An Agent-based Simulator for Urban Air Mobility Scenarios

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Abstract

In the next years, flying cars are expected to become a real opportunity to realize Urban Air Mobility (UAM) systems. Most of the appeal is given by the opportunity of avoiding congestion, gaining time and reducing environmental impacts with respect to conventional mobility. However, UAM implementation is not trivial as it has several implications in manifold areas like safety, security, traffic control, legal issues and urban design among the others. To investigate on the impacts of UAM, a dedicated agent-based framework has been designed. The results of some preliminary tests carried out to verify the capabilities of this simulator are presented.

Keywords

Flying cars, Simulator, Software agents, Transportation network, Urban Air Mobility

1. Introduction

In the wake of Icarus, thanks to recent technological advancements, Personal Aerial Vehicles (PAV) and Passengers Unmanned Aerial Vehicles (PUAV) moving on both land and aerial modalities, also known as “flying cars”, make it real the opportunity to realize an *Urban Air Mobility* (UAM) for point-to-point connections. To this aim, a growing number of flying cars is being developed or tested all over the world also by commercial companies like Uber [1], which is planning to start with aerial services [2] when technical, urban, legal and economic criticisms will be solved. Indeed, until now UAM requirements have not been considered neither in urban planning policies (e.g., landing and take-off spaces for transition from ground to aerial mode and vice versa) nor from laws and regulations point of view (e.g., safety, security and privacy issues due to flights over or close to buildings have not been considered yet).

Consequences on urban transportation contexts and economic convenience of UAM scenarios are not fully understood and, therefore, there is the need to investigate about them. To this aim, the state of a transportation network [3], where conventional vehicles coexist with flying cars, has to be simulated. In particular, interactions and decision processes not taken into account in

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usual traffic simulations (e.g., interactions of flying cars with other vehicles and obstacles or criteria adopted to choose of moving in aerial or ground modality) have to be considered for evaluating their effects in UAM scenarios.

Intelligent software agent technology (from here on only agent) has been extensively applied to simulate and manage different aspects, at different level of detail, of a wide variety of transportation systems [4, 5, 6, 7]. In transportation systems, agents can play different roles (e.g., travelers, vehicles, signals, etc.). Many studies have explored the opportunity of taking advantage from the autonomous, adaptive, learning, pro-active and social abilities of agents [8] as well as their capabilities to work in large, centralized or distributed contexts also in presence of uncertainty or dynamic behaviors [9, 10].

Such agent features well fit with the need to simulate autonomous vehicles, their motion on transportation networks and their choice processes. Therefore, the agent technology has been adopted also to implement an UAM simulator by associating an agent with each moving flying or ground vehicle that, similarly to Connected Automated Vehicles (CAVs), has been assumed to be fully automated. By using this UAM simulator, we want to investigate on the potential advantages, in terms of travel times, deriving by the possible, future realization of UAM scenarios but without to simulate other aspects which depend from laws and regulations that at the moment are not defined. To this aim, some test transportation networks of different size have been considered, in order to have comparable scenarios. In fact, it is expected that UAM scenarios in existing urban contexts of different size, to which transportation networks refer, will be affected by the urban features, such as location of spaces for landing and take-off, urban structure, building height and specific vertical obstacles among the others, which will result in specific requirements for each tested real network. Then, to avoid specific-feature effects and provide appropriate comparisons, in this study modular test transportation networks have been used, which are based on the aggregation of suitable, unitary modules and refer to the same urban features. The preliminary campaign of experiments carried out on these modular transportation networks of different size has allowed to calibrate the agent-based simulator, including agents' behaviors.

To compare UAM scenarios, the index called "Travel Time Advantage" (TTA) has been introduced, which is the ratio between travel times computed when both ground and flying mobility are allowed on the examined transportation network and travel times computed when only ground mobility is admitted.

