Drones – How this Ubiquitous but Disruptive Technology is Augmenting our Quality of Life

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Drone technology that has the potential to disrupt and augment our quality of life is swiftly evolving. Drones are rapidly growing in popularity and are used in various applications such as agriculture, emergency response, border control, asset inspection, intelligent transportation, and many more. This is primarily to the rapid advances in mobile embedded computing that allow for various sensors and controllers to be integrated into drone platforms enabling them to sense and understand both their internal state and the external environment. We showcase relevant drone technologies, explore research opportunities, and demonstrate through three use-cases how research can drive forward these disruptive systems within our social, economic and scientific activities.

Introduction

The term drone is haphazardly thrown around by many outlets, and is ubiquitously appearing in several conversations between consumers, whether it is related to their holiday shopping lists, their hobbies, their job or even when they discuss news. In its original context, a drone refers to an unmanned aircraft either preprogrammed with a flight plan or remotely controlled; the term "drone" in fact originates from its two literal meanings, more specifically male bees or a monotonous buzzing sound – which multi-rotor drones are now famous for. More recently, "drone" has evolved into a catchall term including any unmanned robot. This includes robots designed for water, land, and air use. In the context of this article however, we strictly refer to aerial drones. Whether called Unmanned Aerial Vehicles (UAVs), or Remotely Piloted Aircraft Systems (RPAS) – their formal name - drones are rapidly growing in popularity. While they are still considered in their infancy stage in terms of mass adoption and usage, they have already surpassed rigid traditional barriers in industries which otherwise seemed impenetrable by similar technological innovations and advancements. Furthermore, over the past few years, drones have become central to the functions of various businesses and governmental organizations and have managed to pierce through areas where certain industries were either stagnant or lagging. More importantly however, they are now considered among the most disruptive technologies that are expected to augment our quality of life.

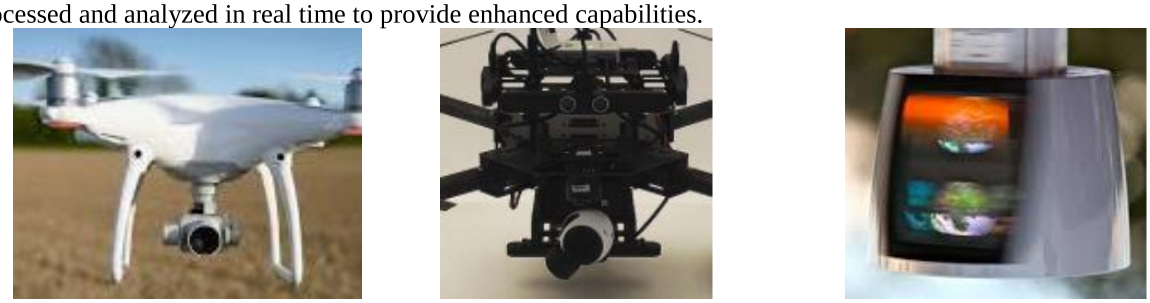
Typically, drones are classified as fixed wing (with longer range, higher altitude flight capabilities and less power consumption) or multi-rotor (better hovering and maneuvering abilities, but lesser range and altitude and more power consumption). Just like other disrupting technologies, the military has been the major benefactor of drones initially. However, once the flight technologies advanced to the point where multi-rotor drones have become extremely easy to operate, are able to maintain strict safety standards, and are equipped with sensors and other electronically-assisted safety features that warrant their safe passage over multiple environmental conditions, the civilian sector has started adapting them, with the photo and video producing industries the first beneficiaries of this innovative technology. Gradual reduction in their price has only magnified this global phenomenon; drones are now listed as toys, tools, hobby items, entertainment, gadgets, etc. and have long left the photo and video industry as their primary commercial application. In fact, commercial usage of drones is gaining steady momentum and multiple industries are working with drones as part of their daily regular business functions. It is estimated that the market for commercial and civilian drones will grow at a compound annual growth rate of 19% between 2015 and 2020, compared with 5% growth on the military side, according to BI Intelligence, Business Insider's premium research service.

