Introducing Digital Air Traffic Controllers for Urban Air Mobility to Ensure Safe and Energy-efficient Flight Operations

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Research Article

Keywords: urban air mobility, air traffic control, automation, artificial intelligence, digital controller, control zone

Posted Date: December 20th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-3771775/v1

Additional Declarations: No competing interests reported.

Abstract

Facing the continued growth of cities, the introduction of urban air mobility intends to reduce traffic congestion and improve the quality of services such as on-demand-transport, reduced travel times and increased connectivity. Nevertheless, its integration into existing air traffic flows remains one of the biggest challenges ahead, especially once controlled airspace overlaps with urban air mobility areas, such as at airport control zones. Here, air traffic control needs to coordinate among urban air mobility vehicles and conventional air traffic. In 2022, DLR conducted a human-in-the-loop simulation with ten air traffic controllers to validate previously developed workflows for that coordination task applied for Hamburg airport. The simulation results revealed that additional urban air mobility traffic increases controllers' experienced workload up to 30% while slightly reducing their perceived situation awareness. Thus, a majority of controllers participating in the trials suggested to introduce an additional controller working position to exclusively control airtaxis and traffic following visual flight rules. This option is assessed as owning a high potential as cost intensive adaptions of regulations and procedures can be omitted. Nevertheless, the feasibility of this option is rather low due to the limited availability of endorsed human controllers.

This study proposes a concept for a digital controller taking the responsibility of guidance for airtaxis under visual flight rules traffic (abbr. VFR) within a control zone. This digital controller is named "UAM digital controller" (abbr UDC) and based on algorithms calculating slots and trajectories which have been validated in previous DLR projects. The UDC coordinates with the human controller once a potential conflict is detected. Within the study, first the concept of the digital controller is defined, following existing work. As a second step, a theoretical evaluation based on an air traffic control task model and an operational concept for airtaxi integration will analyse the task load reduction for the human controller. Last but not least, the expected energy saving of flight operations by the digital controllers will be assessed.

1. MOTIVATION

The European Commission mentions in its flightpath 2050 particularly the reduction of door-to-door travel times and a seamless transport as one of the important objectives for the future air traffic system (cf. [1], p.63ff.). Specially in Germany this objective is challenging as all transport modalities are expecting an increase of passenger traffic (cf. [2], Tab. 2). Hence, flexibility for synchronizing the transport modalities is missing and additional capacities need to be raised.

The air traffic system has at least one potential to be expanded: The usage of the very low airspace for urban and short-haul flights (cf.[3], ch. 1). By introducing airtaxis for inter- and intra-city connections, congestion on the road and rail systems can be overcome. As these airtaxis do have the option to be electrically powered (cf. [3], ch. 4), reduced travel times in combination with environment-friendly transport are possible. A major challenge to this approach is the integration into the existing air traffic system. Additional traffic requires additional air traffic control which is lacking of staff (cf. [4]).

This paper proposes to introduce a digital controller. This controller is designed to handle the urban and short-haul air traffic automatically. Based on a use-case of Hamburg the duties of the digital controller are derived and summarized in a concept of operations. Following the concept of operations, the technical requirements are specified and a system design is suggested. The paper is concluded by a critical discussion of the system design and an outlook onto the future research activities to prove the feasibility of the digital controller for urban and short-haul flights.

2. EXISTING WORK

system was subject to former research of the German Aerospace Center (abbr. DLR) in the project HorizonUAM (cf.[3]). Based on the example of Hamburg, efficient airway and landing spot design was achieved as shown in Figure 1 (cf. [5]). Moreover, fast time simulations proved that the urban traffic is mostly independent from the conventional air traffic except for crossing of the final approach as well as emergency situations (cf. [5]).

Although the airtaxi route network is sufficiently separated from the conventional traffic, air traffic control still needs to provide clearances according to ICAO rules (cf. [6], ch. 5.2.1): Comparable to special VFR traffic, the airtaxis are operating within the controlled airspace and need to be considered once IFR traffic is operating. Through human-in-the-loop simulations, DLR evaluated the impact of introducing airtaxi operations onto air traffic controllers (cf. [7] and [8]). Given the traffic load of up to 15 airtaxis per hour, a workload increase of about 30% was observed. Controllers participating in the simulations stated that in principle traffic was manageable, as they were mainly monitoring the urban traffic but they would like to delegate it to a second controller in case of increasing traffic. This second controller can focus on the urban traffic and coordinate with the tower controller once the final approach needs to be crossed or conflicts with conventional traffic are building up.

This additional staff for a second controller is hardly available today (cf. [4]). As a DLR fast-time simulation shows, automation through two validated algorithms might provide a solution to guide airtaxis (cf. [9]). One algorithm uses a slot-based approach ensuring that airway and airport capacity is not exceeded (cf. [9], ch. II A). The second algorithm is based on 4D trajectory calculation and allows for detailed traffic pre-calculation (cf. [9], ch. II B and [10]). Both algorithms demonstrate that a delegation to automation in theory is possible.

Both algorithms could be used as the basis to delegate the urban air traffic to an automatic air traffic control unit. To ensure a safe and efficient guidance, a comprehensive integration into ATC procedures is required. Therefore, DLR designed the concept of the digital air traffic controller as shown in Figure 2 (cf. [11]).

The digital controller is designed to replace the planner in a single controller operation at a radar center and redefine the workshare between human and automation. As such, it receives summarized data from a data service entity which gathers and merges multiple sources. The data is analysed and the overall situation assessed. Out of this situation and the monitoring of the flight, an activity plan is generated.

This list of tasks and clearances is communicated to the air traffic controller in command by highlighting certain flights or areas at the Air Situation Display (abbr. ASD) or at a special interaction display dedicated to this purpose. Additionally, it is able to implement certain tasks automatically. This solution is under validation for use cases in enroute and approach airspace. A similar concept could be also implemented in an air traffic control tower environment.

