being over-ridden with operators manual control in any phase of the flight. Ideally, the autopilot system would also function hand-in-hand with advanced sensory equipment, which includes but is not limited to a stabilised camera gimble, image recognition modules, emission sensors, radiation sensors, various radars etc.

Up to present date, there have been no known events of configuring a tactical-size-UAV Autopilot's flight dynamics on a device separate from the actual airframe and in controlled laboratory environment before the actual maiden flight. To achieve this, a 3 DOF motion platform, which mimics airframe's exact behaviour in flight, was developed. Using this equipment, flight dynamics and other primary functions of the Autopilot were configured first,

following by the evaluation of its performance during various normal and emergency situations which arise in actual flights. Note that all of the above occurred before the actual airframe took autonomous flight.

The paper is organised as follows: In section 2. the autopilot architecture including control module, flight management system, data link and ground station is presented. Commercially available UAV autopilot Micropilot MP2028, used in "Karantanija", is reviewed in Section 3. Section 4 describes the development and use of the 3 degrees-of-freedom aircraft motion platform for configuration of the autopilot's flight dynamics.

2   Autopilot architecture

Every UAV autopilot must contain certain functionality in order to conduct autonomous flight activity. Most important major components of a UAV autopilot system include the Control Module, Flight Management System, Data Link and Ground station [1].

2.1   Control Module

The autopilot's Control Module is what truly controls the UAV's flight. The control module reads the aircraft's position and attitude from an array of sensors. Typically, solid-state gyroscopes (electronic gyrosco-pes) and magnetometers (electronic compass-es) are used to determine the aircraft's attitude, whereas the GPS and barometric probes tell the autopilot about the position, altitude and speeds. However, attitude sensors accumulate errors over time, known as drifts. These occur due to physical properties of such sensors and/or electronics used for interpretation. The disagreements between the actual data derived from attitude sensors and indicated GPS and barometric data are resolved with digital signal processing, most often a six-variable Kalman estimator. The six dimensions are usually roll, pitch, yaw, altitude, latitude and longitude. Besides variables and their derivatives also biases can be estimated, so the dimension of the estimated state vector can be up to eighteen. Once filtered, the obtained 6 states are regarded as "true" and are used for actual aircraft steering. Intelligent use of Kalman filtering also enables the autopilot to function without GPS positioning data for a limited period of time, which should suffice to bring the UAV back to its home base or predefined position. Wind estimation is also performed in a similar manner.

The core of autopilot's Control Module comprises of controllers, adjusting various predetermined parameters e.g. mean climb power, descent profile etc., set points and gain scheduling, depending on how broad is the flyable speed envelope of the UAV. In case of Micropilot MP2028 there are 12 individual feedback loops to be adjusted, each consisting of P-, PI- and PID-type controllers. Some of the feedback

loops allow for feed-forward gain adjustment in order to stabilise the flight in a more robust manner.

2.2 Flight Management System

A Flight Management System (FMS) is the part of the UAV's autopilot which keeps the pre-programmed flight-plan, communicates with the user interface (typically computer software with an intuitive graphic interface) and governs the control module of the autopilot. The operator can access the Flight Management System prior or during the flight and influence the flight plan/progress by determining the trajectory (route), altitudes, speeds and target special events e.g. engaging video surveillance, convoy following, probe release, weapon launch etc.. Tab. 1, 2 and 3 illustrate the general capabilities of the MP2028 autopilot's FMS.

Tab.1 Basic MP2028 FMS capabilities

Longitudinal Control / Hold functions	Lateral (directional) Control / Hold functions
Pitch attitude	Bank angle
Altitude	Heading / Track
Airspeed (Mach number), groundspeed	Turn rate at constant altitude and airspeed
Climb / Descent rate	Zero lateral acceleration (yaw dumper)

Tab. 2 Navigational modes of MP 2028

Navigational modes	
Climb / Descent to target altitude	Trajectory intercept and hold
Trajectory (route) following	Convoy following
Sector patrol	Target surveillance with stabilized camera control

Tab. 3 Recovery modes of MP 2028

Special manoeuvres / features	
Automated take-off	Hand launch control
Automated landing	Terrain and obstacle avoidance
Critical attitude recovery	Manual control override (real-time steering)
Manual control override (direct control)	

2.3 Data link

A two-way Telemetry Data link is essentially a sort of continuous radio communication between the UAV and the Ground Station. Publicly obtainable and commercially available systems capable of such kind of radio communication use frequencies of either 900 MHz or 2.4 GHz. In most parts of Europe, including Slovenia, the 900 MHz band cannot be used in practice, as it is either congested or legally reserved. This leaves the developers and users with the 2.4 GHz option, which among other issues results in much shorter on-line operational range of the UAV. A viable solution is also to conduct control and telemetry transfers at below 900 MHz ensuring better range,

whereas separate the large volume data transfers to the 2.4 GHz band.

