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EXTENSION OF THE CAPABILITIES OF AN AUTOMATIC LANDING SYSTEM WITH PROCEDURES MOTIVATED BY VISUAL-FLIGHT-RULES

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Abstract

The automatic flight capabilities of a CS-23 aircraft are enhanced by automating maneuvers, based on Visual-Flight-Rules (VFR), currently adhered to by manned flight. The system presented in this paper is capable of guiding the aircraft to a predefined landing trajectory, by using existing modules of an automatic flight control system with safety monitoring. The finite state machine developed in this paper enables the user to provide high-level commands that enable the automated system to guide the aircraft to the selected pre-planned trajectory based on VFR. The approaches and the go-around maneuvers were planned offline with waypoints, which are used for the guidance and control. The system was integrated into the automatic flight software of the Institute of Flight system Dynamics in the course of the C2LAND project. Software-in-the-Loop (SiL) and Hardware-in-the-Loop (HiL) tests were conducted with an incremental test plan, to ensure the safety and robustness of the code. The system was then successfully demonstrated on the institute's optionally piloted Diamond DA42 aircraft during an extensive flight test campaign.

Keywords: Automatic Landing, General Aviation, VFR

1 Introduction

Landing is the most critical flight phase, since the increasing proximity of the aircraft to the ground results in increased risk to the safety of the aircraft [1]. Precise and timely maneuvers are necessary to ensure a safe landing at the designated airfield. Current, certified automatic landing systems for large civil aircraft (CS-25) are capable of guiding the aircraft to touchdown and deceleration using ground based ILS systems [2]. Miniaturization of electronics recently enabled several academic teams, to perform automatic landing on small general aviation aircraft (CS-23) using SBAS corrected GNSS/INS navigation [3]. Recently, an automatic emergency landing system has been patented, which is able to automatically land a CS-23 aircraft, in case of an emergency [4].

The Institute of Flight System Dynamics at the Technical University of Munich has developed an automatic flight guidance and control system for a Diamond DA42-M-NG general aviation aircraft, which was retrofitted with a electromechanical fly by wire system [5]. Figure 1 shows the aircraft.

The automatic flight system is capable of performing waypoint flight, auto-pilot flight, automatic take-off and landing [6]. The automation extension proposed in this publication was implemented in the system automation and interacts mainly with the Automatic Takeoff and Landing (ATOL) and the trajectory generation module. Figure 2 shows an overview of the automatic flight control system.

In previous work in research project C2LAND, a team of academic and industrial partners have realized the demonstration of Automatic Landing (AL), while navigation was monitored by an on-board camera system. This provides a higher level of safety and aims towards a certifiable strategy for the flight in heights lower than 200 ft above ground level. However, for activation of AL, the aircraft had to be manually flown to the start of the desired landing trajectory by the pilot, and then activated by the operator. [7]

Figure 1 – Diamond DA42-M-NG Demonstrator Aircraft OE-FSD

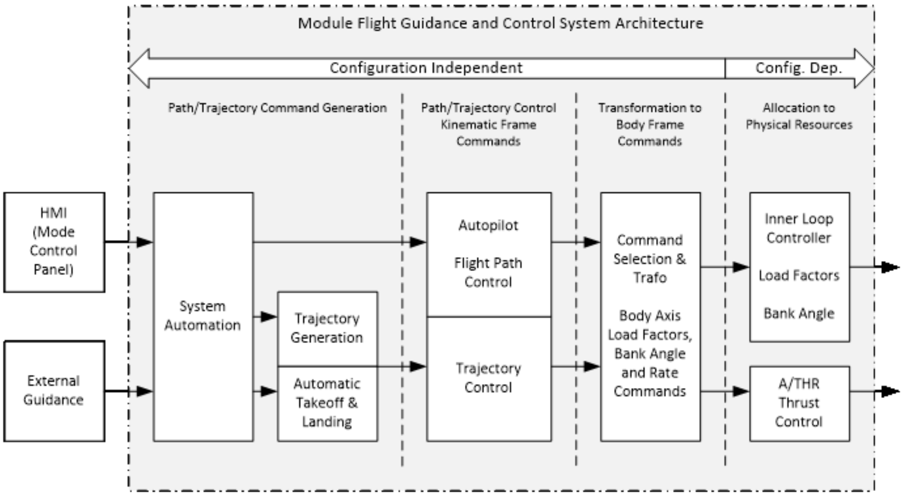

Figure 2 – Modular automatic flight guidance and control system developed at the Institute of Flight System Dynamics [6]

This paper presents the development of the guidance to the Autoland trajectory, the automatic Autoland activation, and the development and integration of high level automation strategies to the current automatic flight system. The developed system was demonstrated during an extensive flight tests campaign.

