PLANNING, IMPLEMENTATION, AND EXECUTION OF AN AUTOMATIC FIRST FLIGHT OF A UAV

M. E. Kügler*, F. Holzapfel*
*** Technical University of Munich, Institute of Flight System Dynamics, D-85748 Garching bei München, Germany**

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Abstract

Executing the first flight of a novel aircraft configuration presents one of the riskiest activities in flight testing. This challenge is even greater when performing the first flight of an unmanned aerial vehicle (UAV) that operates fully automatically. This paper presents the design and planning of the first flight mission of the SAGITTA Demonstrator UAV and discusses its implementation in the automatic flight guidance and control system of the aircraft. Besides the nominal mission profile itself, this includes provisions for various contingencies in order to provide options of action to the test crew in case of unforeseen events. Results and experiences gained during preparation and execution of the first flight test campaign of the SAGITTA Demonstrator conclude the paper.

1 Introduction

The first flight of a new aircraft configuration presents the ultimate proof of concept for both its design and its realization. Despite the extensive possibilities of simulation and preflight testing that are generally utilized in advance, the maiden flight remains one of the most critical activities in flight testing.

This challenge is increased even further, when the configuration under test is an advanced unmanned aerial vehicle (UAV). In the case of a manned aircraft, a skilled test pilot is available, who could react to unexpected aircraft behavior or unforeseen events. In comparison, during operation of a highly automated UAV, there is generally less human involvement. Besides issues like lower situational awareness and increased reaction time, the options of action that are available to the test crew are generally very limited and essentially defined by the functionalities provided by the automatic flight system of the vehicle, see [1].

At the Institute of Flight System Dynamics of the Technical University of Munich (TUM-FSD), such an automatic flight guidance and control system has been developed for the novel 'SAGITTA Research Demonstrator.' A consortium of industrial and academic project partners in Germany has newly designed and built this fixed-wing UAV as a technology-testing and demonstration platform, see, e.g., [2] or [3]. Figure 1 shows the aircraft, which features a diamond-shaped flying-wing configuration (wingspan: 3 m, maximum take-off mass: 150 kg), during its fully-automatic first flight, see [4].

This paper presents the design considerations and the implementation of SAGITTA's first flight mission in the UAV's automatic flight system. For this, a general overview of architecture and functionalities of the system is given in Section 2. A detailed description of the mission objectives, planning, and implementation follows in Section 3.

Fig. 1 The SAGITTA Demonstrator UAV during its fully-automatic first flight [5]

Furthermore, Section 4 explains the implemented safety precautions and options that are provided to be able to react to inflight contingencies. Results and experiences from the actual first flight of the SAGITTA Demonstrator are discussed in Section 5, before a summary concludes the paper (Section 6).

2 Automatic Flight Guidance and Control for the SAGITTA Demonstrator

The workshare of TUM-FSD within the SAGITTA project included the definition of the hardware system architecture for the flight control system and the development of the its functional software including flight control algorithms and higher-level automation, see, e.g., [6, 7, 8].

2.1 System Architecture

In its first flight configuration, the FCS of the SAGITTA Demonstrator corresponds to a single-string full-authority digital fly-by-wire system. It consists of sensor equipment including an integrated navigation system with differential GPS, an air data system, and a radar altimeter, as well as a flight control computer (FCC), on which the functional software for automatic flight guidance and control is executed.

2.2 Modular Guidance and Control System

A modular design for the FCC software algorithm has been developed at TUM-FSD to be able to adapt the functionalities to the requirements of different target platforms. Figure 2 depicts the setup used for the SAGITTA Demonstrator.

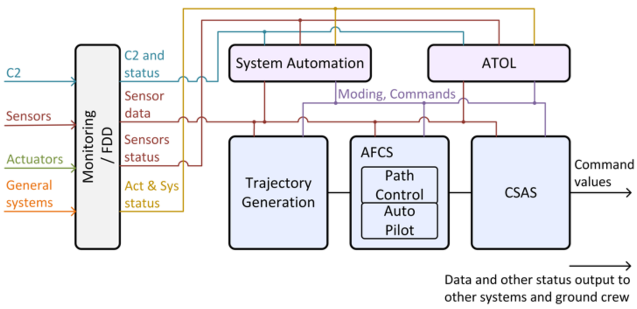

Fig. 2 Modular structure of the auto flight system algorithm of SAGITTA [7]

