A MODULAR URBAN AIR MOBILITY SIMULATION TOOLCHAIN WITH DYNAMIC AGENT INTERACTION

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Abstract

This paper presents a modular simulation toolchain for urban air mobility (UAM), used to investigate interdisciplinary challenges in research fields like transportation planning, air-traffic management, control systems and telematics. The simulation framework can be enhanced to evaluate the connection between travel times and demand, or the interdependence of urban airspace regulations and self-separation performance. In an example scenario, UAM demand is based on the share of passengers using existing modes in a transportation model. Missions for urban air routes are computed on a layered grid, and conflicts are resolved in a pre-departure scheduling. A multi-agent simulation framework based on OMNeT++ integrates complex dynamics, and guidance, navigation and control algorithms, as well as different communication protocols like 5G. We evaluate a workflow for the city of Hamburg with several thousand flights, based on transportation-related key performance indicators.

Keywords

Urban Air Mobility; Multi-Agent Simulation; U-Space; Deconfliction; Demand Modeling; V2X-Communication

1. INTRODUCTION

While Urban Air Mobility (UAM) promises a future of rapid point-to-point transportation, diverse effects on urban mobility patterns, the environment and society are expected. The realization of UAM poses challenges in different research fields, like transportation planning, airspace integration, communication and control [1], requiring interdisciplinary collaborations.

On the one hand, the expected high costs of a UAM system means that detailed knowledge of where demand for UAM would occur is essential to prioritize the placement of infrastructure for landing and charging, known as vertiports, so transportation planning insights are needed to plan UAM networks [2]. On the other hand, the placement of UAM infrastructure affects the level of service available to potential UAM users, and therefore the uptake of UAM [3].

Furthermore, urban airspace, or 'U-Space', design influences traffic times, traffic complexity and separation conflicts [4], determining potential traffic throughput. Replacing a small percentage of conventional traffic leads to large airborne traffic densities, posing a challenge for safe management of flights [4], requiring efficient concepts for urban airspace and air routes [5, 6]. Existing concepts involve flights in direct paths [7], noise-optimized paths [8] or on a predefined grid [9]. Moreover, under the assumption that UAM will involve highly autonomous vehicles, there exist numerous additional challenges regarding control and communication [6, 10, 11]. Since safe operation has to be guaranteed for large numbers of autonomous vehicles, centralized control schemes might not be applicable, leading to distributed control schemes that require information exchange between agents and sensing capabilities [12]. Therefore, the integration of a fast and reliable information management system to mitigate collision risks and maintain separation is crucial. While this enables inter-agent communication, attention must be paid to the investigation of bandwidth limitations, latency, message overhead and real-world effects such as weather and loss of line-of-sight that may disrupt communication, leading to potential high-risk situations.

The benefits and detrimental effects of hypothetical UAM systems have been assessed from environmental, transportation-related and socio-economic angles, with safety as a non-negotiable factor [13, 14]. Initial environmental evaluations, considering e.g. energy requirements and greenhouse gas emissions, have been performed [15, 16], but not yet integrated into simulations of UAM travel [17].

Due to the complex challenges the design of UAM concepts poses, each concept should be studied extensively in simulation workflows prior to any real-world implementations. Simulations allow the investigation and assessment of concepts of operation and the various potential conditions under which UAM

doi: 10.25967/570247

systems will be implemented [18]. This, however, leads to the challenge of designing a highly modular and extendable simulation workflow that can address the topics stated above. While many frameworks for investigating different aspects of UAM exist [7, 19, 20], to our knowledge no framework addresses all of these issues.
Hence, the interdisciplinary research project ULTRAS[1] (**U**rbane **L**uft**tra**nsport**s**imulation, German for 'Urban Air Transportation Simulation') provides a modular urban air mobility simulation toolchain with dynamic agent interaction for the investigation of the aforementioned challenges. To this end, we build on the integrative framework structure developed in [7] to design, simulate and evaluate UAM operations, covering transportation planning, air traffic research, control systems and communication.
The setup of this paper is as follows: Section 2 presents an overview of simulation tools and frameworks relevant for UAM. In Section 3, the ULTRAS framework and its stages are explained. In Section 4, one particular workflow and the utilized modules are described. Simulation results for this workflow are presented in Section 5. Finally, Section 6 gives a conclusion and directions for further research.

2. RELATED WORKS

In recent years, a variety of tools and frameworks for analyzing different aspects of UAM have been published [18]. In [21], the authors present a dynamic trajectory-based UAM simulation framework that allows for the evaluation of UAM trajectories. Among others, this simulation tool can evaluate planned trajectories in terms of feasibility, separation and efficiency. While general scenario aspects of UAM can be explored with such trajectory-based frameworks, the investigation of the challenges related to control and communication require agent-based simulations. In [22], the authors investigate potential travel time savings of UAM compared to ground-based transportation in an agent-based simulation utilizing the open-source mobility simulation framework MATSim. Their simulation includes models for UAM infrastructure, agents and operations. Furthermore, the impact of congestion is considered. The framework gives the potential for detailed evaluations of UAM's impact on traffic systems, as in [14], for example. However, this framework does not consider information management, and UAM flights are modeled as simple point-to-point trips.
One framework allowing studies of the communication aspect in networked transportation systems is Veins [23]. Veins is an open-source framework for vehicular network simulations which combines the discrete-event simulation framework OMNeT++ and the road traffic simulator SUMO. However, since this framework is limited to 2D scenarios, it is not suited for the investigation of UAM.
One UAM simulator incorporating control and communication capabilities on an agent level is presented in [24]. In this framework, the authors present the simulator UTSim based on the Unity game engine, allowing specifications of different unmanned air vehicle (UAV) types, and including algorithms like trajectory planning and collision avoidance. While game engines can simulate UAM in photorealistic environments, rendering environments on the scale of whole cities and potentially thousands of agents is computationally expensive. Furthermore, the authors only focus on the UAV simulation aspect of UAM, and do not consider demand modeling or air traffic management aspects in their simulator.

