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Flying Smartphones: When Portable Computing Sprouts Wings

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For decades, pop culture has imagined for us a future filled with robotic companions that attend to our daily chores. While often featured in science fiction, this vision of the future might be more accurate—and near-term—than expected. What the movies and TV shows might have gotten wrong, however, is the form of our future robotic companions. Instead of humanoids, it's aerial drones that seem to be rapidly approaching adoption for everyday tasks.

FROM PCS TO SMARTPHONES TO DRONES

At first glance, aerial drones might seem a non sequitur in the list of PCs and smartphones; however, they might indeed represent the next step-change in technology that connects the physical and digital worlds. PCs were the first technology to provide digital processing power to the average person.

Smartphones brought the next step-change in technology, because they're not only mobile but also integrate a basic set of sensors into a processing platform. Fusing a processor with a GPS receiver, accelerometers, magnetometers, and Internet connectivity has enabled so many unique applications that app developers will be exploring the design space for decades to come.

Drones mark the next leap in this progression. Along with a processor and sensor suite, drones incorporate actuators—propellers to move themselves around and (potentially) grippers to manipulate objects in the world. The fusion of these three elements (computation, sensing, and actuation), along with developments in the theory of robot autonomy,[1] allow drones to actively engage with the world around them. This is in contrast to the relatively passive interactions between humans and PCs and smartphones.

INTRODUCING SMARTDRONES

Not all unmanned aerial vehicles are consistent with a comparison to smartphones. Remote-controlled aircraft have existed for decades but, lacking any form of autonomy, can't be considered "drones" and are likely to remain strictly a hobbyist's pursuit. On the other end of the spectrum lie military drones, which are typically very expensive, complex, and highly task specific. The type of drone for which we draw parallels to smartphone technology—arguably the type that will have the most impact on the average person's daily life—are drones that we will refer to as *smartdrones*.

Smartdrones have several defining features, first of which is their *affordability*. To achieve wide-scale use, smartdrones will likely fall in the same price bracket as smartphones and modern laptops (US$500–$2,000), which makes them affordable for a common household.

The second defining feature is their *lightweight structure*. Many potential applications for smartdrones will directly or indirectly involve operations in proximity to human subjects. This immediately makes safety an important issue. Safety depends on not only a robust software architecture for autonomy but also the drone's physical design. Lighter weight, slower drones are inherently safer and thus will be the platforms of choice for operation in human-centric environments.

Another important feature is *standardization*. To enable use in a wide range of applications, smartdrones will share a quasi-standardized set of hardware and a unified control/autonomy structure. Hardware will range from components typical of smartphones

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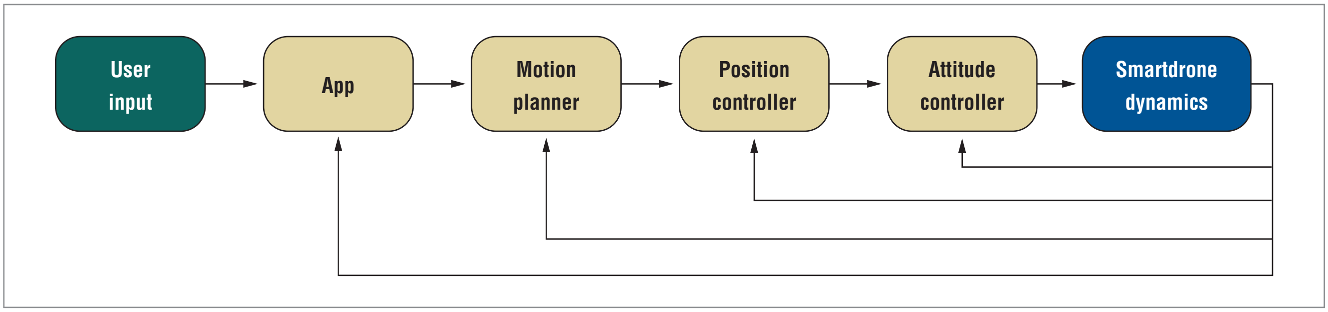

Figure 1. A high-level control/autonomy structure for smartdrone platforms.