2.4 Ground Station

No UAV operates without a Ground Station. The Ground Station functions hand-in-hand with the onboard Flight Management system and is fully dependent upon the Telemetry Data link. The operator behind the Ground Station console has a complete overview of UAV's status, past activity and programmed flight plan. Naturally the very console is used to program the UAV's behaviour prior or during the flight. Certain Ground Stations also incorporate live picture/video feeds and tactical information from the UAV's sensor array as well as offer further manipulation and distribution of the data obtained.

New generations of Ground Station software/hardware are capable of monitoring and controlling multiple UAVs at the time. This new tactical approach to UAV operations will trigger a range of multiple-agent surveillance, reconnaissance and/or assault missions, which remain unprecedented at this time.

3   Micropilot MP2028

Nowadays small and medium sized UAV development teams rarely decide to develop own autopilot systems, as ready-made highly capable and miniaturized autopilot packages are commercially available on the market world-wide. Such autopilot systems are based on various microprocessor architectures and opt future improvements /functionality to be implemented by a simple software update, providing the UAV operators with an up-to-date solution for years. Choosing the most appropriate autopilot system for a particular UAV and type of sortie however often remains a tedious task.

Micropilot is a Canadian manufacturer often regarded as the leader in UAV autopilot industry. Although a little large in physical size their primary autopilot product M2028 has been used in more than 300 applications and remains one of the most sought-after autopilot due to its modular architecture. While its modular architecture directly results in having a mesh of wires and connectors packed inside the aircraft's fuselage, this allows the UAV builders to choose between different communication modems, I/0 interfaces, servo controllers etc. when necessary. Its operational features cover just about every aspect of UAV use and the ground station, although not perfectly implemented, supports simultaneous control over multiple UAVs at a time.
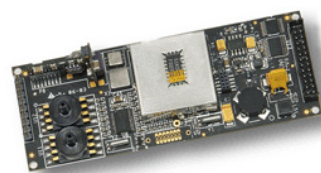

Fig 1. MP2028 autopilot main board

MP2028 is an autopilot for a demanding user and applications where functional flexibility and/or use of unconventional equipment is required. This is the reason why this autopilot was the first choice of the team developing Slovenia's first UAV, the 'Karantanija'.

3.1 Specifications review

Table 4 includes specifications of the MP2028. Please note that not all features of of the autopilot are mentioned and that the autopilot is by no means limited to the mentioned features only. The table has been assembled from various sources by author's best knowledge.

Tab.4 MP2028 specifications

		MircoPilot M2028
Physical properties		
dimensions (W x L x H)	[mm]	40x100x15
mass	[g]	28
rigid casing		option
external voltage	[V]	4.2 – 26
power rating		140 mA @ 6.5 V
ambient temperature limits	[°C]	?
Internal features		
barometric altimeter		integrated
max operating altitude	[m]	12,000
pitot-static airspeed indication		integrated
pitot-static probe		NO
max operating speed @ SL	[km/h]	500
3D accelerometer		integrated
2D accelerometer		/
max sustained acceleration	[Gs]	2
gyroscope (roll, pitch, yaw)		integrated
max. angular velocity	[°/s]	150
GPS receiver		integrated
GPS signal refresh rate	[Hz]	1
ground speed indication (GPS)		YES
GPS antenna		YES
active GPS antenna		option
core calculation rate	[Hz]	30
radio altimeter		option
3D digital compass		option
voltage monitoring / low battery		YES
voltage monitoring f/ separate power		YES
Input / Output		
servo output ports (native)		3
servo output ports (additional)		8/16/32
servo output refresh rate	[Hz]	50
separate power source f/ servos		YES
servo output D/A resolution	[bit]	11
digital signal outputs		NO
A/D & D/A user module		integrated
PPM and PCM receiver coupling		YES
aileron ctrl (1x servo)		YES
rudder ctrl (1x servo)		YES
elevator ctrl (1x servo)		YES
elevator ctrl (2x servo)		YES
V-tail, X-tail support		YES
elevon ctrl (flying wing)		YES
flaps ctrl (1x servo)		YES
flaps ctrl (2x servo)		YES
flaperon mode		YES
aileron & flaps (4x servo)		YES
throttle ctrl		YES
brushless electromotor control		YES

