Towards the integration of aerial transportation in urban settings

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ABSTRACT

The idea of flying has always fascinated mankind. A century ago it became a reality when in 1914 the first commercial flight was offered. In recent times, many entities are planning, developing and testing aerial vehicles and systems that will move goods and people in urban scenarios. Consequently, the need to develop appropriate planning tools for this kind of transportation is needed.

This paper presents some of the important research gaps that must be addressed before this emerging transportation mode can be integrated into the current transportation system. Close collaboration between transport demand modeling, network design and physical system development is considered to be of high importance in order to have reliable, efficient and safe integration of aerial vehicles in the urban setting. As a consequence, coordination between researchers and stakeholders is necessary to reach these goals. In this paper, concepts that incorporate these research areas and their interaction, for integrating and simulating on a large scale of both manned and unmanned aerial vehicles are proposed.

INTRODUCTION

History of transportation of people and goods is as old as mankind. In the earlier times, the movement of people was done on foot and the transportation of goods was also human powered. Later, animals were domesticated which provided a faster and easier way to move both people and goods, subsequently the spatial reach of humans increased. The invention of the wheel further increased the sophistication of transportation and the reach of people. These inventions brought disruptive effects to the behavior of people by allowing them to reach further, adapt their daily routines and provide them with more freedom.

In the more recent times, during the industrial age, disruptive effects were brought with the inventions of automobile and locomotive. These enabled new, faster and more efficient ways of freight and passenger transportation. The idea of transportation with fixed network and routes was however not new. One of the oldest known predecessors of locomotive is an ancient wagonway in Babylon from around 2250 B.C. where the wagons were pulled by both men and animals along the tracks grooved in stone which prevented it from diverting from the road *(1)*.

On the other hand, the idea of flying has always fascinated mankind. To quote Schmitt and Gollnick *(2)*: "Behind the imagination of flying, which can be found in all old cultures and civilizations, there are also the basic emotional elements of mankind about freedom and mobility." On the 1st January 1914 a first commercial airline flight happened and the dream of easily and quickly reaching any part of the world transformed into reality.

At the moment of writing this paper the transportation system has already seen the testing and in some areas of the world the introduction of autonomous ground vehicles. On the other hand, commercial Unmanned Aerial Vehicles (UAVs) have also undergone testing and some were recently used to transport small sized goods. Additionally, encouraged by the fast paced technological development certain entities are already developing aerial vehicles and systems that will move people in urban settings. The opportunities and disruptive effects that this innovation in the transportation system might bring are vast and they need to be analyzed.

When talking about urban aerial vehicles we have to distinguish two types of vehicles, manned (Manned Aerial Vehicle (MAV)) - those human operated and unmanned (UAV) - fully autonomous vehicles that can be used to either carry goods or people. In order to distinguish between unmanned aerial vehicles carrying passengers and those carrying goods we adopt the following nomenclature - Passenger Unmanned Aerial Vehicles (PUAV) and Cargo Unmanned Aerial Vehicles (CUAV). The introduction of urban commercial manned and unmanned aerial vehicles and their interaction with already existing transportation modes (both traditional and modern) in the transportation system brings many new research questions that are in need of investigation.

It is the purpose of this paper to present concepts for the integration and simulation of aerial vehicles (both manned and unmanned) in the urban transportation system. Moreover, the paper describes research questions necessary to answer before the incorporation of this emerging mode of transportation in the urban system can take place. A methodology to investigate on a large scale the impacts of the introduction of such a system is presented, as well as why the exchange of the information between transportation planners and physical system developers is germane for the development and demand forecasting for this new transportation system.

What follows is a short summary of the state of the art. This will be followed by explanations of our proposed methodology for investigating and forecasting the impacts of the introduction of aerial vehicles in the urban transportation systems. And finally, we give a discussion on the research questions needed to be answered and tackled before this kind of transportation can be introduced.

