TOMISLAV RADIŠIĆ, PhD[1]
E-mail: tradisic@fpz.hr
ANDRIJA VIDOVIĆ, PhD[1]
E-mail: avidovic@fpz.hr
JURICA IVOŠEVIĆ, PhD[1]
E-mail: jivosevic@fpz.hr
WANG BO, PhD[2]
E-mail: bo305@hotmail.com
[1] Faculty of Transport and Traffic Sciences
University of Zagreb
4 Vukelićeva ulica, 10000 Zagreb, Croatia
[2] Ningbo University of Technology
201 Fenghua Rd, Jiangbei Qu,
Ningbo Shi, Zhejiang Sheng, China

CHALLENGES AND SOLUTIONS FOR URBAN UAV OPERATIONS

ABSTRACT

Unmanned aerial vehicles are transforming our way of thinking about flight operations and services that can be provided by them. Visions of tomorrow imagine UAVs as ubiquitous platform for many applications in urban setting. Vertical take-off and landing as well as electrical propulsion and short endurance of today's small and micro UAVs make the urban environment the best possible place for adoption of advanced UAV-related services. Adoption, however, is stymied by many challenges which are inherent in urban flight operations. In this paper, we examine the technological challenges faced by future urban UAV designers and operators, and we provide possible solutions to some of those challenges.

KEY WORDS

UAV; urban area; surveillance; navigation; anti-UAV; challenges; solutions

1. INTRODUCTION

Reduction of production costs of unmanned aerial vehicles (UAVs), sensors and actuators, along with the recent technological improvements, made UAVs easily accessible for industrial and private purposes. UAVs are a product created by the merging of two technological branches - remote controlled aircraft systems and fully autonomous vehicles. Scientists and industry invest significant resources in developing UAVs and evaluating their social and economic influence. However, many aspects of this rapidly evolving technology remain unexplored, including the infrastructure that should enable their operations in urban areas.

The current market share of civilian hobby and commercial UAVs is relatively small compared to military, $3 billion or 11% market share in 2016 [1]. However, the forecasts agree on the rapid growth of civilian use of UAVs and their economic impact on the world market. Goldman Sachs predicts that by 2020, 30% of the total estimated $100 billion of the global UAV market will be in the civilian sector [2]. UAVs already are intensively used in agriculture, aerial photography, geodesy, law enforcement, advertising and, more recently, in building safety and package and food delivery. The industry's largest representatives such as Amazon, DHL and Google have already tested and used UAVs for different civilian purposes, e.g. package delivery. Former London Mayor Boris Johnson called for package delivery solutions with UAVs to help solve the problem of congestion in the city [3].

Increased use of UAVs in urban settings will increase the risks of accidents and incidents which are likely to result in the loss of human life or material damage. It is also inevitable that in the near future UAVs and manned aircraft will share the same airspace. This puts many obstacles and challenges for the UAV design engineer. The problem of collision avoidance in the air could become one of the limiting factors for further development of unmanned aviation systems.

In this paper we systematically searched for challenges and solutions for urban UAV operations. We present the challenges that need to be solved in order to make urban UAV operations possible in a safe and efficient manner. Challenges are identified from the literature, incident reports, and expert interviews. Solutions, where available, are also presented. Challenges are broadly categorized into areas of surveillance, navigation, communication, coordination, air policing and ground services.

2. SURVEILLANCE

Surveillance of air traffic is a basic prerequisite for many functions of air traffic management (ATM) [4]. In the current concept of operations, surveillance is achieved by using primary and secondary radars, and automatic dependent surveillance (ADS). Surveillance gives the air traffic controller the information needed for maintaining the safe and efficient air traffic. This data is displayed on a screen which the air traffic controllers use to decide how to solve conflicts. To avoid work overload, the airspace is divided into sectors and each sector is assigned to a team of two controllers (planning and executive) [5]. Currently, the approximate number of aircraft that are simultaneously monitored in a single sector is around 30 to 40.

This concept of operations translates poorly into the urban UAV environment. Radar-based surveillance methods used in conventional ATM assumes line of sight visibility between one or more radar stations and aircraft. In urban canyons such visibility is not guaranteed, and even if it were, there are other issues that are inherent to UAVs. Firstly, they are small and slow and therefore easily mistaken for birds. Secondly, there are no easy methods for decluttering the display when the radar is aimed at urban environment with many moving objects that need to be filtered out, such as cars, pedestrians etc.