3. THE ULTRAS FRAMEWORK

In the ULTRAS framework, the individual domains of urban air mobility are interconnected, in order to study the emergent system behavior. The overall goal of the project is thereby to evaluate concepts of UAM for the Hamburg metropolitan area, considering realistic demand, ground infrastructure and airspace configurations, with a particular focus on weighing the positive and negative societal impacts. At the same time, simulations shall be performed with realistic, autonomous vehicle models while using realistic communication models. The required functionalities are thereby designed as individual modules which can then be combined in an overall simulation workflow. The developed modules are integrated and connected in an RCE (Remote Component Environment [25]) workflow, allowing for a convenient remote execution of modules from multiple sources and disciplines. RCE handles each module as a black box, ensuring the provision of the defined inputs and outputs. The in- and outputs of the modules are stored as XML files using the Common Parametric Aircraft Configuration Schema (CPACS) [26] format. In this way, the modules can be executed one after another, enriching the common CPACS file with new data at each step and providing it as input to the next module. This modular and flexible approach results in a framework in which modules can easily be modified or exchanged, allowing for iterative module development. Moreover, with this approach, existing modules can be combined in new workflows as long as interfaces between functionalities are defined properly. This enables the simulation of both individual aspects of UAM and large-scale interdisciplinary interdependencies, allowing transportation-related and socio-economic key performance indicators to be evaluated.
The ULTRAS workflow is organized in the four stages of *scenario generation*, *mission planning*, *multi-agent simulation* and *evaluation*, as depicted in FIG. 1.
In the following, these stages and their contributions to the workflow will be explained individually.

[1]This project is funded by the BMWK - Federal Ministry for Economic Affairs and Climate Action in LuFo VI-1 under grant id 20E1911.

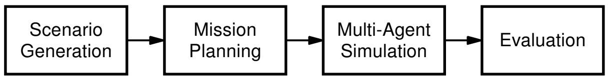

FIG 1. ULTRAS workflow stages.

3.1. Scenario Generation Stage

Here, the generation of a UAM scenario refers to the determination of the number and location of all vertiports and the selection of vehicles based on performance, as well as the volume of passenger demand for each vertiport pair per hour. This is in line with the scenario definition in [27].
Vertiports are the central building block for UAM, providing a facility to begin and end a journey [28]. This is where UAM vehicles take off and land and passengers board and disembark. The location of vertiports has a large impact on the uptake of UAM [22, 29], and therefore the travel demand should be considered when modeling the locations of vertiports.
However, the logit models used for demand determination in transportation planning require intermodal travel times in trips incorporating UAM to be known, which require vertiport locations to be known [3]. Two approaches found in the literature to solve this problem are through iterative processes [30] or by setting the vertiport locations based on other criteria [31].
In general, demand for UAM is expected to be influenced strongly by factors such as travel time, cost, and vertiport accessibility (which are themselves dependent on the placement of vertiports) as well as personal factors (such as affinity to automation or online services) and geographic factors (integration into existing transportation networks) [29]. As a first estimate of potential UAM demand, existing commuter flows can indicate relations with likely flight demand and, therefore, locations where vertiports are preferred to be placed [32].
So far, the workflow is carried out in a linear fashion; demand is calculated based on traffic models and travel time assumptions, and vertiports placed in assumed locations.
The framework also allows for an iterative workflow, where the actual UAM travel times from the simulation output can be used to produce more realistic estimates of UAM demand. The model can also be extended to incorporate travel time differences and socio-demographic factors influencing the demand for UAM, as well as locating and sizing vertiports based on demand.

3.2. Mission Planning Stage

Airspace rules, governing where and how flights can be carried out, are crucial for urban air mobility [33], as trajectory shapes precipitate travel times and separation conflicts. Air routes can be created in a grid, in other patterns, e.g. hexagons [9] or in a neighbor-based manner [33]. Flights should avoid no-fly-zones around sensitive areas [8], necessitating detours. Depending on the routes and the traffic picture, the ability of the agents to self-separate may vary in unpredictable ways.
Mission planning generates flight plans based on the scenario by creating a route network, calculating trajectories and scheduling for each flight. In this work, we aim to investigate the separability of traffic on a route network. Route network design directs vehicle positions and determines where separation conflicts between vehicles can arise. We create a network of nodes and edges, with parallel edges that maintain a minimum separation distance, thus preventing conflicts between parallel flights. Due to the large amount of traffic, separation conflicts are expected. Therefore, we detect conflicts between planned trajectories and resolve them subsequently. Nonetheless, simulated trajectories deviate from planned ones, so that an additional layer of airborne conflict resolution is required.