Multi-rotor drones have dominated the commercial market in the last few years, mainly due to their affordability and ease of taking off and landing, while fixed-wing drones feature different characteristics and as such, target specific high-end markets beyond military, and come at a hefty price. On the other hand, multi-rotor drones feature characteristics which are suitable for a wider range of applications such as mapping & surveying, and asset inspection, due to their ability to hover, maneuver in narrow and uneasy terrain conditions, and take-off and land in very limited space. Gradually, on-board sensors such as gyroscopes, accelerometers, magnetometers and altimeters have been integrated on the drone's flight control computer. The drone flight capabilities have therefore been augmented to accommodate various application needs. Coupled with customizable computing solutions that can run various data analysis and pattern recognition algorithms, a drone is now an intelligent, partially autonomous and partially self-aware system that can function either individually or as part of a swarm.

To showcase the potential of these systems, and present the research challenges and emerging opportunities, we present a brief overview of the technology that powers these intelligent drones. We also attempt to provide a roadmap and directions towards identifying current challenges and opportunities that research in intelligent drones is facing. Further we showcase how our own work is currently developing intelligent drones to be used as tools for first responders in emergency response, to monitor power lines, and to operate as a large-scale, real-time traffic monitoring tool.

Technological Considerations for Drone Applications

Sensor technologies have greatly advanced through the years and are often the secret sauce inside drones that enables their use in numerous remote-sensing applications (Fig. 1) providing them with the ability to sense and understand their environment and become self-aware of their surroundings and the context that they are flying in to potentially take evasive and reactive actions. A drone platform can carry a variety of payload equipment consisting of relatively simple sub-systems (such as a fixed camera with fixed lenses having a mass as little as 200 grams) to more advance payloads (such as a video camera system with adaptive zoom support, and pan and tilt functions). Evidently, larger drone platforms can carry a combination of different types of sensors (e.g., thermal imagers, radar scanners, etc.) to collect various data elements that can be processed and analyzed in real time to provide enhanced capabilities.



(a) (b) (c)

Fig. 1: Example of Drone Sensor Technologies: (a) High definition camera equipped on a drone is the most standard payload used today. (b) Drone obstacle avoidance system with ultrasonic sensors and cameras are becoming more widespread. (c) Lidar sensors with reduced cost will be a more frequently used payload used in future drones.

Sensors that aid the drone in flying

These sensors are primarily used to assist in the drone flight by measuring the state of the drone and guide its motion with respect to the environment such as its position in space, velocity, orientation and others.

◦ Accelerometers: Used to determine position and orientation of the drone in flight.
◦ Gyroscope**:** Detect angular velocity in three axes, so they can estimate rate of change of angle in pitch, roll and yaw.
◦ Digital Compass: Provides sense of direction to the drone. It gives data of magnetic field in three dimensions.
◦ Barometer: Helps the drone in navigation and measures the altitude.
◦ GPS: Global Positioning System sensors offers access to location information from geo-stationary satellites. At least three satellites are needed to determine longitude and latitude coordinates, and one satellite to determine the altitude of the UAS. Typically, satellite data is fused with other readings to provide a higher level of accuracy, precision and stabilization.

Sensors for environment perception and data collection

External sensors and payloads can be integrated into a drone to enhance its understanding of the environment, collect data for offline processing, and make decisions on how to navigate and act in missions.

◦ High definition cameras: Most drones are equipped with cameras for providing intelligence about particular situations, especially since drones can hover over remote areas which can be difficult for people to access. Camera resolution, frame-rate and field-of-view are important parameters for each application. Camera sensors can be used to computer vision and scene analysis to the drone.
◦ Thermal sensors: Thermal vision cameras construct images or video from heat (infrared thermal radiation), invisible light that is, also part of the electromagnetic spectrum. Most thermal cameras produce a video output in which color encodes the temperature reading of the scene. Thermal energy is radiated off nearly every material, hence, thermal vision cameras can capture images and temperature variations emitted from people and objects, etc., thus used a wide range of applications.
◦ Lidar: Light Detection and Ranging (Lidar) is sensing technology where the environment is usually scanned with a pulsed laser beam to measure relative distance of the objects sensed by the sensor. Thus, the drone can be enhanced with obstacle detection and avoidance for safe navigation, day and night. A potential drawback is the high cost, and bulky form factor.
◦ Radars: Radar systems work by sending out radio waves and using the echoes that bounce back to create topographical maps or avoid obstacles. In contrast to lidar and cameras, they can be designed to rapidly scan large areas and they are less affected by weather, smoke and dust. However, the data collected by radar sensors are accurate only up to a certain extent and cannot distinguish between different classes of objects.
◦ Telecommunication Sensors: Drones equipped with telecommunication hardware such as Wi-Fi antennas, may provide clues about someone's position. In emergency situations such equipment can also be used on the drone to quickly re-establish cellular signal coverage over areas that experience outage.

