Developing transport management system for integrating drones with smart cities

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Summary

Nowadays, society and policymakers have been continuously working on smart city developments, while the economy found it a well-explanted future business [1]. Depending on the researchers’, developers’ point of view, smart cities have 5–8 significant components: smart infrastructure, transportation, environment, services, governance, people, living, and economy [2]. From these, smart mobility, smart transportation is one of the most important for society and the economy.

Smart mobility, intelligent transportation includes (i) smart infrastructure (roads, rails, tracks, waterways, bridges, tunnels, stations), (ii) smart people, smart economy, (iii) smart vehicles, (iv) smart info-communication and control system (from traffic lights, up to operation centres), (v) optimization principles, and (vi) smart policy-making and legislation [3], like traffic rules, can solve several transportation problems, such as traffic jams, accidents, pollution, fuel cost, or high insurance costs. According to the investigation of the IDEA-E project [4], [5], [6], smart transportation is a slightly larger system, including all the transportation means, all infrastructure covering roads, rail tracks, tunnels of underground transportation, bridges, or multi-modal transport hubs.

From the management point of view, the transportation system is recommended to be classified as (i) passive or non-cooperating, (ii) semi-active or simple cooperating, (iii) active or cooperating, (iv) contract-based, and (v) priority transports, as well as (vi) supporting partners. With IoT and highly automated systems, transportation management is shifting from active control to passive observation. In addition, traffic management to reduce congestion is a crucial topic in the smart city context, and numerous studies related to this topic were published [7], [8], [9].

The smart transportation system, or intelligent transportation system (ITS), focuses on economic and social interest, the reduced travel times [10], utility-based dynamic road pricing for optimal traffic flow management [11], a heuristic for dynamic road environment-type detection using fuzzy similarities on a special gragh [12], the fuel consumption, pollution, as well as improving traffic safety. Several smart transportation system applications rely on the Internet of Things (IoT), including smart roads [13], intelligent parking systems [14], real-world connected vehicle data [15]. Numerous studies deal with the environmental impact of smart cities, smart transportation, including life-cycle analyses [16], [17], and the stochastic shortest path problem [18], while just a limited amount of papers discuss the possible environmental reduction by optimizing total transportation. Instead of that, some parts of transportation and optimization are investigated, like the impact of using electric vehicles [19].

Besides, science and technology are ready to develop and produce an extensive series of low-cost small remotely controlled or autonomous air vehicles as drones (generally
unmanned aerial vehicles/systems – UAV, UAS, including even small pilot-less air vehicles, air taxis). The market of their civil application generated by the economy and social needs is rapidly growing. On the other hand, a severe problem blocks the rapid introduction of drones in city operations and smart city transportation [20], [21], [22]. The existing air traffic management system (ATM) cannot control the predicted amount of drones operated at low altitude in the urban area between large buildings and complex environment (with, e.g., reflection), due to, e.g. (i) the limitations in the system capacity, (ii) the required workforce, (iii) the expected cost, (iv) the required duration of the system development.

To enable drones to be operated regularly as an integral part of the urban air transportation system, it is essential to develop technical solutions, formulate regulatory frameworks, and design management systems to safely conduct operations, both in the air and the ground. Regarding technologies and models, researchers have focused on altitude control and trajectory tracking control problems. Several scientific reports have presented the altitude control problem in the literature [23], [24], [25], [26]. Concerning the management system, the operation of a drone must follow the International Civil Aviation Organization (ICAO) [27]. Several scientific reports focused on the management of drones in smart cities [28], [29], [30], [31]. However, given the anticipated large amounts of drones and widely varying performance characteristics, it is far beyond the capabilities of conventional Air Traffic Management (ATM) systems to deliver services for drones in a cost-effective manner. Traditional ATM framework is mainly established for human-crewed aircraft, while the absence of a pilot on-board will pose a unique set of management issues not seen in human-crewed aircraft operations, such as avoidance collision, tracking trajectories, path planning, communication, and control.

Hence, integrating drones in smart city transportation is an essential task, which requires innovative, highly automated, autonomous solutions.

The main objective of this thesis is to develop an intelligent total transportation management system for integrating drones with smart cities. This objective is divided into four sub-objectives, including (i) to develop the concept of an intelligent total transportation management system for future smart cities; (ii) to develop drone-following models to manage many drones in traffic flow; (iii) to improve a method for managing drones based on the Internet of Thing (IoT) and the Internet of Drones (IoD) technologies; (iv) to investigate the landing process of UAVs.

