Air Mobility Routing Considering External Factors Digital Twin (AMRCEF-DT)

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Introduction:

Urban Air Mobility (UAM) may one day to transform how people and goods move around our urban communities. The economic benefits to industry and the public can be great, but for societal acceptance, UAM must be integrated into communities in a way that prioritizes safety, privacy, and limits nuisances that affect quality of life. These external factors (sometimes called third-party risks) that are imposed by UAM operators and users onto non-users must be considered, evaluated, and minimized both in the inherent design of the UAM transportation system, but also leveraging the power of real-time data.

UAM vehicle routing has been extensively studied and often focuses on airspace-related outcomes, such as congestion, where simulation and modeling are a common approach. For example, Pinto Neto et al., proposed a trajectory evaluation simulation where one of the aims was to optimize routing to increase airspace safety [1]. Related to external factors, previous research has been conducted using various methodologies to understand third-party ground safety risks for UAM operations. Melnyk et al. assessed third-party ground safety risk of flying a small UAV anywhere in the United States using county population density from US census data. Using a crash impact area model, and a Target Level of Safety based on General Aviation accident statistics, they concluded that the third-party ground safety risk of operating a small UAV is lower than General Aviation risk for 97% of the United States[2]. Another study, by Choi et al., also used a crash impact area third-party ground safety risk in Seoul. Using government-provided hourly population data, building location, and building height data segmenting Seoul into a grid of 250m x 250m area to create a probabilistic model for sheltered and unsheltered population throughout the city. They concluded that they could assess UAM ground risk and compare it to a Target Level of Safety[3].

A digital twin is a recently popularized concept where a physical system is modelled virtually (the virtual twin) with bidirectional real-time or near real-time data transfer to and from the physical system (the physical twin). Bidirectional data transfer between the twins is the differentiator of a Digital Twin [4].

To design an optimized UAM transportation system a Digital Twin approach is proposed as both a predictive Digital Twin (a so-called Digital Twin Prototype, DTP [5, p. 95]) using static data, historical data, and engineering data, as well as to provide a proof of concept of a smart transportation system digital twin using the calibrated modelling/generalizations derived from the DTP, with the addition of live positional data of non-users enabling real-time analysis and feedback to the physical system that can help to maximize safety, privacy, and indirectly minimize quality of life nuisances, for non-users. The maturity level of data used in the proposed digital twin is varied, as there is as yet no operational UAM data, and real-time mobility data is somewhat limited, so this digital twin can be considered an Augmented Digital Twin (ADT)[6]. Leveraging 3d capabilities, this approach enables unique metrics and insights that are not possible with other approaches. These outcomes fill a critical need in understanding how UAM transportation decisions affect urban areas, and with a feedback loop to the physical world will allow for optimization functions to actively limit negative external factors.

The first objective is to present a method of constructing a UAM digital twin that mixes available data sources, with domain-specific modelling/simulation to create a high-fidelity DTP of UAM users and non-users in an accurately modelled 2d/3d world. The second objective is to validate that a Digital Twin can be used to optimize flight approach paths of UAM vehicles when real-time mobility data is available and Air Traffic Management is implement using the outputs of the digital twin to route UAM traffic to minimize external factors. The third objective is to provide insights into proposed UAM transportation systems to help guide the creation and updates of standards, regulations, and policies.

Methodology:

The design of AMRCEF-DT includes a thorough assessment of functional and non-functional requirements to achieve the study objectives. The Digital Twin Prototype needs to have the ability to 1) use input data in a variety of formats 2) visualize in 2d/3d a representation of an urban environment including transportation features and buildings, 3) represent or model users and non-users of UAM located in an urban area as their positions change with time, 4) assess and output External Factor metrics, 5) demonstrate the utility of changing UAM vehicle routing to minimize External Factors. A general-purpose modelling and simulation platform was chosen that satisfies all of these requirements. It supports agent-based modelling and discrete event simulation which will be used to realistically model the behaviors of users and non-users of UAM. Figure 1 shows the design of AMRCEF-DT. The elements are colour-coded to provide context for the nature of each.