3.3. Multi-Agent Simulation Stage

The multi-agent simulation stage (MAS stage) simulates the flights planned in the previous stage on a vehicle level. One important design decision of the ULTRAS project is the choice of an appropriate tool for modeling and simulating arbitrary dynamics, control and communication functionalities. While there exist several open-source frameworks providing communication or control functionalities (see [24, 34, 35]), these frameworks are designed for either dynamics, control or communication simulation, but not intended for the combination of all three. Thus, to our knowledge, there exists no framework for handling large-scale 3D scenarios with the required specifications.
In the ULTRAS framework, we chose the open-source framework OMNeT++ [36] for dynamic communication and control simulations. OMNeT++ is an extensible, modular, component-based C++ simulation library and framework, primarily for building network simulators. Several OMNeT++-based libraries supporting communication protocol development are also present. Due to its highly modular and extensible design, as well as its capabilities for simulating mobile network nodes, OMNeT++ enables the integration of complex vehicle dynamics and control structures.
Each agent is modeled as a mobile network node in OMNeT++, with the movement being determined by Dynamics, and Guidance, Navigation and Control (GNC) modules inside each agent. For modeling agent interactions, we encompass modules and interfaces for a sensor system and communication infrastructure inside the agent. The sensor system further allows fusion of sensor data and generation of situation pictures to aid control and segregation decisions. As a pragmatic approach, ground infrastructure to support agent interactions and monitoring is also modeled.
Moreover, provisions are made to model system delays and information loss caused by effects on the

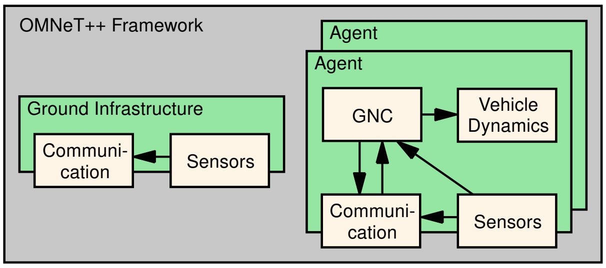

FIG 2. ULTRAS OMNeT++ framework.

propagation channel, to evaluate the behavior of the multi-agent system under real conditions.
Due to its modular structure, the OMNeT++ simulation framework can easily be extended. In FIG. 2, an exemplary block diagram of the OMNeT++ framework is depicted, with multiple agents and ground infrastructure with sensing and communication capabilities.

3.4. Evaluation Stage

The evaluation of a UAM system in Hamburg, and the weighing of its pros and cons, is a key aim of the ULTRAS project and workflow. For the evaluation of the benefits and challenges of UAM systems, assessment factors can be grouped into environmental (e.g., energy consumption, noise emissions and air pollution), transportation-related (e.g., travel time savings, number of UAM trips, ground congestion and car kilometers traveled in the transportation system overall), socio-economic (e.g., affordability, accessibility of workplace) and safety (number of accidents) [13, 14].
The RCE workflow enables the investigation of each module's output files, with the use of the CPACS data format allowing the information flow to be followed throughout the workflow. In particular, the availability of detailed data on the flights of all UAM vehicles in the multi-agent simulation facilitates analysis of system performance. In this paper, the focus is initially on transportation-related indicators such as total vehicle travel time and distance, total passenger time and distance travelled and the proportion of the overall passenger demand that can be served by UAM.

4. EXEMPLARY WORKFLOW

In this section, one example workflow using the ULTRAS framework is described. The developed scenario thereby simulates one day of air traffic in the city of Hamburg. The interconnection of the RCE modules implemented for this workflow, and their assignment to the stages defined in Section 3 is depicted in FIG. 3. In the following, the capabilities of the used modules will be explained in detail.

4.1. Scenario Generation

Scenario generation sets the foundation for the subsequent stages.

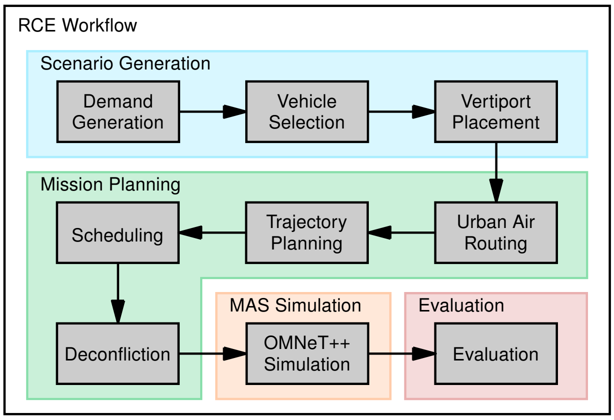

FIG 3. Exemplary workflow stages and modules.

4.1.1. Demand

In this paper, UAM demand is calculated between the districts of the city of Hamburg, based on traffic estimates from the city transportation model. This is used internally for understanding traffic flows and evaluating transportation projects by various stakeholders. Access to the model was generously provided by the Hamburg transportation agency, the 'Behörde für Verkehr und Mobilitätswende'. UAM demand is estimated as a factor of the already-modeled demand for car traffic and public transport. A minimum hourly demand threshold can also be set. In this scenario, the hourly UAM demand is made up of 1% of car and 1% of public transportation demand from the model. Routes where the hourly demand is at least one passenger are passed to vertiport selection.

4.1.2. Vehicle Selection

We provide a vehicle database, containing the relevant parameters for the framework. A homogeneous fleet of vehicles with a range of $50\,\mathrm{km}$ [37] is selected, which is capable of covering the required distances.

4.1.3. Vertiport Placement

As a starting point, one vertiport is simply set-up for each of the 103 contiguous districts of Hamburg. They are manually placed by the nearest public road to each district's centroid using a Geographic Information System (GIS) program. Placement in a no-fly zone is also avoided. Since UAM is stated to be mainly effective at larger distances [22], only routes more than 10km long are considered going forward.

4.2. Mission Planning

The missions are generated from the scenario and passed to the OMNeT++ simulation.