3. METHOD

the area of tower control. The result of this transfer is called UAM digital controller (abbr. UDC). The decision-making core of the UDC is based on the existing slot- and trajectory algorithms for a safe and efficient guidance of the urban air traffic. The transfer is conducted in four steps as shown in Figure 3.

The preceding human-in-the-loop simulations (cf. [7] and [8]) specified a set of ten operation rules (cf. Annex A) which are the basis for all following steps. The rules are focussed on the conducted simulation (e.g. adapted to a given scenario, written for quick understanding) and were examined by air traffic controllers and air traffic management experts. As such they are a valid basis to define a more general operational concept.

3.1. Operational Requirements

The first step of the design process is to take the ten rules and reformulate them as general operational requirements following a standard requirement scheme (cf. [12], ch. 4.2). Thereby, five requirements are derived which define:

- Takeoff clearance at the vertiport of Hamburg airport (so called vertiport east)
- Landing clearances at the vertiport of Hamburg airport.
- Clearance to enter the control zone prior to takeoff from any inner-city vertiport.
- Approval to leave frequency short before or after landing at any inner city vertiport.
- Rerouting of a flight

3.2. Operational Tasks

As a second step, each requirement was particularized into a sequence of the necessary tasks. Therefore, a certain set of tools is assumed to be available for the controller for instance an air situation displays (abbr. ASD), a voice communication system (abbr. VCS) and an electronic flight strip display (abbr. EFPS) which are utilized to fulfil the tasks. Out of the five requirements, 42 single tasks were derived. For example, the requirement to clear an airtaxi upon a reroute request broke down into the following sequence:

1. ASD: Traffic conflict detected
2. ASD: Check new route clear of traffic
3. EFPS: No traffic assigned for the new route

4. VCS: Clear airtaxi to proceed to new waypoint
5. EFPS: Enter new route on the flight strip
6. UAM: Send route update

3.3. Operational Requirements

The design step three consists of two actions. Initially a deduction onto the technical requirements of a standard working position for a human controller was performed. Hereby, 22 technical requirements were specified, again following a standard requirement scheme (cf. [12], ch. 4.2) and being linked to one or more operational tasks. The first task of the rerouting for instance manifests into “The airside situation display must offer the possibility for the air traffic controller to see the current and future positions of all aircrafts and airtaxis relevant to her or his area of responsibility (abbr. AoR)”.

The next action was to reformulate the requirements of a standard working position into requirements for the UDC. Therefore, the functionality of the human controller was added and reformulated as requirement for the UDC. Again, given the example of the first rerouting task:” Detect traffic conflict” which resulted into “show aircraft / airtaxi position” as a standard technical requirement extended to “the digital controller must be able to receive the position data of all aircraft / airtaxi in the airspace under control”, “the digital controller must calculate a 4D trajectory” and “the digital controller must detect conflicts in the trajectory”. In total, 25 requirements for the digital controller were specified (cf. ANNEX C).

To conclude the design, the basic structure of a digital controller is used, extended and adapted in accordance to the requirements. The resulting structure of the UDC is presented within the next chapter. To verify the controller a static testing is applied and so-called walkthroughs (cf. [13], [14]) based on the simulation scenario with 15 aircraft were conducted.

4. RESULT

4.1. Component-Structure

The structure of the digital interactive radar controller as designed in [11] and shown in Figure 2, requires some adaption to meet the requirements of the UDC. In contrast to the digital interactive radar controller, this controller is designed to independently guide traffic, rather than conducting planning actions and using as a support for an active controller. Moreover, an additional interface to coordinate with the UAM system is required. The resulting components structure is shown in Figure 4.

The data service component is replaced by multiple data interfaces to allow for UAM interaction (Figure 4 left side). The connection to the air situation display is eliminated (Figure 4 right side) and replaced by a clearance generator component. This generator translates a certain action into the commands for the different systems. For example, a takeoff clearance is translated into a takeoff message for the UAM system, a takeoff-status for the flight plan and an audio clearance for the airtaxi pilot.

4.2. Class Structure

The component structure is further detailed into a class structure with each class serving a functionality. To better visualize the classes within the paper, the class structure is visualized by the input part (data analysis and situation evaluation component) and the output part (activity plan, monitoring and clearance generator). Figure 5 shows the input part.

The input class diagram shows how the different data sources are merged. Audio (e.g. pilot requests), aircraft position and flightplan data are associated with the referenced flight. In this process, audio data requires special treatment as the audio stream must be translated into commands initially (cf. [15]). The multiple flight objects are then joined into a traffic situation object which is enhanced by a calculated UAM network plan. The slot algorithm (cf. [9]) is the basis of this calculation.

Based on the traffic situation class, the transfer into clearances (audio output) and system handling (e.g. route updates) are managed by the output part as shown in Figure 6.

Within the output part, the traffic situation is analysed by the task model and the monitoring class. The task model checks in which state each flight is and acts according to the operational concept (cf. ANNEX A). If for instance an airtaxi owns the status „departed“ and asks for landing clearance, the specified actions of checking the vertiport for traffic and then issuing the landing clearance are conducted. All activities are fed into an activity list which serves as a buffer for the execution. All non-nominal cases (e.g. traffic conflicts) are handled by the monitoring class. This class checks the traffic situation and if the execution is in conformance with the issued clearances.

4.3. Activities

The UDC consists of a large set of activities. As pointed out in chapter 4.2 the task model and the monitoring activity are the two activities which determine the general behaviour of the controller. The monitoring activity as show in Figure 7 is basically triggered whenever a rerouting is requested or a deviation from the calculated trajectory is detected. In consequence, a new trajectory is calculated, checked against conflicts and forwarded as three activities (direct-to-command on the VCS system, flightstrip update and UAM message).

