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VIGA – Virtual Instructor for General Aviation

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ABSTRACT

The most common cause of incidents and accidents in aviation is linked to the category "Loss of Control Inflight" [1]. Remarkably in consequence this means that aircraft without any technical defect or such with manageable defects according to certification requirements are involved. The research project "Virtual Instructor for General Aviation" (VIGA) was aimed to validate an idea that addresses this problem by an entirely different approach. The idea can be best described by looking at the way a flight instructor takes decisions to intervene. A human pilot has an expectation of the maneuvers and the corresponding trajectories that can be flown in the future based on the present flight conditions. Decision making is based on the analysis of the consequences of the expectations. This approach is one of the key principles of the project, and is completely different to any known AFCS system.

Yet technical implementation requires considerable effort. Essentially it comprises a faster than real time simulation with an adequately accurate aerodynamic model of the particular aircraft in combination with a module to evaluate the results of the simulated exit trajectories. In consequence this idea requires an autopilot module capable of tracking the calculated three-dimensional trajectories which then resulted in the need to design and develop a completely new type of autopilot algorithm.

The objective of this project was to test and demonstrate principle functionality thereby also finding pathways determining future developments as well as to analyze system behavior. Therefore, the project was deliberately designed to help the pilot by depicting the solutions on the PFD. Direct intervention of the system with aircraft flight controls did not take place. This also raised the question of how to design an effective visual human interface.

Fortunately, all results proved to be very satisfying. The underlying idea could be validated and was demonstrated both in a simulation environment and in flight test. The path tracking algorithm was developed in a parallel project and also showed very satisfactory results, meeting all requirements.

Keywords: VIGA, Simulation, General Aviation, Human Interface, Path Tracking Algorithm, Loss of Control, UPRT, EGPWS.

The Concept behind VIGA

The generation of recommended actions is based on an algorithm which represents the real flight conditions. The calculations are carried out in a single processing unit that combines measurement data and a model of the real aircraft in a numeric simulation. The idea behind this concept lies in the approach that the simulation can estimate the flight situation in the near future upon the current conditions. By these results it is possible to evaluate both, the calculated as well as the current flight situation and to proceed with a comparison of the remaining margin of the aircraft's aerodynamic and performance characteristics. Based on the results of the comparison, recommended actions will be presented to the pilot to avoid a detected hazardous situation. The necessary flight data for the simulation will be provided by a measuring system. Since "Loss of Control Inflight" is the main cause of accidents in aviation, several different systems aimed at helping pilots not to get into hazardous situations have been developed. Some of these are required to be installed on transport or commuter category aircraft. The most advanced system at present is EGPWS which generates a warning in case an aircraft comes too close to an obstacle or the ground. The mandatory implementation of this device in large transport and commuter aircraft has improved accident statistics significantly. Yet it has to be noted that the pilot is left alone once the system is activated.
Current systems all use static parameters to trigger warnings. In other words, any kind of action is based on one or more static if – then conditions. This approach has significant inherent disadvantages and in addition it also implies a restriction on the maneuvering envelope a pilot can use. In principle these systems help the pilot to recognize a potentially hazardous situation but do not give any problem-solving assistance.
Sadly, there have been several accidents where a system designed to help the pilot was a contributing factor in confusing the situation finally leading to disaster.

VIGA takes a fundamentally different approach. By looking at the way a flight instructor takes decisions it is possible to design a much more aviation-like concept of dealing with potentially hazardous situations. One basic part of piloting experience is the ability to estimate what an aircraft is capable of, by having a feeling for the aerodynamic characteristics and the performance of a particular aircraft type. Transferred into a technical language, a feeling for the aircraft is equivalent to having an aerodynamic and flight dynamic model. This is the basis of every simulation.

Analyzing the pilot's way of dealing with the situation leads to the crucial conclusion on which this project is based: Instead of using static if-then conditions, it is the result of the simulation that has to be analyzed and used in order to decide whether a situation is potentially hazardous. This idea has very significant further consequences:
By using simulation results it will be possible to generate problem solving assistance. Flight envelope limitation can be completely withdrawn. This means that unlike any present system the entire maneuvering capability of an aircraft can be used to overcome a hazardous situation.