Special manoeuvring capabilities	
take-off (runway)	YES
take-off (ramp)	YES
take-off (launch)	YES
take-off (hand)	YES
flight mode differentiation	YES
landing (runway)	YES
landing (deep stall)	YES
parachute deployment	YES
RC manual override	YES
in-flight route modification	YES
max. navigation waypoints	1000
pre-programmed search/hold flight	YES
multiple UAVs per ground station	YES
error detection control	YES
"Dead Reckoning" navigation	YES
RPV / UAV mode switching	YES
Data link	
integrated data modem	NO
3rd party data modem support	YES
dual link / duplex communication	YES
telemetry	YES
telemetry rate [Hz]	5
on-board data storage	YES

4   3 DOF aircraft motion simulator

The decision to build the aircraft motion simulator was made after considering the eventual high material loss involved in case of losing the airframe during the maiden and initial flights using autopilot steering and guidance [2]. "Karantanija" is a high-performance, slippery, electric powered UAV with reconnaissance capabilities using a visual spectrum or thermal imaging camera. Losing the only existing specimen at the time would bring a significant delay to the development and cause numerous problems with the re-acquisition of the necessary equipment.

4.1 Development

The aim of building the aircraft motion simulator was to obtain a time and cost efficient solution for initial configuration of the autopilot's flight dynamics, which would take place inside controlled laboratory environment without jeopardising the actual UAV's integrity. As this has, to the best of author's knowledge, not been attempted before, it was also unknown whether mimicking roll, pitch and yaw would suffice to persuade the Autopilot as if it is actually flying an airframe.

With most experience in modelling and I/O communications in Matlab/Simulink, this was the chosen environment for the modelling of the actual aircraft. Equations of aircraft motion were used to produce a non-linear model tailored to the proportions and specifications of the "Karantanija" design. A full set of equations of motion [3] are as follows in (4.1) through (4.12).

$$\dot{V} = \frac{1}{m} \cdot \left(F_x \cos\alpha\cos\beta + F_y \sin\beta + F_z \sin\alpha\cos\beta \right) \qquad (4.1)$$

$$\dot{\alpha} = \frac{1}{Vm\cos\beta} \cdot \left(-F_x \sin\alpha + F_z \cos\alpha \right) + q - \left(p\cos\alpha + r\sin\alpha \right)\tan\beta \qquad (4.2)$$

$$\dot{\beta} = \frac{1}{Vm} \cdot \left(-F_x \cos\alpha\sin\beta + F_y \cos\beta - F_z \sin\alpha\sin\beta \right) + p\sin\alpha - r\cos\alpha \qquad (4.3)$$

$$\dot{p} = P_{pp}p^2 + P_{pq}pq + P_{pr}pr + P_{qq}q^2 + \\ + P_{qr}qr + P_{rr}r^2 + P_l L + P_m M + P_n N \qquad (4.4)$$

$$\dot{q} = Q_{pp}p^2 + Q_{pq}pq + Q_{pr}pr + Q_{qq}q^2 + \\ + Q_{qr}qr + Q_{rr}r^2 + Q_l L + Q_m M + Q_n N \qquad (4.5)$$

$$\dot{r} = R_{pp}p^2 + R_{pq}pq + R_{pr}pr + R_{qq}q^2 + \\ + R_{qr}qr + R_{rr}r^2 + R_l L + R_m M + R_n N \qquad (4.6)$$

$$\dot{\psi} = \frac{q\sin\varphi + r\cos\varphi}{\cos\theta} \qquad (4.7)$$

$$\dot{\theta} = q\cos\varphi + r\sin\varphi \qquad (4.8)$$

$$\dot{\varphi} = p + \dot{\psi}\sin\theta \qquad (4.9)$$

$$x_e = u\cos\theta\cos\psi + v(\sin\varphi\sin\theta\cos\psi - \cos\varphi\sin\psi) + \\ + w(\cos\varphi\sin\theta\cos\psi + \sin\varphi\sin\psi) \qquad (4.10)$$

$$y_e = u\cos\theta\sin\psi + v(\sin\varphi\sin\theta\sin\psi - \cos\varphi\cos\psi) + \\ + w(\cos\varphi\sin\theta\sin\psi + \sin\varphi\cos\psi) \qquad (4.11)$$

$$H = -(-u\sin\theta + v\sin\varphi\cos\theta + w\cos\varphi\cos\theta) \qquad (4.12)$$