The task model as shown in Figure 8 owns more tasks than the monitoring activity. It is either triggered whenever an airtaxi is in 2NM distance to the final approach fix (abbr. FAF) or a request of an airtaxi is received.

The activity is designed as a basic decision-tree-structure which can be summarized as the following cases:

- Enter control zone (airtaxi departing from inner-city vertiport): Check traffic load and vertiport clear of approaching / departing aircraft.
- Leave frequency (airtaxi landing on inner-city vertiport): Check airtaxis is short of vertiport

- Ready for departure (airtaxi departing from airport): Check traffic load and clear of traffic on final approach / departure
- Airtaxi 2NM from Final Approach Fix (airtaxi landing on airport): Check clear of traffic on final approach.

The design is concluded with the presented activities. The class diagram and the activities form the basis for the evaluation in the next section.

4.4. Evaluation

The evaluation took the 15 airtaxi flights from one human-in-the-loop simulation scenario (cf. [7]). Each flight was performed as a theoretical walkthrough. The simulation recorded takeoff- and landing times of the airtaxis and the conventional traffic. These times were used to initiated the walkthrough. Initially, the content of traffic situation object was generated by collecting all active aircraft five minutes prior to the landing / takeoff. These aircrafts were used as the content of the traffic situation object. Based on this object the task model activity and the monitoring activity were theoretically calculated step by step. The outcome was evaluated regarding safe and efficient air traffic. Figure 9 shows an example of a walkthrough for an airtaxi taking off at an inner-city vertiport.

In total, 15 airtaxis with 35 situations were examined in the evaluation. As a result, the following deficiencies in the model were detected:

- Data synchronisation: The current model assumes that data input and activities are sequential. In the operational system the data of the different sources will not be synchronized thus a component to buffer and collect the data is required.
- Hold Strategy: Currently the UDC commands an airtaxi to hold, but the point in time when the airtaxi is cleared to continue, especially in situations when multiple airtaxis are on hold. A sufficient strategy needs to be designed therefore.
- Output speed: In the current design, the UDC sends commands whenever the decision is made. Depending on the implementation this can generate a very fast sequence of commands or even synchronous commands upon using parallel computing. For humans interacting the UDC this can lead to misunderstandings (cf. [16]).

5. DISCUSSION

The paper derives a design for a UAM digital controller, capable of actively handling airtaxis in the control zone of an airport. Nevertheless, all assumptions made here are derived from a human-in-the-loop scenario of Hamburg. On other airports a different design might lead to better results. Nevertheless, as it was shown that a transfer of the general challenge from Hamburg to other airports is possible (cf. [5]), it is assumed that the basic structure of the UDC is also applicable to other airports.

A challenge currently not addressed in the design in detail is the coordination with the human controller and the possibility to transfer airtaxis to the human controller once the UDC is unable to find a solution. For those cases a comprehensive interactions design and integration into the UDC design is required.

6. OUTLOOK

As a next step, the UDC needs to be enhanced by the specified deficiencies and implemented. To prove the operational feasibility, the UDC should be validated in human-in-the-loop simulations. These activities are planned within a new DLR project for summer 2025.

Beside the further research on the UDC, digital controllers in general own a high potential. Specially for local air traffic control at the airport, comprehensive concepts are required.

Declarations

FUNDING

This research received no external funding.

CONFLICTS OF INTEREST

The authors have no competing interests to declare that are relevant to the content of this article.

INFORMED CONSENT STATEMENT

Informed consent was obtained from all subjects involved in the study.

Author Contribution

S. Schier-Morgenthal wrote the main manuscriptR. Abdellaoui prepared the operational tasks and requirementsI. Metz contributed with the related work

