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ORIGINAL PAPER

Introducing digital air-traffic controllers for urban-air mobility to ensure safe and energy-efficient flight operations

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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 amobng 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 analyze 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.

Keywords Urban-air mobility · air-traffic control · automation · artificial intelligence · digital controller · control zone

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

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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

The integration of urban flights into the existing air-traffic 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 Fig. 1 (cf. [5]). The so called vertiport east (abbr. VPO) is the landing and takeoff spot for all airtaxis to and from Hamburg airport. The connected routes are defined for arriving and departing traffic. The traffic is vertically separated. Departing traffic has to be established on the assigned altitude when passing the final approach fix (abbr. FAF). Arriving airtaxis are allowed to leave their cruise altitude at the FAF. The labeled waypoints in Fig. 1 show the location of non-compulsory waypoints to be used for air-traffic control clearances. Moreover, fast time simulations proved that the urban traffic in this network is mostly independent from the conventional air traffic except for

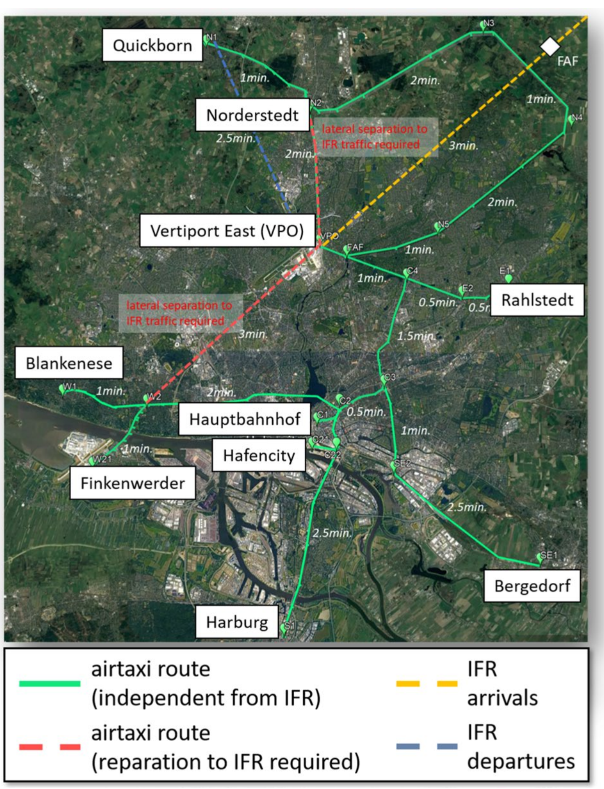


Fig. 1 Chart of airtaxi routes as used in [5] and [7]

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, 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 Fig. 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 are analyzed 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.

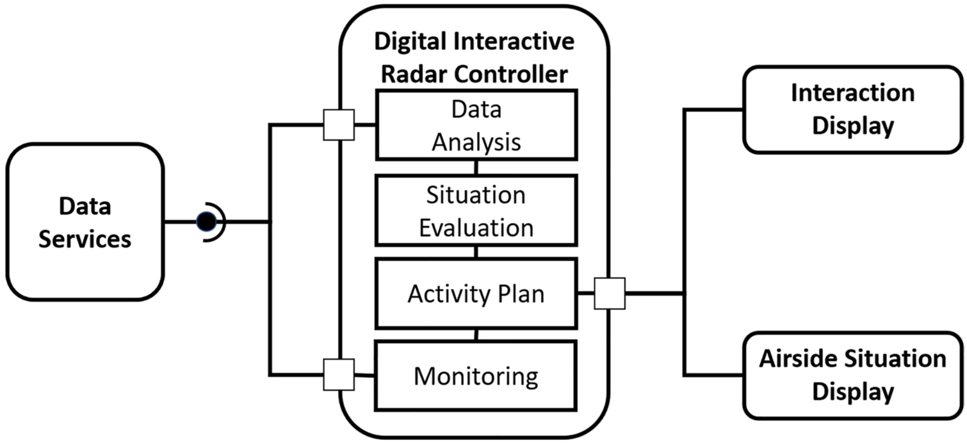


Fig. 2 Design of the digital controller for enroute applications (based on cf. [11], Fig. 5)

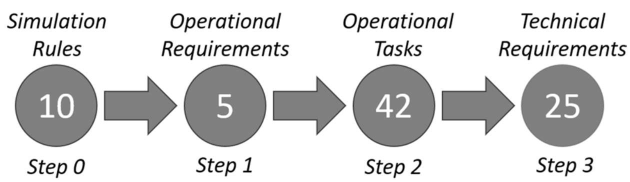


Fig. 3 Steps towards the design of the UDC

3 Method

This paper transfers the approach of the digital controller to 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 Fig. 3.

The preceding human-in-the-loop simulations (cf. [7, 8]) specified a set of ten operation rules (cf. Appendix A). These ten rules (step 0) were defined following ICAO procedures for air navigation service (cf. [14]) and critically reviewed by the participating air-traffic controllers of the simulation study. For this paper, the derived ten rules are transferred into requirements (step 1). This step is a formal step. The phrases and wording used in the ICAO procedures document as well as by the air-traffic controllers are translated into a requirement wording. Based in the requirements, the operational tasks are defined. Therefore, the controller working position setup as used in the simulations is considered. In sum, 42 operational tasks were derived. As a last step (step 3) the operational concept which defines the roles and responsibilities of human and digital controller is compared with the operational task. Each task that is within the responsibility of the digital controller is translated into a technical requirement for the digital controller. If a requirement is derived multiple times only one requirement is maintained.