◦ <u>Electronic Sniffers</u>: Devices that sample air and provide information about nuclear, toxic or any kind of chemicals existing in the area to monitor pollution.

The different drone payloads used for each application can have an impact on the drone characteristics and requirements. Drones can have a very limited payload capacity which largely depends on the power of the motors and propeller combination, as the weight of the payload can negatively impact the flight time. In addition, the capacity of the drone's main battery plays an important role when the payload needs to be powered by the drone itself thus impacting the overall flight time. Another choice to consider is the level of autonomy of the drone. The drone autonomy can vary from fully autonomous operation to fully controlled by a remote pilot. The fully autonomous operation requires a multitude of sensors to sense and understand the environment as well as a suite of algorithms to interpret data from sensors. The drone would have to make decisions about where to fly, classify objects captured by its camera. In addition, sufficient computing power for real-time processing on the "edge" on tiny, light computers. Alternatively, processing can be offloaded to the "cloud", however, this presents a tremendous challenge on the communication links both in terms of bandwidth and privacy/security, limiting the application spectrum to non-latency critical tasks. On the other hand, when the flight and planning is done by a human operator the requirements can be relaxed and hence the drone can be equipped only with the necessary application-specific sensors. As it becomes cheaper and easier to customize commercial drones, by utilizing emerging innovative embedded and mobile sensing and computational solutions, new opportunities will arise to facilitate research and innovation in a wide array of niche applications.

Research Opportunities and Challenges

In these early stages, research has focused on the low-level controls that could be applied by resource constraint onboard computers for altitude stabilization and maneuvering of individual drones. Over time, more effort was put on more advanced tasks including indoor localization and navigation. To achieve these tasks, research has focused on optimizing embedded system algorithms for remote sensing, digital signal processing and fault-tolerant control, all coupled together to achieve good real-time performance. Furthermore, as cameras are now a standard equipment in most drones, a large body of research is focused on utilizing advanced computer vision algorithms to make drones fly autonomously, track a target through obstacles or deliver a payload to a certain location. These technologies have matured to the level that it is now possible to investigate how complex missions can be achieved either by a single drone or a swarm working in collaboration. Evidently, coordinated teams of drones can achieve significantly greater capabilities than what is possible by a single agent and thus this research track has received considerable attention recently. Broadly speaking, these missions can be classified into the following 4 main categories (Fig. 2): Data Collection and Surveying, Monitoring and Tracking, Temporary Infrastructure, and Delivery of Goods.

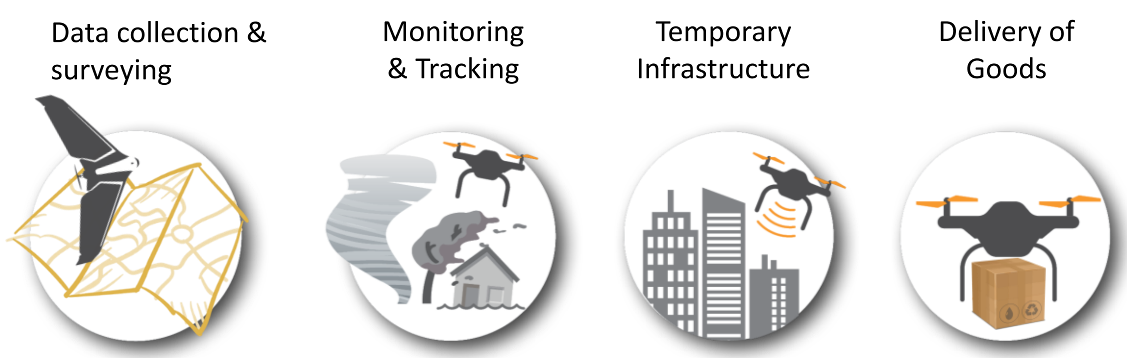


Fig. 2: The four main categories of drone-based mission types.