In section 2 the developed high level automation including the integration of the human-machine-interface (HMI) is presented. Section 3 shows the development of the waypoint based guidance to the landing trajectory and the planning of the automatic go-around based on the flight chart of the airfield, in order to be compliant with visual flight rules. Section 4 explains the activation procedure of the automatic landing module including the monitoring. Section 5 describes the integration and testing of the proposed system, and section 6 presents the results from the flight tests with the institute's aircraft. Section 7 concludes the paper.

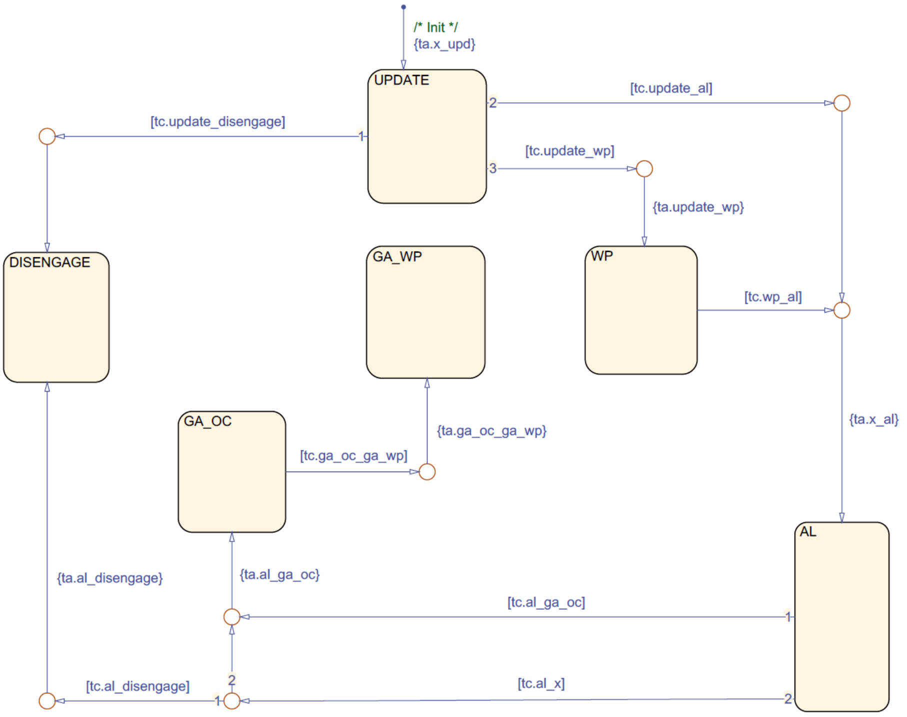

Figure 3 – Schematic Finite State Machine for high level Automation

2 HMI State Machine

2.1 Overview

The high level automation of the HMI was implemented by using a finite state machine. The state machine reacts to operator inputs from the C2Land display and determines, which submodules to activate for the execution of the maneuvers in the flight phases. The transition conditions for the states have been designed in order to achieve a high level of automation and thereby reduce pilot workload. Figure 3 shows the schematic of the developed state machine exported as a simplified Matlab Stateflow (R) Model. Each Box is a state. The duration of the state transition is one time step on the condition that the escape conditions is met. The period of the time step of the flight control computer is 10 ms. In case the state machine transitions to another state, a new command is generated. The horizontal arrows with square brackets show transition conditions, which are saved in the data structure tc. The state transition conditions are evaluated in order of the numbering. For example the UPDATE state has 3 possible escape conditions in order of priority 1 to 3:

1. tc.update_disengage
2. tc.update_al
3. tc.update_wp

The conditions are evaluated in order 1 to 3 and if a condition is met then the transition occurs within the timestep and remaining conditions are abandoned.
The naming convention for the elements of the tc and ta show at first the former state separated with an underscore from the next state. In case one of the two is arbitrary, it is replaced by an x. The nodes (small circles) are not states, but only serve for a better visualization; the state does not remain at the nodes.