This approach delivers specific results for Hamburg airport operations, as the distinct rules and working position of the simulation are considered. Nevertheless, the procedure in general is applicable to other airports. This potential is discussed in the outlook.

3.1 Operational concept

The airtaxi traffic for Hamburg is operating within the control zone. In here, air-traffic control is responsible for separation among IFR flights and VFR to IFR flights (cf. [14]). Therefore, the tower controller must issue a clearance once air traffic enters and exits the control zone. This is the case once the airtaxi departs or lands at a vertiport apart from the airport. The vertiport at the airport is in close location to the active runways. The design allows for independent approaches, but requires landing and takeoff clearance. Throughout the flight the tower controller must monitor the airtaxi whether a separation infringement to IFR traffic can occur. In the Hamburg environment, only a shortcut for the airtaxis crossing the final approach of runway 23 owns this risk, assuming that airtaxis follow the cleared route.

The general operational concept of a digital controller is described by Jameel et al. (cf. [11]). It aims to high automation as defined in (cf. [12], Fig. 4, p. 10) or beyond. By definition, high automation can initiate tasks. As soon as the area of human responsibility is affected, a coordination among human and automation is required. The application in this paper delegates specifically the responsibility for the airtaxi traffic to the digital controller. The digital controller provides the clearances for airtaxi control zone entry, control zone exit, takeoff at Hamburg airport and landing at Hamburg airport. A coordination among human tower controller and the digital controller is required if an airtaxi crosses the final approach of runway 23. This can affect the IFR traffic under the responsibility of the human controller. The digital controller itself is not interacting with the IFR

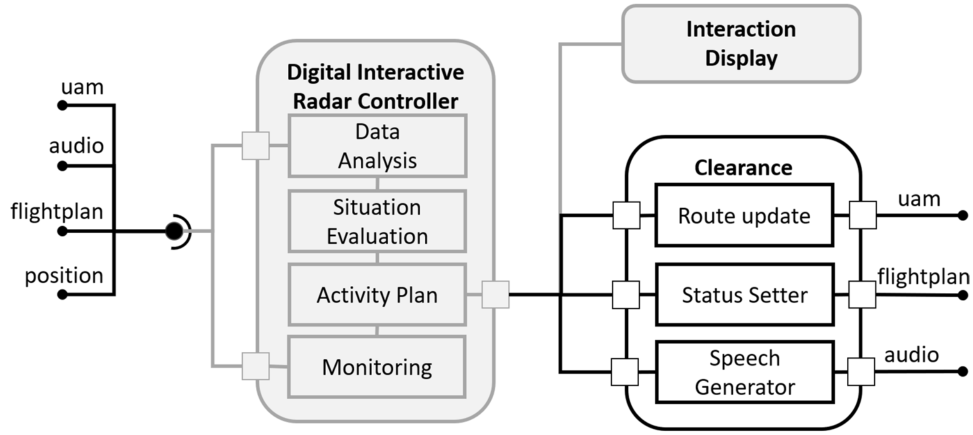


Fig. 4 Component structure of the UDC

traffic directly. A detailed description of the tasks is provided in (cf. Appendix B).

3.2 Operational requirements

The first step of the design process is to take the ten rules as specified in Appendix B and reformulate them as general operational requirements following a standard requirement scheme (cf. [15], ch. 4.2). Thereby, five requirements are derived which define:

- takeoff clearance at the vertiport of Hamburg airport (VPO)
- landing clearances at the vertiport of Hamburg airport (VPO).
- clearance to enter the control zone prior to takeoff from any inner-city vertiport.
- approval to leave radio frequency short before or after landing at any inner city vertiport.
- rerouting of a flight.

The detailed operational requirements are specified in Appendix B.

3.3 Operational tasks

As a second step, each requirement was particularized into a sequence of the necessary tasks. Therefore, a controller working position is assumed to be available for the controller. The working position consists of an ASD, a voice communication system (abbr. VCS), an electronic flight strip display (abbr. EFPS) and an interface to the UAM system. The interface to the UAM system is required to communicate for instance trajectory changes to the airtaxi operators (cf. [13], ch. 3.17, p.70). 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:

- ASD: detect possible traffic conflict;
- ASD: check new route clear of traffic;
- EFPS: no traffic assigned for the new route;
- VCS: clear airtaxi to proceed to new waypoint
- EFPS: enter new route on the flight strip;
- UAM: send route update

3.4 Technical requirements

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. [15], 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. Appendix 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. [16, 17]) based on the simulation scenario with 15 airtaxis were conducted.

4 Result

4.1 Component-structure

The structure of the digital interactive radar controller as designed in [11] and shown in Fig. 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 Fig. 4.

The data service component is replaced by multiple data interfaces to allow for UAM interaction (Fig. 4 left side). The connection to the ASD is eliminated (Fig. 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 require special treatment as the audio stream must be translated into commands initially (cf. [18]). 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 Fig. 6.