**Thesis content**

Four chapters were designed in this thesis to achieve its goal. Chapter 1 presents a brief overview of the smart city, urban total transport management, and drone applications in smart cities, demonstrating the issues raised in the smart city total transport management and drone applications. The motivation here is the demand for air traffic management integration
with a total transport-managing system to create an operational link between air navigation actors and the traffic-management system. This approach represents a formal and collaborative commitment between all the actors in a total transport-management system. An intelligent total transportation management system for future smart cities is presented in chapter 2. Such a system uses IoT to integrate vehicles with infrastructure, apply big data surveys of demands, require sub-model developments for safe and optimized transport management, and implement highly automated total management. In particular, the urban total transportation system may include very different vehicles, solutions, such as users, service providers, transport managing, infrastructure, nature/built environments, regulations, competence & knowledge centres, supporting sub-systems, and passive and active interactions with other essential systems. The transportation segments’ classification partly used a hierarchical concept is presented in this chapter, including passive or non-cooperating vehicles, semi-active or simple cooperating, active or cooperating, connecting vehicles, contract-based vehicles, priority transport, and supporting partners. A developed optimization method to solve the traffic optimization problem can be applied to optimize the vehicles’ energy during their operation from the departure until the arrival point. Chapter 3 presents drone-following models, including the safe distance (SD) model that keeps safe velocity according to drones' related position. The Markov model described how a safe distance between two drones is maintained due to relative velocities. These models also represent the one-by-one following drone process in the traffic flow, which can be considered one kind of microscopic model in the transportation system. The numerical simulation results are also presented in this chapter, demonstrating no accident and no unrealistic deceleration. Simulation and testing to verify the concepts are presented in chapter 4. Besides the concept's requirement, the UAVs’ landing process is investigated to show the trajectories' shapes in different initial conditions. Furthermore, the chapter introduces a cloud-based drone managing system to manage and control a drone in a real-time environment. Experiments have been conducted with the results demonstrating the validity and effectiveness of the proposed approach.

**Significant Results**

- **A total transportation management system in smart cities**

  The developing traffic-managing system is that net-centric uses the military-strategic command concept in the highest level called C4ISR (Command, Control, Communications, Computers and Intelligence, Surveillance, and Reconnaissance). The system uses a vast distributed network of sensors for surveillance and recognition of the different cooperating and non-cooperating vehicles, extreme traffic situations (Fig. 1). The system has three layers: physical, info-communication, and control generation. The physical part including all the vehicles, the available infrastructure, the sensor network, and traffic controls integrated into the infrastructure. The infrastructure takes part in the system entirely. That means, for
example, a series of signal lights are built into the line dividing the lanes. The communication is based on the wireless system, partly on using the Internet. The control layer is a hierarchically organized software set. It is used to recognize and classify vehicles, traffic situation awareness, conflict detection, and resolution, including the sense and avoidance of obstacles, other vehicles, people, etc. Such a system is working as a single system, while it deals with four different classes of tasks, including handing the non-cooperative vehicles, traffic management based on the cooperative vehicle information, contract-based traffic management, and priority transportation management.

![Figure 1. The traffic-managing system architecture (NCV - non-cooperative vehicle, CV - cooperative vehicle)](image)

- **An intelligent total transportation management system for future smart cities**

  The urban transportation system is a sub-system of the overall transportation system that guarantees the safe, environmentally friendly, effective, and sustainable mobility and transportation of goods in urban/city areas. Figure 2 shows all the transportation means such as road, rail, water, and air transports operated by the cities. The transportation means may include very different vehicles, solutions. For example, rail transportation operates trams, underground, overhead, cogwheel railway, railway in urban areas, high-speed rail passing in/nearby city, trains, rail/magnetic rail connecting the airport with city centres.
Figure 2. Urban total transportation system: I - industrial area (factories), II - Forest area, III - urban area, IV - airport area, 1 - underground, 2 - road, 3 - upper ground, 4 - path, 5 - railway, 6 - highway, 7 - freight transport, 8 - urban air transport, 9 - water transport.

The classification of the transportation segments uses a hierarchical concept (see Fig. 3). However, vehicles can be grouped depending on their participation in the transportation system (Fig. 3a), namely on the level of their cooperation with the operation centre (Fig. 3b).

Figure 3. Hierarchical classification of the vehicles and primary information transmissions (a) cube of hierarchical structure, (b) system interconnections.

The recommended concept is total transport and total management system. It means that all motions of people and goods (including walking, sport, travels, freight transport) are realized by any vehicles (from electric scooters up to the supersonic business jets) as elements of the single transportation system are monitored and controlled by a particular hierarchical concept (Fig. 4).