This new approach implies challenging questions regarding the modeling, simulation and control of the involved processes. As a result of discussions within our scientific group the decision was taken to set up and use an own simulation environment in order to have control over every mathematical step that comes into use.

A significant part of the large spectrum of questions needs to be answered in order to achieve the desired results. Many can only be answered by comparing flight test data with simulation results and if necessary by altering modeling and simulation setup. Some questions are:

- What kind of problem-solving algorithms can be used?
- How to set up an aerodynamic model and what is the impact of the spread between the model and reality?
- To what results does the interaction between the biases of the different parts of the simulation process lead?

The aerodynamic model needs to meet contrary requirements. It has to be adequately accurate within the entire flight envelope of the underlying aircraft, yet sufficiently simplified in order to allow very fast computation. This also applies to certification in the future where transparency and traceability are of crucial importance. Also, it has to be adaptable with reasonable effort to varying conditions like a change in aircraft mass or center of gravity which can differ on every flight and even during flight.

Measuring System

The Measuring System MACS (Modular Airborne Computer System) was developed to provide data acquisition for flight testing of light aircraft and drones as well as to provide the graphical user interface to the pilot comparable to the primary flight instruments. This design allows the pilots to perform the flight testing with the same data from the measurement devices that is used in post processing and flight analysis. The generated data is used for calculations of flight performance figures and for the evaluation of flight characteristics. Moreover, MACS is involved in the department's scientific environment and is accepted by the German Aviation Authority for the certification of light aircrafts. In the VIGA project, MACS is used for the generation of the flight data needed for the simulation process. The measuring system is fully self-sufficiently powered and therefore works independently from the aircraft's electrical system. MACS incorporates different sensor devices which form a network that is controlled by a single embedded computer. This processing unit takes synchronized measurements of all sensors at an acquisition rate of 50 Hz. In addition, the unit performs all calculations needed to obtain physical values from the raw measurement data, provides live view of the data in flight and stores the collected data in a binary file format for later analysis in spreadsheet programs. The sensor setup of MACS includes the following devices:

- An inertial measurement unit NAV 440 (Crossbow) and another inertial measurement system iNAT FSLG-01 (iMAR) based upon fiber optical gyros acquiring inertial data, three axis accelerations, rotation rates and Euler-angles.
- A GNSS receiver BD 970 (Trimble) used for the provision of GPS data.
- A Digital Incident Flow Gauge (DIFG-05, Steinbeis Flugzeug- und Leichtbau) employed in MACS consists of an air data probe (prandtl probe) which is located on the top of a boom of approximately 2.0m length. It provides data of calibrated and true airspeed, barometric altitude as

well as angle of attack and angle of sideslip. The boom is adaptable and can be mounted to an aircraft's wing.

- A specially developed system is used for the measurement of all control surface deflections. Each of the developed sensors consists of a potentiometer circuit and a Wi-Fi module and is capable of measuring the deflection angles of ailerons, elevator and rudder.
- The sensor network is completed by a control stick for the measurement of control forces. The composition of the sensors is shown in figure 1.

In addition, the set of sensors will be extended in the near future by a propeller shaft module which will deliver propeller thrust, shaft power and propeller speed.