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Figures

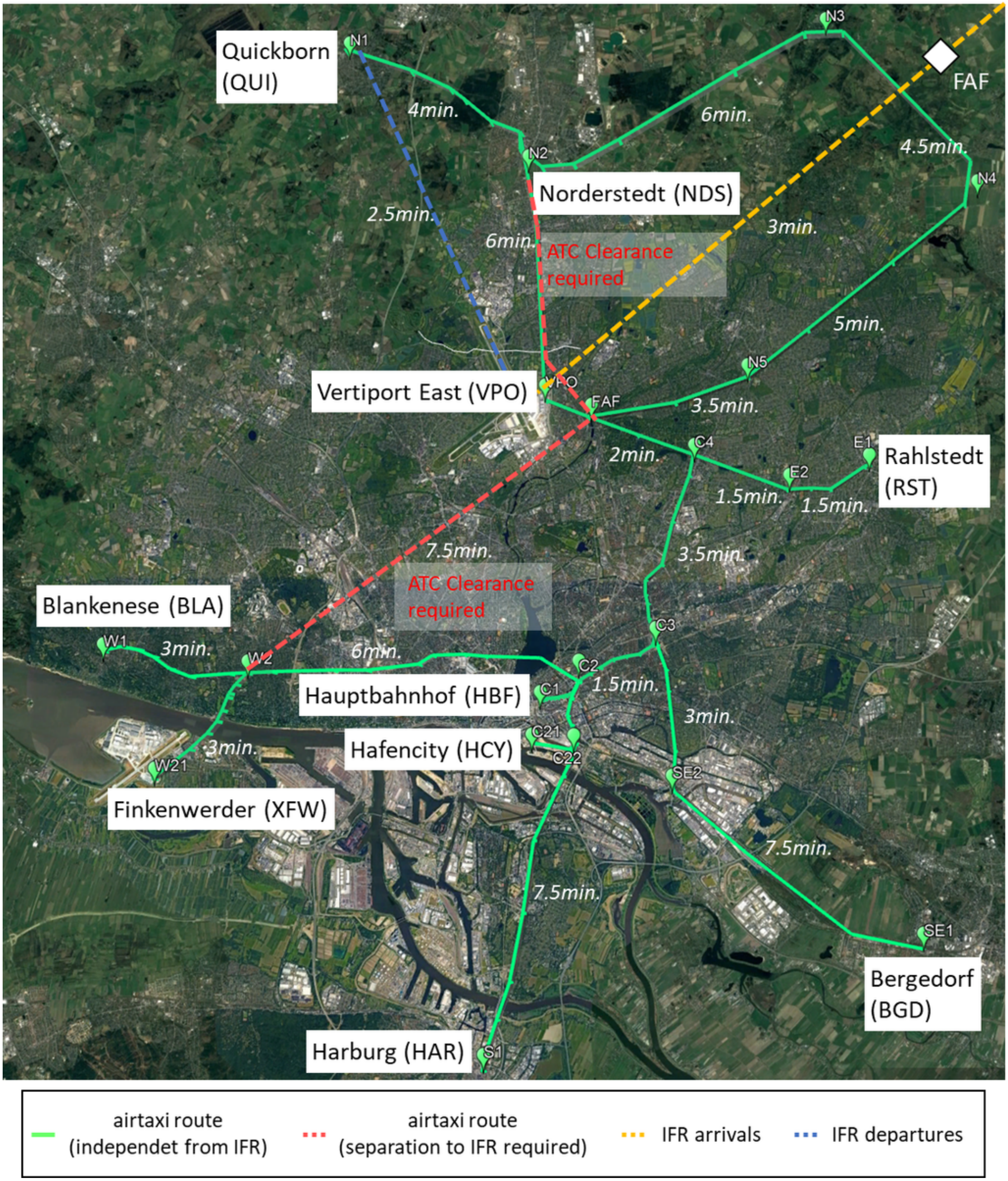

Figure 1

Chart of airtaxi routes as used in [5] and [7]

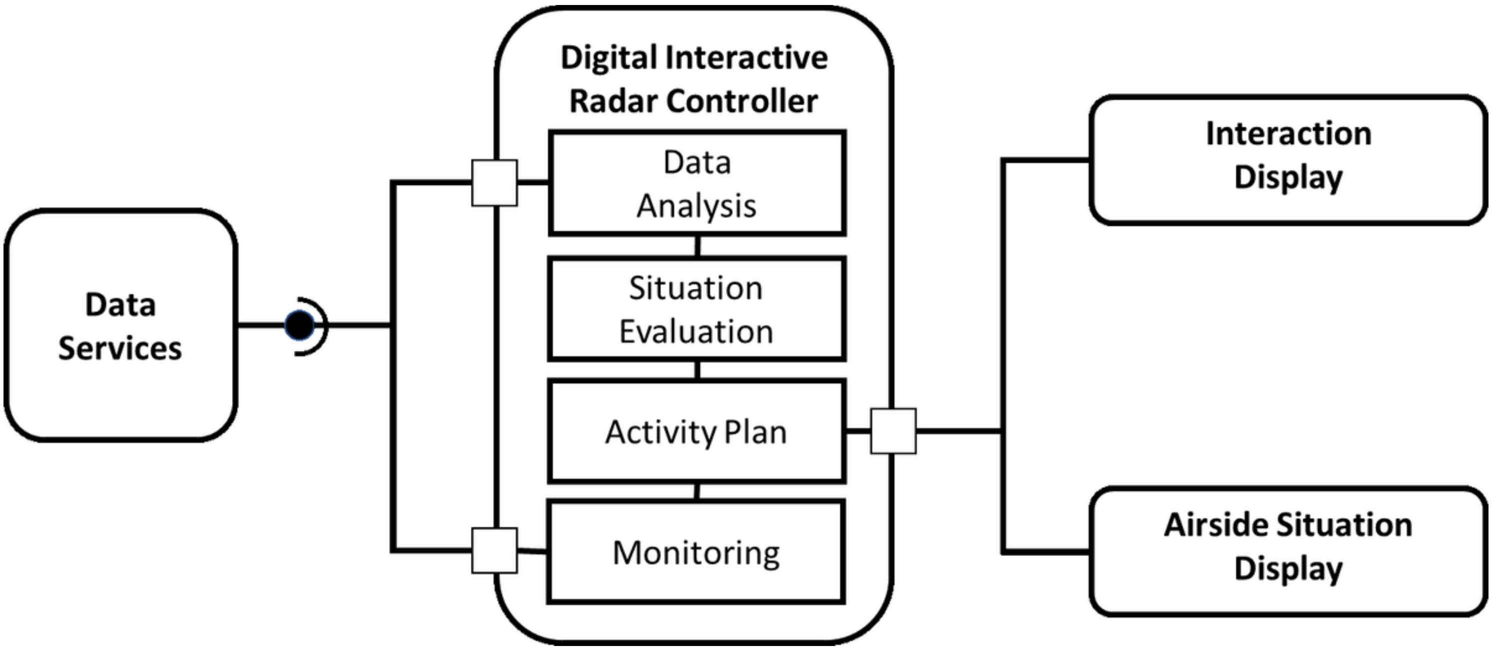

Figure 2

Design of the digital controller for enroute applications (based on cf. [11], fig. 5).