(accelerometers, gyros, barometers, cameras, thermometers, and even microphones), to propulsive systems and manipulator/grasping mechanisms for payloads. On the software side, with a standardized GPS module and communication protocol, smartdrones will need to behave identically when it comes to avoiding restricted airspaces.

Yet arguably the most critical feature is *autonomy*. Beyond just being robust and reliable, smartdrones must also be intuitive to use. In the same way that a smartphone can be used by anyone, regardless of prior computer knowledge, smartdrones must be easily usable by those with no technical background. To achieve this, drones will have to be highly autonomous—relying on the onboard processor for all low-level control and leaving only application selection and a few input options to the user.

Note that thus far, we have made no distinction between quadrotors and fixed-wing aircraft when referring to smartdrones. This is because both can meet our definition, so either can be adopted. The hover capabilities of quadrotors tend to add an additional safety layer over fixed-wing aircraft, making them the more attractive option for applications in human proximity. Fixed-wing aircraft, on the other hand, offer much greater range and endurance. Hybrid craft, such as tiltrotor craft, would also fit our definition of smartdrones.

DEVELOPING AUTONOMOUS DRONES

Hereafter, we further focus on the autonomy feature, reviewing the technology itself, its safety aspects, and the range of applications it enables.

Understanding the Control/Autonomy Structure

A unified control/autonomy structure is key to the smartdrone concept, so app developers will know that the software they develop will interact with firmware and hardware in much the same way, regardless of the smartdrone model or manufacturer (similar to how an app can be released on Android or iOS with little additional work). The unified control/autonomy structure will likely mirror the structure that has been developed for many research-based quadrotors (see Figure 1).

The control structure is composed of a set of nested loops. Outer loops, responsible for more abstract decisions, feed information down to inner loops, usually in the form of *setpoints* or *reference targets*, which drive the direct control of the smartdrone hardware. Sensors provide feedback about the state of the smartdrone to the relevant control layer.

Specifically, the user selects an application for the smartdrone, and the app produces a set of high-level objectives. The motion planner fuses these objectives with information about the world—such as obstacle locations, no-fly zones, or speed restrictions—to come up with a feasible plan for achieving the objectives. The position controller is tasked with executing the plan by comparing the desired position from the motion planner with the actual position read by the sensors and performing feedback control.

The attitude controller is tasked with stabilizing the aircraft and executing the positioning commands from the position controller. Because most drone platforms are underactuated, the attitude controller is a “slave” to the position controller in that arbitrary positions and velocity can’t be achieved independent of attitude, so the attitude controller accommodates the desired positions and velocity. While the outer loops of the control structure will employ sophisticated optimization, control, and decision-making techniques, the inner loops will likely apply simple yet robust proportional-integral-derivative controllers.

Ensuring Safety

As PCs, smartphones, and smartdrones introduce progressively more powerful technological applications, they also carry an ever increasing burden of risk—an example of the proverbial double-edged sword. For example, PCs allowed average people to digitize most of their personal credentials and financial information. This greatly simplified tedious tasks such as filing taxes, but it also opened the door to risks such as identity fraud. The primary safety aspects that are being addressed as smartdrones are adopted in wide-scale use fall in the categories of sensing, planning, verification, and system-level integration.

Sensing. Each layer of the smartdrone control/autonomy structure requires its own sensing hardware, which is used to estimate the current state of the craft. The innermost layer—the

Figure 2. Demonstrating real-time kinodynamic planning on a quadrotor dodging a fencing blade.

attitude controller in Figure 1—is, for the most part, a solved problem. Even inexpensive, off-the-shelf inertial measurement units are sufficient to estimate and control attitude. This is why you can purchase a quadrotor "toy" for less than $50 and have it hover and perform basic motions. Such remote-controlled toy quadcopters are often well trimmed, so they can hover in place fairly reliably. Being well-balanced to avoid drifting during hover is, however, very different from autonomously controlling the drone's position.