There are specialized systems for UAV detection, such as SharpEye™ X-band radar with electro-optic coupling which can detect typical UAVs at a range of 1 km (Figure 1. a). This system can be used to protect airports, power plants or other critical national infrastructure (CNI), however it cannot be used in urban environment due to line-of-sight requirements [6]. Other approaches rely on detection of radio-frequency (RF) emissions from UAVs such as Aaronia Drone Detection System (Figure 1. b). This system can detect UAVs based on the commonly used frequencies, such as 35 MHz, 430 MHz, 460 MHz, 2.4 GHz or 5.8 GHz, all commonly used for communication with UAVs. Detection range is up to 7 km and angular detection resolution is 2°-3° [7]. Another interesting feature is that the system can also detect the operator. For this system to work one precondition needs to be met and that is that the UAV emits a signal which is not always the case, especially for illegal operators.

The one obvious solution to the problem of UAV surveillance is equipping UAVs with transponders. However, this implies cooperation from the UAV operators. Probably all legally operated UAVs could be equipped with a transponder but the challenge is with surveillance of those non-cooperative operators. One possible solution is a surveillance network consisting of sensors attached to highest buildings and tethered balloons. Police UAVs could also be used to patrol the skies and check for legal transponder operation. This challenge ties in with the challenge of air policing. Namely, what to do when the illegally operated UAV is detected (see section 6. Air Policing)?

Figure 1. SharpEye X-band radar (a) and Aaronia Drone Detection System (b)

3. NAVIGATION

Navigation of small and micro UAVs has many things in common with navigation of conventional aircraft, however, there are many challenges which are specific to the UAV operations. Conventional aircraft, here defined as those operating in general and commercial aviation environment, rely on a layered navigation infrastructure consisting of ground-based systems, satellite-based systems and on-board systems [8]. These systems overlap in function and availability, thus providing redundancy over the whole range of operations. In addition to these navigation systems, all manned aircraft are also able to operate based on the visual navigation which is the main mode of navigation for some aircraft or a backup for others. UAVs have comparatively fewer systems available, whereas those that are available are not suitable to support all types of activities which are expected of UAVs (Table 1) [8].

Table ***1.*** *Comparison of Navigation Systems used in Conventional Aircraft vs. Micro UAVs [8]*

Navigation system	Conventional aircraft	Small and micro UAVs
Ground-based radio-navigation systems (NDB[1], VOR[2], DME[3], ILS[4])	Widely used. NDBs are being phased out.	Not used. Receivers have not been miniaturized, accuracy too low for the intended purposes.
Satellite-based systems (GPS, GLONASS, Galileo, ABAS[5])	Widely used. Considered the back-bone of the future air traffic management.	Widely used. In most cases this is the sole provider of navigation information.
On-board systems (INS[6])	Used in commercial aircraft, not as much in general aviation. Highly accurate systems are used to provide autonomous long-range navigation.	Widely used. Low-cost, low-accuracy systems are integrated with GPS to provide high-frequency attitude and position information. INS is not used for autonomous navigation.
Visual navigation	Always available, sometimes used. Commercial air transport relies on visual navigation mostly for take-off and landing or as a backup. General aviation pilots use mostly visual navigation for all phases of flight. Visual navigation is primary source of position information for all low-altitude operations (SAR, law-enforcement, industrial operations such as crop dusting, logging, power-line inspection etc.).	Currently used for experimental purposes. Commercial solutions do not exist yet.

[1]NDB – Non-directional beacon
[2]VOR – VHF omni-directional radio range
[3]DME – Distance measuring equipment
[4]ILS – Instrument landing system
[5]ABAS – Airborne-based augmentation system
[6]INS – Inertial navigation system

As can be seen in Table 1, small and micro UAVs lack the redundancy of navigation systems which is available to conventional aircraft. Radio-navigation receivers could be miniaturized and deployed on UAVs, however, their accuracy is not good enough for the type of operations which are expected of UAVs. Among other environments, micro UAVs are expected to operate within urban areas, flying safely, accurately, and precisely in close proximity to buildings and people. Flying in GPS-denied environment, such as indoors, will further push the limits of UAV navigation. Interaction with ground objects is also one of the activities which will drive future application of UAVs.