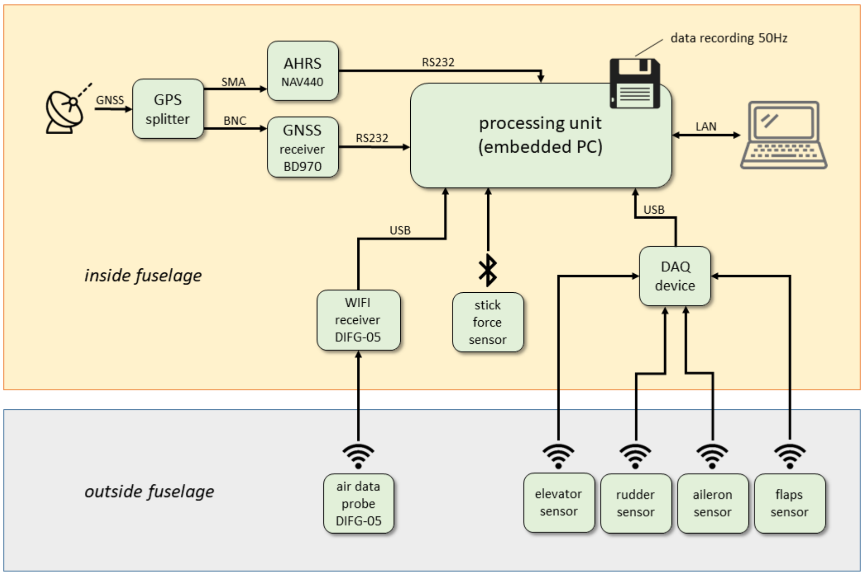

Fig. 1: Measuring system MACS

The software used for the development of the interface layout and for the data acquisition is based on the development environment LabVIEW (National Instruments, 2019). The advantage of LabVIEW is in its graphical programming code and in its many possibilities of integrated device interfaces which makes it easier to combine sensor data of different sources. Thereby the integration of new devices is facilitated and the changes on the user interface can be accomplished quickly. The layout of the interface itself is also customizable since the concept of LabVIEW to imitate real instruments helps to develop own representations of aircraft specific displays. The general user interface of MACS is an imitation of the cockpit's instruments. The concept of a configurable measuring surface can be extended to the needs of VIGA. Therefore, the existing measuring software will be implemented in the VIGA simulation algorithm to provide the necessary flight data. To enable future integration of the measurement software, the simulation algorithm is also programmed in LabVIEW.

Simulation

The idea of an own simulation for VIGA is necessary because of the fact that VIGA will make estimations of a flight situation in the future. This means that own algorithms for recognition of flight situations have to be implemented in a holistic system. Moreover, the own algorithms have to be evaluated which makes it evident that the implementation of the aircraft's simulation needs to be carried out in VIGA as well. In this way, the functionality of the simulation can be examined before the effects of the implementation of controlling algorithms in VIGA are evaluated. The aforementioned evaluation purposes will first take place at a static test environment in a laboratory structure. Like MACS also the test environment for the VIGA algorithms is programmed in LabVIEW. Figure 2 demonstrates the conceptual block diagram structure of the software.