Position control—the second innermost layer in Figure 1—presents a greater challenge because position estimation requires considerably more sophisticated hardware than that of attitude control. For absolute position, a smartdrone would require a GPS module. Such modules are relatively expensive, running at $80 for a hobby-grade component. Furthermore, GPS alone might be insufficient to guarantee safe operation. GPS relies on line-of-sight to GPS satellites, making it unreliable in environments with partial or full obstruction of the sky (as can occur in canyons, in forests, near tall buildings, or indoors). Thus, smartdrones will likely have to supplement GPS information with localized position information to provide terrain-relative position data. Several sensor types are capable of achieving this, including sonar, light detection and ranging (lidar), and vision sensors. In the end, position estimation will be achieved using a mixture of these technologies.

Planning. Even with perfect and complete sensor data and an infallible controller, a major issue exists in how to decide what trajectory a smartdrone should take through a complex, dynamic world. These questions have been at the center of the field of robot motion planning for years.

Smartdrones present a particularly challenging form of robot motion planning, because they require the consideration of a high-speed robot in a changing environment. This form of motion planning, termed real-time kinodynamic planning, is an active field of research. Recent work at the Autonomous Systems Laboratory at Stanford University has developed a framework for solving such problems in real time.[2] The framework operates on an offline-online computation paradigm, whereby a library of trajectories is precomputed offline and then efficiently pruned online when environment data becomes available. Machine learning and optimal control techniques make such a procedure fast and accurate, in the sense that near-optimal trajectories are repeatedly computed every few milliseconds. Figure 2 shows the application of such a framework to the control of a quadrotor that dodges a fencing blade.

Verification. Recent work has sought to verify the safety of smartdrone systems by embedding verification directly into the design of the control/autonomy module. The field of formal methods, which was traditionally developed to verify the correctness of computer programs, has now been applied to design drone control systems that are correct "by construction." For example, work at the Stanford Multi-Robot Systems Lab and the Boston University Robotics

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Lab has led to formal methods algorithms that construct provably safe trajectories for multiple smartdrones to perpetually monitor an environment, while scheduling sufficient time to recharge their own batteries.[3]

System-level integration. The US Federal Aviation Administration (FAA) has recently overhauled its regulations regarding the use of Unmanned Aircraft Systems. It now requires private operators to register their drones in a national database, and it prohibits the flying of recreational drones near airports and other areas with sensitive airspace. As drone capabilities grow, and as autonomous features find their way into commercialized drone technology, the FAA is incrementally taking steps to integrate drones into the already complex US airspace (www.faa.gov/uas). Likewise, the European Aviation Safety Agency is taking precautions to integrate private drone usage safely into the European airspace (www.easa.europa.eu/easa-and-you/civil-drones-rpas). Nonetheless, significant challenges remain to safely integrate drones—whether commercial or private—into the airspace, and the regulations governing drone usage are expected to evolve considerably in the coming years.

Reviewing Smartdrone Apps

Some of the first applications for quadrotors (and more generally, smartdrones) were realized in the laboratory. Due to their ease of control and their robustness to changing configurations, quadrotors became an excellent demonstration platform for navigation, planning, and network algorithms.[4] These research demonstrations paved the way for many of the commercial and military applications we see being developed today.

Perhaps the application that has received the most attention by the public is the proposed use of unmanned aerial delivery platforms such as Amazon Prime Air. Drone delivery has the potential to radically change the way we access consumer products, because it would reduce the delivery time for online purchases from days to minutes. Amazon's delivery system doesn't quite match our description of smartdrones, however, because it involves expensive, large, task-specific aerial robots; not flexible, inexpensive platforms usable by the public. Restaurants, on the other hand, could use the more universal smartdrone concept for delivery of small food items to local communities. Similarly, medicine and first-aid supplies could be delivered to remote or hazardous areas during disaster events.