The collected data are stored in the Traffic Situation class as the result of the input. The output part accesses this data storage. The traffic situation is analyzed 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. Appendix 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 behavior of the controller. The monitoring activity as show in Fig. 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

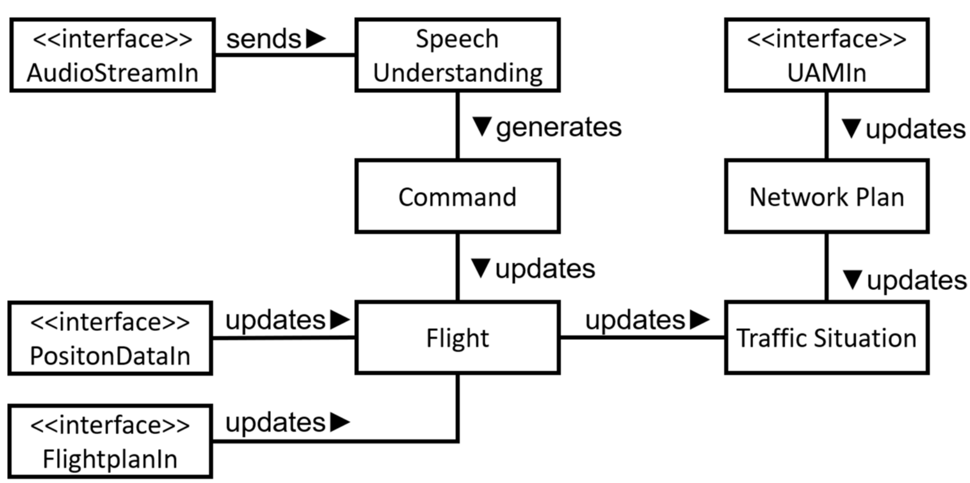


Fig. 5 Class structure of the UDC input part

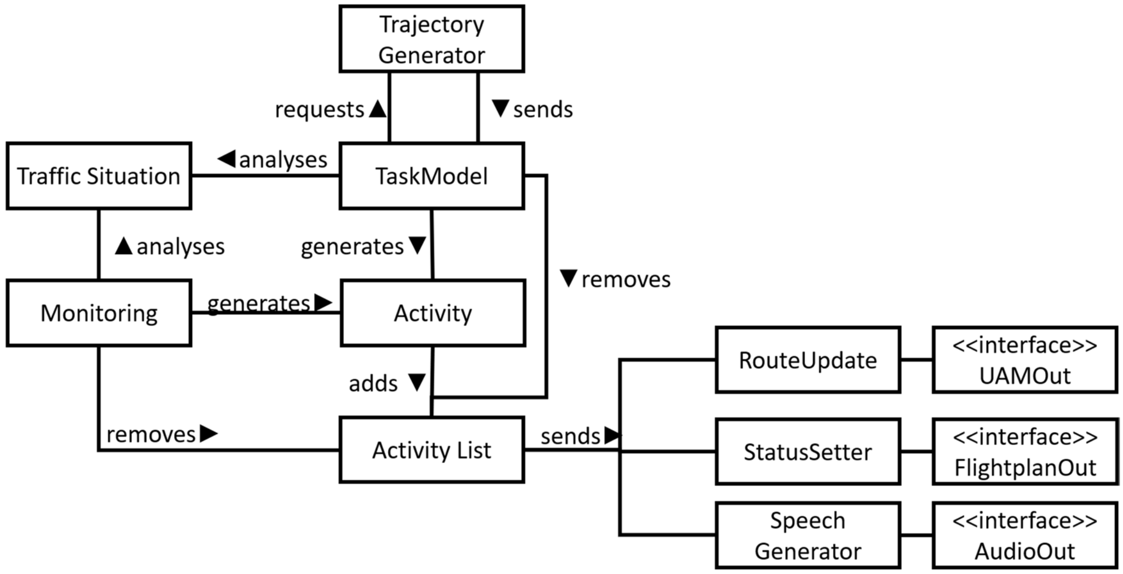


Fig. 6 Class structure of the UDC decision and output part

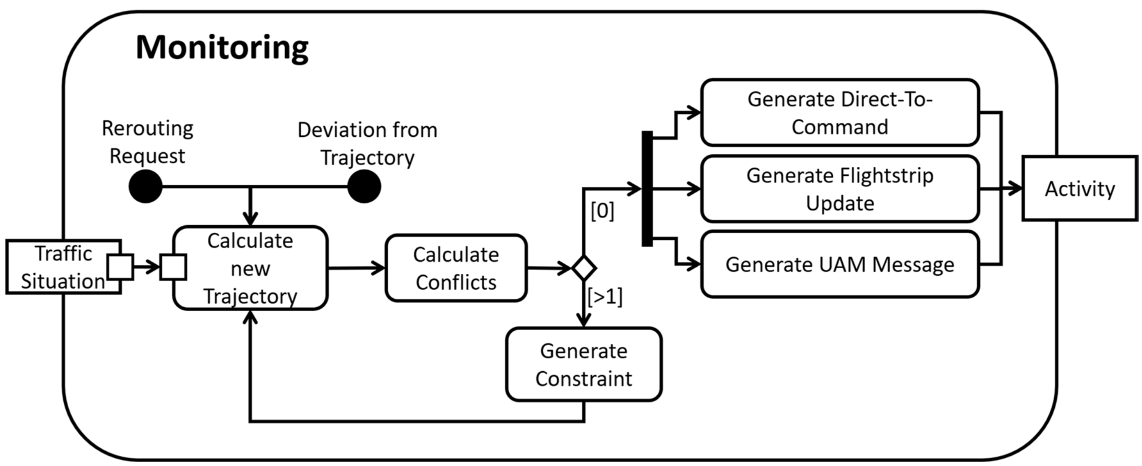


Fig. 7 Activity diagram of the monitoring task

(direct-to-command on the VCS system, flightstrip update and UAM message).