BACKGROUND

Traditional four-step demand models in transportation are recently being replaced by agent-based models since they are not suitable to forecast the demand for new transportation modes like ridesharing, carsharing, bikesharing or autonomous vehicles. As stated by Shaheen and Rodier *(3)* the need for models that can incorporate both land use and demographics is needed in order to properly simulate these new modes (at that time autonomous vehicles were not the topic, but fall under the same category). Moreover, the availability of these modes in both space and time needs to be considered, which the four-step approach cannot on an appropriate level. This is obviously also true for the simulation and demand modeling of aerial vehicles in the urban setting.

There are many commercial simulation tools for air traffic (SIMMOD *(4)*, AirTop*(5)*, RAMSrams plus *(6)*). Researchers have also developed air traffic simulators (e.g. see ATOMS *(7)*, FACET *(8)*, ELSA *(9)*). They all aim at representing in detail air traffic control. However, taking into account the importance of representing the transport system in the urban environment where the interaction between different entities is high, none of these tools are able to represent people on an individual agent-based level during a whole day. The only known attempt to simulate commercial flights using an agent-based approach, where both aircraft and passengers are modeled on an agent level on all segments of the flight was by Grether and Nagel *(10*) using Multi-Agent Transport Simulation (MATSim)*(11)*. Here MATSim was used to simulate commercial airplane flights over Europe. Aircraft are represented microscopically, while the air traffic network used was implemented at a low level of detail since the goal was not to provide an air traffic management tool. The results presented by the authors show that MATSim is able to simulate the air traffic in Europe realistically However, simulation of urban aviation was not attempted and therefore it is the purpose of this paper to bridge this research gap. MATSim has already been used to simulate ground autonomous vehicles in recent years *(12, 13)* and their impacts on the transportation system. Consequently, developing a urban aerial system as part of MATSim is a natural next step.

Previously some research has already undertaken investigation of how Unmanned Aerial Systemss (UASs) could impact the operations at airports *(14)*. The authors explain that with the faced paced technological developments this is not a far distant future. On the other hand, at the moment of writing this paper several entities are planning to commence operation of urban aerial transportation services with different characteristics. Airbus is currently developing a PUAV capable of transporting people in the urban area *(15)*. Amazon has already performed a packet delivery using a drone in December 2016 *(16)*. Swiss Post has also tested drone delivery in Lugano, Switzerland in 2017 *(17)*. Uber has made plans to install aerial taxi service in Dallas and Dubai *(18)*. In Dubai, the government officials are highly motivated to have PUAVs moving people within the city boundaries in the next couple of years. In *(14)* the prospects of autonomous flying at the airports is aslo envisioned in the future. All these plans and ideas are a signal that proper planning and research on this topic is urgently needed.

Considering the technological advances of aerial vehicles, it is clear that the world is moving towards a new transportation era where these vehicles will play a substantial role. In fact, cars could be slowly replaced by aerial vehicles and it is expected that the introduction of these technologies in the current transportation framework would reduce the traveling time needed by users to move during their daily routine.

In general, it is possible to divide aerial vehicles in categories depending on their size and their autonomous capabilities. Nowadays, small UAVs with low autonomous capabilities are widely used in applications such as: precision agriculture; surveillance; traffic monitoring and Search and Rescue *(19)*. In these applications, UAVs are usually remotely piloted and their motion is bounded to remain always within the pilot Visual Line-Of-Sight (VLOS). As a natural evolution, in the last years a great effort was undertaken by international companies to create a goods delivery system based on small CUAVs with high autonomous capabilities. In this case, CUAVs fly Beyond Visual Line-Of-Sight (BVLOS) and the path to be followed is decided *a priori*, hence a high level of autonomy is required in order to react to unexpected events such as possible collisions or changes in meteorological conditions.

To give some numbers on the growth of this market, in 2010, the Federal Aviation Administration (FAA) estimated that 15,000 unmanned units would be employed by 2020 *(20)*. Surprisingly, in December 2015, with the introduction of the rule for small UAV registration, within the first two weeks of online registration, over 160,000 UAVs had registered, and today, the number has risen to 750,000 *(21)* demonstrating again the great interest behind this technology.