A classic problem that arises in surveying and collecting data over a spatial field of interest is how to cover the area faster with the least number of resources. Research challenges include task assignment, scheduling and path planning, considering the physical resource limitations of the drones including the total number of drones, their battery levels and their communication ranges. Problems that arise in monitoring and tracking missions consider the derivation of accurate models of the underlying dynamics and investigate strategies which generally seek to minimize the tracking error for all detected events/objects.

Drone deliveries have the potential to significantly reduce the cost and time of making last-mile goods shipments. Research in this domain focused on the management of job allocations to minimize the overall cost subject to delivery time limits taking into consideration the limitations in battery and payload capacity. Drone deployments have also been considered to provide over-the-top services including the setup of an aerial communication platform, illuminate fields for night operations and make voice announcements across the horizon. To do that, problems of node placement for coverage and topology control are being looked at to address the communication and computation challenges that arise.

In all mission types the ability of a drone to analyze visual data and determine its location and next action can have tremendous benefits and increase its capabilities. Beyond the use of computer vision algorithms for object detection and recognition tasks another area of focus is vision-based navigation and control. Systems that rely on the GPS can achieve little better than 3-metre resolution at best — which is not good enough for urban areas or indoor settings. In extreme cases, drones could be sent into earthquake-damaged buildings to look for survivors, which would mean avoiding all sorts of obstacles and move into free space without relying on external connectivity. To do this, a drone requires a complex system of cameras, as well as advanced algorithms to figure out where it is — and where the obstacles are and how to navigate this area based on its understanding of the environment.

In carrying out any of the main mission categories recent research has also demonstrated that swarms of drones can be more effective. Data collection and search-and-rescue missions are faster and more efficient with a team of drones to pool data and provide redundancy in case some machines fail. But the use of more vehicles also adds complexity and drones working together must be able to communicate with one another and make collective decisions.

It should also be emphasized that many of these problems are interrelated and thus need to be investigated jointly in order to optimize mission objectives. For instance, searching for and tracking of objects across the field could result to competing objectives that need to be resolved in an intelligent way. Clearly, searching is necessary to detect events/objects before accurately tracking them. At the same, a drone may need to abort tracking a particular object if exploration could reveal a new set of objects in the area. We focus our research effort in investigating problems that involve such complex mission objectives and seek to device intelligent solutions that approach these problems in a holistic perspective.

The success of drone deployments across the aforementioned application categories has created safety and security issues not just to the aviation sector but also to every other aspect of social life. However, there are great challenges in effectively addressing these issues mainly due to the fast evolution of technology. Current efforts focus mainly on regulating operation through both legislative and technological means. As part of the envisioned technology, which is our primary focus in this article, novel air traffic control solutions are being researched to monitor and control flights, while various ground and aerial systems are being considered for intercepting rogue drones

Case Studies of Drone Applications

We are currently working on several interesting projects using drones. Based on our work we present three case, that illustrate interesting and challenging applications of drones in real-world problems: (a) road transportation networks monitoring, (b) powerline inspection, and (c) civil defense protection.

◦ <u>Road Transportation Networks Monitoring:</u> Monitoring the state of road networks is fundamental for efficient traffic management. Current sensing technologies provide different types of measurements such as vehicle counts at a single point, traffic density over a road stretch and vehicle speed and location from moving vehicles. Nonetheless, such technologies suffer from high installation time and cost, capture part of the spatio-temporal traffic evolution, while different technologies measure only a fraction of the traffic parameters of interest (e.g., traffic flow, speed, vehicle density, turning ratios at intersections). Drones are emerging as a promising technology that can overcome these limitations because it is a non-invasive technology that requires no installation cost and provides frequent spatio-temporal measurements for the entire network. Nonetheless, using drones for traffic monitoring leads to several challenges that need to be dealt with regarding their deployment in such a way to maintain the line-of-sight, and the development of computer vision algorithms for the detection of traffic entities (e.g., pedestrians, vehicles, buses).