2.2 State Transitions

At first, the nominal path to the right of figure 3 is described, including the states UPDATE, WP, AL and DISENGAGE. Then the go-around is described, containing the states GA_OC, GA_WP and DISENGAGE. At the end follows a description of the activation and deactivation of the state machine.

2.2.1 Autoland Activation

In the event that a trajectory is selected by the operator using the C2Land display, the state machine initializes in the Update state as shown in figure 3. During this time-step the the automatic flight system is set to attitude hold and a fixed indicated air speed command. The Update to Disengage state transition occurs if tc.update_disengage is satisfied in the event that an invalid route is selected by the operator. In this case no new command is generated and therefore the aircraft remains in attitude hold. In the event that Automatic landing is possible and the condition tc.update_al is satisfied the state machine transitions from Update to AL. [1]. The selected predetermined Automatic Landing trajectory is loaded and overall system navigates the aircraft along the trajectory until 'touchdown' and 'roll-out' phase of the landing maneuvers are completed. The state machine remains in the AL state until the landing maneuver is completed and the automatic flight system system is shut down by the operator.

If the condition tc.update_al is false, the condition tc.update_wp is evaluated. This condition ensures, that the route selection is valid. If it is, the action ta.update_wp is executed. This action activates the waypoint based trajectory generation and loads a waypoint list to the trajectory generation, which directs the airplane to the beginning of the landing trajectory, as described in section 3.1. The condition tc.wp_al then continuously checks if the activation of the AL module is possible. As there are checks related to trajectory flight, this condition differs from tc.update_al. As soon as tc.wp_al is true, the action ta.x_al mentioned above is executed to activate automatic landing.

2.2.2 Go-around Maneuver

The condition tc.al_ga_oc checks if the monitoring of the AL module has detected a critical state. The action ta.al_ga_oc starts a contingency maneuver with a go around. In the state GA_OC the aircraft performs the first two phases of the go-around. At first, full thrust is commanded and the attitude is stabilized. Then an open climb maneuver is performed by the autopilot while holding the track angle command of the runway. The condition tc.ga_oc_ga_wp checks if the aircraft is at a safe state, which includes checking the height to be greater than a fixed threshold height above ground level. The action ta.ga_oc_ga_wp then activates the waypoint based trajectory generation. The go-around is flown with trajectory flight according to the airport procedure; the design of the waypoints is discussed in chapter 3.2. The condition tc.al_x checks for a cancellation command provided by the operator of the C2Land display. Then the condition tc.al_disengage is checked. The condition checks for an internal value of the AL module called flight_phase_lgx. In case the aircraft is in the horizontal section of the landing trajectory, the action ta.update_disengage is executed and the aircraft is set to attitude hold and indicated air speed hold. If tc.al_disengage is false, al_fligh_phase_lgx is at a later stage and the aircraft is already in descent. In this case, the state switches to GA_OC and a go-around maneuver is executed.

2.2.3 Interaction with command inputs

The state machine is inside an enabled subsystem, to ensure robustness and simplicity. The enabled subsystem with the state machine is initialized to be inactive. When inactive, all outputs are predefined default values and no state is active. When the operator selects a landing with the C2Land display, the enabled subsystem is activated.

If the state machine is active and the operator selects a new landing, the state machine is deactivated and then reactivated in the following time step. This is however only possible, if the state machine is not in the state AL or GA_OC, as these states are in flight phases with a low height above ground. Thereby it is ensured that close to ground, the only way to abort the AL remotely is by sending a cancel command with the C2Land display, which triggers a go-around maneuver to guide the aircraft to a safe height above ground.

Besides the glass cockpit there are other control inputs on board, which can provide inputs according to a command hierarchy. There is a mode control panel (MCP), which is used to activate the autopilot. And there is the passive stick, which is used to provide angular rate commands to the inner loop of

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[1] The activation criteria checks, that the selection is valid, and checks the condition described in section 4

the automatic flight system. The rising hierarchy order is: MCP, C2Land display, passive stick. If the state machine is in state AL or GA_OC, the passive stick cannot take over control.