The task model as shown in Fig. 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:

- Entering control zone (airtaxi departing from inner-city vertiport): Checking traffic load and vertiport clear of approaching / departing aircraft.
- Leave frequency (airtaxi landing on inner-city vertiport): Checking airtaxis is short of vertiport
- Ready for departure (airtaxi departing from airport): Checking traffic load and clear of traffic on final approach / departure
- Airtaxi 2NM from final approach fix (airtaxi landing on airport): Checking 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

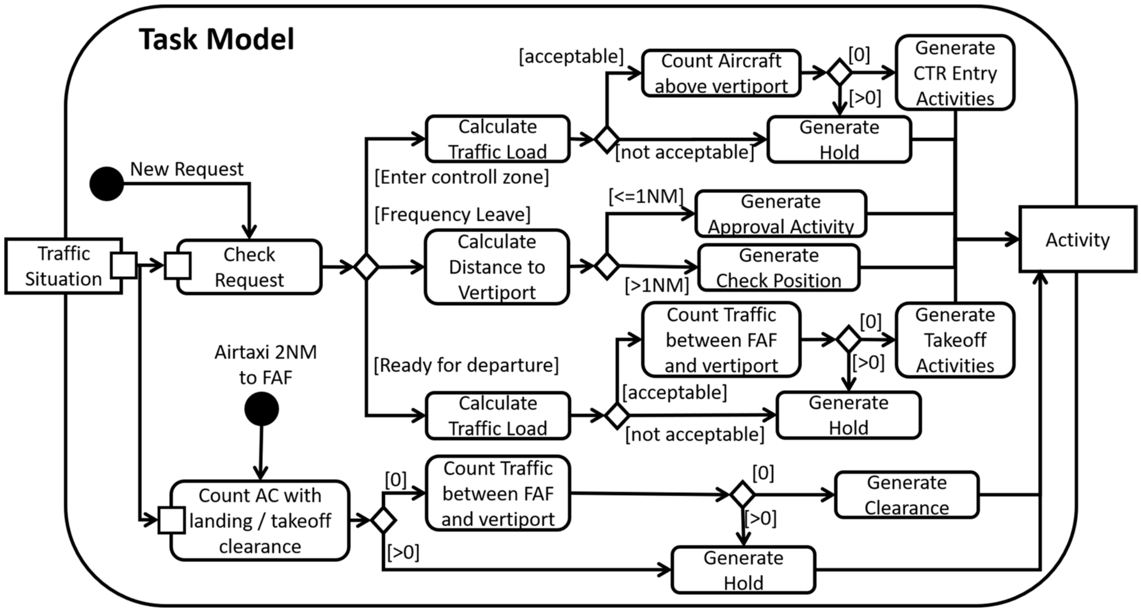


Fig. 8 Activity diagram of the task model

performed as a theoretical walkthrough. The simulation recorded flightplans, takeoff and landing times of the airtaxis and the conventional traffic. To utilize this data a synchronization of the different simulation sources (e.g., flightplan server, radar data, voice communication, etc.) was required. This synchronization is not specified in the defined UDC algorithm although operational data will also be transmitted by different sources. This finding is subject to later discussion.

The derived takeoff and landing times as well as the radio requests were used to initiate 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. Figure 9 shows an example of a walkthrough for an airtaxi taking off at an inner-city vertiport. The initial departure time (12:20) was taken to derive the first event (request to enter control zone). Afterward the traffic object was checked whether the traffic load is within acceptable limits and no aircraft is above the vertiport. Finally, the approval to enter the control zone is given.

The decision on the traffic load is based for all calculated walkthroughs on the active traffic in the control zone as shown in in Fig. 10. Due to the feedback of the air-traffic controllers each aircraft that would have exceeded a load of six aircrafts in a 5-min interval, received a Hold-Command. This was applied to four airtaxis.

The decision on the traffic above the vertiports was taken based on the estimated landing times. Landing-sequence diagrams as shown in Fig. 11 were generated for the decision to approve a landing or hold the airtaxi. Only for the Vertiport East holdings had to be applied. In Fig. 11 this can be observed by the overlapping boxes around minute 20 and 40 leading to four holding decision.

In total 45 activities from the task model (control zone entry, takeoff, landing, control zone exit, holding) and the monitoring task (rerouting) were calculated with the time of the activity. Figure 12 shows the activities per flight over time.

It can be observed in Fig. 12 that all flights were calculated to their end, symbolized by the green dot of the landing time. Initially, this was not possible to the flights for which a holding is applied (circle symbols) as the algorithm does not specify when to end the holding. For this walkthrough a rough first come first serve strategy was applied as a first fix which needs further optimization.

Moreover, Fig. 12 shows that reroutings and holdings could be applied following the defined algorithm. Reroutings occur in times of less activities (before minute 10 and after minute 30), while holdings occur around minute 20 where numerous activities take place. The frequency of the events is further analyzed in Fig. 13.