Input data to the FCC are initially processed by a monitoring / fault detection and diagnosis (FDD) module, see [9]. Different operating modes of the system are handled by a system automation module, see [8]. It facilitates the operation of the aircraft at different levels of automation:

- In a so-called low-level command mode, the aircraft can be flown manually by a remote pilot with attitude control provided by the control and stability augmentation system (CSAS). [6, 10]
- A medium-level command mode is available for automatic flight with autopilot functionality, as provided by an automatic flight control system module (AFCS). [11]
- The automatic following of flight plans, which are predefined as waypoint lists, represents the high-level command mode. This involves the online trajectory-generation [12] and path-control modules [13].
- A separate module covers automatic take-off and landing (ATOL). It implements the automatic conduct of these maneuvers and related contingency procedures by utilizing the available control modules in the system setup. [7, 13].

3 First Flight Mission Design, Planning, and Implementation

In this section, the design considerations that lead to the definition of the first flight pattern of the SAGITTA Demonstrator are presented.

3.1 Objectives and Requirements

Generally, many factors influence the mission planning of a first flight and may result in contradictory requirements. Yet, the essential objective remains solely a safe take-off, en-route flight, and landing, cf. [1].

In the case of UAV, the paramount challenge is that the means of risk reduction in advance of the first flight are limited, because a stepwise putting into operation is not possible. All systems must function right on the first flight. Of course, exhaustive simulation trials are compulsory. Yet, their validity is restricted by the inevitable uncertainty of the simulation models employed for design and testing. Especially if the first flight of a novel configuration is to be conducted fully automatically, it is thus a major goal to make the design as robust to uncertainties as possible. In the case of the SAGITTA Demonstrator, the following aspects were considered:

- Operation close to the center of the predicted flight envelope, especially with respect to airspeed and climb gradients
- Nominal length of the flight leaving fuel reserves for unexpected alterations
- Favorable runway characteristics, especially dimensions, vertical profile, and terrain profile in runway extension
- Sufficient dimensions and shape of the segregated operation area and suitable location of the aerodrome within it
- Predominant wind conditions at the aerodrome restrict the selection of an appropriate runway and mission pattern
- Possible restrictions of technical systems, e.g., data-link or ground tracking-system range, GPS reception taken into account

3.2 Mission Pattern and Altitude

Considering the outlined objectives, it was found that the pattern of the first flight mission is predominantly driven by the design of automatic take-off and landing, as these two maneuvers must be connected to each other with the mission pattern.

The horizontal extent of the take-off maneuver is primarily affected by the climb gradient and the altitude to be attained. Thereby, a compromise must be made between the goal to establish a safe terrain clearance as quickly as possible on the one hand. On the other hand, the climb gradient should be low enough so that a safe margin to the anticipated maximum climb performance of the aircraft is maintained. In the case of the SAGITTA Demonstrator, a design climb angle of 3° was set, which relates to an expected maximum achievable climb angle of about 4.5° to 5° in the take-off configuration.

An en-route altitude of approximately 100 m above the ground was specified for the maiden flight profile. Again, this has been a result of contradicting requirements. Compared to the altitude range available for operation of the UAV, this value is quite low. However, the expansion of the flight envelope is generally not in the scope of a first flight. Apart from that, a lower en-route altitude reduces the extension of the required mission area, because the footprint area on the ground that may be affected in case of a crash is smaller. Moreover, visual tracking of the comparatively small UAV from the ground is easier when its altitude of flight is lower.

Based on the available area for operation, two principal flight patterns have been evaluated for the first flight. A ‘teardrop pattern’ involves a procedure turn after completion of the take-off and a subsequent landing in the opposite runway direction, see Figure 3. The advantages of this profile are that only a short distance needs to be covered and that the operation is confined to one side of the aerodrome. Disadvantages are though that either take-off or landing would most likely be in tailwind conditions and that the UAV moves relatively far away from the aerodrome.

Moreover, a ‘racetrack pattern’ corresponding to an extended traffic circuit has been evaluated and finally selected for the first flight of the SAGITTA Demonstrator, see Figure 4. The advantages of this pattern are that the UAV stays relatively close to the aerodrome and that both take-off and landing can be conducted in similar wind conditions, preferably headwind. On the downside, the pattern is typically longer and a large area around the aerodrome is affected by the operation.

Finally, a fuel planning must be made for the flight so that the aircraft ideally remains well below its maximum take-off weight, yet, enough fuel is available for go-arounds or contingencies.