On the other hand, the introduction of aerial vehicles, whether manned or unmanned, for the transportation of people, is following a different path and it is fundamentally slowed down by the need of satisfying user's requirements and flight and safety regulations. This is why, taking into account the interest of industry to create an aerial transportation system, it is necessary to analyze the performance of these vehicles and design a proper transportation system that is able to integrate the aerial mode with more traditional modes.

The adoption of flight simulators able to realistically simulate aerial vehicle dynamics is of paramount importance to tune the transportation system on the basis of aerial vehicles dynamics and performance. Hence, a proper exchange of information between a flight simulator and MATSim is envisaged.

Consequently, close collaboration is needed between different stakeholders and research fields in order to obtain viable solutions for the integration of and demand forecasting for aerial urban systems in the transportation networks. Transport planners need to have a close exchange of information with aerial vehicles developers in order to properly plan, develop and forecast the usage of aerial systems. It is the purpose of this paper to propose concepts necessary for the integration and simulation of aerial vehicles in urban systems, that will take into account the interplay between different research fields. We propose a methodology based on an agent-based transportation model that through the communication with a flight simulator of aerial systems will give valuable insights for the possible solutions of the integration of aerial systems in the urban transportation networks.

CONCEPTS

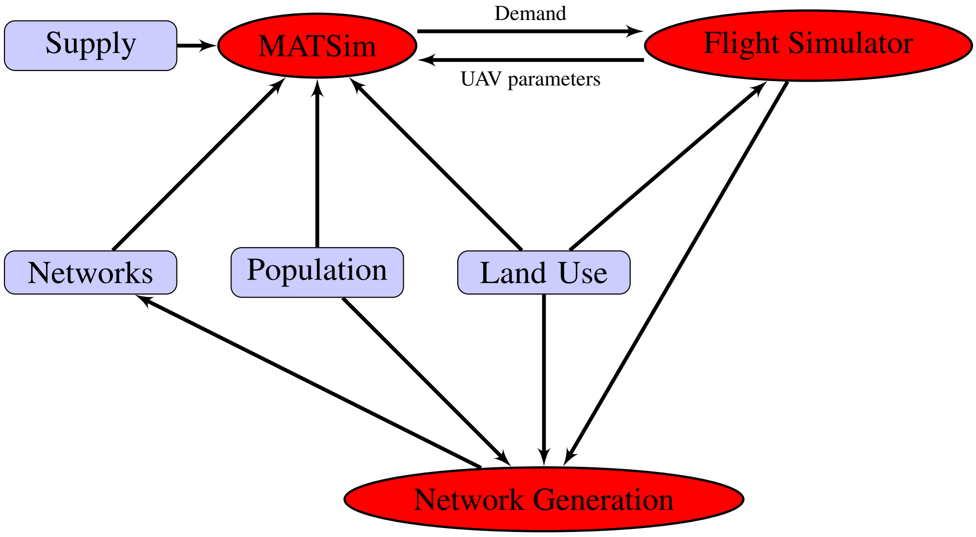
The integration of MAVs and UAVs in the transportation system will not be sudden, but probably have different stages of integration before the technology, regulations and infrastructure will allow for the widespread use of these services. We envision that different stages of integration will be: I) Only MAVs are implemented and the distances served are in mid-range (10 - 50km). Longer flights would probably not be economical in the long run, since not many people have commutes of this range (in Switzerland, this might be different for other countries). Shorter distances are probably also not expected since the infrastructure would need to be densely built in order to allow these kind of trips. II) CUAVs are widespread and small package delivery is performed using aerial vehicles. CUAVs share the airspace with MAVs. III) Full autonomy of AVs, airspace is shared between CUAVs and PUAVs.

Furthermore, we envision three main areas of research needed for the integration of urban aviation into the transportation system. Those are UAV system design, network design and demand modeling. It is important to note that close interaction between these three areas of research is needed in order to provide a reliable and efficient transportation system that incorporates urban aviation.