The paper is organized as follows. In Section 2 some of the main characteristics of flying cars and some scenarios are presented. In Section 3 the agent-based UAM model is described and in Section 4 the UAM agent-based simulator is presented and discussed. Section 5 some related work are described and, finally, in Section 6 some conclusions are drawn.

2. Urban Air Mobility (UAM)

In this Section the main features characterizing (prototype) flying cars and UAM scenarios will be shortly introduced.

The main flying car characteristics can be summarized in:

1. Vehicle architecture. Shape and size of vehicles must be compatible with both flying

(e.g., aerodynamic) and land (e.g., road lanes width, take-off, landing and parking spaces) constraints [11]. Vehicles mainly differ for take-off and landing (TOL) operations, which can be Conventional (CTOL) or Vertical (VTOL). In urban contexts, VTOL vehicles are expected to be preferred to CTOL ones for the smaller TOL spaces required and the higher maneuverability [12].

2. Operability. Different aspects can influence the vehicle operability [13, 14, 15, 16], which is usually defined in terms of:
    a) Range - the maximum flight distance, measured on the ground, traveled for the maximum fuel/charge capacity;
    b) Endurance - the maximum flight time with respect to the maximum fuel/charge capacity;
    c) Speed - with respect to both “on-the-road” and “in-flight” modalities.
3. Vertical position and main flight rules. The vertical position of flying objects in low level space may be identified by the following vertical distances, namely:
    a) Height - measured from the Above Ground Level (AGL);
    b) Altitude - measured from the Mean Sea Level (MSL);

    Flying conditions [17] currently operating are:
    a) Visual Flight Rules (VFR), for Visual Meteorological Conditions (VMC), permitted until $3000\ ft$ from the ground or sea level;
    b) Instrument Flight Rules (IFR), applying to Instrument Meteorological Conditions (IMC) [18].

    Flying car VFR conditions are expected to be realized at a Very Low Level (VLL) airspace, i.e. $0 - 500\ ft$ AGL, where cabin pressure plant does not need.
4. Automation level. Flying-cars can have different automation/autonomy and flight assistance degrees, depending on the on-board driving systems [19, 20] and communication features, e.g. FANET [21]. Note that autonomous vehicles are expected to be driverless and fully automated (e.g., they monitor the environment around them to adapt their positions/behaviors).

The main expected UAM scenarios are:

I) Point-to-point services between origin/destination prefixed points (i.e., from/to relevant places to/from suitable collecting areas), by certified transportation operators with authorized flight plans;

II) Long/medium-distance trips, with flying mode for the longer legs and ground mode within cities, and with take-off and landing areas on external or dedicated transition roads completely separated from ground mode operations;