The introduced new concept, addressing the intelligent total transportation management system, has essential novelties related to the hierarchical classification of the transportation system and the application of the own management methodology to each class, and the overall system. The possible management with the significant classes of
vehicles are management of non-cooperating vehicles, cooperating vehicles, contract-based traffic management, and priority transportation management.

![Smart city total transport management diagram](image)

**Figure 4.** Representation of the management with smart city total transportation system

Intelligent total transportation management uses a particular data processing and decision support sub-system. It is unique because it synthesizes the latest computing methods (artificially intelligent) with ubiquitous computing (locally distributed partially optimized, embedded sub-systems) to reach the high ambition goals: operate an effective, sustainable transportation system that meets the needs of the society and economy, and has a minimum impact on the environment, while being safe and secure. Such a system uses sensors integrated into the infrastructure, environment, cooperating and contract-based vehicles, drivers, enterprises, institutions, surveillance systems, and technology developments. The information depending on its value is used in different management concepts such as passive control, active control, dynamic management, and proactive management.

- **Drone-following models in smart cities**

Generally, UAVs follow a reference trajectory to do their task. The reference trajectories are usually planned as straight lines, curves, or a combination of both. To achieve an excellent autonomous flight, a precise, robust, and effective trajectory-following guidance law is required [32], [33], [34], [35]. However, when the number of drones increases, severe accidents can appear in the sky, even in simple situations. The investigation of drone traffic safety and the intelligent transportation system's development requires drone-following models describing one-by-one following process in the traffic flows.

The first drone-following model is based on the principle that it keeps a safe distance
according to relative velocity (SD). Such a model describes situations that the drone’s velocity depends on the traffic situation, namely on the distance to the drone ahead and its velocity. This approach has led to the linear models assuming that its controller controls the followed drone’s acceleration to keep zero relative velocity to the drone ahead.

The SD model is given as follows:

\[ \ddot{X}_n(t + T) = \lambda \frac{[\dot{X}_n(t)]^p}{[X_{n-1}(t) - X_n(t)]^q} [\dot{X}_{n-1}(t) - \dot{X}_n(t)] \]  

(1)

Where, \( \ddot{X}_n(t + T) \) – the acceleration of \( n \)-th drone after a reaction;
\( X_{n-1}(t) - X_n(t) \) – relative distance between the \((n-1)\)-th drone and the \( n \)-th drone;
\( \dot{X}_{n-1}(t) - \dot{X}_n(t) \) - relative velocity of \((n-1)\)-th to the \( n \)-th drones in time \( t \);
\( T \) – delay time of a controller;
\( \lambda \) – a weight coefficient related to the controllers;
\( p, q \) – parameters related to velocity and distance of the drone ahead.

The second drone-following model is the Markov model based on approximating the stochastic process of velocity decision.

\[ \ddot{X}[k + 1] = c_v (\dot{X}_{n-1}[k] - \dot{X}_n[k]) + c_x (X_{n-1}[k] - X_n[k]) - \Delta X_{pdn} + \epsilon[k] \]  

(2)

Where, \( c_v \) and \( c_x \) are coefficients that can depend on the time, given drone and controllers; \( \Delta X_{pdn} = [\ddot{X}(t)] \) is the predefined safe distance between the drones; \( k \) is the number of steps in a chain \( (t = k\Delta t) \); \( \epsilon(k) \) is the random value disturbing the process.

The numerical simulation experiments on the SD and the Markov models show that there is no accident and no unrealistic deceleration. The velocity of the followed drone is changed according to the speed of the drone ahead. However, the followed drone can react quickly compared to the leading drone’s reaction because of the difference in its acceleration.
The Cloud-based drone managing system (CbDMS) motivated by IoT and the Internet of Drones (IoD) technologies have shown exemplary performance in dealing with complicated and active traffic flows. This platform has three main layers: (i) physical layer, including connected drones and fundamental infrastructure; (ii) cloud layer, including storage, computation, and interfaces, is based on the wireless system, using the Internet, and (iii) control layer is a hierarchically organized software set used to control and manage drones in the traffic flows (Fig. 7).

We carried out tests with a drone to validate the proposed approach and assess its achievement - the test situation of following a set of waypoints with a real drone in a particular area.

Figure 6. The comparison of the SD and Markov models

Figure 7. The Cloud-based drone managing system
The experimental result is demonstrated in Fig. 9. Initially, the drone was placed at a home position. When it received the command from the ground control station (GCS), it take-off and did a mission, visiting the created waypoints. It is seen that the desired trajectory and actual trajectory are correlated. The gap between the two trajectories represents GPS location because the drone receives the GPS location.