3 Automatic guidance with Visual-Flight-Rules

The automatic landing trajectories were designed for the airport in Wiener Neustadt (ICAO code LOAN) using an in-house toolbox [8]. The waypoint based guidance, which is described in section 2, was planned according to Visual Flight Rules (VFR), by using the chart provided by the airport. This ensures the compatibility of the automatic flight system with the other cooperative traffic of the airspace. The trajectories were furthermore designed in order to fly over areas with low population density.
The approach to runway 09 required flying over challenging terrain with high gradients in elevation. The area west of the airport includes mountains, which are higher than the intermediate approach. Therefore, the guidance was carefully planned and tested, to ensure sufficient obstacle clearance. The successfully proved concept shows the suitability for this approach in case of flying over challenging terrain with high obstacle density.

3.1 Initial Approach

For the initial approach, a procedure was designed to ensure a safe guidance to the AL trajectory. The pilot flies the aircraft to a predefined area, in which the operator requests an automatic landing with the C2Land display. When the trajectory generation is activated, the first waypoint is set to the current position of the reference point of the aircraft. The rest of the waypoints are pre-planned offline and ensure a safe guidance to the landing trajectory. The waypoints were planned with the institute's tool [9]. Each automatic landing has its own activation area and its own initial approach in form of a pre-planned waypoint list. Figure 4 shows an example of a designed approach.

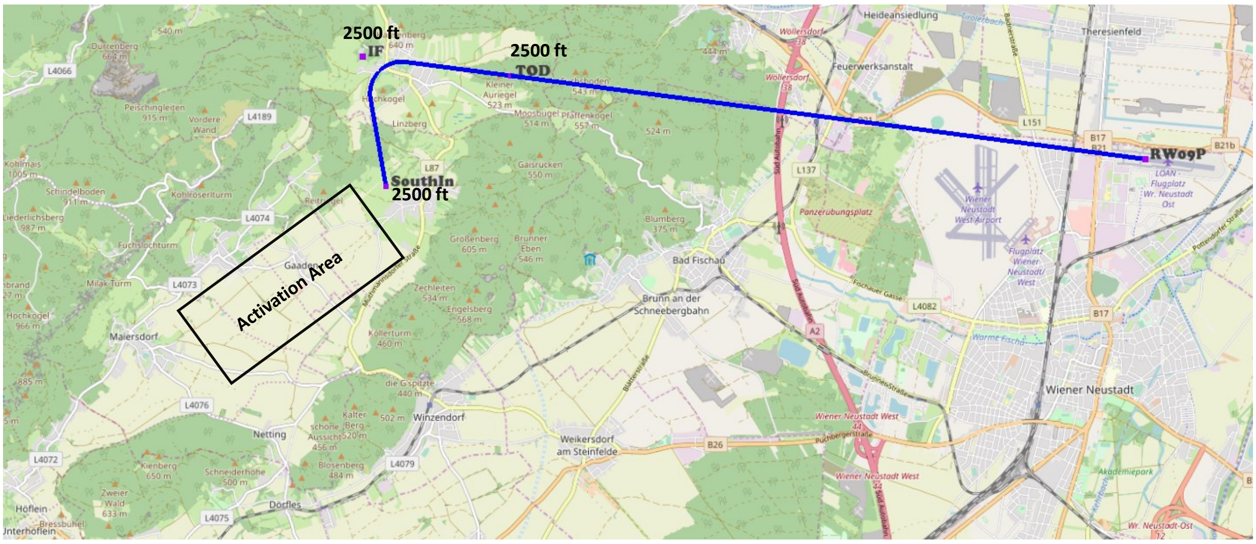

Figure 4 – planned approach for landing LOAN_RWY09P_SOUTHIN_3 with its activation area.

Waypoint lists for initial approaches for Runway directions RWY27 and RWY09 were created. For both Runways the initial approaches were tested with trajectories with glideslope angles of 3° ,4° ,5° and 6°. The last two waypoints of the initial approach lists were designed to match the intermediate approach of the pre-planned AL trajectory.