4.2.1. Urban Air Routing

The Urban Air Routing module creates a 2D route for each origin-destination pair, on which the vehicles are permitted to travel. For this, a network of nodes and edges is created as an input to route generation. Each

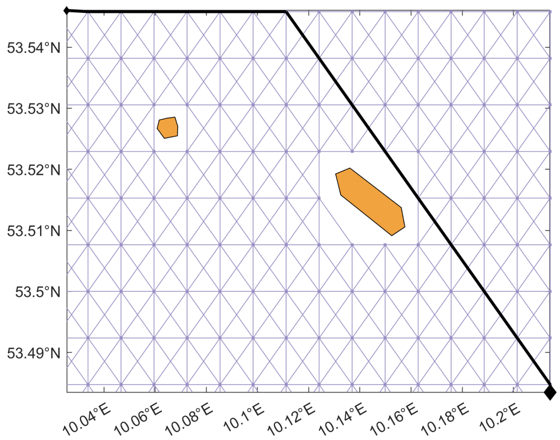

FIG 4. ULTRAS grid and exemplary route around no-fly zones. Nodes (violet point), Edges (violet lines), No-Fly Zones (orange), Route (black line), Origin (large black square), Destination (small black square).

node is connected to the eight nearest nodes, creating rectangles with a cross inside (see FIG. 4). From the vertiports, edges to the nodes in the surrounding rectangle are generated. Nodes and edges touching no-fly zones are deleted. We set the distances between nodes such a way that two parallel segments are free from separation conflicts. The least-cost path algorithm [38] is used to find 2D routes between vertiports. The cost function considers distance as well as penalizing course changes, so that routes with the minimum number of turns are preferred.
Due to the lateral dispersion of the 89 vertiports that contain flights, many of the 1,064 routes share segments or intersect in lateral space. Therefore, the planned flights are expected to have separation conflicts with one another.

4.2.2. Trajectory Planning

The trajectory module creates trapezoidal trajectories in 4D [7] on the provided routes on the grid.

4.2.3. Scheduling

The scheduling module creates flight plans for each route, based on the hourly passenger demand [7].

4.2.4. Deconfliction

The deconfliction module detects conflicts that violate the separation between the planned trajectories and removes conflicting flights in the pre-departure phase. Conflicts are detected using a grid-based approach [39]. Trajectories are interpolated in $10\,\mathrm{s}$ increments, and conflicts between trajectory points that violate a minimum distance of $600\,\mathrm{m}$ laterally and $45\,\mathrm{m}$ vertically are detected. The number of authorized flights is maximized by solving an optimization problem under the constraint that conflicts are prohibited. Due to the fact that conflicts in the climb and descent phases are resolved, deconfliction provides schedule separation for the vertiports.

4.3. Multi-Agent Simulation

Our framework is capable of simulating complex vehicle dynamics and guidance, navigation and control (GNC) algorithms together with the communication protocols required for UAM.

4.3.1. OMNeT++ Simulation

Dynamics and Control
For the simulated scenario, a kinematic agent model is utilized. This model can be seen as an abstract representation of a multicopter vehicle (for example the VoloCity air taxi by Volocopter). The vehicle is then controlled via a distributed model predictive controller, considering physical vehicle limitations, such as maximum velocities and accelerations. This can, however, result in deviations from the actual trajectories compared to the planned ones in the Mission Planning Stage, causing additional conflicts. Therefore, the predictive controller uses communicated data from neighboring vehicles to resolve airborne conflicts and to avoid collisions in a decentralized manner.

Sensing and Communication
In the simulated scenario, considering sensors inside the agent, the GPS is modeled as an ideal sensor without real noise measurements. In terms of communication, our framework is capable of modeling V2X-communication (vehicle-to-everything communication); that is, both air-to-air (A2A) and air-to-ground (A2G) communication possibilities are enabled. The exchange of own state information and neighbor information at any given time between the agents and between agents and the ground station is considered as A2A and A2G messages respectively. The current iteration can simulate A2G communication in both the ideal scenario and with 5G protocols. The choice of studying the integration of 5G communication was made as it provides very high bandwidth, improved capacity with ultra-low latency [40] and the potential for direct communication [41] establishment. For 5G implementations, the OMNeT++ based library simu5g [42] is used, and the real effects of shadowing and fading are inspected in the Urban Macro path loss channel model. In addition, our framework includes a ground station module that accumulates agent localization data. In the current iteration, A2A communication is simulated as ideal communication. For safe navigation, it is required that the agents are aware of the other agents in close proximity, but not necessarily of all the agents in the entire network. For this reason, we have restricted the A2A message transmission to a neighbor detection range of $2\,\mathrm{km}$ rather than broadcasting the messages to all the available agents.

Module	Runtime [hh:mm]
initialization	00:01
passenger demand	00:01
vehicles	00:01
vertiports	00:03
routes	00:08
scheduling	00:02
trajectories	00:09
deconfliction	02:33
simulation	27:18
evaluation	00:27

TAB 1. Approximated runtime of workflow modules.

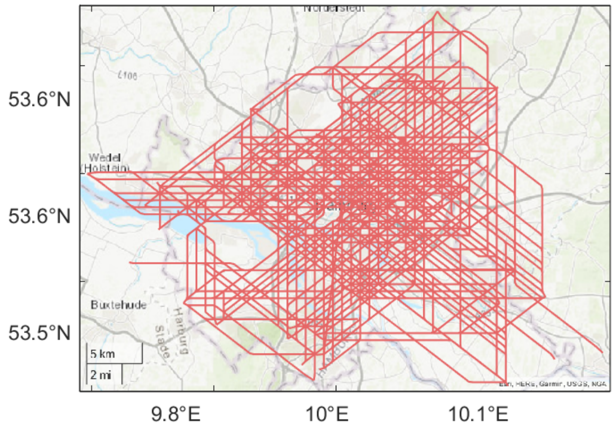

FIG 5. Planned trajectories over Hamburg.