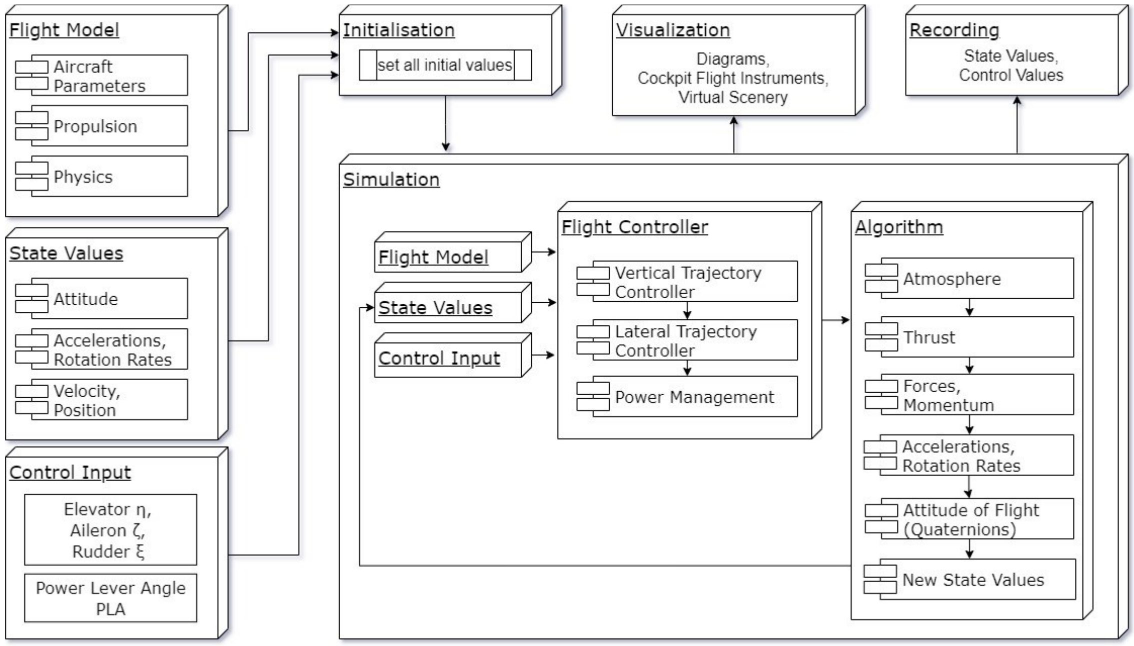

Fig. 2: Schematic of the simulation

During the initial phase of the project the software of the simulation environment and an appropriate graphical user interface were created on a desktop computer for evaluation purposes. The front panel of that simulation is presented in figure 3.

The aim of the simulation is to provide a test environment to validate the own control algorithms. For this purpose, the simulation covers the system "aircraft" as a control system (offers control around all axes), its aerodynamic and flight mechanical equations that describe the movement of an aircraft in a three-dimensional system. The developed test environment can be used in two ways: firstly, it is possible to edit every equation in the system that describes the aircraft's flying behaviour and secondly it is possible to implement and test the own algorithms in detail. The test environment additionally enables rapid changes on input interfaces as well as on the user interface.

The parameterization of the simulated aircraft is done via an input screen which is shown in the bottom half of figure 3. The input parameters concern the aircraft's geometry and aerodynamic, the initial flight condition as well as the control parameters. The test environment covers the same interfaces that are used in the measuring system MACS which enables the implementation of the measuring software.

Fig. 3: Front panel of the simulation environment

Testing of the flight model aiming at correct representation of the flight behavior requires precise emulation of the flight characteristics and also includes the manner of maneuvering control of the aircraft. Based upon the desktop version of the simulation environment a full-size flight simulator has been developed which supports ground tests of the software's algorithms. The simulator features a precise control input that has realistic control feedback like the real airplane, a touch display for the autopilot operation, a touch display for simulator and VIGA operation, a visual system displaying a virtual scenery and a display of the cockpit's flight instruments. For visualization purposes the scenery of x-plane10 is used. The whole simulator is operated by three computers which share the simulation data via a network connection. The schematic of that setup is shown in figure 4.

The simulation of the VIGA-algorithm in a faster-than-real-time-simulation takes place with reference to data from a real time simulation on a different computer. The data interface is capable of either working with the data from that real time simulation or from the measuring system MACS which enables easy adaptation for real flight tests.