Communication

Figure 1 presents the communication and directions of information flow between different parts of the methodology. Main inputs to the system are represented with rectangular blocks: land use, supply, population of the area and road and transit networks. *Land use* represents the location of buildings in an area containing home, work, shopping, leisure and other locations where activities are performed and the height of buildings which will be important for the network generation. *Supply* contains the information on the supply of different modes of transportation (transit, carsharing, ridehsaring, etc.) *Population* represents the information on the socio-demographics of all people in the simulated area and their daily schedules. Three main parts of the proposed methodology are represented with ellipses and they will be described in more detail below. The flight simulator will of course have additional inputs on the performance of different aerial vehicles, but those are omitted here to maintain compactness.

FIGURE 1 Interplay between different research areas.



Aerial Vehicles Performance

Nowadays, international companies, such as Uber or Amazon, have demonstrated great interest in the concept of aerial transportation, either for people or for goods. First successful demonstrations of goods transportation have been carried out by Amazon, where an UAV has been used to deliver packets. On the other hand, Uber is tackling the problem of transportation of people which will be slower and will follow predefined steps necessary to guarantee a high level of safety. This is why, in a first phase Uber will adopt semi-autonomous aerial vehicles with trained pilots on-board and only when the technology is mature enough it will move towards completely autonomous systems.

The future technological development of UAVs is certainly connected to the need of reaching a high level of safety in particular if the integration of unmanned vehicles into the civil airspace is envisaged. To this end, it is necessary to analyze and simulate UAVs capabilities and limits in order to properly design a safe and profitable transportation model.

As far as Unmanned Aircraft Systems (UAS) are concerned, the level of reachable autonomy and safety is strictly connected to the following functions

- **Guidance Navigation and Control (GNC)**
- **Situational awareness and decision making capability**
- **Command and Control (C2)**
- **Take-off and Landing**

A definition of GNC systems can be found in *(22)*. In particular guidance navigation and control represent the processes of driving a UAV to achieve assigned mission goals (guidance) by manipulating the inputs to the UAV dynamical system to obtain a desired effect on its output (control), and monitoring its movement from one place to another (navigation). For long range and autonomous operations it is usually necessary to rely on high-performance navigation systems, where the integration of Inertial Measurement Units (IMUs) and Global Positioning Systems (GPSs) *(23)* is usually augmented with Elector-Optical (EO) sensors *(24, 25)*.

A further important step to obtain autonomous systems is the situational awareness and decision making capability of an UAV that must be able to detect and identify failures, possible collisions and losses in communication link and react to them. Collision avoidance is one of the most important requirements for the introduction of UAVs into the civil airspace, this is the capability of an UAV to detect static (e.g. ground, buildings) or moving (other vehicles) obstacles and avoid them during the flight. In the last decade many researchers have tackled this problem *(26–28)*. In more detail, collision avoidance can be divided in cooperative and non-cooperative. In the first case, obstacles positions are transmitted or known *a priori* and the avoidance maneuver is performed accordingly, in the second case, obstacles positions are unknown and the collision is avoided thanks to sensing systems usually based on active (lidars, radars) and/or passive (cameras) sensors.

Command and control (C2) is a common military terminology that refers to the management of personnel and resources *(29)*. When dealing with the transportation of people using autonomous vehicles, it is conceivable that users will have the possibility to control the flight in case of emergency or change the desired destination. On the other hand, a traffic monitoring infrastructure will be necessary to control the airspace, as a consequence, in order to permit one to many C2 operations, a proper encrypted/protected data link to receive aircraft state and send decisions must be designed.

Finally, a further important element that will drive the design of the future network is the take off and landing capability of the aerial vehicles which determines the landing area dimensions and characteristics.

All these elements represent research gaps that must be further addressed and when possible simulated in order to integrate aerial vehicles in the current transportation system and design the network as discussed in the next section.

Network Design

The importance of transportation networks is known since the ancient times. Romans used to construct roads in order to move around their vast empire quickly and efficiently allowing them to dominate large regions with their military power. Modern transportation networks, even though much more complex than those in ancient times, still serve as a mean to efficiently move people and goods. They are the backbone of every transportation system, big or small, urban or rural. Therefore, it is crucial that research is done in order to create efficient urban aviation networks. This was also highlighted in the recent work by Vitins *(30*) and the author's work on the future network design is one possibility to move forward in this domain.