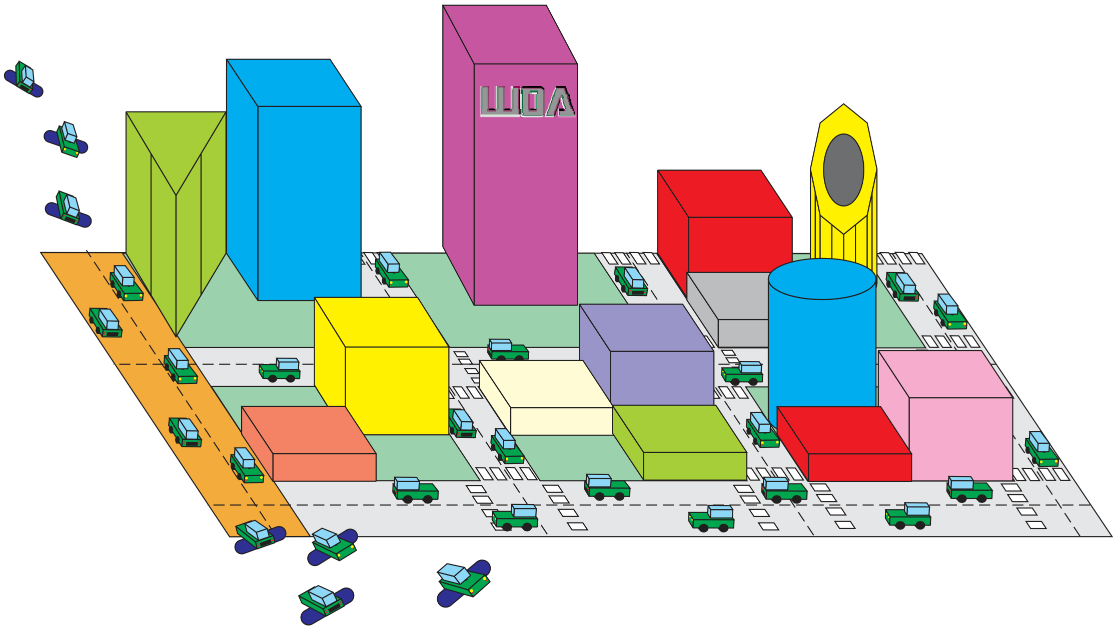

Figure 1: Case C: Short/medium-distance trips within cities.

III) Short/medium-distance trips (Figure 1), where flying cars can move both between city pairs and almost everywhere within cities, although TOL operations happen only at dedicated areas linked to roads for only ground mode.

The agent-based simulator has been designed for the latter one, which includes the main features of the other two cases.

3. The Agent-based UAM Model

In this Section we describe the within-city trip scenarios (case III in Section 2) for which the agent-based UAM simulator (see Section 4) has been designed. Simulation results have been evaluated based on the travel times required to move between origin/destination pairs. Moreover, agents simulate flying cars assumed to be electric and autonomous (coherently with expectations for the still-in-progress CAVs models) to *i*) keep separations in the three dimensions, right trajectories and altitude (according to meteorological conditions) and *ii*) exchange data to be processed on-board to avoid collisions or wake turbulence effects.

The interactions among *i*) flying cars, *ii*) flying and ground cars and *iii*) flying cars and ground obstacles (e.g., buildings, cables) have been considered. Security issues have not been explicitly simulated, while safety aspects have been considered in terms of suitable distances kept from each type of obstacle, including other moving objects. Interactions among flying and ground cars within the city have been allowed only at pre-fixed “transition areas” (TAs) (*i*) placed where the urban structure is sufficiently dispersed, at no less than d_{min} from each other transition area and (*ii*) sufficient to provide safe conditions for entering/leaving the ground transportation network also along the TAs [22]. Moreover, flights have been allowed only along prefixed, safe routes. Other issues concerning rules and prescriptions for security reasons are behind the focus of this research.

To obtain realistic simulations, we assumed that: (*i*) flying cars keep safe distances with ground obstacles and other flying cars; (*ii*) TOL transition areas are suitably connected to the ground transportation network; (*iii*) flying mode can be chosen to move between TAs by maintaining a height suitably greater than the highest building or ground obstacle.

In detail, the agent framework has been specified as follows:

1. Vehicles are homogeneous for characteristics and equipment and each vehicle i is associated with an agent A_i.
2. For each couple (A_i, A_j) of agents:
    a) In ground mode, each A_i follows A_j at a minimum distance $d_{ij} = t \cdot v_{gi} + s_{ib}$, where: $t = 1\ sec$ is the time to start braking; v_{gi} is the ground speed of A_i; s_{ib} is the braking space at a constant deceleration.
    b) In flying mode, the vertical position of A_i, flying over A_j, is $h_i = d_0 + n \cdot s_z$, where: d_0 is the minimum height to overfly urban areas; n is the number of agents under A_i on the z axis; s_z is the minimum vertical separation between agents. Note that more vehicles can use the same horizontal route but at different heights.
    c) In flying mode, $\forall A_i$ that follows A_j on the same horizontal route, their minimum gap s_x is constant.
    d) Transition from ground/flying to flying/ground mode happens at dedicated TAs based on a booked and confirmed time slot authorization; the time slot depends on the estimated arrival/leaving time at the TA depending on ground and flying traffic conditions.
3. For a given origin/destination (O/D) pair [23] the following conditions hold:
    a) The flying leg of a trip follows the Euclidean route. If the Euclidean distance of a trip is greater than d_{min} it will take place by combining ground and aerial links, otherwise it will be only on ground mode.
    b) For each O/D trip, the minimum travel time path is computed as $t(f_g) = l_g/v_g + l_f/v_f$. The ground speed v_g is empirically computed for urban roads as $v_g = c_1 - c_2 \cdot f_g$, where f_g is the traffic volume (i.e., the number of agents) on the ground link at a given time, $c_1 = 37.5$ and $c_2 = 8.5 \cdot 10^{-6}$ (for v_g measured in Km/h) are coefficients empirically computed for averaged road features (e.g., width, slope, etc.), l_g, l_f and v_f are respectively the length of the ground link, the length of the aerial link and the speed on the aerial link. Note that, congestion effects have been assumed to be caused only by ground traffic flows [24].
    c) Agents are autonomous in their choices, although coordinated by a central Agency to/from which they send/receive information about their position, those of other agents and obstacles in their neighboring and about the status of the transportation network.

Combined ground and aerial trips will start only after agents receive information by the Agency, in order to avoid congestion effects at the transition areas

d) All the agents adopt the same TOL procedures.

To compare UAM scenarios at increasing network size, the index "*Travel Time Advantage*" (TTA) is computed as the ratio between the total "flying-ground" travel time and the total ground travel time for "only ground" mode to move between an O/D pair over all the agents and O/D pairs, has been considered:

$$TTA = \frac{\sum_i T^{G+F}_{O/D,\, i}}{\sum_i T^{G}_{O/D,\, i}} \tag{1}$$

where, for each A_i, (*i*) $T^{G+F}_{O/D,\, i}$ is its travel time in ground+flying mode and (*ii*) $T^{G}_{O/D,\, i}$ is its travel time in only-ground mode.

4. The Agent-based UAM Simulator

This Section describes the agent-based simulator designed to implement the UAM model presented in Section 3 and the preliminary results obtained. This simulator has been written in C++ by expanding the one developed for simulating the ground mobility, exploited in [25, 26], and it is not equipped with a graphical user interface.

More in detail, each agent represents a vehicle and it is an object implemented by a specific class. All the vehicles (i.e., agents) can move on both ground and flying modalities and are assumed to be provided with homogeneous features (a reasonable assumption because it is expected that they will have standardized features and equipment).

Agents can autonomously decide in which modality to move among O/D pairs on the basis of the information that they mutually exchange with the other agents and with the Agency, that acts as a Traffic Controller. Information are exchanged by messages having a simplified JADE-like structure and implemented as objects of a dedicate class. In particular, each message stores information about (*i*) sender, (*ii*) receiver, (*iii*) type of the content (e.g., Information, Route, Action) and (*iv*) content (e.g., O/D pair, route, ground/flight modality flag, coordinates on the three axes, speed, action required).

As specified in Section 1, the aim of this simulator is to investigate UAM advantages in terms of travel times, with respect to transportation networks of different sizes. Because of real urban transportation networks have evolved without considering UAM features (e.g., TOL spaces for flying-cars, which should be based on standards for commercial flying cars that are still undefined), the simulation results could not be completely comparable among them if the simulator is applied to real contexts of different size. As introduced in Section 1, network size plays a role in the assessment of potential benefits coming from UAM contexts. Therefore, without loss of generality, we exploited artificial, modular transportation networks based on a specific transportation network module object. In this way, all the transportation networks are intended to share the same urban design, such as building heights and position, road features, and with particular attention to the location of TAs for flying-cars transition from/to flying mode to/from ground mode.