In this context, recent research efforts have been geared towards developing software tools to address these challenges by formulating and solving appropriate optimization problems for the efficient deployment of drones to ensure line-of-sight for all roads of the network and by developing accurate and real-time algorithms for the detection of vehicles using data from on-board cameras. Vehicle detection is achieved by analyzing the visual data through an integrated computer vision processing pipeline that dynamically extracts roads segments and robustly detects vehicles in the resulting network by combining the results from two different approaches (Fig. 3). The first uses motion algorithms to find moving vehicles, while the second employs convolutional neural networks to detect still vehicles using deep learning techniques. Finally, post-processing of the results can help in the derivation of individual vehicle trajectories and the computation of traffic parameters of interest.

◦ <u>Powerline Inspection:</u> Providing uninterrupted supply of electricity is an essential everyday commodity. Nonetheless, properly inspecting and maintaining the vast, aging and often inaccessible powerline network of a country to detect or prevent the occurrence of faults is a very difficult and costly task. Drones provide an attractive alternative to manual inspection that can increase productivity and reduce the inspection time and cost, by patrolling the lines using visual equipment to detect issues that need to be fixed. This is a very challenging task as powerlines are too thin and not easily distinguishable in poor lighting and background conditions, obstacles may block the drone path, while faulty components may be very hard to be detected even with manual expert inspection.

Fig. 3. Vehicle detection using drones: (a) vehicles detected using motion, (b) vehicles detected using still images, and (c) combined detection of vehicles.

For this problem, part of our recent work is towards developing methods and software tools for drone-based powerline monitoring with minimum intervention from the operator to detect and report cut powerlines or poles, broken insulators, vegetation or other items touching or near the lines (Fig. 4). Towards this direction, drones are programmed to autonomously take off, follow the shortest path to go over each pole and then land back in a safely and timely manner. High-definition, infrared and thermal cameras are used to take closeup images and video, which are processed in real-time to detect and geotag faults using computer vision algorithms. The use of multiple sensing technologies and computer vision algorithms allows for the detection of distinct faults. For instance, the use of thermal cameras helps with the identification of overheated insulators, while different computer vision algorithms help with the detection of powerlines and vegetation in different backgrounds (e.g., pavement, rough terrain).

Fig. 4. Drone-based powerline inspection. (a) Detection of overheated insulator, (b) destroyed insulator, and (c) Powerlines as viewed by a thermal camera.

◦ <u>Civil Defense Protection:</u> Drones are considered as future autonomous first responders for civil defense protection. At the current stage, drones can support firefighting operations, enhance the capabilities of civil protection forces, and improve the response of rescue teams. In this context, drones can support several missions related to the early detection of abnormal situations, assist disaster preparedness for various physical or man-made disasters (i.e., forest fire, floods, earthquakes, landslides, etc.) and support search and rescue operations.

Fig. 5. Drone as future first responders can: (a) assist civil protection units in organization and planning, (b) provide situational awareness of disaster-stricken areas, (c) locate disaster survivors with thermal cameras.

Our recent work is geared towards developing software and hardware technologies to support a multitude of civil defense applications (Fig. 5). Using high-definition and thermal cameras, drones can locate disaster survivors such as trapped civilians after an earthquake or shipwreck survivors in the sea. Search and rescue operations can also benefit from autonomous deliveries using customized robotic arms to pick up and drop emergency response packages**.** Another technology we are currently working on regards the establishment of a temporary infrastructure to support various functionalities such as communication connectivity using a network of internet-enabled drones or area illumination using drones equipped with special lighting equipment. Finally, constructing 3D maps of a terrain can help emergency managers assess the impact of a disaster on different regions and prioritize operations.

Conclusion

Drones and their underlying enabling technologies are advancing at a rapid pace; in the not too distant future not only will your grocery shopping be delivered by a drone, but you as well will commute via a flying autonomous vehicle. Development of hundreds of more uses of drones are underway due to the multiple investments pouring into this promising industry. Almost every aspect of our lives will be impacted by the presence and usage of drones in one way or another. It is a very exciting time to be working in this area of research with many real-world problems and interesting applications that can be solved using innovative drone technology. Specifically, there is great promise in developing novel swarm optimization techniques and autonomous control algorithms so that a group of drones can collaboratively execute a task much more efficiently. Also, there will be a lot of opportunities to utilize machine learning for improving the drone perception capabilities by taking advantage of large amounts of data that are becoming available for numerous applications. Finally, as drones are integrated more and more in our society the security and safety aspects will take central role in forming how drones can be used in many consumer applications.

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