Currently, we envision different stages of development of these networks. First, we assume that these networks in the beginning will be sparse and that first urban flights will be mid distance flights (as also suggested by Uber in their attempts to create a first urban aerial transportation systems in Dallas and Dubai), therefore the effort needed for the design will be rather low. However, as the development of aerial vehicles, the infrastructure and the reduction of the operating costs of these vehicles in the urban areas start to allow for more short distance trips, the design of the network will become more complex.

Close collaboration between network design efforts, transport planners and physical system developers will be crucial. Network capacity will be an important topic and one example of the estimation of airspace capacity can be found in *(31)*. The authors also state that with the reduction in the controller workload the capacities can be increased which will be the case for UAVs as human factor will be substantially lower. Safety measures (avoidance, navigational errors) would need to be incorporated in the design. The efficiency of the designed network will also depend on its capacity and connectivity with the already existing transportation system. The urban network will no longer be a two dimensional graph of links, but will move into the third dimension where the altitude will start playing an important role. The design of the network will have to take into account land use, population densities, geo-fences and meteorological conditions on the basis of historical data. Environmental effects will need to be considered, like noise or carbon pollution. The importance of careful network design becomes even higher if we consider that the altitude limit for CUAVs might be only 400ft (122m) *(32)*. Consequently, it will be necessary to relax this limit for the integration of PUAVs as they would require more space.

An important advantage of the aerial network is that it is virtual, there are no physical boundaries. The only infrastructure needed are the landing stations. This creates opportunities for real-time adaptations of the network in order to increase its performance or in case of emergencies in order allow for certain vehicles to move faster through the network.

Demand Modeling

Modeling and forecasting the demand for this new transportation mode is challenging. Careful planning and exchange of information between network design, physical simulation and demand modeling is required. In the first stages of the introduction of the aerial urban transportation, we envision large scale packet deliveries that will effect travel demand by reducing the necessity for shopping trips. This will allow for more efficient usage of the existing road networks. Aerial transportation of people will in the beginning probably be small scale, but with time it will grow. As UBER officials have recently presented *)(18)*, they expect that the costs for aerial transportation in the urban areas with full automation will fall below the costs for car ownership. With all this in mind and as explained previously four-step models are not suitable to model this kind of transportation mode. Therefore, we advocate to use an agent-based model which can represent each player in this complex system on an agent level and which can represent both land use and socio-demographics. We propose to use a multi-agent transport simulation (MATSim).

Short introduction to MATSim

MATSim through its use of the agent paradigm *(33)* simulates daily life of individuals. Each agent in MATSim has a daily plan of trips and activities, such as going to work, school, leisure or shopping. The initial daily plans of agents are provided in the initial demand together with supply models, e.g. street network and building facilities. The plans of all agents are executed by a micro-simulation, resulting in traffic flow along network links, which can cause traffic congestion. The execution of these plans is then quantitatively measured and assigned a score. Traveling between the activities reduces the agent's score while working (earning money) and other activities increase the score. The goal of each agent is to maximize the score of its daily plan by re-planning its day, which is based on a co-evolutionary algorithm (see e.g., *(34)*). The daily plans are evaluated, and 'bad' daily plans (plans with low performance, respectively low score) are deleted, which corresponds to survival of the fittest in co-evolutionary algorithms. Thereafter, new plans are generated based on the previous set of plans. The re-planning algorithm, in the current state, has several degrees of freedom, such as changing routes, departure time, travel mode or location choice of agents. The execution of all plans, its scoring and re-planning is called an iteration. The simulation is an iterative process, which approaches a point of rest corresponding to a user equilibrium, called relaxed demand. The MATSim simulation loop can be seen in Figure 2. More details about the conceptual framework and the optimization process of the MATSim toolkit can be found in *(11)*.