Figure 13 confirms the observation that specially in the minute 20 and 25 a high number of activities takes place. For the algorithm itself and the applied theoretical walkthrough this is no problem. The algorithm in principle is well-designed and sufficient to conduct the traffic. Nevertheless, a timely design how to cope with multiple activities in a short timeframe is required. A high number of activities as shown in Fig. 13 might be a challenge to the used hardware

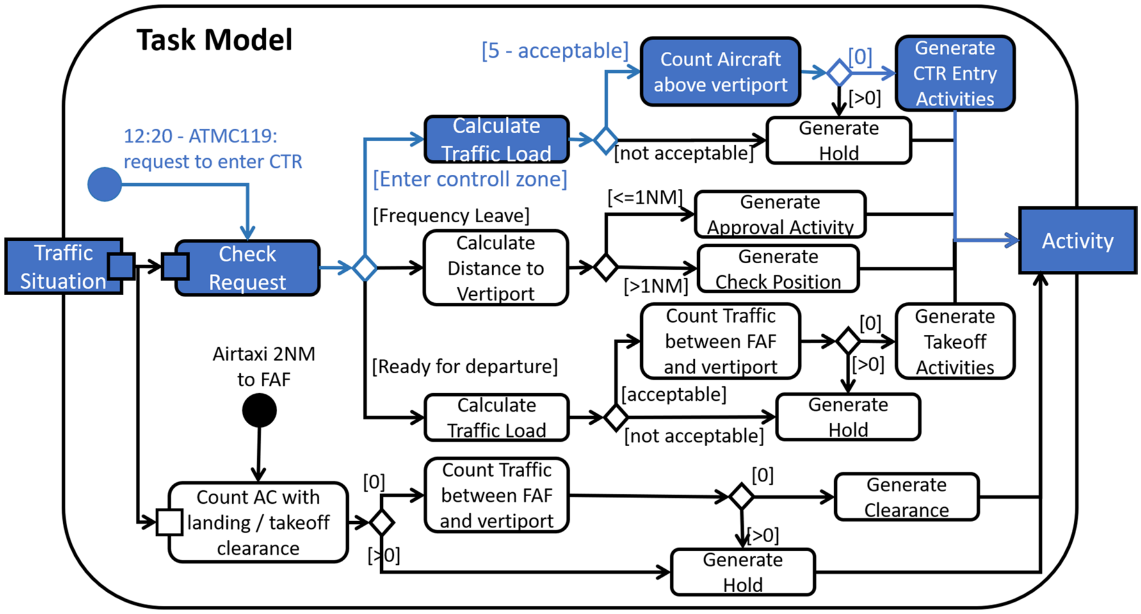
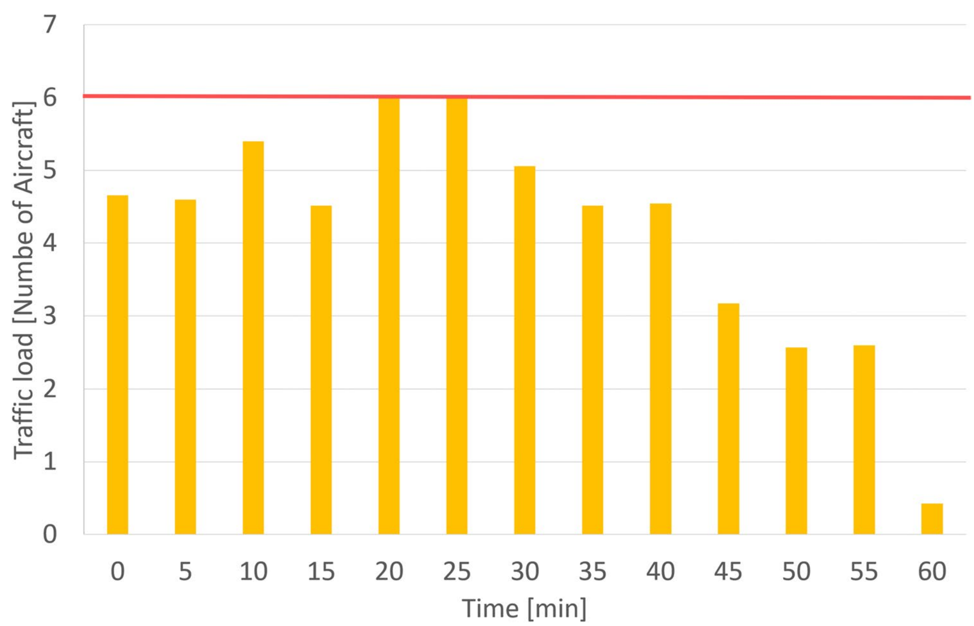


Fig. 9 Theoretic walkthrough (example)

Fig. 10 Traffic load



and can cause significant problems for the communication channel (e.g., radio, datalink). In the current specification there is no limitation on the number of transmissions. Here, a protection is required to prevent an overload.