Current situation can be summarized as follows [8]:

- Small and micro UAVs use single source of navigation information (integrated GPS/INS).
- Flying in urban environments requires redundancy.
- Flying in GPS-denied environment requires other sources of navigation information.
- Interaction with ground-based objects requires high accuracy and precision.
- Research is already underway with purpose of enabling autonomous visual navigation for UAVs.

A large body of research has been produced on the topic of visual navigation with application to UAVs. The aim of the visual navigation is primarily to localize the UAV by mapping the surroundings. It can be made by building the local map or by matching the features of the terrain to the pre-existing map. For example, in [9] dense three-dimensional reconstruction from downward looking camera images from UAV is presented, while in [10] a complete UAV setup for autonomous exploration is demonstrated. In [11], a visual algorithm for long term object following was presented. It specifically uses global geometric matching to ensure that the object is followed in global coordinate system.

4. COMMUNICATION

Current ATM systems use voice communication in VHF aeronautical spectrum (118-137 MHz) and controller-pilot data-link communication (CPDLC) also in the VHF aeronautical spectrum. ADS-B uses 978 MHz and 1.09 GHz, airport ground radio uses 460 MHz, and various radar systems operate in L and S bands (e.g. ASR-11 uses 2.7-2.9 GHz, L-STAR uses 1.5 GHz). Commercial UAVs communicate in the several parts of the spectrum which are shared with many other users. These frequencies are [12]:

- 35 MHz: Older RC gear in Europe
- 72 MHz: Older RC gear in the US
- 420-450 MHz: **UAV control links**, amateurs in emergency communications
- 902-928 MHz: **UAV video and telemetry**, Industrial, Scientific and Medical (ISM) equipment, cordless phones, computer networking, walkie-talkies, amateur TV, repeaters
- 1.24-1.3 GHz: **UAV video links**, amateur TV, voice, data, GPS
- 2.39-2.485 GHz: **UAV control links, video and telemetry**, Wi-Fi, Bluetooth, microwave ovens, wireless headphones, cordless phones
- 5.15-5.825 GHz: **UAV video**, Unlicensed National Information Infrastructure (UNII) devices, 5G routers

Each of these frequency bands has its own advantages and disadvantages. Lower frequencies, like 430 MHz and 900 MHz, suffer less multipath distortion, have lower susceptibility to bad weather, have longer range with equal power, but also, they do not support broadcast of quality video, 900 MHz is dedicated for GSM in Europe, and they can experience interference in urban areas due to the wide use of cordless phones.

Higher frequencies, on the other hand, enable broadcast of quality video, have smaller transmission antennas, but they require line-of-sight operations, their range is affected by humidity in the air, they need higher power than the lower frequencies for the same range, and they can experience interference from wide variety of appliances and devices commonly used in urban areas (e.g. microwaves, wi-fi, cordless phones, etc.).

One advantage of urban operations is good availability of 4G mobile networks which can enable transfer speeds of up to 50 Mbit/s. Using the existing infrastructure, such as mobile networks, for video link in use cases where a small delay is tolerable, can be a solution when it is difficult to maintain longer range line-of-sight high-frequency communications link. Control links could also be established through the existing mobile networks but only for UAVs with higher degree of autonomy, since small delays could make direct control difficult.

Another solution for interference problems is local pre-flight interference analysis [12]. Operator can use special equipment to test for other signals on the frequencies which are required for UAV operations. This test can then show if the test site can be characterized as “positive transmitting environment”. If not, mitigation measures can be made, such as switching to other frequencies [12].

5. COORDINATION

Coordination in the context of this paper is used as both coordination among UAVs and coordination between UAVs and ground services. In civil aviation, aircraft rarely coordinate among themselves directly. Usually, the coordination is mediated by air traffic controllers (ATCOs). ATCOs detect possible conflicts and solve them by making changes to the heading, airspeed or altitude of one or more aircraft. Coordination in terminal and ground operations is similar, with only difference of another constraint in terms of ground infrastructure capacity. Conventional aircraft coordinate among themselves in visual flight rules (VFR) operations or as a final safety measure during the traffic collision avoidance system (TCAS) resolution advisories.