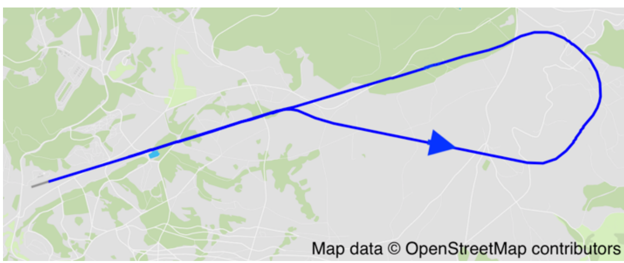

Fig. 3 2-D map view of a ‘teardrop pattern’ as investigated for the first flight of the SAGITTA Demonstrator.

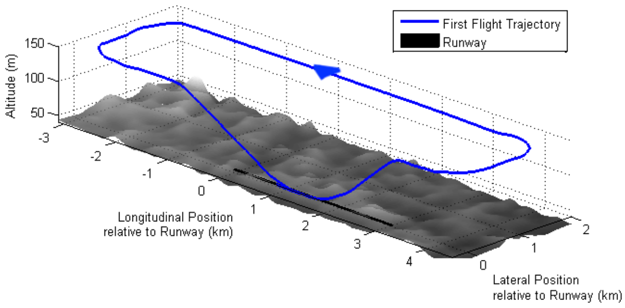

Fig. 4 3-D view of the trajectory of the first flight of the SAGITTA Demonstrator UAV. (Vertical axis not true to scale.)

3.3 Configuration Changes

Besides the planning of the mission pattern, the question arises, which functionalities of aircraft and FCS shall be tested, cf. [1]. A trade-off must be made between the extended operational possibilities resulting from more advanced system functions on the one hand, and the increased complexity and proneness to errors on the other hand.

In the case of the fully-automatic first flight of the SAGITTA Demonstrator, the guideline "as simple as possible, as complicated as necessary" has been applied for the planning of the flight test. It was decided to use only one of the available flight modes of the FCS in addition to ATOL. The flight pattern was thus implemented as a waypoint list for flight in high-level command mode with 3-D trajectory generation and control (see Section 2.2). In this case, the benefits of a predefined flight plan and automatic trajectory following outweighed the increased complexity of this operation mode with a comparatively high level of automation.

Consequently, the nominal procedure of the first flight consists merely of automatic take-off, high-level command mode, and automatic landing.

In addition to the FCS considerations, changes to the aircraft configuration must be assessed, e.g., high-lift devices or landing gear. On the one hand, these expand the usable flight envelope and possibly increase the margin to the boundaries thereof. On the other hand, such configuration changes inevitably entail the risk of a malfunction that would likely result in severe damage or even a total loss of the aircraft.

As the SAGITTA Demonstrator does not feature high-lift devices, only the question of landing-gear retraction was applicable. It was decided to leave the landing gear down as this avoids inflight reconfiguration of flight control laws and simplifies landing gear requirements. On the downside, the flight envelope of the aircraft is reduced by the additional drag. However, the performance of the SAGITTA Demonstrator permitted the flight with extended gear, which is not generally the case, see [1].

4 Contingency Action Planning

Despite great efforts for high-fidelity simulation models (see, e.g., [3]), it must be expected that the behavior a novel aircraft configuration differs from simulation. Moreover, considering the complex setup of ground and air systems required for UAV operation, unforeseen events, system faults, or failures could occur.

In order to increase the probability of being able to recover from such contingencies, the FCS design must provide adequate reconfiguration possibilities in flight and the test crew must be well prepared for the available options, cf. [1].

In the following subsections, contingency considerations are outlined that were made in conjunction with the FCS design for SAGITTA's first flight.

4.1 During Take-off

The automatic take-off system was designed to enable a take-off abort as long as the rotation for lift-off has not been initiated. During an abort, the throttle would be cut off and the ground controller would apply the brakes and maintain centerline tracking until standstill. A take-off abort could be initiated either manually by the UAV operator or automatically by the take-off system itself. It has been designed to continuously monitor the status of the flight control system as well as certain take-off-maneuver-related conditions, such as the remaining runway distance. If an anomaly is detected, the system automatically aborts the take-off, see [9, 14].

The moment of lift-off and the initial climb are particularly critical as this is the first time that the aircraft must be aerodynamically controlled by the FCS. Several reconfiguration options were briefed with the test crew for a scenario in which the automatic take-off system provided inadequate control of the UAV. Depending on the situation, the flight operator could engage the medium-level command mode. By this, the autopilot controller would be engaged instead of the trajectory controller. Moreover, the external pilot could be asked to take manual control of the UAV. This would revert the FCS to the low-level command mode and engage the attitude-control law. It was clear, however, that due to its speed the aircraft would move out of the line of sight of the external pilot quickly after the take-off.