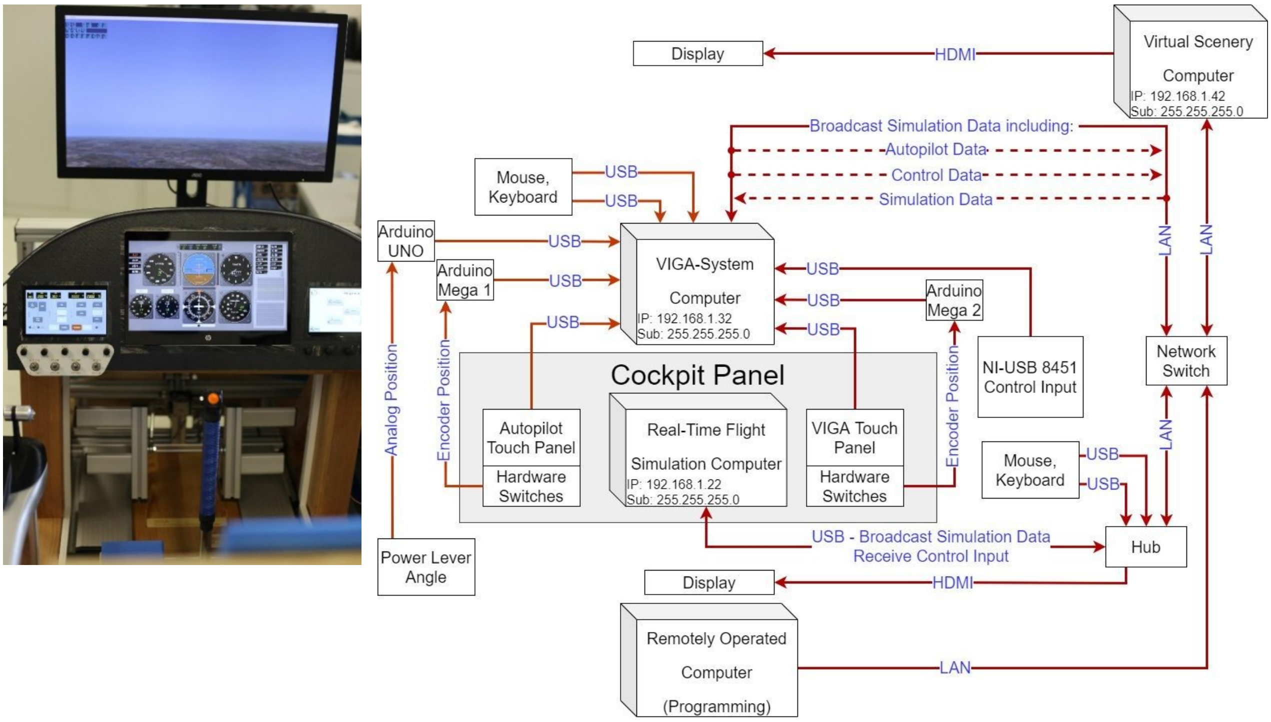

Fig. 4: Full-size simulator and schematic

The control of the simulation in the test environment is realized by hall sensor input devices. Moreover, the simulation covers basic autopilot functions such as Vertical Speed Climb / Descend, Heading Select, Heading Hold and Altitude Hold which form the basis for the implementation of the virtual instructor functionalities. The control algorithms within the simulation are generated by a Matlab-Simulink simulation of the aircraft and are validated in the test environment.

VIGA Algorithm

A basic requirement for the system is a fast simulation. To accomplish this goal, several issues need to be solved in first place:

- skillful modeling of the aircraft
- smart, robust calculation algorithms that are optimized far enough (as detailed as necessary, as simple as possible)
- a calculation of the flight path in three dimensions
- a control system for maneuver specification and path tracking [2]

In VIGA, the chosen approach was to simulate scenarios and analyze the results, since a simulation would otherwise have too many variables. In the analysis, a trajectory evaluation is carried out using the V-n diagram and then a decision is made as to whether the flight condition is to be classified as permissible or inadmissible in the future. Various interception strategies, which were evaluated in advance by the simulation environment, are calculated as scenarios. As a result of the evaluation, if an inadmissible flight condition is determined, a warning is output to a display instrument. The flowchart of the VIGA algorithm concept is shown in figure 5.