Where:

V - aircraft velocity (speed)

α - angle of attack

β - sideslip angle

p - angular velocity around x axis (roll rate)

q - angular velocity around y axis (pitch rate)

r - angular velocity around z axis (yaw rate)

ψ, θ, φ - yaw, pitch, roll

$F_{x,y,z}$ - force in direction of x, y, z axis

L, M, N - torque around x, y, z axis

Pii, Qii, Rii - constants which are derived from aircraft proportions and specifications.

Having assembled the non-linear model of "Karantanija", where the inputs were: deflection of all control surfaces (including flaps), throttle and atmospherical conditions (air density, temperature etc.) disturbances (wind, turbulence) and the outputs were all 12 previously mentioned states, it was discovered that the non-linear model cannot be computed in real-time in Simulink on given hardware

– Matlab R14, Intel P4, 2.8 GHz, 1 GB RAM. Hence, the model was linearised [4] at several airspeed and angle-of-attack operating points, spread across the flyable envelope of "Karantanija".

Using a Matlab S-function the State Space model matrices A and B (C is I, D is zero) were interpolated on-the-fly given the actual airspeed and angle-of-attack computed in the previous simulation step. Testing and code optimisation showed that the model can be computed real-time up to 20 times per second on the same hardware.
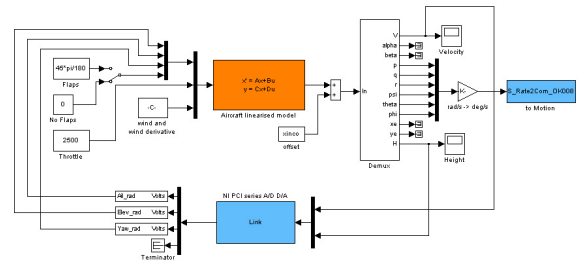
Fig 2. Simulink model

Having obtained a working real time quasi-non-linear model of "Karantanija" (Fig. 2) it was necessary to develop a way to transmit the computed real-time outputs to the 3 DOF motion platform.

The motion platform comprises of 3 mass balanced metal frames with bearings and a plexy-glass platform where the test equipment can be fixed (Fig.3). The motion of the platform is driven by 3 powerful Graupner servo motors, which are normally used in large remote controlled aircraft models.
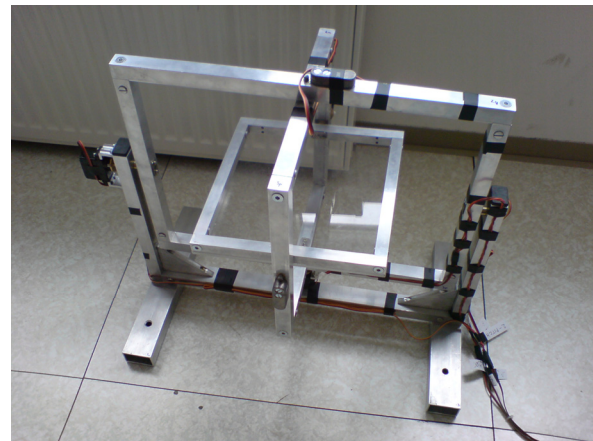
Fig 3. 3 DOF motion platform