Besides these manual reconfiguration options, a contingency procedure has been implemented in the automatic take-off system for a GPS-loss scenario, which was considered reasonably probable. In this case, the take-off system would automatically disengage trajectory tracking and engage the autopilot instead. Based on magnetic heading, barometric altitude, and a timing by the ATOL system, the take-off could be safely completed without GPS, see [14].

4.2 En Route

As pointed out in Section 3.3, the en-route part of the flight is nominally conducted in high-level mode. An ‘immediate loiter’ functionality has been implemented in the FCS to make the UAV hold in a circular pattern at an arbitrary position. Remaining fuel permitting, this may be used to pause the mission and could give additional time, e.g., for issue solving or decision making.

Otherwise, if the UAV shall be landed as quickly as possible, two different ‘return-to-base’ flight plans were implemented as special high-level-command modes, cf. [8]. They allow the flight operator to command the aircraft to automatically return to a suitable position for landing from anywhere in the mission area. Figure 5 shows a map view with the track of a simulated first flight (blue line). As long as the aircraft is in the lower part of the mission area, the return-to-base list 1 would be selected, consisting of the waypoints marked in light blue. It guides the aircraft onto the extended centerline and then towards the runway threshold.

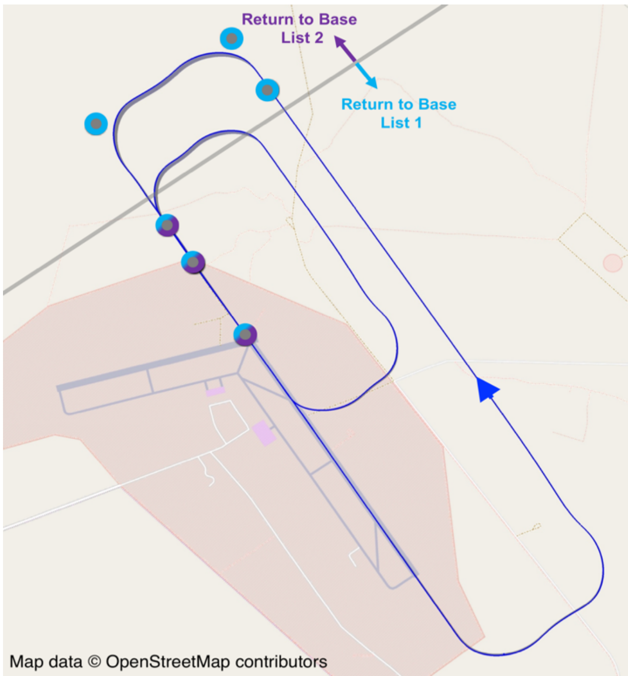

Fig. 5 2-D map view of a simulated first flight of the SAGITTA Demonstrator UAV with go-around (blue line). Waypoints of the return-to-base list 1 (light blue) and list 2 (purple).

If the aircraft is in the upper part of the mission area (above the grey line at the top of Figure 5), return-to-base list 2 would be more suitable (purple). It does not involve the turns onto the extended centerline, but merely consists of the last part leading to the threshold.

Besides the return-to-base application, these two flight plans are also automatically invoked by the FCS in case of a complete data link loss to the ground control station, see [8]. By this, the aircraft would automatically return to the airfield where data link reception should be best.

In case of a GPS loss during the en-route flight, the FCS would automatically revert to medium-level command mode. The operator would then have to navigate back to the airfield with heading-, altitude-, and speed-commands.

4.3 During Landing

The automatic landing system of the SAGITTA Demonstrator features an automatic go-around procedure, cf. [14]. Analogous to during take-off, the system continuously monitors the progress of the landing maneuver and the FCS status. If a condition is violated, the system automatically performs a go-around, as shown in Figure 6.