Visions of future urban UAV operations include large numbers of UAVs operating in a very complex environment with many obstacles. To ensure collision detection and avoidance there should be multiple safety nets. First, possible conflicts could be detected and resolved in the planning stage of a flight; this is called strategic conflict resolution. To enable strategic conflict resolution, UAV trajectories must be known and executed with great accuracy. Also, obstacles must be identified in advance and taken into account during the planning phase. This concept of operations is slowly being implemented in European air traffic under the name of trajectory-based operations (TBO). However, there must be a way to maintain safety when capability to maintain TBO fails, e.g. when an aircraft suffers degradation in navigation capabilities. In the case of civil air traffic, there will be an ATCO with all necessary surveillance tools to help maintain safety, in coordination with pilots, when such degradation occurs. For UAVs there is a need for similar backup system which can maintain safety once TBO plans become impossible to realize.

Possible solution to this challenge is to increase capacity of the UAVs to sense their environment and to develop algorithms for conflict resolution and obstacle avoidance. However, most of the currently used commercial UAVs have very limited knowledge of their surroundings. Almost all UAVs today come equipped with the ultrasonic or LIDAR-based height sensor. Increasingly, higher-end and special purpose professional UAVs are equipped with obstacle sensors and avoidance algorithms for multiple directions. These are based on:

- Stereo Vision – uses two cameras to take two images at slightly different viewpoints which are then processed to identify same points in both images. The distance to those points can then be established by triangulation. One example of such system, developed for UAV purposes, is Centeye RockCreek™ vision chips (Figure 2. a).
- Ultrasonic (Sonar) – sends a high-frequency pulse and then measures time it takes for the signal to reflect off the obstacle and return to the microphone. Ultrasonic sensors have relatively short ranges (e.g. HC-SR04 has range up to 5 m, Figure 2. b), wide detection angles and low spatial resolution. They cannot detect size or shape of the obstacle.
- Time-of-Flight camera – it is made of an integrated light source and a camera. It can measure distance information for every pixel in the image by emitting a light pulse (flash) and calculating the time needed for the light to reflect back towards the camera. Small ToF

cameras have shorter ranges, e.g. ELISA 3DRanger™ by Heptagon works at distances up to 5 m (Figure 2. c).

- LIDAR - calculates distances and detects objects by timing how long it takes for a laser pulse to travel from the sensor to an object and back, calculating the distance from the speed of light. LIDAR can be made in single point, single plane or multiplane versions (full matrix). They are used for mapping, however, in obstacle detection role they have been only recently introduced to the UAV market. One example of small LIDAR that is light enough to be used for UAV obstacle detection is Velodyne Puck LITE™, which weighs only 590 g and scans up to 600,000 points per second (Figure 2. d).
- Monocular vision - most UAVs are equipped with a monocular camera. However, almost none of them use the monocular cameras for detecting and avoiding obstacles; they are mostly used for station keeping by employing optical flow algorithms. Monocular vision systems use advanced algorithms to match sequential images taken by the same camera to determine distance to objects in the image. These algorithms, however, cannot sense moving objects.

All of the technologies mentioned above can be used to detect large obstacles, but only some of them can be used to detect other UAVs or small obstacles. These are ToF cameras, some LIDARs, and stereoscopic systems. ToF cameras, at least those small enough to be mounted on UAVs have relatively shorter ranges which makes them useful for detection of obstacles when the UAV is moving slowly enough. Stereoscopic systems work only during the day. Therefore, the best, and most expensive, choice for collision detection are LIDARs. For detection of conflicts among UAVs, transponder-provided locations could be the easiest way of coordinating conflict resolution.