Selection of such components contributed to cost-efficiency of the project. To control the servo motors, the SSC-32 PWM servo controller by Lynxmotion (Fig. 4) was selected. It offers 32 channels of 1 microstep resolution servo control (1μs resolution of PWM signal) and Bidirectional communication with Query commands [5].
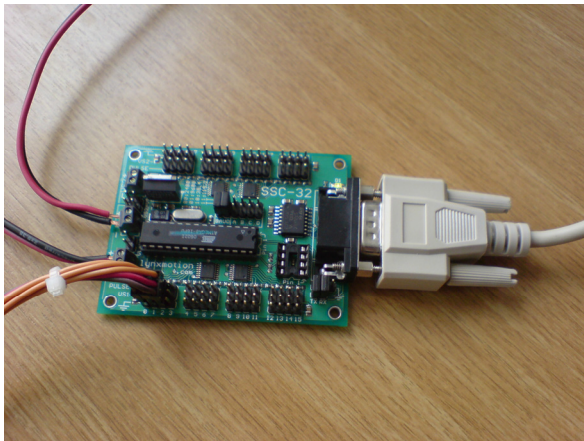
Fig 4. SSC-32 controller

The SSC-32 controllers connects to Matlab using conventional RS-232 communication where commands can be sent and received with Matlab built-in functions "serial", "fopen", "fprintf" and "fclose". Again, a Matlab S-function was used to transmit the calculated model outputs (roll, pitch, yaw) to the SSC-32 controller, thus the motion platform.

Upon completion, the 3 degrees-of-freedom motion simulator i.e. open loop system response was tested using a joystick input and validated for realistic results.

4.2 Hardware in the loop

In order to configure the autopilot it was necessary to intercept the position of the control surfaces, commanded by the autopilots Control Module, and route them into the inputs of the "Karantanija" Simulink model. To achieve this, servo motors to be used on the aircraft were modified and fitted with an extra set of wires which transmitted the position of the servo motor (voltage) to Simulink, using a National Instruments A/D converter. The voltage corresponding to the position of servo motor (control surface) is then adapted and used as a numerical input to the Simulink model. Schematic of Harware In the Loop configuration of the 3 DOF aircraft motion simulator is shown on Figure 5.
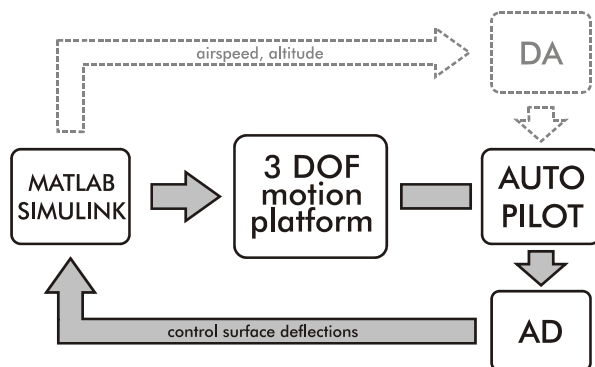

Fig 5. HIL schematic

4.3 Configuring the MP2028 Autopilot

With the MP2028 mounted on the 3 DOF motion platform it and the Hardware In the Loop mode established, it was first necessary to disable the MP2028's GPS input by using the "FFFF" command over the serial connection. The Compass Module replaced the GPS to provide the MP2028 with information about heading. What followed was the tuning of the 12 feedback loops with either P-, PI- and PID-type controllers. There are also possibilities of incorporating feed-forward control to improve the coordination of e.g. aileron and rudder inputs. Tab. 5 indicates all 12 feedback loops featured in MP2028's Control Module.

Tab.5 Available feedback loops

Name	Input	Output
0	Roll (rate)	Aileron
1	Pitch (rate)	Elevator
2	Sideslip	Rudder
3	Heading	Rudder
4*	*Airspeed*	*Throttle*
5*	*Altitude*	*Throttle*
6	Altitude	Pitch
7**	*AGL*	*Pitch*
8	Airspeed	Pitch
9	Heading	Roll
10***	*Crosstrack error*	*Heading*
11	Descent rate	Pitch

* left at default values as the exact engine power was not yet known

** impossible to simulate with precision, left at default value

*** impossible to simulate indoor with no GPS data

While the tuning of loops 0-3, 9 and 11 on the 3 DOF motion simulator was carried out with relative ease [6, 7], loops 4,5,6 and 8 proved more difficult. The reason was simple, yet not easy to overcome. During feedback loops tuning, the pitot (airspeed probe) tube and static port (altitude probe) were blocked and set to a constant level in the middle of the flyable envelope. To carry out the tuning of loops 4,5,6 and 8 it was therefore necessary to design a system which would provide differential and static pressure to the autopilot's main board and where these pressures would fluctuate according to Simulink model outputs. To achieve this, a system of two small air pumps and relatively large (100 ml) buffer bottles were connected to the pressure ports of the Autopilot. The pressure pumps were driven by Simulink model outputs, adapted and routed through a National Instruments D/A converter.