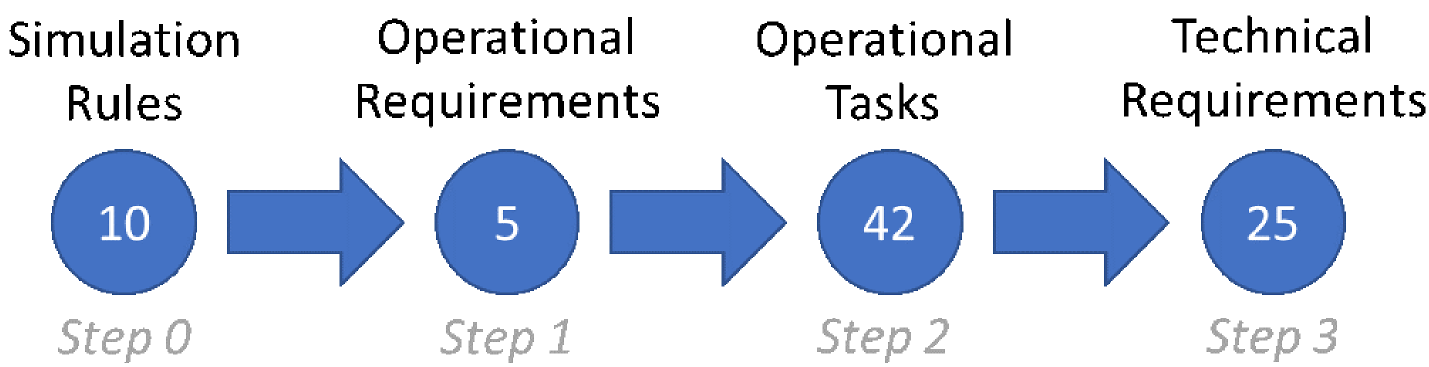

Figure 3

Steps towards the design of the UDC

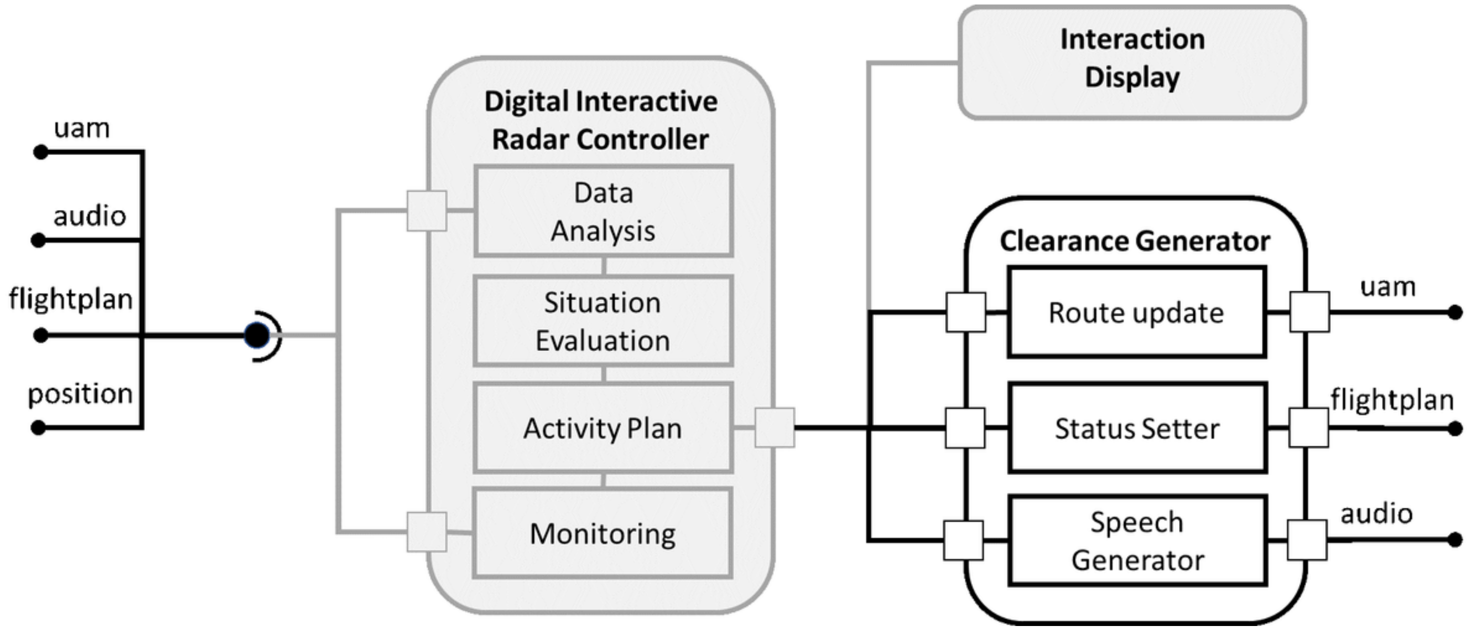

Figure 4

Component structure of the UDC.