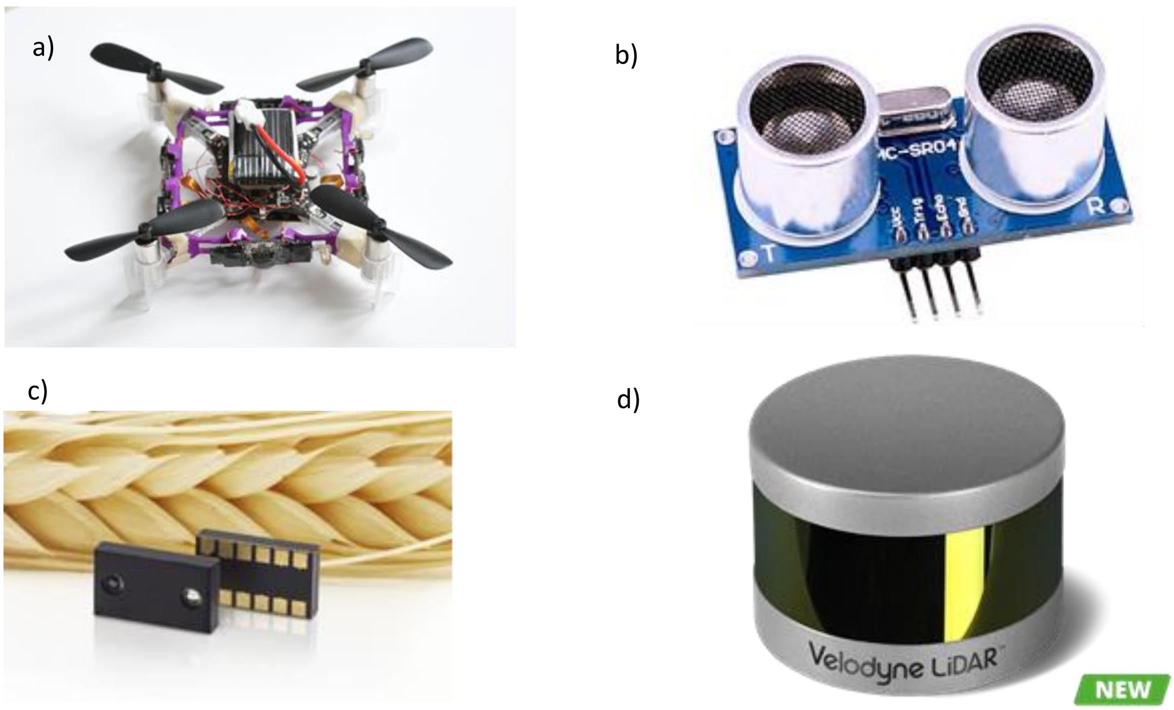

Figure 2. Centeye RockCreek (a), HC-SR04 ultrasonic sensor (b), ELISA 3DRanger ToF sensor (c), Velodyne Puck LITE (d)

6. AIR POLICING

In conventional operations, a system exists to prevent unlawful operations. Once the intruding aircraft is identified fighter jets are scrambled to escort that aircraft and force it to land. Obviously, there is little sense in employing such solutions for policing of UAVs in the urban environment. Incidents with UAVs have become so common in recent years that the new methods of law enforcement are being actively developed. Examples of such incidents are injuries to the bystanders (e.g. a toddler lost an eye in the UK [13], a woman knocked unconscious by a falling UAV [14], etc.), damage to other aircraft (e.g. UAV collision with a Black Hawk helicopter [15]), invasion of privacy (e.g. looking into people's homes [16]), and possible acts of espionage (e.g. flying near chemical plants [17] and nuclear power plants [18]).

Anti-UAV technology can be divided into several categories:

- Projectile guns – along with conventional guns there are guns which fire nets or even nets with built-in signal jammers (e.g. OpenWorks Engineering SkyWall 100, Figure 3. a). Net throwers are effective up to 100 m.
- Signal jamming – there are multiple signal jamming solutions which work by jamming navigation and control signals. They operate on usual frequencies used by UAVs and some of them even have the capability to spoof the control signal of common UAV types in order to force them to land (e.g. Battelle DroneDefender, Figure 3. b). Signal jamming guns are effective at distances up to 2,000 m (e.g. DroneShield DroneGun Mk2, Figure 3. c). Researchers have demonstrated the ability to control and capture the UAVs by spoofing the GPS signal [19].
- Lasers – so far only one prototype of this technology has been built by Boeing. It is called High Energy Laser Mobile Demonstrator (HELMD) and it can detect and destroy UAVs up to at least 5 km. Its large size precludes it from being routinely used as a police tool (Figure 3. d).
- Trained animals – French, Dutch, and Swiss authorities trained eagles to intercept and catch UAVs (Figure 3. e). While proved effective in the training environment, the eagles would not always do what they were trained to do and their training proved to be more expensive and complicated than anticipated. Because of this police in the Netherlands has stopped using the birds for UAV interception [20].