Figure 9. The difference between desired and real trajectories (pink line – desired trajectory, blue line - real trajectory)

Figure 10. The difference between desired and actual altitude of drone, green line – desired altitude, red line – actual altitude
The CbDMS is an advanced approach for managing drones to meet critical features. The CbDMS associates with real-time streaming, Cloud computing, regularly refreshed information, and intelligent acknowledgment to dynamically varying situations. With CbDMS, complicated missions can be taken with efficiency, improving safety and applicability. However, it is necessary to examine the limitations of the proposed method, such as controlling and managing real-time drones over the network is highly dependent on a guaranteed quality of assistance.

- **Obstacle avoidance method**

Along with drone applications' spreading trend, drone collision’s flight safety with buildings, helicopters, and the landscape becomes an urgent issue for civil and defense agencies. A collision avoidance system is necessary for drone flights, especially for autonomous drones in dense airspace shared with other aircraft to guarantee airspace security. Conflict detection and collision avoidance is also a valuable tool for highly automated and autonomous vehicles. The obstacle model is one of the critical parts of these systems, described as the following. Assume that each obstacle is prescribed in a cylinder with the center \( C_{Bl} \) and radius \( r_{Bl} \), as shown in Fig. 11. The surfaces of cylinders can then be used to form constraints for obstacle avoidance. Accurately, the safe distance \( d_{s,l} \) from the obstacle \( l \) is calculated from the cylinder center to its surface at the flying height.

![Obstacle representation and safe distance calculation](image)

**Figure 11.** Obstacle representation and safe distance calculation

- **Managing drones as a formation to avoid obstacles in smart cities**

Formation motion means a group of vehicles moving together and following a leader vehicle. In such a case, the motion of the group of vehicles can be managed by only controlling the leader vehicle, as originally developed for advanced air traffic control. The formation flight modes are considered more than relevant for the coordination of drones, as
conventional air traffic management techniques and tools are powerless in dealing with such a high number (and complexity) of movements. The model can be relatively easily adapted to the road or urban traffic systems.

The formation can be represented by a simple system of the linearized equations:

\[
\begin{align*}
    \dot{s}_i &= Ps_i + Qu_i \\
    \dot{s}_0 &= As_0
\end{align*}
\]

where, \(s_i \in \mathbb{R}^n\) is the drone \(i\)'s state, namely it is a state vector and \(u_i \in \mathbb{R}^n\) is the drone \(i\)'s input, input vector, which can only use local information from its neighbour drones. Matrix \(P = [p_{ij}] \in \mathbb{R}^{n \times n}\) is a diagonally dominant matrix or state transition matrix. The matrix \(Q\) is of full column rank. \(s_0 \in \mathbb{R}^n\) is the state of the leader drone.

With the assumption that the pair \((P, Q)\) is stabilizable, the drone Formations (3) and (4) is said to be achieved if, for each drone \(i \in \{1, \ldots, N\}\), there is a local state feedback \(u_i\) of \(\{x_j; j \in N_i\}\) such that the closed-loop system satisfies \(\lim_{t \to \infty} ||s_i(t) - s_0(t)|| = 0\) for any initial condition \(s_i(0), i = 0, 1, \ldots, N\).

We use the control law for drone \(i\) as follows:

\[
    u_i(x) = \sum_{j \in N_i} ||s_j - s_i - d_{ij}||^2
\]

where, \(d_{ij}\) is the desired inter-distance related to the position vector. A drone \(j\) is the neighbour of drone \(i\).

- **Investigating the landing process of UAVs**

The landing approach is one of the critical stages of the entire flight to bring the UAV to land safely at the desired location. Common landing approaches consist of the following stages: (i) heading against the direction of the wind, (ii) descending, (iii) slowing down. However, this process will be influenced by several factors such as wind disturbance, general aerodynamic force, the traction force of an engine, and the propeller's reaction moment.

Methodologies used to determine and calculate the landing areas are based on solving the aircraft’s motion equations and analytical methods. Based on the landing areas, the desired landing orbit is estimated, within the UAV can land accurately at the desired position.

UAVs' landing processes consist of three stages: the directive stage, the descending stage, and the deceleration stage. These stages are determined when the UAV is into each landing zones. Landing zones will be determined by knowing the radius of each region. The most common method is to investigate UAVs' kinetic dynamics by solving the differential motion system. Therefore, UAV dynamics will be used to calculate the deceleration zone, and then the remaining landing areas will be identified by analytical methods.
Based on the landing areas, the desired landing orbit is estimated, within the UAV can land accurately at the desired position. The simulation results for UAV landing in the given direction are shown in Fig. 13 and Fig. 14.