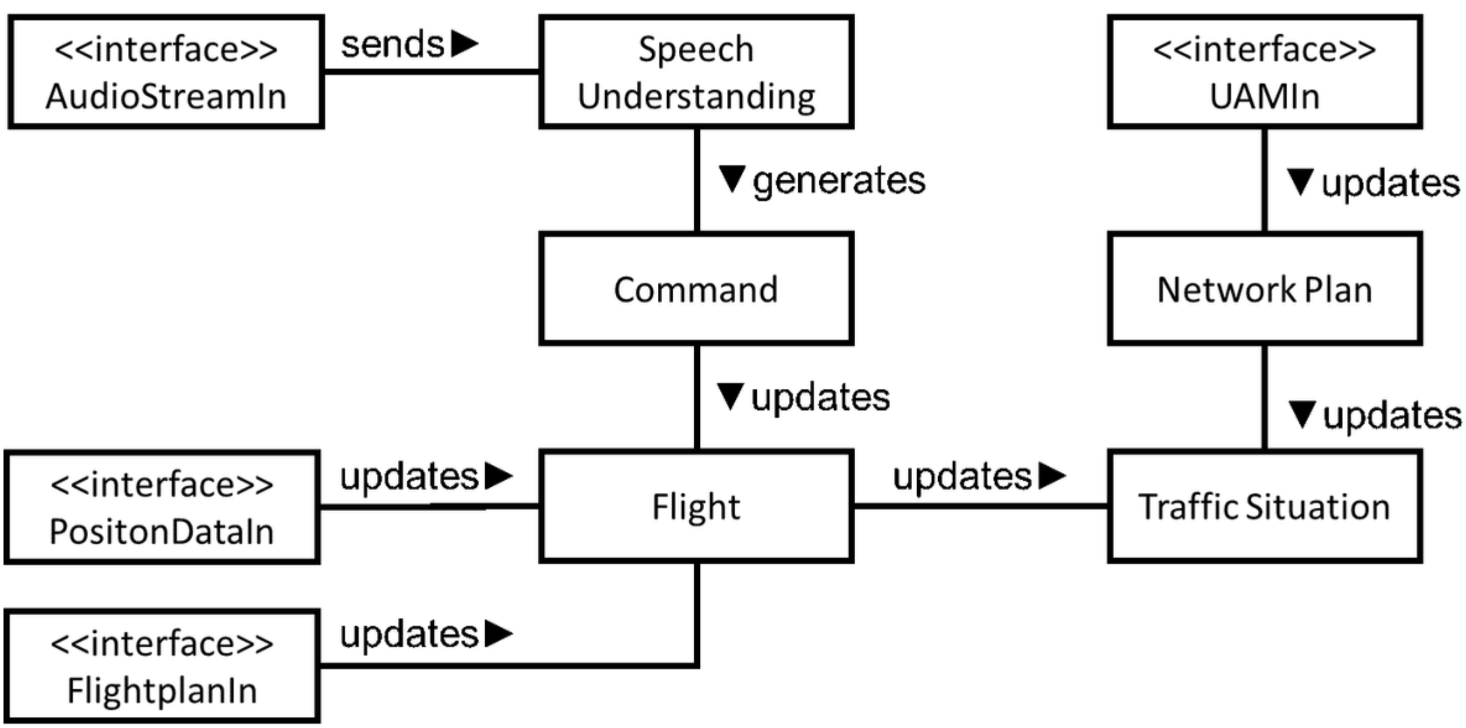

Figure 5

Class structure of the UDC input part.

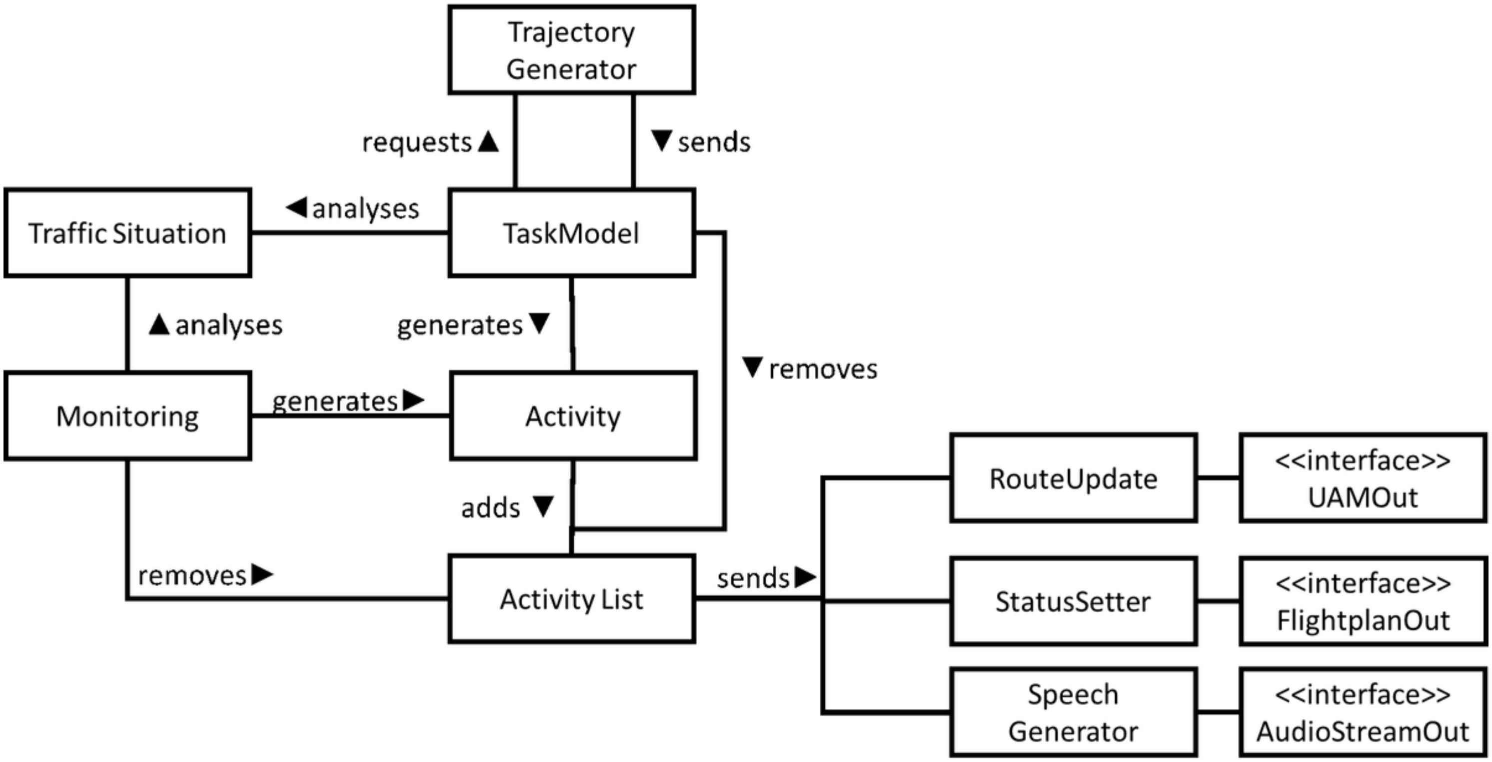

Figure 6

Class structure of the UDC decision and output part.