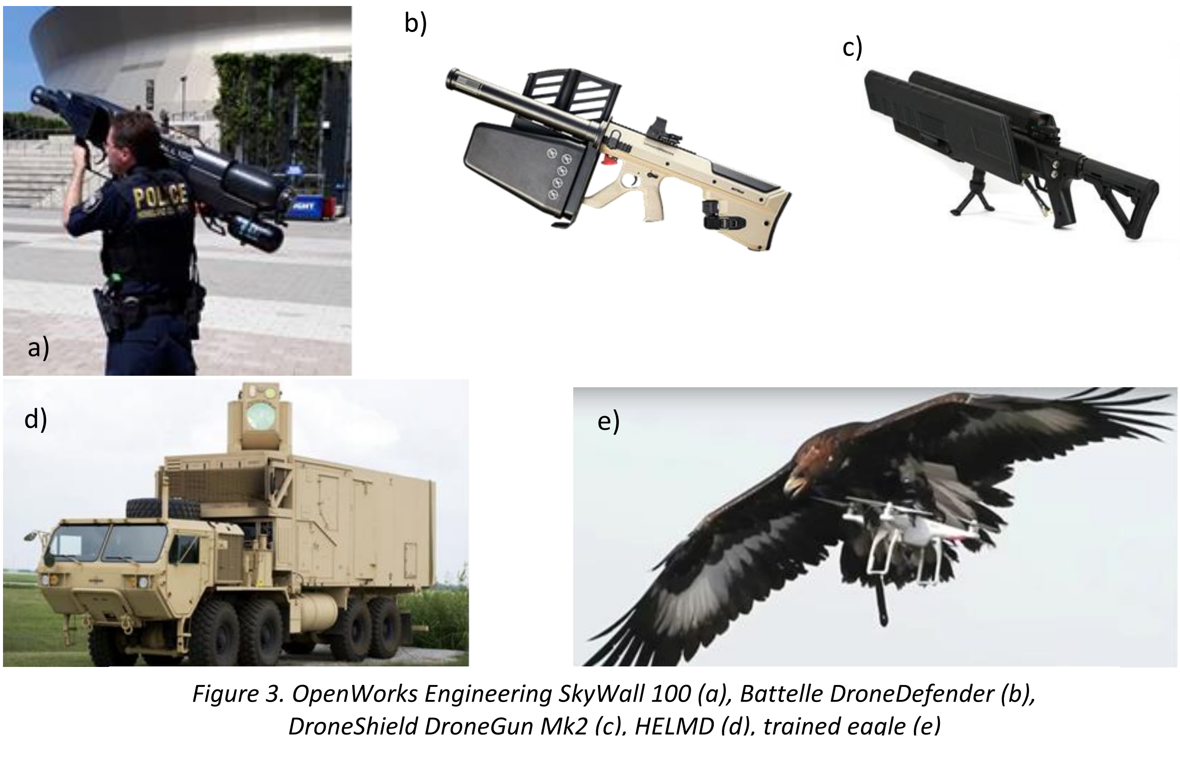

Figure 3. OpenWorks Engineering SkyWall 100 (a), Battelle DroneDefender (b), DroneShield DroneGun Mk2 (c), HELMD (d), trained eagle (e)

Overall, these systems do provide a level of protection from unlawful UAV operations, but tying them into surveillance systems and training the police in using them is still a major hurdle. Unlike conventional guns, anti-UAV technology is not deployed routinely and is not at hand to all police officers at all time. Also, discerning unlawful operators from legal operators is made difficult because there are no surveillance systems in place. Also, anti-UAV guns rely on visual detection and identification of illegal UAVs by police officers which is not possible during night or with UAVs flying through clouds or fog.

7. GROUND SERVICES

Airports, airfields and helidromes are areas reserved for operation of conventional aircraft. The utility of these areas for urban UAV operations is minimal. In urban setting, especially if the visions of future ubiquitous UAV operations are to come true, there are not enough areas reserved for landings and take-offs. Most major urban centres have some helidromes, usually attached to hospitals or large office buildings, but this is not nearly enough to support the expected rise in number of aircraft once UAVs enter the market. Also, using the existing helidromes for UAV operations means that all UAV services need to be centralized at several points in the city which reduces the advantages of UAVs. Reserving areas for UAVs closer to users of their services (businesses and consumers) would keep the UAVs away from helicopters, thus avoiding mixed operations, and use the full potential of UAVs. Such areas could be on rooftops or attached to the sides of the buildings. Besides providing landing areas, they could also provide:

- Navigation services – as mentioned in previous sections, visual navigation is possibly one of the main solutions for accurate navigation in complex urban environments. Coded visual markings and coded lights could be attached at the landing site for aiding in visual navigation. Also, in terms of other navigation options, real-time kinematics (RTK) GPS corrections could be broadcast to increase accuracy of GPS navigation on the local level.
- Surveillance services – built-in cameras and video processing algorithms can detect local obstacles and traffic to ensure safe sequencing for landing. In some cases, where longer range is needed and terrain configuration allows (top of building, away from obstacles and people), it is possible to add the radar as well.
- Communication services – dedicated datalinks for control and high-bandwidth data transfer.
- Charging services – current battery technology limits the flight time of the electric UAVs to around 30 minutes. Automatic battery charging or swapping services could increase the fraction of the time the UAV remains operational. Further challenge here is the lack of standardized charging or swapping interface.
- Storage – since the UAVs will spend most of the time on the ground, it will be necessary to ensure that they are protected from strong winds, rain and snow. These parking spaces will have to be built in the numbers greater than the number of operational UAVs due to clustering of UAVs in parts of the city during certain times of day. Storage can be provided by protective covers and/or automatic housing for one or multiple UAVs, possibly combined with charging service.
- Other services – such dedicated space could also provide other specific services such as conveyor belts for packages or maintenance services.

Overall, a lot of the solutions to the challenges mentioned in the previous chapters could be implemented at such dedicated landing areas.

8. REVIEW OF CHALLENGES AND PROPOSED SOLUTIONS

In previous chapters we have identified most-glaring challenges and presented existing or proposed novel solutions. Here we review the lessons learned (Table 2).

Table 2. Review of Challenges and Solutions to Large-scale Introduction of UAVs in Urban Environment

Challenge	Solution
Surveillance in urban canyons is difficult because radars and optical sensors need line-of-sight visibility, acoustic detectors have very short range, and RF detectors have low spatial resolution.	UAVs equipped with transponders combined with surveillance network to detect unlawful operators (possible use of police UAVs to patrol the lower areas). Surveillance of non-cooperating UAVs is still unsolved.
Navigation in urban setting using GPS can be highly inaccurate due to multipath errors (especially non-line-of-sight multipath). There needs to be a backup navigation capability.	Visual navigation can be used to bridge the gaps in GPS reception and, when more developed, even to be a backup for GPS. Night-time visual navigation is still not solved.
UAV control, telemetry, and video links work on frequencies shared with many other users.	Use existing 4G mobile networks (5G in near future). Perform interference analysis prior to flight. Establish more flexible procedures for dealing with link failure.
In-flight conflict detection and resolution does not exist. Limited obstacle avoidance capabilities.	Implement conflict detection and resolution algorithm based on locations obtained via transponder. Further miniaturization and lower costs of LIDAR sensors will enable easier obstacle avoidance, even during night.
Anti-UAV technology is limited by visual detection of UAVs by police officers (impossible during night or in clouds or fog). It is not clear how will law enforcement officers decide on whether an UAV is operated legally or not without working surveillance and alerting system.	No solution available currently. Surveillance and alerting system is needed to facilitate identification of unlawful operators.
No ground infrastructure and services. No battery charging or swapping standards.	Landing pads can be developed to provide necessary reserved landing space. Additional navigation, surveillance, and communication services could be integrated as well.

9. CONCLUSION

In this paper we tried to identify technological challenges to large-scale introduction of UAVs in urban environment. Other challenges, which we did not tackle, exist as well, such as regulatory, architectural, societal, and cultural.

Some of the challenges we examined are purely technological and they will probably be solved in near future. One example of challenges in this group is the challenge of visual navigation. Great strides towards better and more capable algorithms are being made yearly. Another example is collision detection and avoidance which can be solved with LIDARs even today if not for their relatively large size and weight. Further miniaturization of LIDARs will surely ensue and collision detection will not be an issue anymore.

Other type of challenges are those which are constrained by fundamental physical limits. Such are the challenges in surveillance of UAVs. Their small size, small acoustic and thermal footprint, combined with complex urban environment, make for very difficult detection. Solutions for surveillance problems mainly involve cooperation from the UAV operators (e.g. installing transponders). Detection and surveillance of unlawful uncooperative UAVs and their operators remains unsolved.

Final type of challenges are those related to organisation and standardization of services. For example, battery charging or swapping is not a difficult technological issue, however, there are no standards which enable universal autonomous charging of UAVs made by different manufacturers. Agreement on issues like these will be needed in order to implement many of the proposed solutions.

