Guest Editorial
Can Drones Deliver?

DRONES, autonomous or teleoperated flying machines, have been an active area of research for decades. In my area of research—dynamics and control—flying machines offer a unique challenge: they are relatively straightforward to model in steady conditions, but defy pragmatic first-principles modeling approaches during high-performance maneuvers. They are thus ideal test beds for bridging traditional model-based automation and control approaches with modern data-driven ones.

Drones have recently captured the imagination of the general public. In December 2013, Jeff Bezos, CEO and founder of Amazon.com, announced on the "60 Minutes" show that drones could be used to speed delivery of packages to consumers. As of April 2014, the "Amazon Prime Air" video received more than 14 million views on YouTube and stimulated speculation and discussions around the world.

There was interest in small flying machines as a means of delivering payloads well before this announcement. For example, in early 2009 my research group started receiving a large number of e-mails from would-be entrepreneurs, asking us if we could help them develop a pizza delivery system using drones. Why us? When I moved to ETH Zurich in late 2007, we created the Flying Machine Arena (FMA), "a space where flying robots live and learn."[1] We started to release videos of quadcopters performing athletic feats in early 2009, and this attracted people with aspirations to monetize these capabilities. After pizzas came burritos and a wide variety of other fast foods, but also document delivery, and even goods to hikers in the Swiss Alps.

I received a more serious inquiry from the folks at Matternet in late 2011.[2] Their vision was to create a transportation network based on flying machines, and to initially address niche markets such as medicine delivery in underdeveloped and hard to reach areas. Unlike all the people who had contacted me to date on the subject, Andreas Raptopoulos, one of the Matternet founders, had connected my work on flying machines with Kiva Systems, the robotics and logistics company that I co-founded with Mick Mountz and Pete Wurman. In a Kiva warehouse, hundreds of autonomous mobile robots move inventory in distribution facilities. What Matternet wanted to do was basically Kiva Systems in the open air. Coincidentally, as it relates to this story, Kiva was bought by Amazon in 2012.[3]

Impressed by Andreas' tenacity and entrepreneurial energy, in early 2012 I did a feasibility analysis of package delivery for his upcoming Solve for X talk, "Andreas Raptopoulos on physical transport."[4] Part of this analysis, which addressed the feasibility and costs associated with energy and power, is included below.[5] The very high-level operating assumptions were the following:

1) Payload of up to 2 kg.
2) Range[6] of 10 km with headwinds of up to 30 km/h.

It was assumed that these would be battery powered vehicles for the simple reason that many economic factors were pushing to improve the performance and reduce the cost of battery technology, an assumption that has since been validated by the tremendous success of Tesla Motors and their battery powered vehicles, and the recent announcement by its founder and CEO Elon Musk of a new "gigafactory" for battery production that will drive costs down by more than 30%.

Let's first explore feasibility. The power consumption in kW can be approximated by

$$\frac{(m_p + m_v)v}{370\eta r} + p \qquad (1)$$

where

m_p payload mass, in kg;
m_v vehicle mass, in kg;
r lift-to-drag ratio;
η power transfer efficiency for motor and propeller;
p power consumption of electronics, in kW;
v cruising velocity, in km/h.

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[1]The roots of the FMA can be traced back to the late 90s and early 00s: The system architecture is modeled after the Cornell RoboCup team, and many early prototypes involving quadcopters were developed at Cornell at that time.

[2]Matternet is a spinoff from Singularity University, a private institution offering executive education, whose mission is to "educate, inspire, and empower leaders to apply exponential technologies to address humanity's grand challenges."

[3]Also coincidentally, several of Kiva's early hires were former Cornell graduate students with quadcopter and flying machine expertise. As a result, quadcopters were a topic of water cooler conversation at Kiva since its early days, and one of our old decommissioned quadcopter prototypes from Cornell graced Kiva's electrical engineering work area.

[4]Solve for X is an effort launched by Astro Teller and co-workers at Google on the Google[x] team "to accelerate progress on technology moonshots."

[5]The full analysis included vehicle and system architecture, overall system costs, safety considerations, and vehicle routing.

[6]In the Matternet scenario vehicles fly from charging station to charging station, so the range is the maximum distance that a vehicle can fly on a single charge.