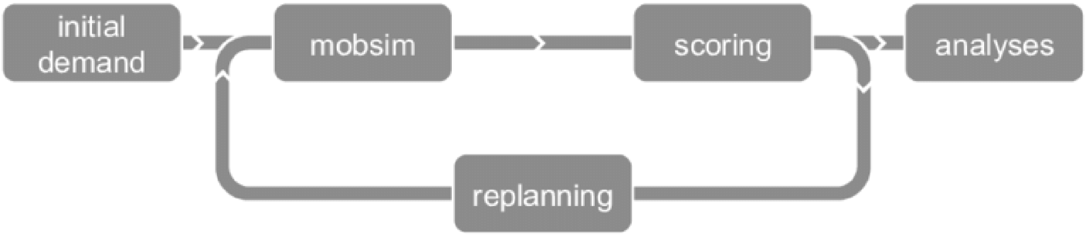


FIGURE 2 MATSim simulation loop.

The introduction of the UAVs can in early stages be simplistic. Agents mode choice will be extended with this new way of transportation. Travel times will be estimated and agents will be moved between the origin and destination without physically simulating the vehicles on the network. This will provide an approximation of the behavior of people, costs and environmental effects of the introduction of the PUAVs. However as the PUAVs become widespread, PUAVs will need to be physically simulated on a network designed. The simulation of aerial vehicles will be supported by the parameters received from the Physical Simulation where the speed-flow relationships can be observed. The aerial network will need to provide high degree of connectivity to the existing road and transit networks. This will give us an opportunity to look at many effects of aerial systems on demand, environment, land development, accessibility, user satisfaction etc.. Furthermore, optimization and analyzes of profitability of the service will be possible with this approach.

The research areas presented in this section are the ones we find most important for the integration of MAVs and UAVs in transportation systems. However, there might be others which can be avoided at this stage of development and some that might arise as the research community starts dealing with these problems in greater detail. Some of these are, but not limited to: planning for construction of the necessary infrastructure, charging stations for electric MAVs and UAVs, different solutions for landing platforms, boarding times and how they influence throughput, parking location when not in use, etc..

The concepts we presented are important for the investigation of aerial urban systems since they incorporate knowledge and inputs from different parts of this complex system. This interplay between different views on aerial systems will provide stable, reliable and efficient solutions for the design of this not so distant mobility solution.

SUMMARY

The idea of flying has always fascinated mankind. On the 1. January 1914 it became a reality for everyone when a first commercial flight was offered Today, certain entities are already developing aerial vehicles and systems that will move people in urban settings. Consequently, the need for developing appropriate tools in order to investigate these systems and their impacts.

In this paper we presented the concepts for the integration of aerial vehicles in urban transportation systems. We discussed three main areas of research that we envision for this future transportation mode: network design, physical simulation and demand modeling. We propose to use an agent-based model in order to model demand because it can represent every actor on an agent level, socio demographics of people and land use. Network design is crucial because it will need to take into account both demand and physical parameters of the aerial vehicles in order to provide certain level of capacity and safety. The network design will need to move away from two dimensions as the need for the third dimension - altitude will appear. Moreover, the assumed limit of 400ft for the altitude limit imposes an additional constraint which needs to be tackled. Physical simulation interacts with both network design and demand modeling, by providing necessary information on the flow-speed dependencies, which will be used in the other two research ares. It is clear that an interplay between these research areas described above is germane for the careful evaluation and planning of these future transportation modes. Furthermore, collaboration between researchers and stakeholders is necessary in order to reach these goals.

The paper also presents envisioned different stages of development and integration of aerial vehicles and necessary degrees of sophistication needed in the framework that we propose. Different levels of integration and sophistication will give an opportunity to start with simpler solutions that will give an approximate evaluations. Nevertheless, they will be important for the later stages when more sophisticated solutions will be needed and implemented.

The goal of this paper was not to list all possible research questions arising with the introduction of aerial vehicles in the transportation system. It was to show concepts that will allow to model the demand for this future transportation mode with high level of reliability.

The next step will be an effort to show how MAVs could impact the demand in the urban systems. This will provide first insights as to the possibilities this mode can bring. It is a long-term goal of this research to develop the proposed methodology and to use it in order to evaluate potential impacts of first MAVs and then both CUAVs and CUAVs on the transportation systems, demand, accessibility and environment.

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