3.2 Go-around

As described in chapter 2, the state machine transitions from the open climb of the go-around to a waypoint flight after reaching the cruise height. There is one go-around waypoint list for each

Runway direction. The waypoints are designed to follow the go-arounds suggested by the chart for VFR Flights and guide the aircraft back to the activation area of the landing of the respective Runway. This enables the operator to command the next landing with the C2Land display while the automatic flight system stays constantly in control. Figure 5 shows an example of a designed go-around.

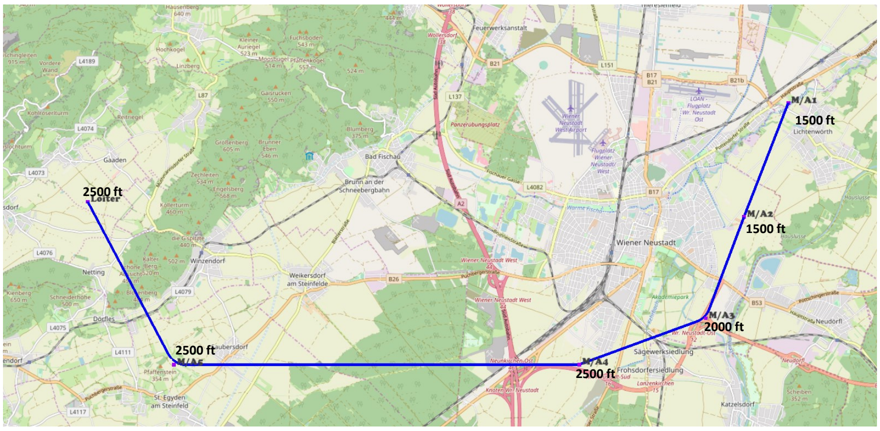

Figure 5 – planned go-around for landing LOAN_RWY09

4 Activation of automatic landing

For the activation of the automatic landing, a large set of sensor monitoring and flight state monitoring tests are evaluated by the ATOL system, which are based on a previous project at the Institute of Flight System dynamics and further developed to follow the requirements of C2LAND [10].

Therefore, a three dimensional activation corridor is defined in the runway coordinate frame, with the position of the aircraft reference point and the final two waypoints transformed from the WGS84-coordinate frame to the runway coordinate frame of the selected landing resulting in $(x\ y\ z)_R$ and $(x\ y\ z)_{WP}$ respectively. The runway coordinate frame is defined as discussed in [11]. The coordinate frame origin is at the intersection of the runway threshold on the centerline, the x-axis points along the RWY heading. The z-axis points down and the y-axis completes the coordinate frame to a right hand system.

Since the last two waypoints were placed on the horizontal leg of the predefined landing trajectory, they are used as the basis of the activation corridor.

The first condition is that the aircraft's reference point on the x-axis x_R is between the last two waypoints $x_{WP_{n-1}}$ and x_{WP_n} according to equation 1.

$$x_{WP_{n-1}} < x_R < x_{WP_n} \tag{1}$$

This ensures that it is on the intermediate approach. For the lateral deviation, the activation criteria should become more strict as the aircraft approaches the top-of-descent. Therefore the allowed lateral deviation linearly reduces from the second last to the last waypoint, as expressed in equation 2. The two parameters Δy_{min} and Δy_{max} can be used to adjust the strictness of the activation criteria.

$$|y_R| < \frac{\Delta y_{min} - \Delta y_{max}}{x_{WP_n} - x_{WP_{n-1}}} \cdot (x_R - x_{WP_{n-1}}) + y_{max} \tag{2}$$

The allowed vertical deviation was designed in similar as the lateral deviation, but adding the height of the top-of-descent waypoint as an offset. It is shown in equation 3. The two parameters Δz_{min} and Δz_{max} can be used again to adjust the strictness of the activation criteria.

$$|z_R - z_{WP_n}| < \frac{\Delta z_{min} - \Delta z_{max}}{x_{WP_n} - x_{WP_{n-1}}} \cdot (x_R - x_{WP_{n-1}}) + z_{max} \tag{3}$$

The monitoring of the lateral and vertical deviation ensures a smooth transition from waypoint flight to the predefined landing trajectory.