**Figure 12.** The proposed UAV landing zones

**Figure 13.** The desired trajectory for UAV landing in the given direction.
Figure 14. The altitude, vertical velocity, and roll angle when the UAV must land in the given direction.

In this case, the desired landing orbit consists of two curves and two lines. At the height $H = 500 \text{m}$, the UAV completes two turning with the desired roll angle $\gamma \leq 20^0$. Between these two times, a straight flight takes place with speed $V = 40\text{m/s}$. Then, the UAV flies in the right orbit in the given direction, starting to descend the altitude and finally straight flight at decreasing speed. The simulation result given is reasonable and necessary to implement controlling orders. The result shows that the landing direction is the direction from the current point of the UAV to the desired landing point, and this landing distance is the shortest one.

**New scientific results**

- **Thesis I: I have proposed a total transport management system in smart cities.**
  - I proposed a system that used the vast distributed network of sensors for surveillance and recognition of the non-cooperating, cooperating, contract-based, and priority transport vehicles, including three layers: physical, info-communication, and control generation.
  - I have analyzed and developed an ICT concept based on the wireless network as distributed sensors and actuators and the Internet as IoT, which integrated into vehicles, infrastructure, individual vehicles, and a conventional single control system.
  - I provided the control layer that is a hierarchically organized software set. It is used to recognize and classify vehicles, traffic situation awareness, conflict detection, and resolution, including the sense and avoidance of the obstacles, other vehicles, and people.
  - I have demonstrated the system allows us to optimize the total traffic depending on objectives practical or energy or environmental impact minimization.

  Related publications: J-2, B-3, B-4, B-5, C-3

- **Thesis II: I have proposed an intelligent total transportation management system for future smart cities.**
✓ I have introduced a vision and a concept of managing the total transportation system by defining the concept, the methodology, and the required sub-model developments for the future intelligent transportation related to smart cities.

✓ I have classified the transportation segments partly used a hierarchical concept, including passive or non-cooperating vehicles, semi-active or simple cooperating, active or cooperating, connecting vehicles, contract-based vehicles, priority transport, and supporting partners.

✓ I have developed an optimization method to solve the traffic optimization problem that can be applied to optimize the vehicles' energy during their operation from the departure until the arrival point.

✓ I have presented the role of data processing, applying the big data survey and methods of soft computing and artificial intelligence.

Related publications: J-2, B-3, B-4, B-5, C-3

• *Thesis III: I have developed the drone-following models to manage drones for smart city air traffic flow.*

✓ I have developed a model based on the principle that keeps a safe distance according to relative velocity.

✓ I have developed another Markov drone-following model based on the approximation with the stochastic diffusion process of speed decision.

✓ I have created the numerical simulation environment that demonstrates the safe distance between drones is maintained; namely, there is no accident in the traffic flow.

✓ This approach can be applied to dense traffic flow. In addition, the first model can be useful for studies of local stability.

Related publications: J-1, J-4, C-4, C-6

• *Thesis IV: I have proposed a new managing system for integrating drone motion into urban air traffic using the cloud-based approach.*

✓ I have created a framework based on cloud devices and services such as computation, storage, and web services.

✓ I have improved a communication approach that allows users to control and monitor drones as connected objects in a real-time environment, which provides the management and control of drone applications for delivery, surveillance, security, ambulance, and emergency response.
✓ I did an experimental study, aiming to evaluate the real-time performance of monitoring and controlling drones.

✓ This approach's development used increasing the frequency of updating GPS coordinates or adding filtering techniques (e.g., Kalman filters) that can improve the monitoring more accurate and reduce noise.

Related publications: J-1, B-1, B-2, C-6

• Thesis V: I have developed a methodology for determining and calculating the landing stages for UAVs.

✓ I have improved the differential system equations of specialized UAV motion using a parachute system to determine the more accurate the landing areas with reducing environmental impacts.

✓ I have developed a particular fuzzy control based orbits-straight line trajectory for increasing the UAV landing accuracy.

✓ I have created the simulation in a Matlab environment that calculates the shortest landing orbit, which is a desired one.

✓ The created methodology can be applied to the more complex task landing in city areas and moving or oscillating platforms.

Related publications: J-1, J-3, C-2

Own related publications

Journal papers


Book chapters


**Conference papers**


References