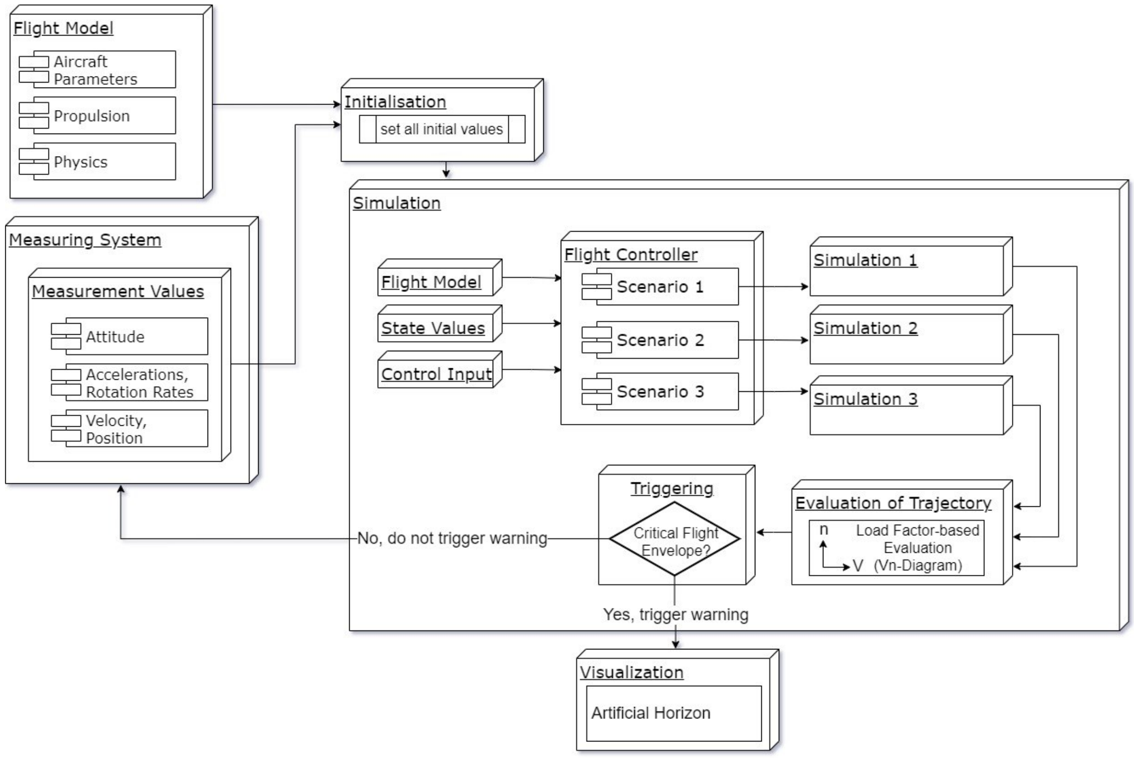

Fig. 5: VIGA simulation schematic

Human Interface Design

The human interface device in VIGA enables the pilot to react faster to initiating hazardous situations in flight. The information to the pilot is offered in a manner that corresponds to research results of neurology and situational awareness. Studies of pilots with high workload reveal [3] that trained pilots are less susceptible to stressful situations than pilots with less experience. Moreover, it was shown that the untrained pilots lost their auditive perception at first. The research results need to be countered in the design of the human interface in VIGA. For this reason, the information to the pilot may be offered in three escalating stages: auditive via speakers and headset, visually by animations on a screen and tactile by stick shaking.

Visual advice plays an important role, since they offer the opportunity to display all recommended actions as text information and as animations. These are depicted as simple as possible to focus the pilot on the essential actions. In addition, VIGA will determine whether the recommended action has been carried out and will present its advice until the aircraft is in a safe condition. Furthermore, it would be possible to ask VIGA at any time to present a recommended action, even if the system does not consider the situation to be hazardous. Additionally, the system will provide backup material for the pilot to look up in the VIGA system.

The interface represents an artificial horizon that is fed by information from the MACS measurement system and the VIGA simulation system. The difficulty of an intelligible indication is in the manner of how the information is displayed to the pilot. Tests with an indication like the already established Flight Director as a cross-pointer instrument revealed the issue that it is again to the pilot to correctly interpret the Flight Director as a command display and to draw the right conclusions of all necessary control movements. These controls may be simple to estimate on a known flight path, such as an ILS approach, but can become difficult if the intended flight path is unknown. As a result, a display in the form of a separate roll and pitch command with animated elements was developed. These depict the intended maneuvers by the system which the pilot is expected to follow.

In addition to the animated commands, indicators for the target roll angle and for the actual roll angle were created. These indicators help the pilot to aim at the correct amount of control input needed, since the split of both indicators give a technical feeling of the necessary roll control in order to follow the system's instructions.