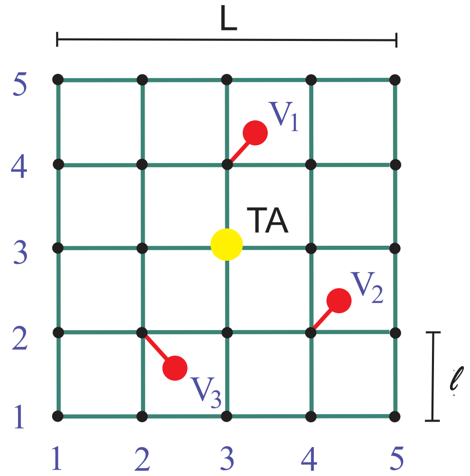

Figure 2: Baseline transportation network module (green lines represents real connections, red line represent virtual connections with trip origin/destination red nodes V, TA is the transition area of the module).

In particular, the basic transportation network module consists of a square mesh grid (see Figure 2) of dimensions $L \times L$ formed by 5×5 nodes and two-way road links of equal capacity and length $l = L/4$. TOL procedures at the transition area TA (represented by the yellow circle in Figure 2) are maintained distinct for ground traffic flows entering to/exiting from it. More in detail, each combined (i.e., ground + flying) trip: *i*) starts from an origin (o) node V_o; *ii*) reaches the transition area TA_o in ground mode; *iii*) takes-off from the transition area TA_o and lands at the destination (d) transition area TA_d in flying mode; *iv*) reaches in ground mode the destination node V_d where the trip ends.

The UAM simulator has been applied on two test transportation networks formed by 2×2 and 3×3 modules and by setting the length of each module to L=1600 m. Moreover, the O/D trip demand has been simulated by adopting an average value of 250 vehicles/h. For each O/D pair, the demand for time intervals of 5 minutes has been generated by using a variation coefficient set to 0.4. The minimum flight height has been set to 50 m[1], by assuming a maximum building height of 30 m. Based on the aerial link length and height, the cruise flying speed varies in the range $80 \div 120$ Km/h. In principle, departure times at a transition area depend on *i*) the expected ground travel time to reach the transition area from an origin node and *ii*) the queue at the transition area. To avoid or minimize waiting times at the transition area (i.e., queues for departures and arrivals), the Agency will inform each agent (i.e., vehicle) about the estimated times:

i) to reach, in ground mode, the transition area from an origin node by considering the current number of agents on the path;

ii) to fly between two transition areas by considering take-off and landing procedures, cruise

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[1] Note that the adoption of a lower minimum flight height requires the assumption of additional conditions and hypothesis on the vehicle equipment, the air traffic control and the urban design.

Table 1
TTA results for the tested networks of 3 x 3 and 4 x 4 modules

Scenario	3 x 3	4 x 4
S_0 (O/D baseline)	0.38	0.35
S_1 (10% O/D increase)	0.45	0.39
S_2 (20% O/D increase)	0.66	0.57
S_3 (30% O/D increase)	0.73	0.65

speed and the time spent until a free slot is available, which depends on the current number of agent on that route.

The structure of the transportation test network is coherent with conventional city organization where only few areas could be available for transition processes, mainly for safety reasons and urban obstacles. Moreover, we assumed that the aerial network is considered virtually not congested because on the same route there is the opportunity of using more lanes, separated from each other by $5\ m$ in height (see Section 3). Note that, for short trips the travel time of only-ground paths could be less than the one of combined ground + flying paths.

Agent moves on the transportation links according to a minimum travel time path criterion [27]. The link travel times are continuously updated by considering the number of agents that are on the links (see Section 3, point b). At transition areas, the maximum acceleration and speed in ground modality have been set respectively to $2.5\ m/sec^2$ and $100\ km/h$ [28].