Concluding the evaluation, 15 airtaxis with 45 activities were examined. All flights could be calculated successfully to the end following the specified algorithm. Nevertheless, the following deficiencies in the model were detected:

- Data synchronization: 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 is not defined. 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

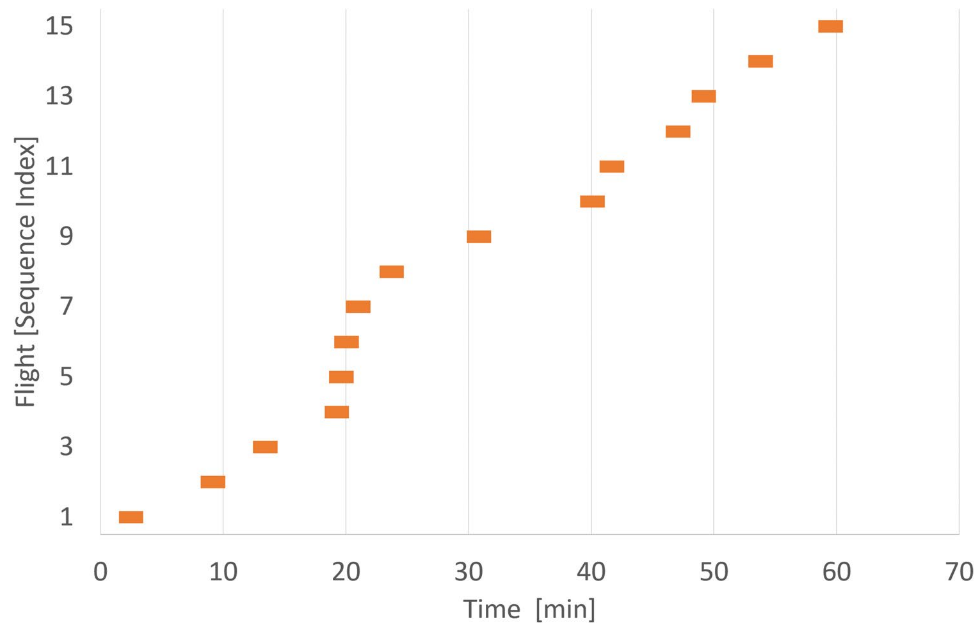


Fig. 11 Traffic sequence above VPO

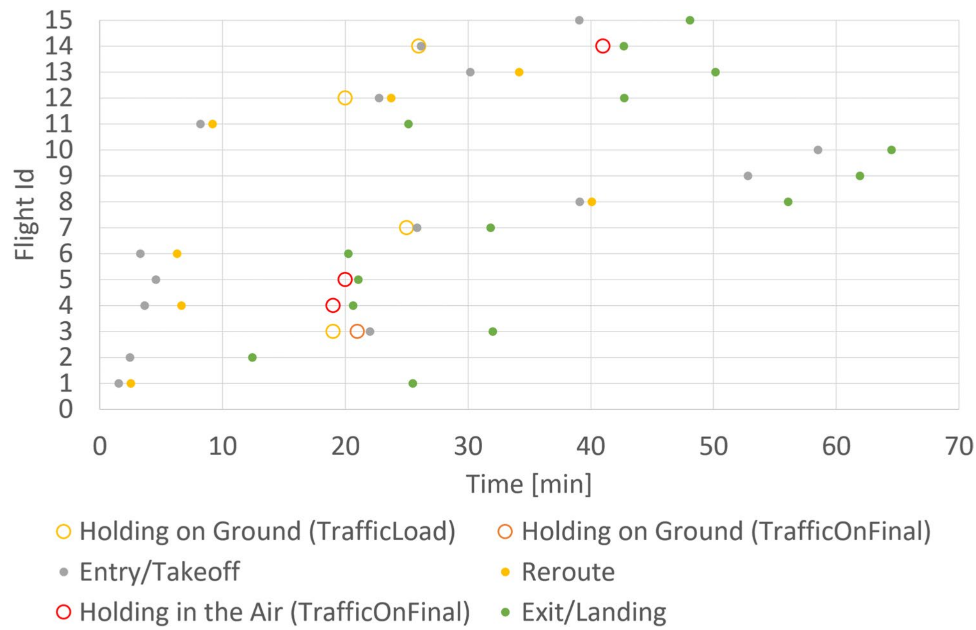


Fig. 12 Activities over time per flight

commands or even synchronous commands upon using parallel computing. For humans interacting with the UDC this can lead to misunderstandings (cf. [19]).

5 Discussion

The paper derives a design for a UAM digital controller, capable of actively handling airtaxis in the control zone of an airport. All flights were calculated until the end and all occurring situations (e.g., rerouting, high traffic) could be solved. Three major deficiencies were observed. All of them can be resolved by existing concepts:

- The identified issue of the missing data synchronization will be possible to solve via standard patterns such as pipes and filters where data can be selected depending on its correctness and merged with other data.
- The hold strategy can be defined as first come, first served to ensure an order and fair air-traffic control process. Nevertheless, for safety reasons, the remaining energy of the airtaxi should be encountered as well as