4.4. Evaluation

Basic statistics on the number of transported passengers as well as vehicle and passenger travel time and distance are output for each route and in total. The UAM travel time for each vertiport pair can be compared to the travel time with cars (calculated using the OpenRouteService API [43]) and public transportation (calculated using the Hamburg transport association's Geofox API [44]). UAM travel time is made up of the inter-vertiport flight time as well as processing times at the origin and destination vertiports and the time taken to access/egress the vertiports. [22] use exemplary processing times of 15 and 30 minutes in their investigation, so a 15-minute time was added in this paper. Access and egress trips from/to the origin/destination vertiports are not considered here.

5. WORKFLOW RESULTS

Results for a day of simulated urban air traffic in Hamburg are provided. The simulation was executed on a virtual machine with an Intel Xeon Gold 5118 CPU @ $2.30\,\text{GHz}$ and $32\,\text{GB}$ RAM. The total runtime of the workflow was approximately 30 hours (see TAB. 1).

5.1. Scenario Generation

Demand between 103 contiguous Hamburg districts for car and public transportation was given as output from the Hamburg transportation model and processed to give the number of UAM passengers for each hour and each vertiport pair. 1,064 routes result from the selection of vertiport pairs at least $10\,\text{km}$ apart with demand of at least 1 passenger during a 1-hour period. The total demand on these routes is 19,652 passengers.

5.2. Mission Planning

In the scenario, 10,036 flights are planned. The number of flights that have pre-departure conflicts is 7,920, that is, $79\,\%$ of flights have conflicts (at least one trajectory point which is in conflict with at least one point of another trajectory). The number of conflicted flight pairs is 9,489, which means that there are 0.95 conflicts per flight (between a conflicted flight pair, at least two trajectory points are separated by less than minimum separation). The number of conflicted point pairs is 41,263, that is, there are 5.2 conflicted point pairs per conflicted flight pair (each trajectory consists of many points, which can be conflicted with several points of other trajectories). After deconfliction, there are 6,269 flights, meaning that $62.5\,\%$ of planned flights are carried out. The trajectories of these flights are visualized in FIG. 5.

5.3. Multi-Agent Simulation

Control Evaluation

For the decentralized control algorithm, each agent considers on average 2.5 neighbors (other agents within a range of $2\,\text{km}$). The maximum number of neighbors is thereby 19. Since the mission planning does not account for physical agent limitations, new airborne conflicts are introduced when the predictive control algorithm is planning the trajectories at runtime. Over all agents, the separation component of the GNC algorithm is active for $1.5\,\%$ of the simulation time and at least once for 4,214 of the 6,269 of simulated flights. With our predictive and decentralized separation approach, 6,135 of 6,269 simulated trajectories ($97.9\,\%$) are free of pre-departure and airborne conflicts.

Communication Evaluation

In the ideal communication scenario, both A2A and A2G communication are considered. FIG. 6 depicts the number of A2A messages exchanged between the neighboring agents within a neighbor detection range of $2\,\text{km}$, in comparison to broadcasting the A2A messages. On average, broadcasting causes 3,413 messages, while with neighbor detection only 106 messages are incurred. This leads to a $96\,\%$ reduction of message overhead, accounting for a total of approximately 125 million messages saved during the entire simulation. A2A messages are exchanged every two seconds, and the maximum number of possible agent interactions observed

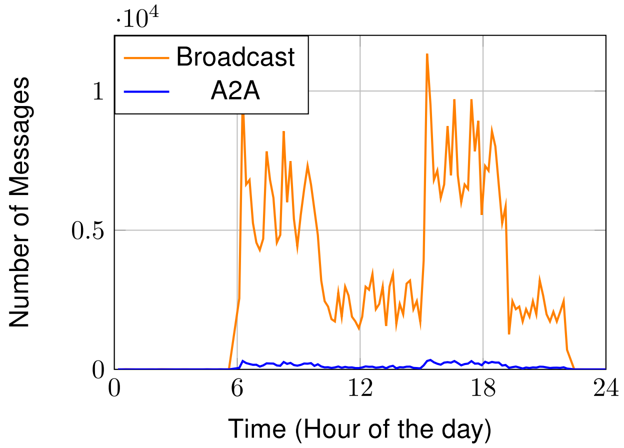

FIG 6. Comparison of number of periodic (every 2 s) messages incurred by A2A communication with neighbor detection (range: 2 km) vs broadcasting.

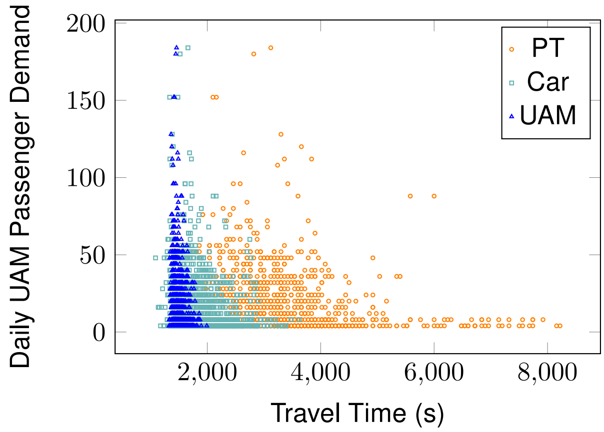

FIG 7. Daily UAM passenger demand for each route vs. travel times by each mode between vertiports, for all 1,064 routes in the simulated scenario. Car and public transportation (PT) travel time are given without congestion, and UAM travel time is given with a 15-minute processing time added, but without access and egress times.

within this period is 393. Periodically every two seconds, A2G messages are transmitted from each agent to the ground station, and 50 messages are detected on average, with a maximum of 108 periodic A2G messages. This signifies that during the day, the highest number of agents available simultaneously in the system is 108. Approximately 1.9 million A2G messages are transmitted within the day, along with 4 million A2A messages. If broadcasted, this would incur 129 million messages.