The reference (i.e., baseline) transportation UAM scenario is S_0, with baseline O/D trip demand level and only-ground mode. For the other scenarios, the O/D trip demand has been increased by 10%, 20% and 30% with respect to S_0. For the S_0 scenario, the value of TTA is 1, while enabling also the flying modality the obtained results are shown in Table 1. As it can be seen, the higher the level of demand, the more the link traffic flows increase that, in turn, causes travel times increase according to a congested network approach[2]. Finally, given that not all individual trip origins and destinations can be reached in a ground mode, and not all the trips are suitable for flying legs, flying and ground modes have to co-exist. However, when ground traffic increases then travel times generally increase and the times to reach transition areas to travel in aerial mode could not be more convenient than using only ground links.

5. Related Work

Decision processes underlying planning and management activities require the knowledge of the state of a system under different conditions and constraints, which can be obtained by using simulation tools to test hypotheses and architectures [3]. To this aim, the agent technology is widely adopted for its advantages, particularly the opportunity of providing agents with different degrees of intelligence, autonomy, learning, adaptive, time-persistent and pro-active capabilities [4, 6]. In the transportation field, agent-based simulations are mainly carried out at

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[2] Agent's path choices change according to link travel times, which in turn depend on agents on the link, thus producing a traffic flow distribution on the network [29, 30].

a microscopic level [31], but there exist also a significant amount of both macroscopic (usually less competitive in terms of design and use of computational/storage resources) and mesoscopic (combining micro and macro aspects) agent-based tools for simulations [32, 33].

Agents have been exploited to study almost all the different aspects involved in usual transportation systems like, among the others, network management [34], transit [35], car-sharing and car-pooling [36, 37], vehicle emissions [38, 39], pedestrian mobility [40], flight recommender [41]. However, given the overwhelming body of researches presented in the literature and the impossibility to provide the interested readers with a comprehensive summary, they could refer to the many existing survey as [4, 42, 43, 44]

In the latter years, an increasing number of research dealt with different aspects involved in UAM and, also in this case, agent-based simulation have been widely exploited to study the opportunities offered by this new promising type of mobility [45]. For instance, high-dense traffic UAM scenarios have been considered in [46, 47] by adopting several scheduling horizons, in [48] airspace integration approaches have been investigated on air vehicle separation issues and in [49] autonomous vehicles, driven by an algorithm with collision avoidance capability, have been simulated on three free-flight scenarios. Other studies have simulated an UAM service on the Sioux Falls area to evaluate several parameter sets and contexts in [50] or by analyzing three case studies to identify possible constraints for UAM services on the basis of mission types or environments in [51].

Finally, communications play an important role for automated/autonomous vehicles and software agents are frequently adopted to simulate communication architecture, routing protocols and the coverage range of the ground infrastructure in complex urban environments. For ground and flying vehicles, Vehicular and Flying Ad hoc Networks (i.e., VANET [52] and FANET [53]) have been respectively proposed to improve the safety of vehicles and prevent collision accidents. In particular, [54] highlights as usual Air Traffic Control (ATC) systems, in presence of high UAM traffic levels and complex urban environments, might fail in monitoring and supporting the vehicle safety and this requires that vehicles should be provided with high levels of autonomous driving.

6. Conclusions

This paper presented an agent-based simulator designed to simulate UAM by considering vehicle interactions (when they are in ground and aerial modality), transition processes, security and air traffic control issues. It allows to evaluate the benefits deriving from UAM, with the desired level of detail, on simulated transportation networks, by means of the value of TTA measure.

Forthcoming researches will test this simulator on different UAM contexts represented by transportation networks of different size and with different demand levels also to evaluate the potential advantage given by UAM with respect to the demand level, flight distance and location of transition nodes. However, note that current regulations do not admit private flights over the city at low altitudes, except some specific, authorized cases and, therefore, before UAM becomes a reality the whole regulatory framework should be changed/adapted to meet some specific requirements.

Finally, further advancements will include the simulation of aerial congestion phenomenon, the optimization of taking-off and landing processes under specific conditions and the effects due to the location of transition nodes.

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