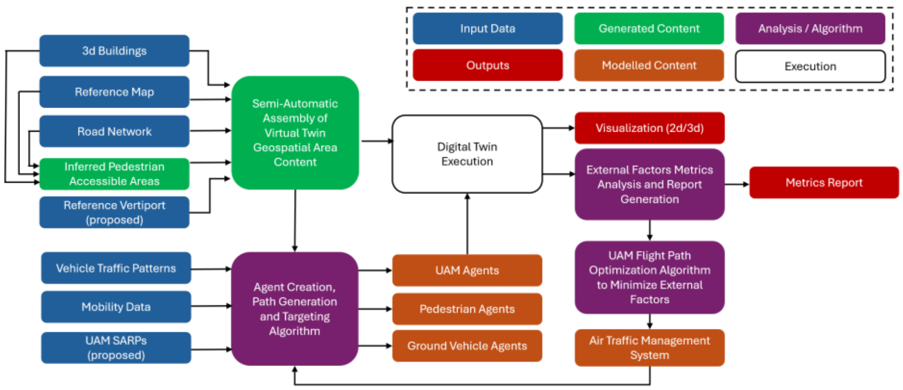

Figure 1 - AMRCEF-DT Architecture

The first step in building AMRCEF-DT is data input processing. OpenStreetMap (OSM) data is used for the road network, and map representation. City of Montreal 3d building geometry including location and orientation data is openly available in CityGML format. A toolchain was developed that generats a database of buildings and converts CityGML data to Collada format for direct usage in the modelling platform, while converting the coordinate system from NAD83 Canadian Spatial Reference System Zone 8, to a coordinate system relative to each building's footprint centroid. UAM vertiport designs and operational characteristics, along with flight paths are being proposed by various sources. The reference vertiport design and suggested landing and departure flight paths were modelled as per FAA Engineering Brief No. 105, Vertiport Design[7]. Using these data sources, the geospatial area is created.

Users and non users are modelled as agents in one of three types; vehicle agents, pedestrian agents, and EVTOL agents. Vehicle agents are created probabilistically at the boundary of geospatial area using the built-in car agent type library and are given a destination. The path finding, and road rule-following functionality is built into the modelling platform which creates a realistic flow of ground-based vehicle traffic that can be modified by changing the probability distribution of sources and destinations. Similarly, pedestrian agents are created probabilistically at various locations around the geospatial area and given a target destination. Using pedestrian walls around roads and buildings, the path finding functionality of the pedestrian library, realistically creates pedestrian movement throughout the geospatial area while limiting the agents' movements to crossing at crosswalks and avoiding walking through buildings. EVTOL vehicle agents use discrete-event simulation and a custom waypoint routine. They fly along a 3d flight path, land at a vertiport and then departs the vertiport in a realistic way. The DTP is meant to model the area immediately surrounding vertiports, so the most important portion of the flight path is the approach and departure vectors. This is the phase of flight where the EVTOL is flying lowest and therefor is physically closest to non-users of UAM. The EVTOL Agent is created outside of the geospatial area, and flies through it. The positioning of the agent source is dynamic and is controlled by a scheduler function.