Overall, we find these challenges both interesting and worthy of future research. In our future work we will take a closer look at possible technological solutions to the surveillance and navigation challenges. Most importantly, surveillance of non-cooperating UAVs is one of the most important issues which have no clear solution as of today.

REFERENCES

[1] Teal Group Corporation. World Civil Unmanned Aerial Systems, Market Profile, 2017 Ed. Available from: http://tealgroup.com/images/TGCTOC/WCUAS2017TOC_EO.pdf

[2] Goldman Sachs. Drones: Reporting for work, 2017. Available from: http://www.goldmansachs.com/our-thinking/technology-driving-innovation/drones/

[3] Press Association. Boris Johnson calls for drones to solve London congestion. [Online] 2014. http://www.theguardian.com/world/2014/nov/28/boris-johnson-drones-solve-london-congestion

[4] ICAO. Doc 444, Air Traffic Management. 16th Edition. Montreal, Canada. 2016.

[5] Cook A. European Air Traffic Management (Principles, Practices and Research). New York, USA. 2016.

[6] Kelvin Hughes. How Kelvin Hughes Security Radar Offers the Most Cost-Effective Solution to Protecting CNI Sites. Available from: https://cdn.kelvinhughes.com/upload/pdf/case-studies/uav-drone-detection.pdf

[7] Aaronia. Drone Detection System Specifications. Available from: http://www.aaronia.com/Datasheets/Documents/Drone-Detection-System.pdf

[8] Radišić T, Ivošević J, Andraši P. Robust Navigation Systems for UAVs, Technical report. PROM-PRO 2015-2017, Workshop Proceedings, 2017.

[9] Faessler M, Fontana F, Forster C, Mueggler E, Pizzoli M, Scaramuzza D. Autonomous, vision-based flight and live dense 3d mapping with a quadrotor microaerial vehicle. J. Field Robot. 2015.

[10] Fraundorfer F, Heng L, Honegger D, Lee G H, Meier L, Tanskanen P, Pollefeys M. Vision-based autonomous mapping and exploration using a quadrotor MAV. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp. 4557–4564. IEEE. 2012.

[11] Fu C, Duan R, Kircali D, Kayacan E. Onboard robust visual tracking for UAVs using a reliable global-local object model. Sensors 16(9), 1406. 2016.

[12] Drozd A. Spectrum-Secure Communications for Autonomous UAS/UAV Platforms. MILCOM 2015 – IEEE Military Communications Conference. Tampa, FL, USA. 2015

[13] BBC News. Toddler's eyeball sliced in half by drone propeller. 26 November 2015. Available from: http://www.bbc.com/news/uk-england-hereford-worcester-34936739?SThisFB

[14] The Seattle Times. Woman Knocked Unconscious by Falling Drone During Seattle's Pride Parade. 29 June 2015. Available from: http://www.seattletimes.com/seattle-news/crime/woman-knocked-unconscious-by-falling-drone-during-seattles-pride-parade/

[15] WCBS-TV. Drone Hits Army Helicopter Flying Over Staten Island. 22 September 2017. Available from: http://newyork.cbslocal.com/2017/09/22/drone-hits-army-helicopter/

[16] CBS Chicago. Man Charged After Drone Hovers Outside High Rise. 12 September 2017. Available from: http://chicago.cbslocal.com/2017/09/12/man-charged-after-drone-hovers-outside-high-rise/

[17] The Buffalo News. Man Charged After Flying Drone Near Lockport Chemical Plant. 5 December 2015. Available from: http://www.buffalonews.com/city-region/lockport/man-charged-after-flying-drone-near-lockport-chemical-plant-20151205

[18] The New York Times. Unidentified Drones Are Seen Above French Nuclear Plants. 3 November 2014 Available from: https://www.nytimes.com/2014/11/04/world/europe/unidentified-drones-are-spotted-above-french-nuclear-plants.html?_r=0

[19] Kerns A J, Shepard D P, Bhatti J A, Humphreys T E. Unmanned aircraft capture and control via GPS spoofing. Journal of Field Robotics. 1;31(4):617-36. Jul 2014.

[20] The Verge. Dutch police will stop using drone-hunting eagles since they weren't doing what they're told. 12 December 2017. Available from: https://www.theverge.com/2017/12/12/16767000/police-netherlands-eagles-rogue-drones