Another drone application that has made its way into mainstream media is that of recreation use, specifically for action/adventure sports. Established drone companies such as DJI, and startups such as Lily Robotics, are planning to offer multirotor aircraft that are designed to autonomously follow a user and shoot video. Although these products aren't yet on the market, the significant number of companies and startups pursuing this concept gives credence to the idea that we will soon see quadcopters chasing skiers down mountains.

Currently, the most economically viable—albeit lesser known—application for drone technology lies in agriculture. Companies such as 3DR are providing autonomous multirotor craft that can survey crops by recording multispectral images of farmland.

The power of the smartdrone concept becomes even more apparent when you imagine collective multidrones acting collaboratively to carry out large-scale tasks. Just as the benefits of smartphones have exploded with the advent of mobile apps for social networking that cull data from a collection of users, the capabilities of smartdrones will explode as the interconnectedness of the drone network increases. Today, mobile apps that mine data from hundreds of thousands of daily users, such as Waze and Tealeaf, can effectively predict phenomena as diverse as traffic and stock prices. Tomorrow, smartdrones will leverage the perpetual networked aerial drone presence to give rich, real-time data about agricultural crops, traffic, weather, the movement of wildlife, and the activities of suspected criminals, giving early warnings for everything from wildfires to freeway pileups.

Furthermore, many of the deficits of the small size of smartdrones, including limited flight time, range, and payload, can be alleviated when you consider the coordinated actions of large groups of drones. A thriving research community in multirobot systems and multiagent control is currently devoted to solving problems of large-scale coordinated autonomy. New decentralized algorithms are emerging for control, perception, and trajectory planning over a wireless network to enable multidrones systems: groups of drones that reach collective inferences about the world and make collective decisions about what actions to take in the world to accomplish a task.

The potential applications of collective smartdrones are vast. Perhaps the first capability that will be realized is large-scale distributed perception. Drones will provide us with a perpetual sensor network in the sky to sense diverse forms of data for a variety of purposes,[5] as Figure 3 illustrates. As mentioned, farmers are already using individual drones for crop sensing to see daily or weekly detailed snapshots of crop health. These snapshots then inform decisions about watering, fertilizing, and applying pesticide to specific areas of the crops where most needed. With the advent of smartdrone networks, farmers could have an on-demand updated computer model of the health of their crops for crop management decisions.

Smartdrone networks will also help search-and-rescue teams find lost hikers in the wilderness, or victims of boating accidents lost at sea. The key is the ability of a smartdrone network to parallelize the task of gathering information over a large area. The larger the area, the more