Note that the waypoint flight described in section 3 is conducted with barometric height, to match the VFR flight rules. The landing trajectory however is defined in a orthometric (WGS84) reference frame, to ensure a calculation of the height above ground independent of the current set QNH during the final approach and landing phase, as the difference of the current height and the runway both in the WGS84 frame. Therefore the height of the final two waypoints of the initial approach account for the difference of the height of the WGS84 ellipsoid and the geoid.
In addition to the position, the current track and path angle are monitored to match the landing trajectory, where they were as well transformed into the local runway. The allowed deviation is for both symmetrically defined as $|\chi| < \chi_{Lim}$ for the track angle and $|\gamma| < \gamma_{Lim}$ for the flight path angle
In addition, multiple parameters of the trajectory module are monitored. The aircraft has to fly toward the last waypoint of the active waypoint list. Furthermore, internal parameter, which describes the current type of the trajectory segment has to be in line mode. Figure 6 schematically shows the developed activation criteria.

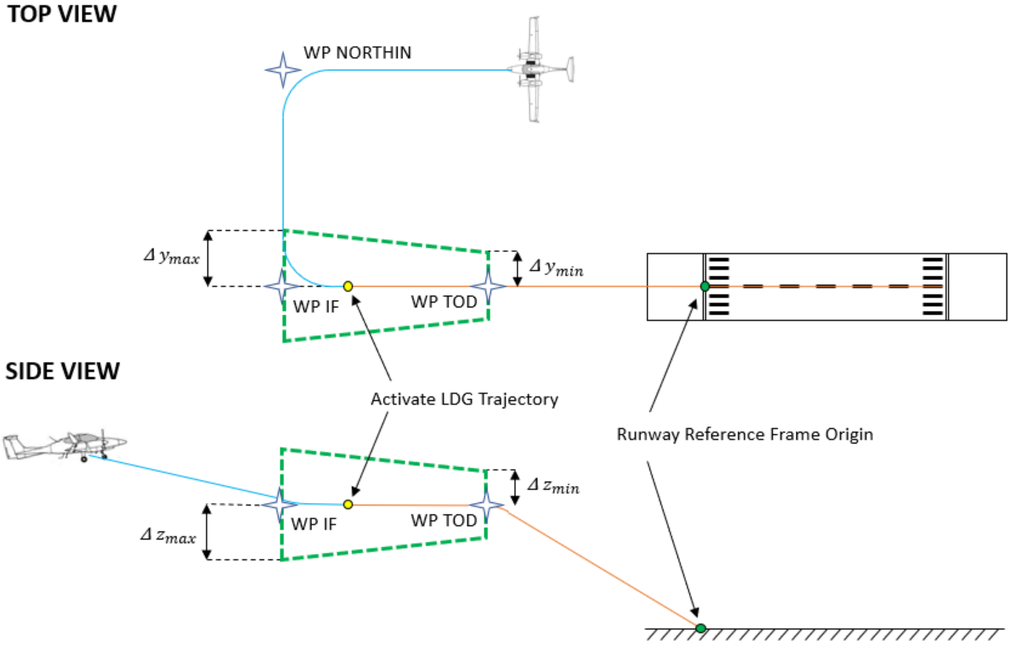

Figure 6 – Schematic position requirements of Autoland activation criteria

In case the automatic landing is not activated, the system automatically conducts a loiter maneuver at the last waypoint of the initial approach list, which is placed in a safe altitude.

5 Integration and Testing

5.1 Implementation

The proposed code is implemented in the module ATOL and System Automation modules of the Institute for Flight System Dynamics, which can be found in figure 2. The implementation was conducted according to the Institute of Flight System Dynamic's guidelines, which ensure the compatibility with model based DO-331 [12]. The Simulink Coder is used to generate ANSI C code. The Institute of Flight System Dynamics created verified a subset of fundamental functions out of the Simulink library, with predefined configuration parameters. Out of these fundamental functions, high level libraries with counters, integrator library were built. By using this library, the real time capabilities and code compliance is ensured.