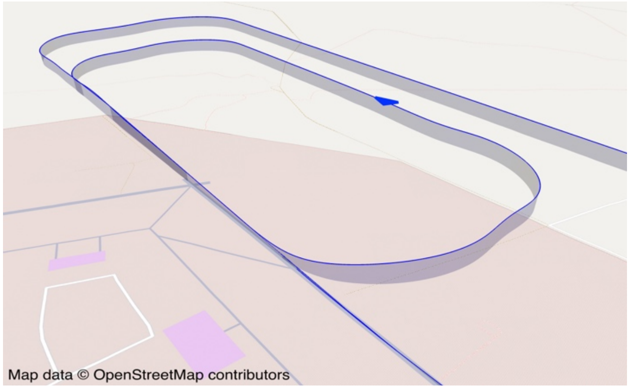

Fig. 6 3-D view of a simulated go-around of the SAGITTA Demonstrator UAV (blue line). The altitude above ground is visualized with the shaded areas below the trajectory. (Vertical axis true to scale.)

The go-around pattern resembles a smaller racetrack (cf. Figure 5) and leads directly back to the intermediate and final approach. Besides automatic activation, the go-around can also be triggered by the flight operator. However, at any case it is only possibly when the aircraft has not descended below a predefined decision altitude.

Again, dedicated procedures were implemented in the automatic landing system for a GPS loss scenario, see [14]. Above the decision altitude, the system would perform a no-GPS go-around procedure, based on heading, barometric altitude, and timing. If a GPS loss occurred below the decision altitude, the automatic landing system would attempt to continue with heading, barometric altitude, and radar altimeter only. While lateral centerline tracking is not possible anymore without GPS, reasonable chances remain to safely descend to the ground.

In case a technical problem prevents the execution of an automatic landing completely, the last resort is a manually-controlled landing by a remote pilot. For this, the aircraft would be maneuvered onto the extended runway centerline by the flight operator either with the return-to-base mode or with medium-level commands. The external pilot would then take control and manually land the aircraft. Due to the limited line of sight from the ground, the comparatively small size of the UAV, and its high speed, such a manual landing was considered very challenging. Nonetheless, simulation trials with the external pilots had proven its feasibility.

5 First Flight Execution of the SAGITTA Demonstrator

Fortunately, the first flight of the SAGITTA Demonstrator UAV was successfully conducted fully automatically with automatic take-off, high-level command mode, and automatic landing exactly as planned.

Anyhow, as is illustrated in this paper, significant effort has been spent on preparing for contingencies. Thereby, some important lessons have been learned.

Besides nominal FCS operation modes for the first-flight mission, it is important to have a range of alternatives that allow flight guidance and control in abnormal conditions. The scope of action available to the test crew is essentially driven by the provided FCS functionality, cf. [1]. The work load and stress level of the crew are easily increased many times over if an FCS function is not available as expected and a workaround or alternative procedure is needed.

To a certain extent, this effect can be mitigated by simulation training. Rehearsals of both the nominal mission and contingency scenarios with the complete test crew have proven highly valuable for training of procedures and tasks as well as to create a common understanding of the technical systems involved.

Finally, in order to enable a timely reaction to unforeseen events, it is important to have discussed, clarified, and agreed on contingency procedures for all thinkable situations in advance of the actual flight. Throughout the preparation for the first fight of the SAGITTA Demonstrator, it was clearly recognizable how the crew became more and more proficient the more contingency scenarios had been trained and handled in simulation.

6 Conclusion

The definition and implementation of an automatic first flight mission for a UAV is a complex task. In this paper, the relevant considerations have been illustrated by the example of the novel SAGITTA Demonstrator UAV.

First, it has been discussed how the nominal mission profile has been specified as a compromise between keeping the aircraft close to the center of its performance envelope and achieving a reasonable maneuver performance. Resulting from the paramount objective of a first flight, i.e., a safe take-off, en-route flight, and landing, it has been found that the mission is essentially driven by the take-off and landing flight patterns. For the SAGITTA Demonstrator, a racetrack pattern has been implemented for the first flight that corresponds to a traffic circuit.

In addition to the definition of the nominal mission, even more effort has been spent on contingency procedures. Especially in the case of an automatically operating UAV, numerous unexpected conditions, faults, or errors may occur. Consequently, it is important to provide the test crew with adequate options of action in the form of versatile and robust functionalities of the flight control system. In this paper, the contingency procedures have been discussed that were designed and implemented for the first flight of the SAGITTA Demonstrator.

Finally, experiences and lessons learned from the execution of the first flight campaign of SAGITTA have been compiled. Thereby, the importance of well thought-out flight-control-system functions and adequate training of the test crew has been emphasized.

Fortunately, the first flight of the SAGITTA Demonstrator could finally be conducted exactly as planned and was successfully completed fully automatically.

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Contact Author Email Address

mailto: me.kuegler@tum.de

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