Thereby, an even more complete Hardware in the Loop functionality was achieved and the missing feedback loops tuned.

With the autopilot being mounted at easy reach it was possible to observe and evaluate unpredictable and emergency situations which may occur in real flight of the UAV. Abnormal situations which were evaluated include:

- Blocked ailerons (both neutral position and displaced)

- Blocked elevator (both neutral position and displaced)

- Blocked rudder (both neutral position and displaced)

- Engine failure

- Throttle stuck at a constant value

- Failure of pressure transmitters

- Intermittent power outage

As the presentation of the results gathered in the abovementioned evaluation can be rather complicated, only the case of engine failure will be displayed in this paper.

The most common issue with engine failure is sudden loss of airspeed resulting in a stall and uncontrollable flight. MP 2028 offers two major ways of maintaining certain altitude and airspeed. The operator can select the obvious "Elevator controls altitude, throttle controls airspeed" mode, or the second "Elevator controls airspeed, throttle controls altitude. While the first yields more precise altitude control, it proved problematic in case of engine failure. Therewith, stall occurs multiple times as a result of the controller attempting to re-establish flight at a predetermined altitude, but failing to achieve due to the lack of available power (Figure 6). The second pitch control mode is slower in response to in-flight disturbances, but handles engine failure in a much safer manner. Stall does not occur and the aircraft starts to descent at a constant airspeed and rate of descent (Figure 7). Figures 6 and 7 present two states, key to evaluation of flight safety in case of engine failure – airspeed and altitude. On both figures, equal altitude span in displayed on bottom graphs is used for clarity. Also, the moment of engine failure is highlighted with a red circle.

As Karantania's engine is electric, which can routinely be stopped mid-flight for staying silent for periods of time during a mission, the "Elevator controls airspeed, throttle controls altitude" mode was used for final implementation.
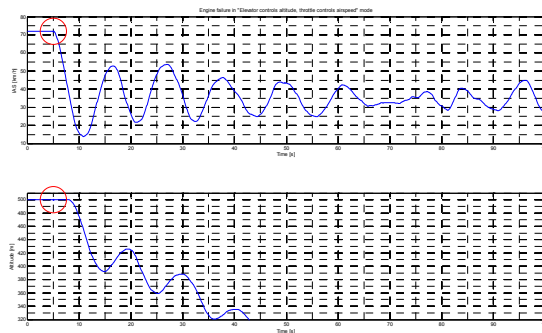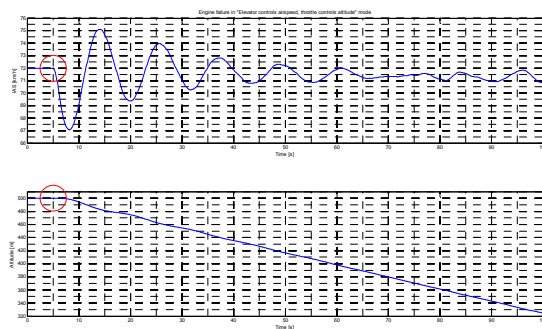

Fig 6. Elevator controls altitude

Fig 7. Elevator controls airspeed

5   Conclusion

Using the 3 DOF aircraft motion simulator combined with model-generated airspeed and altitude feed to the autopilot, it was proven that it is possible to "convince" the autopilot that it is "flying" a real airframe. The low costs of development and the advantage of tuning various elements of the Control Module of the autopilot indoors most definitely outweigh the eventual material loss in case of a crash during maiden and initial flights using autopilot steering and navigation. Also, various unpredictable scenarios which may occur during actual flights were observed. There is no other known method of determining aircraft's response (stability and consistency of flight) using the actual on-board hardware in emergency situations alike, without jeopardising the integrity of the airframe. Hence, the 3 DOF motion simulator is considered invaluable for the development team of "Karantanija".

What is more, the non-linear model used to simulate the behaviour of "Karantanija" on the motion platform can be adapted to replicate the behaviour of another type of aircraft with relative ease. Also, the motion platform can be driven using a different set of motion equations, simulating movements of virtually and moving body in 3 degrees of freedom.

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