5.2 Simulation

For simulation testing aircraft is modelled with a 6 degree of freedom (6-DOF) flight dynamics model. The level 6 model was provided by a partner company and extended with landing specific effects such as the gear forces, a terrain model and extended atmospheric modelling. The on-board sensor are modelled as dynamic systems as well, including digital effects such as discretization in time and measurement value. The software of C2Land display was used as a desktop app, which controls the automatic flight system. The control sticks can be used as inputs as well.

5.3 Testing

An incremental test plan was developed for functional testing using software-in-the-loop (SiL) simulation. This ensures the safety of the system, while keeping the test plan compact. The tests cover inputs from the C2Land display as well as atmospheric disturbances. All nominal procedures were tested. Several random input scenarios with a long line of inputs were generated as well, to ensure the robustness of the system.
Recent development of the Markov Chain Monte Carlo toolchain[13] at the institute has enabled the evaluation of performance of the automatic landing system by simulation[14] based on the inequality constraints formulated from CS-AWO[15] using a method called Subset Simulation[16]. Furthermore the toolchain enables the user to identify parameters that are most sensitive to the exceeding the performance limits of the Automatic Landing system[17].
After the SiL tests, the same test plan was conducted using in the hardware-in-the-loop (HiL) simulation. For the control inputs, the C2Land display, the passive stick and the MCP were used. The flight dynamics model and the sensor models run on a real time computer. Figure 7 shows the C2Land display during a HiL test.

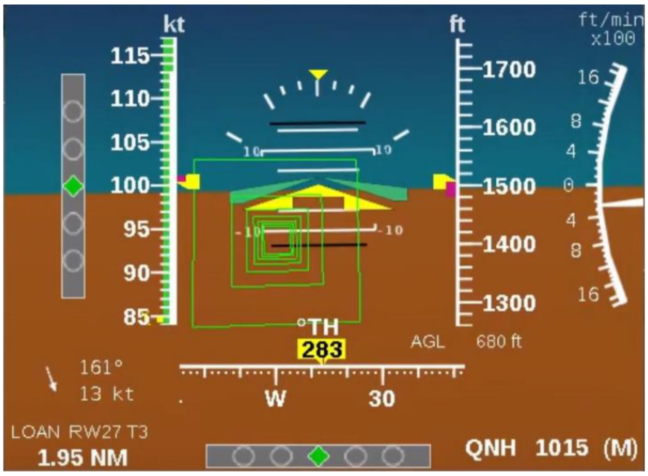

Figure 7 – Glass Cockpit during a HiL simulation of an automatic landing on RWY27

6 Flight test results

The system was then used in several flight tests with the DA-42 demonstrator aircraft. Several successful automatic landings could be demonstrated. Figure 8 shows the top view of a trajectory during a test flight, including the HMI inputs:
At point 1, a test pattern of four waypoints was activated, which was cancelled at point 2. Since the aircraft was then in the respective activation volume, the approach *RWY27 SOUTHIN3* was then activated at point 3. In order to test, that the system restricts inputs after the ATOL system was activated, the approach *RWY27 STRTIN3* was sent at point 4 and rejected by the system. At point 5 the appraoch was cancelled resulting in a go-around maneuver. After automatically rising to cruise height and flying the first leg over the runway, the pilot disengaged the automatic control system and manually flew the aircraft to point 6, as shown by the dotted line. Then the GESGI approach was selected and cancelled at point 7, resulting again in an automatic go-around. The system was then disengaged and manually flown to point 8. Then the approach *RW09p NORTHIN3* was selected, and the system performed an automated landing.
In the extensive flight test campaign, the system extension reliably proved to work as expected and thereby proved its applicability in reality.
The image in Figure 9 shows the belly camera of the aircraft during the *C2Land* flight test campaigns with the human machine interface (HMI) as it can also be seen in the publicly available video of the automatic landing system [18].