Some numbers: the payload mass is set to 2 kg; we assume a vehicle mass of 4 kg, more on this later; the lift-to-drag ratio is set to 3, a pessimistic value, and is meant to capture a vehicle that is capable of vertical takeoff and landing (for comparison purposes, a typical helicopter has an effective lift-to-drag ratio greater than 4); the power transfer efficiency is set to 0.5; the power consumed by the electronics (which includes all sensors) is assumed to be 0.1 kW, and is roughly comparable to a very powerful laptop computer; the cruising velocity is set to 45 km/h. These numbers result in a power consumption value of 0.59 kW. A high-end lithium ion battery has a specific power of 0.35 kW/kg, and thus a 2 kg battery could provide as much as 0.7 kW. This leaves 2 kg for the remainder of the vehicle, a significant, but not unreasonable, value.[7]

The worst-case energy requirement in kW·h can be approximated by

$$\frac{d}{1-\nu}\left(\frac{m_p+m_v}{370\eta r}+\frac{p}{v}\right) \tag{2}$$

where

d maximum range, in km;

ν ratio of headwind to airspeed.

Again some numbers: the maximum range is set to 10 km, while an air speed of 45 km/h and a headwind of 30 km/h result in $\nu = 2/3$. These numbers, and the previous values, yield an energy requirement of 0.39 kW·h. A high-end lithium-ion battery has a specific energy of 0.25 kW·h/kg, and thus a 2 kg battery would suffice.

We now address the economics. The average energy cost per kilometer can be approximated by

$$\frac{c}{e}\left(\frac{m_p+m_v}{370\eta r}+\frac{p}{v}\right) \tag{3}$$

where

c cost of electricity, in \$/kW·h;

e charging efficiency.

The cost of electricity is assumed to be 0.1 \$/kW·h, a rough average of the retail cost in the United States, while the charging efficiency is assumed to be 0.8. These numbers, and the previous values, yield a cost of roughly 0.2 cents per km for a 2 kg payload, a surprisingly low amount.[8]

We next look at the operating cost associated with the batteries, which are assumed to dominate the total vehicle operating costs in the long run, once the vehicles reach a level of maturity comparable to today's automobiles.[9] The average battery cost per km can be approximated by

$$\frac{k}{l}\left(\frac{m_p+m_v}{370\eta r}+\frac{p}{v}\right) \tag{4}$$

where

k battery cost, in \$/kW·h;

l life of battery, in cycles.

A high-end lithium-ion battery costs roughly \$300/kW·h, and can be cycled about 500 times, resulting in a cost of roughly 0.8 cents per km for a 2 kg payload. The total cost of batteries and power is thus 1 cent per km for a 2 kg payload.

So, is package delivery using flying machines feasible? From a cost perspective, the numbers do not look unreasonable: the operating costs directly associated with the vehicle are on the order of 10 cents for a 2 kg payload and a 10 km range. I compare this to the 60 cents per item that we used over a decade ago in our Kiva business plan for the *total* cost of delivery, and it does not seem outlandish.

To make drone delivery practical, automation research is needed to address three main challenges: vehicle design, localization and navigation, and vehicle coordination. Vehicle design encompasses creating machines that are efficient, (most probably) can hover, can operate in a wide range of conditions, and whose reliability rivals that of commercial airliners; this is a significant undertaking that will require many iterations, and the ingenuity and contributions from folks in diverse areas. Localization and navigation may seem like solved problems because of the many GPS-enabled platforms that already exist, but delivering packages reliably, in different operating conditions, in unstructured and changing environments, will require the integration of *low-cost* sensors and positioning systems that either do not yet exist, or are still in development. Finally, thousands of autonomous agents in the air, sharing resources such as charging stations, will require robust coordination which can be studied in simulation. In the medium to long term, I am optimistic.

Additional challenges include initial public reactions, privacy concerns, and government regulation. These will be tough to overcome. Having said that, I believe that ultimately the concerted efforts and lobbying by the many stakeholders who will benefit from goods being delivered by flying machines will result in packages flying above our heads in the not so distant future. For better or for worse.

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[7]The battery, or "fuel," and the payload amount to 2/3 of the total vehicle mass, which is comparable to long-haul commercial airliners.

[8]We were similarly surprised when assessing Kiva's feasibility to learn that running a mobile robot in a 24/7 setting would only result in an electricity bill of 25 cents a day. The takeaway here is that electricity in the United States is too cheap, and does not fully reflect the real and sustaining costs to generate it.

[9]I never cease to be amazed by the robustness and reliability of today's cars: except for consumables such as fuel, fluids, and tires, an automobile needs very little maintenance.