Additionally, a 5G network implementation for the A2G communication is done. A simple scenario with four base stations is taken into account without network planning covering the entire region of Hamburg metropolitan area. Evaluation is carried out for a two-hour time window of a simulation with five flights communicating with one ground station. Delivery delay and delivery ratio are considered as performance metrics, and a delivery delay of 38.4 ms is recorded on average. $43\,\%$ of the time, the delivery delay is less than 10 ms. The minimum delivery delay is 4 ms, with a maximum of 2 s. The average delivery ratio of messages in the system is $74\,\%$. When the delivery ratio per flight is considered, the average delivery ratio observed is $83\,\%$. With proper network planning, we expect that the delays will be lower and the delivery ratio higher.

5.4. Evaluation

5.4.1. Basic Statistics

As mentioned above, there are 10,036 scheduled flights carrying 19,652 passengers, 6,266 planned flights and 6,135 flights with no conflicts in the simulation. These simulated flights carry around 12,000 passengers, meaning over 7,000 passengers' demand remains unfulfilled.

This can be compared to the 3 million total travel demand for car and public transportation between all districts. The total demand for all district pairs used in the simulation was about 1.4 million trips, meaning UAM serves around $1.4\,\%$ of the demand between the district pairs in scheduled flights, or $0.86\,\%$ carried out by flights after deconfliction.

UAM vehicles travel a total of 1,637 vehicle hours and 137,830 vehicle km. For the transportation performance, the passengers spend a total of 3,159 passenger hours in UAM vehicles, to move 264,885 passenger km.

5.4.2. Travel Time

Under the assumption of a 15-minute processing time for UAM on top of the pure vertiport-to-vertiport travel time, as used in e.g. [22], all but 100 routes still showed a faster UAM travel time than car travel, and all routes showed a faster UAM than public transportation travel time. However, this comparison does not include times to get to the origin vertiport and from the destination vertiport.

A comparison between the resulting daily UAM passenger demand and the travel times between vertiports by car, public transportation and UAM is shown in FIG. 7. This shows the potential for travel time savings on many relations, although this comparison is, at first, only valid for trips beginning or ending at or near vertiports.

6. CONCLUSION & FUTURE WORK

In this paper, we present a toolchain for UAM simulations, developed in the scope of the ULTRAS project. Due to the modular structure and integrated multi-agent simulation framework, this toolchain can be used for the investigation of different scenarios and research questions from various domains. We introduce the structure of the proposed framework and demonstrate its capabilities by presenting an exemplary workflow with several thousand flights,

utilizing modules from diverse research areas. Visual and numerical results for the exemplary workflow are provided.
Future directions for research that stem from this work can be addressed under one of two categories. The first will be extending the presented framework and adding new functionalities. This includes the iterative refinement of existing modules to include complex algorithms and the development of new modules to introduce additional functionalities. Parallel to that, we also will be working on releasing the OMNeT++ multi-agent simulation framework as an open-source project. One aspect to highlight is the capability of the developed toolchain to introduce feedback loops such that the outputs of one module are the inputs for another module, shaping each other's results. Therefore, we plan on improving the individual modules contributing to the stages of the workflow such that more pragmatic evaluations can be achieved. One such example is using the UAM travel times and costs that the simulation provides as outputs to feed back into demand modeling, which would allow demand to be calculated much more realistically.
In the second category, the presented framework shall be used to answer research questions related to UAM in the Hamburg metropolitan area and UAM in general. An example for this would be investigating the bounds on the maximum number of safely operated flights depending on airspace organization, communication performance and self-separation algorithms. In addition, based on the detailed output trajectory data, the impact of UAM systems on environment and society can be evaluated. For example, noise evaluations based on vehicle location and power level data at each point in time can be performed.
The ULTRAS workflow thus allows us to support the design of novel concepts as well as the evaluation of the societal impact of UAM.

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References

[1] David Thipphavong, Rafael Apaza, Bryan Barmore, Vernol Battiste, Christine Belcastro, Barbara Burian, Arik-Quang Dao, Michael Feary, Susie Go, Kenneth Goodrich, Jeffrey Homola, Husni Idris, Parimal Kopardekar, Joel Lachter, Natasha Neogi, Hok Ng, Rosa Oseguera-Lohr, Michael Patterson, and Savita Verma. Urban Air Mobility Airspace Integration Concepts and Considerations. In *2018 Aviation Technology, Integration, and Operations Conference, Atlanta, Georgia*, June 2018. DOI: 10.2514/6.2018-3676.

[2] Miloš Balać, Amedeo R. Vetrella, and Kay W. Axhausen. Towards the integration of aerial transportation in urban settings. *Proceedings of the 97th Annual Meeting of the Transportation Research Board, Washington D.C.*, 2018. DOI: 10.3929/ethz-b-000193150.

[3] M. Rimjha, M. Li, N. Hinze, S. Tarafdar, S. Hotle, H. Swingle, A. Trani, and Jeremy C. Smith. Demand Forecast Model Development and Scenarios Generation For Urban Air Mobility Concepts. Virginia Tech and NASA, 2020. Technical Report 20205005881.

[4] Kenneth H. Goodrich and Bryan Barmore. Exploratory Analysis of the Airspace Throughput and Sensitivities of an Urban Air Mobility System. In *2018 Aviation Technology, Integration, and Operations Conference, Atlanta, Georgia*, 2018. DOI: 10.2514/6.2018-3364.