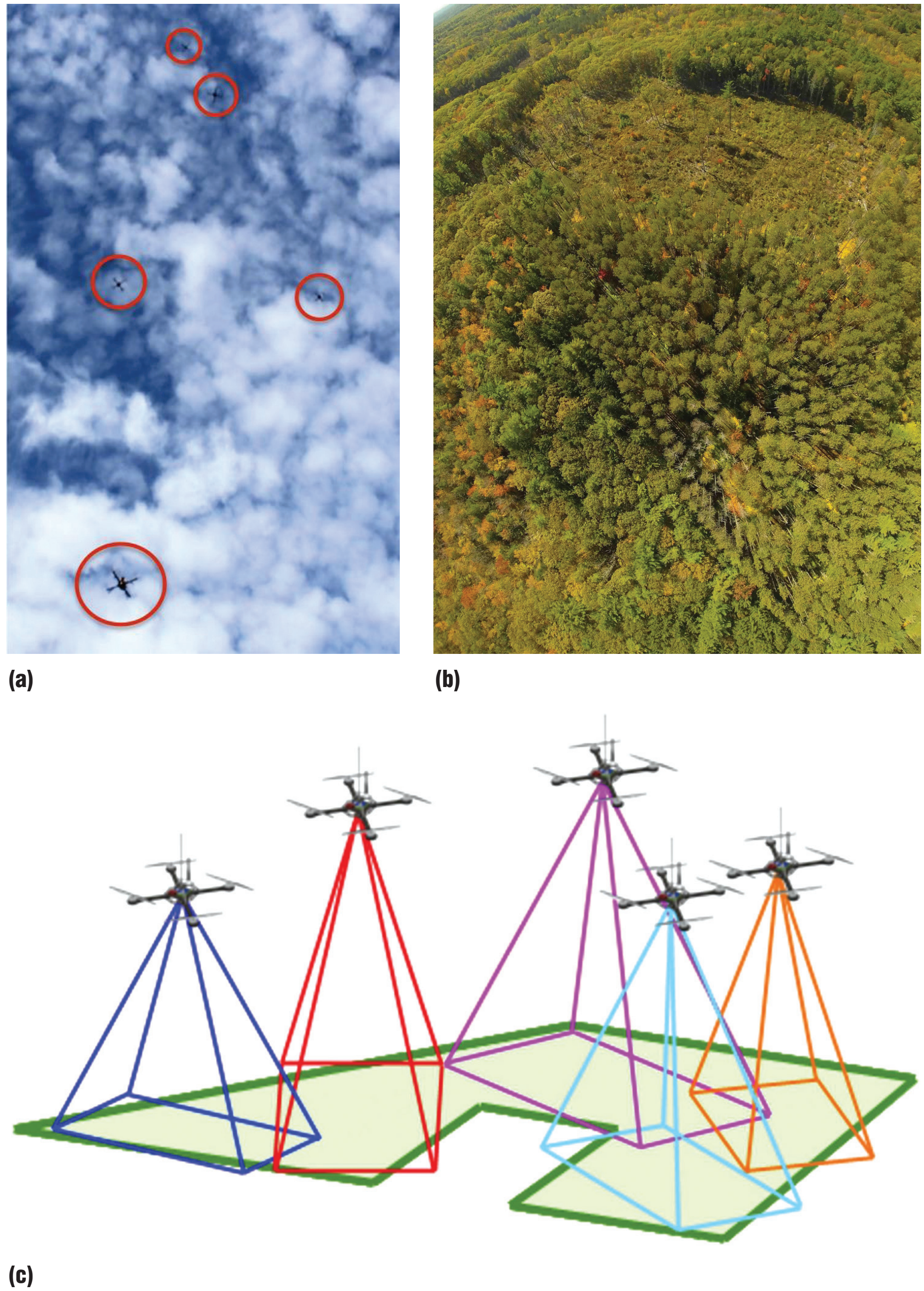

Figure 3. Five smartdrones cooperatively surveying a research forest: (a) a perpetual sensor network in the sky can (b) survey the forest below, (c) parallelizing the task of gathering information over a large area.

drones you can deploy to search it efficiently. Construction sites, which are frequently targeted for theft, and large-scale infrastructure, which requires frequent inspection, could employ smartdrones for persistent surveillance. High-tech border security could implement a fleet of smartdrones that could monitor large stretches of remote terrain.

Beyond merely sensing the environment, smartdrones interacting with the environment (for example with grippers, display lights, and other actuators) will open up a new range of exciting applications. For example, a group of smartdrones with colored LEDs can form a massive 3D display,

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creating a new medium for art, entertainment, communication, and marketing. Researchers at ETH Zurich have already shown the promise of such drone displays.[6]

When equipped with grippers, a smartdrone collective might soon replace cranes in construction sites, collaborating to hoist heavy beams into place to build buildings and bridges alongside human construction workers.[7] One day, national forests might employ groups of autonomous smartdrones to not only monitor for forest fires but also fight such fires with the targeted application of fire retardant. In addition, farmers might use smartdrones to not only monitor crop health but also actively manage crops by applying water, fertilizer, and pesticide with surgical precision. Indeed, the most transformative applications for smartdrones are most likely still waiting to be discovered by the app developers and drone users of the future.

Due to their ability to actively and autonomously interact with the world, lightweight, highly autonomous drones are emerging as the next step-change in consumer electronic technology, much in the same way that smartphones revolutionized personal computing. Although research is ongoing to ensure safe, autonomous operation, smartdrone systems are already being used in several applications, with many more applications soon to emerge. After two decades of research and development, portable computing has finally sprouted wings! P

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