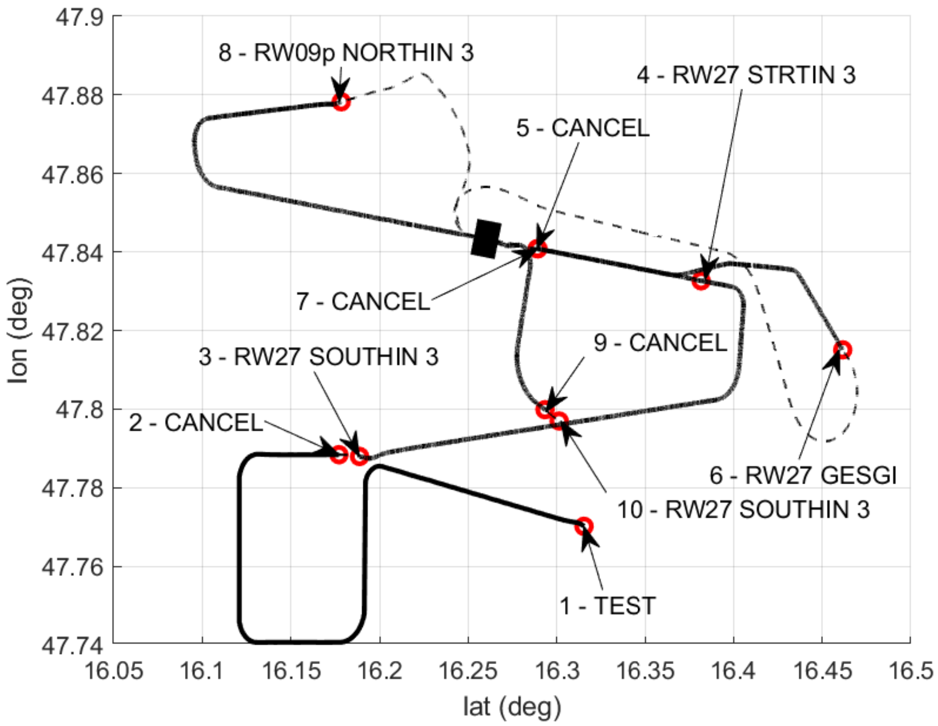

Figure 8 – Trajectory of flight test with inputs from C2Land display

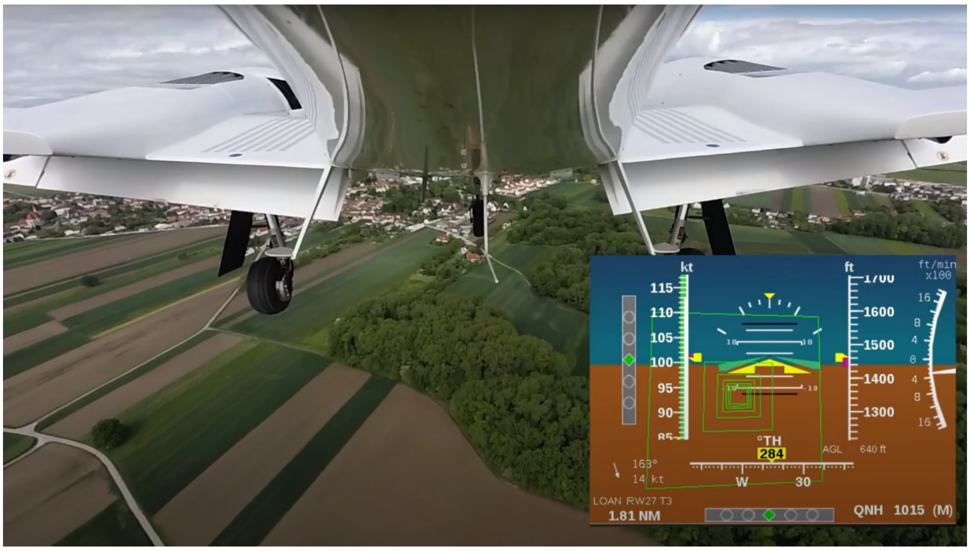

Figure 9 – Automatic Landing of the Diamond DA42 MNG fly-by-wire research aircraft OE-FSD of the Technical University of Munich during the C2Land project

7 Conclusion

The automatic Landing system of the Institute of Flight System Dynamics was extended to automatically follow VFR Rules, when approaching a landing trajectory. An increased level of automation was achieved, by using a discrete state machine. The initial approach and go-around trajectories were planned by using waypoint lists and using the existing trajectory generation module. For the activation of the AL trajectory, a monitoring assures the safety of the mission. The system was integrated in the existing automatic flight control system, tested with SiL, HiL and AiL tests. The capabilities of the system were then successfully demonstrated in several flight tests.

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