[5] Emmanuel Sunil, Jacco Hoekstra, Joost Ellerbroek, Frank Bussink, Dennis Nieuwenhuisen, Andrija Vidosavljevic, and Stefan Kern. Metropolis: Relating Airspace Structure and Capacity for Extreme Traffic Densities. In *11th USA/Europe Air Traffic Management R&D Seminar, Lisboa, Portugal*, 2015.

[6] Aleksandar Bauranov and Jasenka Rakas. Designing airspace for urban air mobility: A review of concepts and approaches. *Progress in Aerospace Sciences*, 125:100726, 2021. DOI: 10.1016/j .paerosci.2021.100726.

[7] Malte Niklaß, Niclas Dzikus, Majed Swaid, Jan Berling, Benjamin Lührs, Alexander Lau, Ivan Terekhov, and Volker Gollnick. A Collaborative Approach for an Integrated Modeling of Urban Air Transportation Systems. *Aerospace*, 7(5), 2020. DOI: 10.3390/aerospace7050050.

[8] Moritz Hildemann and Carlos Delgado. Modelling a Future Routing Concept for the Urban Air Mobility. In Houda Derbel, Bassem Jarboui, and Patrick Siarry, editors, *Modeling and Optimization in Green Logistics*, pages 53–73. Springer International Publishing, Cham, 2020. DOI: 10.1007/978-3-030-45308-4_3.

[9] Michael D. Patterson, Kevin R. Antcliff, and Lee W. Kohlman. A Proposed Approach to Studying Urban Air Mobility Missions Including an Initial Exploration of Mission Requirements. In *Annual Forum and Technology Display, Phoenix, Arizona*. NASA, 2018.

[10] Irene M Gregory. Urban Air Mobility: A Control-Centric Approach to Addressing Technical Challenges. In *IEEE CSS Forum On Robotic and Control Engineering seminar*. NASA, 2021.

[11] Yongs Zeng, Qingqing Wu, and Rui Zhang. Accessing From the Sky: A Tutorial on UAV Communications for 5G and Beyond. *Proceedings of the IEEE*, 107(12):2327–2375, 2019. DOI: 10.1109/JPROC.2019.2952892.

[12] Min Xue. Urban Air Mobility Conflict Resolution: Centralized or Decentralized? In *AIAA AVIATION 2020 Forum*, 2020. DOI: 10.2514/6.2020-319.

[13] Christelle Al Haddad, Mengying Fu, Anna Straubinger, Kay Plötner, and Constantinos Antoniou. Choosing Suitable Indicators for the Assessment of Urban Air Mobility: A Case Study of Upper Bavaria, Germany. *European Journal of Transport and Infrastructure Research*, 20(4):214–232, 2020. DOI: 10.18757/ejtir.2020.20.4.4464.

[14] A. Pukhova, C. Llorca, A. Moreno, C. Staves, Q. Zhang, and R. Moeckel. Flying taxis revived: Can Urban air mobility reduce road congestion? *Journal of Urban Mobility*, 1:100002, 2021. DOI: 10.1016/j .urbmob.2021.100002.

[15] Akshat Kasliwal, Noah J. Furbush, James H. Gawron, James R. McBride, Timothy J. Wallington, Robert D. de Kleine, Hyung Chul Kim, and Gregory A. Keoleian. Role of flying cars in sustainable mobility. *Nature communications*, 10(1):1555, 2019. DOI: 10.1038/s41467-019-09426-0.

[16] A. Pukhova. *Environmental evaluation of urban air mobility operation*. Master's thesis, Technical University of Munich, 2019.

[17] Anna Straubinger, Raoul Rothfeld, Michael Shamiyeh, Kai-Daniel Büchter, Jochen Kaiser, and Kay Olaf Plötner. An overview of current research and developments in urban air mobility – Setting the scene for UAM introduction. *Journal of Air Transport Management*, 87:101852, 2020. DOI: 10.1016/j .jairtraman.2020.101852.

[18] Brandon Sells and William Crossley. Modeling Review and Recommendations for Ubiquitous Urban Air Mobility Operations. In *AIAA AVIATION 2022 Forum*, June 2022. DOI: 10.2514/6.2022-3793.

[19] Prajwal Shiva Prakasha, Nabih Naeem, Patrick Ratei, and Björn Nagel. Aircraft architecture and fleet assessment framework for urban air mobility using a system of systems approach. *Aerospace Science and Technology*, 125:107072, 2022. SI: DICUAM 2021. DOI: 10.1016/j .ast.2021.107072.

[20] Magdalena Peksa and Klaus Bogenberger. Estimating UAM Network Load with Traffic Data for Munich. In *2020 AIAA/IEEE 39th Digital Avionics Systems Conference (DASC)*, pages 1–7, 2020. DOI: 10.1109/DASC50938.2020.9256525.

[21] Euclides Carlos Pinto Neto, Derick Moreira Baum, Jorge Rady de Almeida, João Batista Camargo, and Paulo Sergio Cugnasca. A Trajectory Evaluation Platform for Urban Air Mobility (UAM). *IEEE Transactions on Intelligent Transportation Systems*, 23(7):9136–9145, 2022. DOI: 10.1109/TITS.2021.3091411.

[22] Raoul Rothfeld, Mengying Fu, Miloš Balać, and Constantinos Antoniou. Potential Urban Air Mobility Travel Time Savings: An Exploratory Analysis of Munich, Paris, and San Francisco. *Sustainability*, 13(4), 2021. DOI: 10.3390/su13042217.