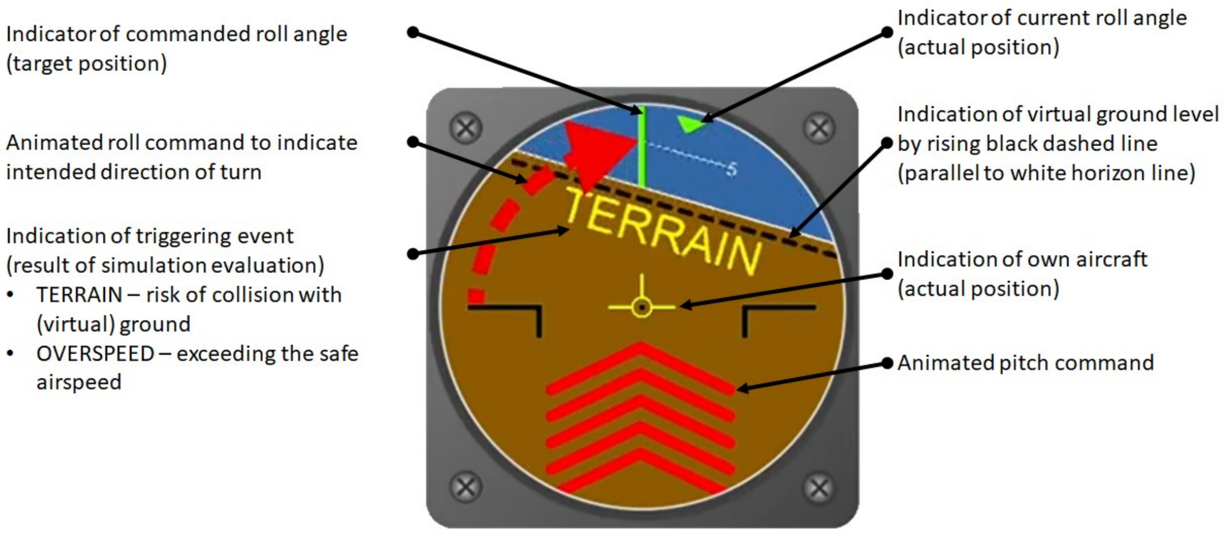

Fig. 6: VIGA interface

Flight tests of the VIGA system took place in october 2021 at Schönhagen airport. The test aircraft was an Aquila A212T which has already been equipped with the measuring system MACS for test flights earlier. Flight data recordings of MACS were used to evaluate the aircraft's aerodynamic model built in the simulation environment. In preparation of the flight tests, the VIGA instrument was displayed on the screen of a laptop and presented to the pilot so that maneuvering according to the indication of this artificial horizon was possible. The test scenario covered a provoked collision with the ground. For this purpose, the ground level was raised to a virtual altitude of 5500 ft for the simulation system. Flying through this altitude therefore represents an impact. To make the ground level visible in the instrument, a rising ground line was inserted, which gradually moves towards the white horizon line. If both lines meet, the programmed ground level is reached.

In a second test scenario, the focus was put on the aircraft's operating speed. The system was proved to indicate an exit strategy to prevent exceeding a programmed (and still safe) maximum airspeed during descent. The respective reason for triggering of warnings was displayed as text on the instrument as shown in figure 6.

As a result of the flight tests, the system performed well. Analysis of the recorded flight data revealed that the indication of the system was in time so that the pilot's reaction to the indicated commands prevented collision with the virtual ground and prevented exceeding maximum airspeed.

Fig. 7: VIGA system and measurement equipment inside luggage compartment

Fig. 8: Air data probe attached to wing

Fig. 9: Test flight in an Aquila A212T

Conclusion and future perspectives

1. The system's approach is totally different to all known comparable systems available on the market to date. The results show that it is possible to run the developed algorithm on board of an aircraft. Flight tests prove that the basic concept of VIGA works. The reached technology readiness level can be estimated between stage four and five (component validation in laboratory environment / relevant environment). Future development will concern hardware optimization tasks. This involves answering the question, how the system will perform with less accurate sensor data or how the difference between the real aircraft and the simulation affects the system's performance.

2. During research it became evident that the implementation of the idea becomes more challenging the slower the underlying aircraft is. This is because a given load factor results in higher rotation rates with dropping speed. At the same time at lower speeds a difference in altitude results in a larger change in speed. This leads to the conclusion that this system, once functionality is proven in a light aircraft, can easily be adapted to fast and high-flying aircraft or even commercial airliners. This corresponds to practical flying experience where it is much easier to deal with an upset situation in a fast aircraft compared to one flying slow.

3. The project is aimed to be a system that does not take direct control of the aircraft. It can analyze the situation and give problem solving assistance but it relies on the pilot to execute the required maneuvers. Our research efforts target to design new algorithms on which autopilots are based upon allowing them to control an aircraft within the entire flight envelope of the aircraft and hence

enabling VIGA to take control of the aircraft in complex maneuvers. In other words, with today's technology, if something goes really wrong: Turn off the autopilot, fly yourself and try to survive. This is the goal: If the trouble gets serious: Turn on the autopilot, it will do the job for you.

4. Self-learning algorithms can improve the aerodynamic model for the weight and center of gravity of the aircraft.

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