Similar to[2], [3], this paper focuses on third-party safety risk as a function of crash impact area. Melnyk et al. provided a thorough review and analysis [2] and concluded that the most accurate approach was the weight-based approach proposed by Ale and Piers where linear relationships between estimated impact area and aircraft weight exist[8]. The impact debris area is modelled as a circle with radius calculated based on the calculated debris area. A failure mode modeled is an unpowered free-fall in the direction of travel. Unlike previous approaches, the Target Level of Safety (TLS) is not considered; instead the metric assumes the failure will occur. The metric compares the total number of agents at risk by a crash that occurs somewhere along the flight path with the total number of agents in the geospatial area.

$$SafetyRisk_{groundCrash} = \frac{\sum Pedestrian_{inCrashZone} + \sum Vehicle_{inCrashZone}}{N_{totalAgents}}$$

Upon execution of the Digital Twin, ground-based vehicle and pedestrian agent traffic are created. The probability distribution of sources and destinations is modified to create the expected distribution of non-users of UAM throughout the geospatial area. Once the simulation model has converged to a steady state, the Digital twin safety metric is pre-assessed at various heading angles using agent positions at time 0. The optimal heading is determined and the EVTOL flight is conducted. Since the positions of agents change throughout the execution of the model, a case study is used to validate the Digital Twin Prototype hypothesis that pre-assessment of an optimal heading, provides a flight path with minimized safety metric.

Case Study Results and Discussion

A case study of an urban area in Montreal is modelled using the methodology as described above. The case study area is a circular area 840m in diameter centered around the Concordia University Hall building in downtown Montreal. There are many configurations of EVTOL aircraft[9] but none are certified yet to fly in Canada, so an early experimental VTOL aircraft design, the Canadair CL-84 tilt-wing design aircraft model and characteristics was used because the dimensions and weight are similar to many current OEM designs. Figures 2 and 3 show the 3d and 2d visualizations of the case study geospatial area.

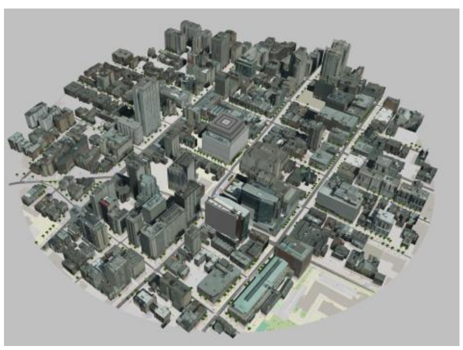

Figure 2 – 3d visualization with accurate 3d buildings

Figure 3 – 2d simplified building footprints

This study is to validate the hypothesis that a Digital Twin can be used to minimize External Factors, not to validate a fully integrated digital twin routing physical EVTOL based on real-time mobility data. For this reason, the ground vehicle and pedestrian traffic were generated to be representative of a typical day based on judgement. Once the model reaches steady-state, the case study data collection commences. The estimated metrics at time 0 are calculated for headings every 30 degrees to predict the heading with least third-party ground safety risk. EVTOL agents (12), located every 30 degrees around the periphery of the geospatial area are flown simultaneously to land on the vertiport. An example output comparing the predicted Safety risk to the measured safety risk is shown in Figure 4.

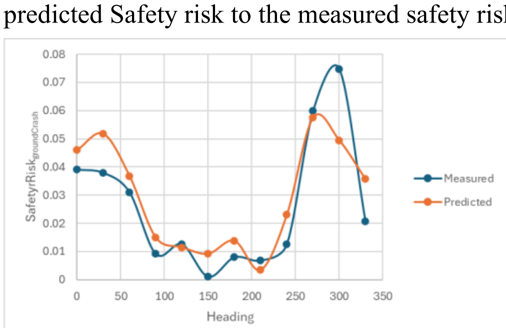

Figure 4 –Predicted Safety vs Measured Safety

While past approaches showed that it was possible to assess third-party ground safety risk of UAM, the geospatial precision was lower and route optimization that minimizes the outcomes based on current conditions were not proven. The case study shows that a Digital Twin approach is a viable method to route UAM traffic in real-time to minimize third-party ground safety risk. The safety metric varies based on heading and the predicted safety is repeatedly representative of the measured safety. Further expansion of the Digital Twin Prototype is planned to assess other External Factors such as additional metrics for third-party safety, privacy metrics of non-users, and nuisance metrics such as airborne noise.

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