[23] Christoph Sommer, Reinhard German, and Falko Dressler. Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis. *IEEE Transactions on Mobile Computing*, 10(1):3–15, 2011. DOI: 10.1109/TMC.2010.133.

[24] Amjed Al-Mousa, Belal H Sababha, Nailah Al-Madi, Amro Barghouthi, and Remah Younisse. UTSim: A framework and simulator for UAV air traffic integration, control, and communication. *International Journal of Advanced Robotic Systems*, 16(5), 2019. DOI: 10.1177/1729881419870937.

[25] Brigitte Boden, Jan Flink, Niklas Först, Robert Mischke, Kathrin Schaffert, Alexander Weinert, Annika Wohlan, and Andreas Schreiber. RCE: An Integration Environment for Engineering and Science. *SoftwareX*, 15:100759, 2021. DOI: 10.1016/j.softx.2021.100759.

[26] Marko Alder, Erwin Moerland, Jonas Jepsen, and Björn Nagel. Recent Advances in Establishing a Common Language for Aircraft Design with CPACS. In *Aerospace Europe Conference 2020*. CEAS, 2020.

[27] Suchithra Rajendran and Jake Shulman. Study of emerging air taxi network operation using discrete-event systems simulation approach. *Journal of Air Transport Management*, 87:101857, 2020. DOI: 10.1016/j. jairtraman.2020.101857.

[28] Gazmend Mavraj, Jil Eltgen, Tim Fraske, Majed Swaid, Jan Berling, Ole Röntgen, Yuzhuo Fu, Detlef Schulz. A systematic review of ground-based infrastructure. Working paper, Helmut-Schmidt-Universität Hamburg, Hamburg University of Technology and HafenCity-Universität Hamburg.

[29] Mengying Fu, Raoul Rothfeld, and Constantinos Antoniou. Exploring Preferences for Transportation Modes in an Urban Air Mobility Environment: Munich Case Study. *Transportation Research Record: Journal of the Transportation Research Board*, 2673(10):427–442, 2019. DOI: 10.1177/0361198119843858.

[30] N. Kainaris, P. Senk, and U. Heidl. Nachfragemodellierung von Mobilität im urbanen Luftraum mit PTV Visum. *Straßenverkehrstechnik*, 66(2):75–78, 2022.

[31] Karolin Schweiger and Lukas Preis. Urban Air Mobility: Systematic Review of Scientific Publications and Regulations for Vertiport Design and Operations. *Drones*, 6(7):179, 2022. DOI: 10.3390/drones6070179.

[32] Parker D. Vascik, R. John Hansman, and Nicholas S. Dunn. Analysis of Urban Air Mobility Operational Constraints. *Journal of Air Transportation*, 26(4):133–146, 2018. DOI: 10.2514/1.D0120.

[33] Zhengyi Wang, Daniel Delahaye, Jean-Loup Farges, and Sameer Alam. Route network design in low-altitude airspace for future urban air mobility operations: A case study of urban airspace of Singapore. In *International Conference on Research in Air Transportation (ICRAT 2020)*, Tampa, Florida, United States, June 2022.

[34] Saba Siraj, Ajay Kumar Gupta, and Rinku-Badgujar. Network Simulation Tools Survey. *International Journal of Advanced Research in Computer and Communication Engineering*, 1(4), 2012.

[35] Nimisha Swami, Amit Bairwa, and Mukesh Choudhary. A literature survey of network simulation tools. In *International Conference On Communication & Computational Technologies*, volume 5, pages 206–208. IJCRT, August 2020.

[36] András Varga. The OMNET++ discrete event simulation system. *Proc. European Simulation Multiconf. (ESM '01)*, 2001.

[37] Robert Brühl, Hartmut Fricke, and Michael Schultz. Air taxi flight performance modeling and application. *14th ATM Seminar*, 2021.

[38] Majed Swaid, Kai quan Cai, Majed Linke, Benjamin Lührs, and Volker Gollnick. Wind-optimal ATS Route Redesign: A Methodology and its Application to Route A461 in China. In *16th AIAA Aviation Technology, Integration, and Operations Conference (ATIO)*, 2016. DOI: 10.2514/6.2016-4360.

[39] Jan Berling, Alexander Lau, and Volker Gollnick. European Air Traffic Flow Management with Strategic Deconfliction. In Karl Dörner, Ivana Ljubic, Georg Pflug, and Gernot Tragler, editors, *Sel. Pap. Annu. Int. Conf. Ger. Oper. Res. Soc.*, Vienna, 2015. Springer.

[40] Aygün Baltaci, Ergin Dinc, Mustafa Ozger, Abdulrahman Alabbasi, Cicek Cavdar, and Dominic Schupke. A Survey of Wireless Networks for Future Aerial Communications (FACOM). *IEEE Communications Surveys & Tutorials*, 23(4):2833–2884, 2021. DOI: 10.1109/COMST.2021.3103044.

[41] 3GPP. Release 16 Description; Summary of Rel-16 Work Items. Technical report (TR) 21.916, 2020.

[42] Giovanni Nardini, Dario Sabella, Giovanni Stea, Purvi Thakkar, and Antonio Virdis. Simu5G–An OMNeT++ Library for End-to-End Performance Evaluation of 5G Networks. *IEEE Access*, 8:181176–181191, 2020. DOI: 10.1109/ACCESS.2020.3028550.

[43] HeiGIT. OpenRouteService API. `openrouteservice.org`. Accessed: 2022-08-09.

[44] HVV; Hamburger Berater Team. HVV Geofox Thin Interface. `gti.geofox.de`. Accessed: 2022-08-09.