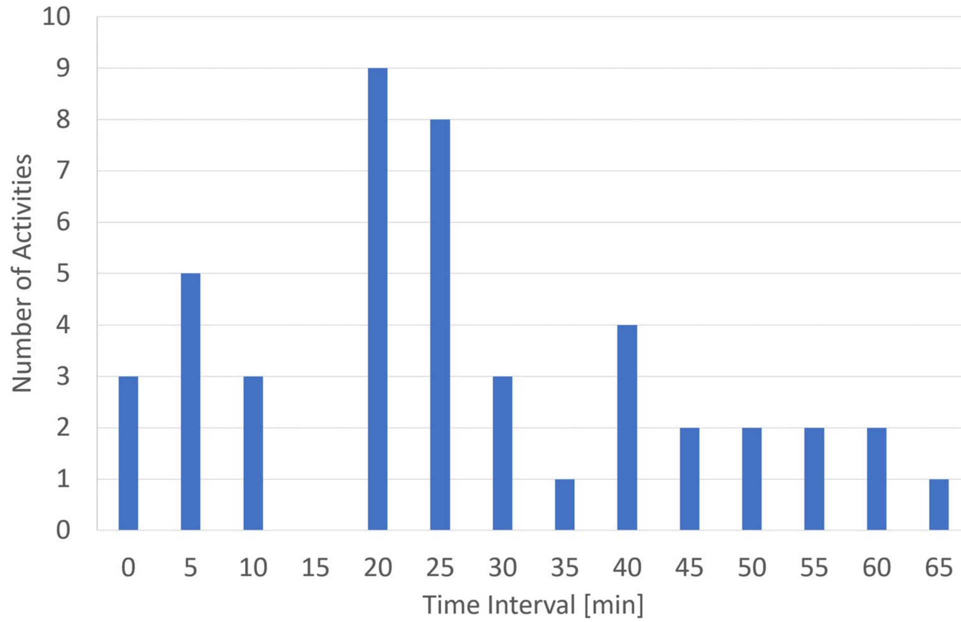


Fig. 13 Frequency of activities

user prioritizations. The prioritizations can be provided by the airtaxi operator to ensure connectivity with other transport modes (e.g., connecting long-haul flights).

The output speed can be reduced to the human speed (cf. [19]). A broader approach can examine operational concepts that allow for parallel communication. These approaches own the advantage of increasing the ATC performance while reducing safety due to depending commands.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 interaction design and integration into the UDC design is required. The UDC design should be checked upon failure cases for each task. Once a failure case can not be covered by the automation of the UDC an appropriate procedure guaranteeing a safe operation (e.g., not extending the clearance limit) and handing the traffic over to the human controller with an appropriate explanation should be defined. For instance, if a request is not understood with a sufficient probability, the UDC can request a repetition of the request. If the request is not understood a second time, the UDC can advice the airtaxi to not exceed the clearance limit and transfer the flight strip to the human air-traffic controller including a remark about the unclear request.

Even if all of the identified challenges and deficiencies are solved, it can still be discussed if the UDC is operable at all airports. The applied design process is based on the human-in-the-loop simulation of Hamburg. Due to different runway layouts, vertiport locations and airspace structure a UAM digital controller for other airports might require a different rule set. Nevertheless, the derived algorithm and the above applied process can be reused to adapt the digital controller to other airports. In general, a review of the operational requirements will reveal if there are additional challenges which need to be addressed by the digital controller. Comparable to a change request, operational tasks and technical requirements can be extended and encountered in the design.

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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 the DLR project IAM OSA for summer 2026.

This paper discusses the application of digital controllers to the integration of airtaxis into controlled airspace. Apart from this use case, digital controllers can support air traffic control at the airport in general. For instance, the clearance delivery position owns a high potential for being supported by a digital controller as aircraft have not started their engine when receiving the enroute clearance. Even if the digital controller shows errors or failures throughout the execution, there is no risk of collision and the human controller can take over without time pressure. But even for cases with close operations (e.g., runway control), digital controllers have the potential to support the human controllers for instance in providing complex calculations on fuel and climate efficiency or doing coordination work (e.g., organize a runway check, coordinate with other control units). As such digital controllers are able to enhance air traffic control at the airports to allow a more efficient, eco-friendly and innovative air traffic.

Appendix A Rules for participants of the DLR human-in-the-loop simulation

Arriving airtaxis

Take-off (inner-city vertiport): Airtaxis request entry into the control zone before departure at the inner-city vertiports. Entry must be authorised if the traffic load is within acceptable limits. Separation from other airtaxis is conducted on own discretion in accordance with the visual flight rules.

Enrouting flight: Separation from other airtaxis is conducted on own discretion in accordance with the visual flight rules. Arriving and departing traffic on the same route is separated via a vertical separation (arrival 1500ft, departure 2000ft).

Landing clearance (Hamburg Airport): A landing clearance for airtaxis may only be issued if no other airtaxi is operating on final approach / initial climb between Vertiport East and the final approach point.

Leaving the frequency: The airtaxis are cleared to leave the frequency when they have touched down or a touchdown is assured.

Departing airtaxis

Take-off (Hamburg Airport): Airtaxis report ready for take-off. Take-off must be cleared if:

- the traffic load allows additional traffic;
- no other air taxi is operating on final approach / initial climb between Vertiport East and final approach point.

Enroute flight: Separation from other airtaxis is conducted on own discretion in accordance with the visual flight rules. Arriving and departing traffic on the same route is separated via a vertical separation (arrival 1500ft, departure 2000ft).

Landing clearance (inner-city vertiport): The airtaxis land and separate on own discretion.

Leaving the frequency: The airtaxis are cleared to leave the frequency when they have touched down or a touchdown is assured.

Shortcut for airtaxis

Route FAF→N2: Crossing the final approach to runway 23 on route FAF-N2 is only permitted with prior clearance from air traffic control. Precondition:

- a sufficient distance to arriving traffic on runway 23 is maintained;
- flight into wake vortices is avoided;
- sufficient distance is maintained from departing traffic on runway 33;
- if necessary, traffic information is given.