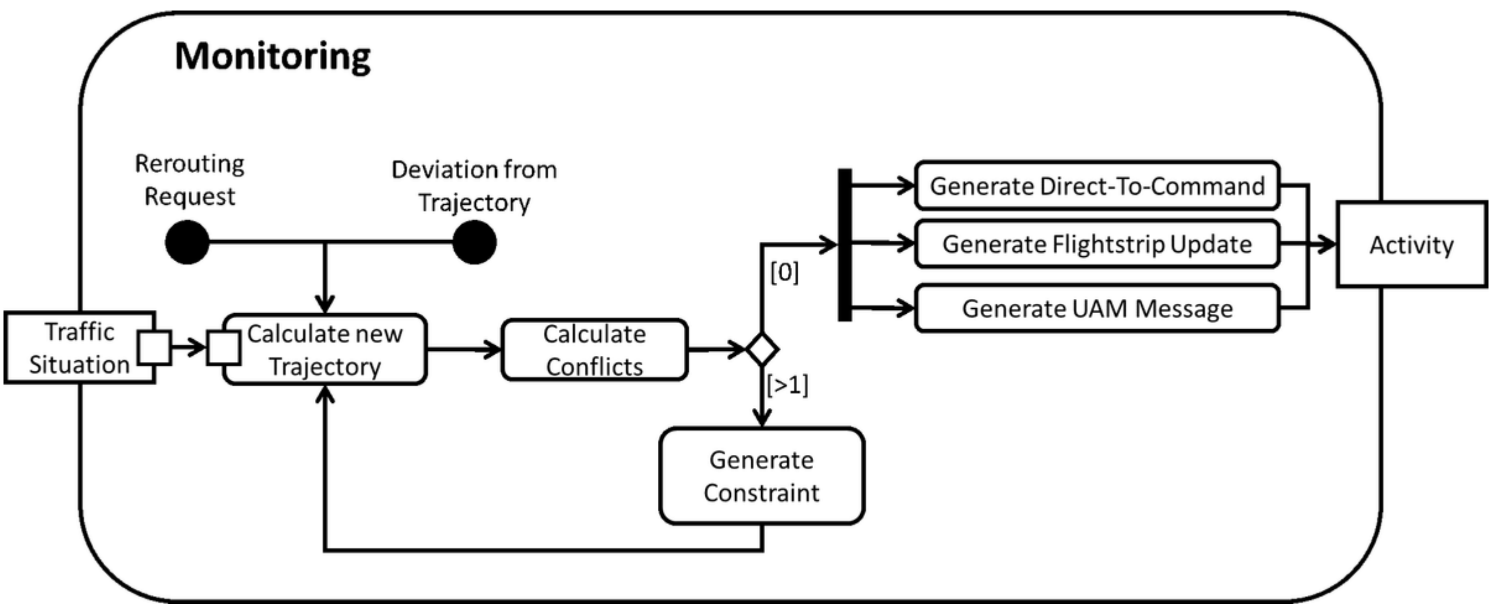

Figure 7

Activity diagram of the monitoring task

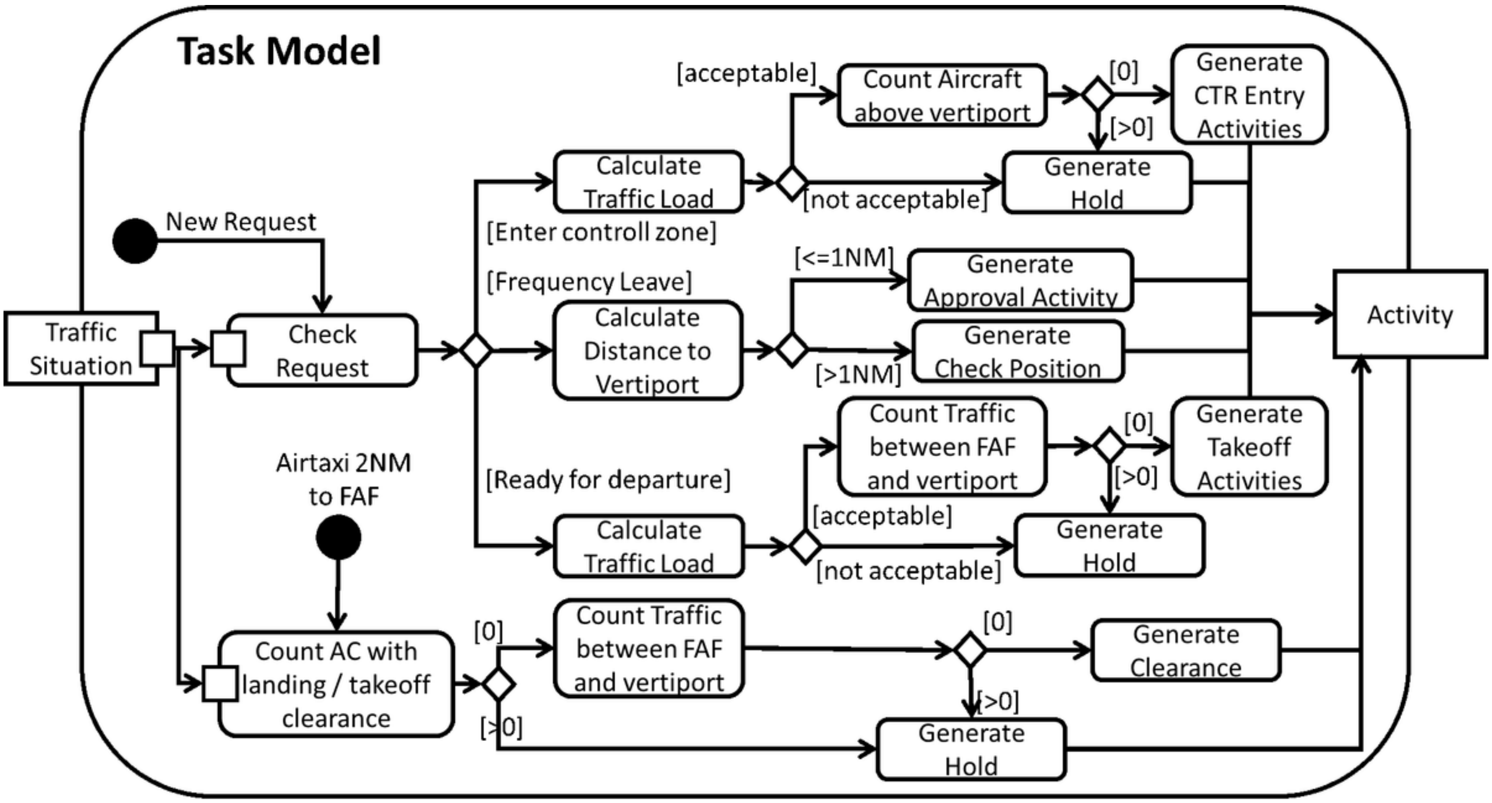

Figure 8

Activity diagram of the task model