Route FAF→W2: Crossing the departure area of runway 23 may only take place with prior clearance from air traffic control. Precondition:

- a sufficient distance to the departing traffic is maintained;
- in the event of a missed approach to runway 23, sufficient distance is maintained

Appendix B Detailed operational concept

Assumption

Inner-city vertiports are apart from IFR final approach or departure paths. A separation upon lift-off between airtaxis and IFR traffic is not necessary.

The beginning of the approach to the vertiport at Hamburg airport is marked with a final approach point. All departing airtaxis are capable of reaching their cruise altitude when passing the final approach point. All arriving airtaxis are capable of reaching the vertiport level when leaving the crusie altitude at the final approach point.

Airtaxi is able to hold above a given point.

The controller has the following systems available: voice communication system (VCS), airside situation display (ASD), electronic flightstrip system (EFPS), advanced guidance movement and control system (ASMGCS), interface to the UAM system (UAM).

Operational requirements

OR1	**Takeoff at inner-city** Airtaxis must be approved to enter the control zone once traffic load is within acceptable limits and no traffic is above the inner-city vertiport
OR2	**Landing at inner-city** Airtaxis must receive a clearance to leave the radio frequency once they have touched down at an inner-city vertiport or the touchdown is assured
OR3	**Takeoff at airport** Airtaxis at Hamburg airport must receive a takeoff clearance once traffic load is within acceptable limits and no other airtaxi is on final approach / initial climb segment between vertiport east and the final approach point
OR4	**Landing at airport** Airtaxis must receive a landing clearance at the vertiport of Hambrug airport once no other airtaxi is on final approach / initial climb segment between vertiport east and the final approach point
OR5	**Rerouting** Airtaxis should receive a rerouting once the new route is clear of traffic

Operational processes

OP1	**Takeoff at inner-city** VCS: Airtaxi requests to enter control zone EFPS: Check Traffic Load acceptable ASD: Check No traffic above vertiport VCS: Approve airtaxi to enter control EFPS: Set status in airtaxi flightstrip UAM: Send actual takeoff message If traffic load is too high or traffic above vertiport: VCS: Command airtaxi to hold on ground EFPS: Set status “Hold” in airtaxi flightstrip UAM: Send delay message When traffic load within acceptable limits / clear of traffic proceed
OP2	**Landing at inner-city** VCS: airtaxi reports landing ASD: Check airtaxi position VCS: Approve airtaxi to leave frequency EFPS: Set status “landed” in airtaxi flightstrip In case ASD show different airtaxi position: VCS: Request airtaxi position report
OP3	**Takeoff at airport** VCS: Airtaxi reports ready for departure EFPS: Check traffic load acceptable ASD: Check no traffic between VPO and FAF VCS: Give takeoff clearance EFPS: Set status in airtaxi flightstrip UAM: Send actual takeoff message ASD: Check airtaxi passed final approach fix EFPS: Set status “Departed “ If traffic load is too high or traffic between vertiport east and final approach fix: VCS: Command airtaxi to hold on ground EFPS: Set status “Hold” in airtaxi flightstrip UAM: Send delay message When traffic load within acceptable limits / clear of traffic proceed
OP4	**Landing at airport** ASD: Airtaxi 2NM to final approach fix or less EFPS: Check no conflicting clearance given ASD: Check no traffic between VPO and FAF VCS: Give landing clearance EFPS: Set status in airtaxi flightstrip ASMGCS: Check airtaxi touched down EFPS: Set status “Landed “ If traffic between VPO and FAF: VCS: Command airtaxi to hold above FAF EFPS: Set status “Hold” in airtaxi flightstrip UAM: Send delay message When clear of traffic proceed
OP5	**Rerouting** 1. VCS: Airtaxi request new route OR 1. ASD: Traffic conflict detected 2. ASD: Check new route clear of traffic 3. EFPS: No conflicting traffic on new route 4. VCS: Clear airtaxi to proceed to new waypoint 5. EFPS: Enter new route 6. UAM: Send route update

Appendix C Technical requirements on the UDC

RE1	The controller must be able to receive audio messages
RE2	The controller must recognize requests to enter the control zone
RE3	The controller must recognize requests to exit the control zone
RE4	The controller must recognize landing reports
RE5	The controller must recognize ready for departure calls
RE6	The controller must recognize route change requests
RE7	The controller must recognize readback errors
RE8	The controller must be able to send audio messages

RE9	The controller must generate approvals to enter the control zone
RE10	The controller must generate approvals to leave the frequency
RE11	The controller must generate takeoff clearances
RE12	The controller must generate landing clearances
RE13	The controller must generate direct to commands
RE14	The controller must assign a status to a airtaxi flight (enter control zone, hold, landed, cleared for takeoff, departed, cleared to land, landed)
RE15	The controller must update a route of an airtaxi
RE16	The controller must calculate the traffic load based on the active flights
RE17	The controller must assess if the traffic load is above the traffic limit
RE18	The controller must calculate distance of traffic to vertiport
RE19	The controller must assess if traffic is above a vertiport
RE20	The controller must calculate distance of traffic to final approach fix
RE21	The controller must assess if traffic is between vertiport and final approach fix
RE22	The controller must assess ground radar data if an airtaxi has landed
RE23	The controller must be able to send messages to the UAM system (actual takeoff, delay, route update)
RE24	The controller must be able to send a request of route change to the human controller
RE25	The controller must be able to receive an acknowledgment of the new route by the human controller
RE26	The controller must be able to receive a denial of the new route by the human controller

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