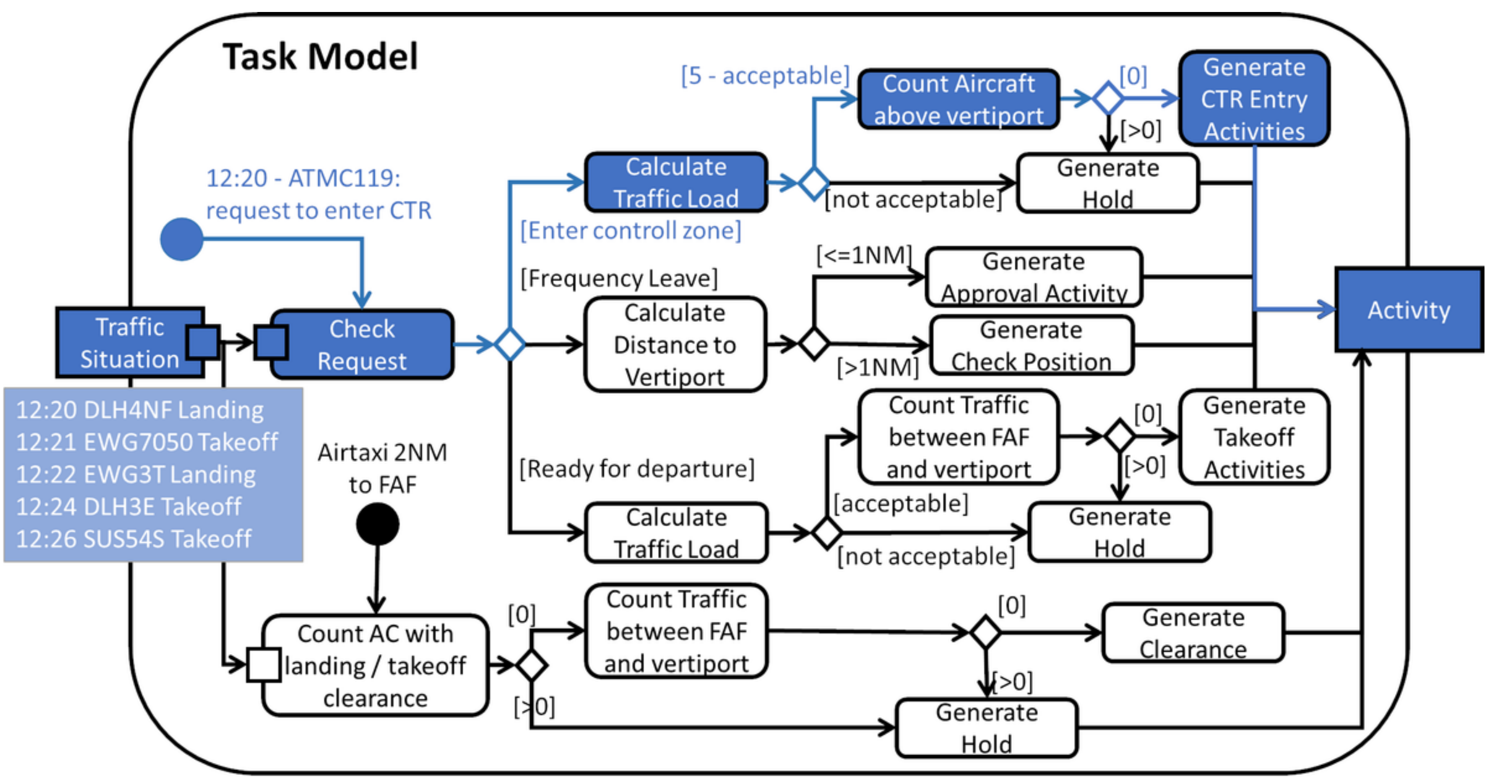

Figure 9

Theoretic walkthrough (example)

Supplementary Files

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- fig0.jpg
- Annex.docx