EXPERIMENTATION, BOTTLENECKS, AND ORGANIZATIONAL FORM: INNOVATION AND GROWTH IN THE NASCENT DRONE INDUSTRY

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Abstract: This paper explores how the choice of organizational form influences the innovation process and performance in entrepreneurial settings. Grounded in a 10-year comparative case study of two leading civilian drone manufacturers, we contribute an empirically grounded theoretical framework that contrasts firm and community-based organizations for problem finding and solving, blending novel insight in organization design and entrepreneurial strategy. Our primary argument is that innovation depends on fit between organizational form, innovation process, and the nature of problems and solutions. More specifically, we argue that communities excel at finding and solving ambiguous problems when solutions are simple or well-known, while firms excel at finding and solving uncertain problems when solutions are complex and novel. Firms, however, fit a broader repertoire of experimentation and problem-solving strategies and are thus more flexible to solve find and solve different types of problems over time.

INTRODUCTION

Innovation is at the heart of why many ventures in nascent markets succeed. Developing a novel product that fits a market need (Gruber, MacMillan, & Thompson, 2008), solving complex technical problems (Ott & Tidhar, 2018), and designing a viable business model (McDonald & Eisenhardt, 2018) are innovation challenges that are each crucial to the long-term viability of technology-based ventures. Indeed, research points to the importance of identifying and resolving innovation bottlenecks such as these to unlock growth (Adner & Kapoor, 2016; Hannah & Eisenhardt, 2018)—a key performance measure that is often intimately tied with survival in nascent markets.

Recent research points to the importance of communities in the innovation process. In contrast to hierarchies, community-based organizations are characterized by open (vs. closed) membership boundaries, public (vs. proprietary) intellectual property, self-selection into tasks (vs. task assignment), and intrinsic (vs. financial) incentives (Lakhani, 2016; Puranam, Alexy, & Reitzig, 2014; Shah, 2006). Communities for innovation became increasingly influential due to falling communication costs, increasingly modular design and production, and growing platform scale. Prominent examples include the Linux and Apache open-source software communities (Finley, 2016), as well as physical goods-based communities, such as the Homebrew computer club (Shah, 2005).

Empirical work shows how communities have the potential to challenge established firms. One example is Wikipedia. In just five years after its founding, Wikipedia surpassed Encyclopedia Britannica and grew to become the largest and most widely read encyclopedia in history (Greenstein & Zhu, 2016; Rosenzweig, 2006). Additional work shows how established firms have successfully harnessed communities for innovation (Dahlander & Wallin, 2006;

Lakhani, Lifshitz-Assaf, & Tushman, 2013). Indeed, a number of firms have successfully adopted hybrid forms, such as LEGO (Lakhani et al., 2013) and NASA (Lifshitz-Assaf, 2017). Overall, these cases and others suggest the potential of communities to both compete with as well as complement traditional forms of organizing innovation.

In parallel, a recent body of theoretical work points to the role of communities in innovation. This research emphasizes that different kinds of problems are most effectively solved by different organizational forms. A consensus is emerging that community-based forms are better-suited to those that require organizations access “hidden” or “distant” knowledge (Afuah & Tucci, 2012; Felin & Zenger, 2014). The logic is that, since community members self-select into the organization and into tasks, membership is more diverse and hidden knowledge reveals itself without need for costly search by managers (Felin & Zenger, 2014). At the same time, modularity and increasingly rich digital communication channels allows communities to harness the efforts of thousands of volunteers to solve costly problems for free (Baldwin & von Hippel, 2011; Lakhani et al., 2013). Overall, many conclude that we are in the midst of a paradigm shift from firm- to community-based forms of organizing innovation (Baldwin & von Hippel, 2011; Lakhani et al., 2013).

Yet, while these arguments are compelling for using communities to innovate, it is not clear whether communities work well in entrepreneurial settings—i.e., for ventures or in nascent markets (Eisenhardt & Bingham, 2017; Santos & Eisenhardt, 2009). First, because market needs often change and product definitions are unclear in entrepreneurial settings, problem finding, not just problem solving, is often relevant. Yet extant research often assumes that problems are known (Afuah & Tucci, 2012; Felin & Zenger, 2014; Lifshitz-Assaf, 2017). Second, because ventures are resource constrained, the specifics of the innovation process matter for success—

particularly when problems are novel and complex. However, research takes a stylized view of the innovation process. For example, theories refer to "search" without considering alternative approaches to experimentation and their implications (Afuah & Tucci, 2012; Felin & Zenger, 2014). Finally, speed and flexibility are important strategic considerations in entrepreneurial settings. However, prior literature evaluates the efficacy of communities and firms based on their "efficiency" (i.e., total resource expenditure), neglecting these alternative strategic considerations (Baldwin & von Hippel, 2011; Hienerth, Von Hippel, & Jensen, 2014).

Overall, while prior work points to the value of community-based organizations and their increasing importance for innovation (Baldwin & von Hippel, 2011; Lakhani et al., 2013; Shah & Tripsas, 2007), it is not clear how this form influences innovation in entrepreneurial settings. Thus, we ask: *How does organizational form (specifically, the choice between firm and community) influence the innovation process and its performance in entrepreneurial settings?*

Given limited theory and our focus on processes, we address this question with an inductive multiple case study (Eisenhardt, 1989). We examine two ventures that began as the global civilian drone industry emerged around 2007: Dà-Jiāng Innovations Science and Technology Co. (DJI) and 3D Robotics (3DR). The founding conditions of each venture were remarkably similar. For example, both were founded by inexperienced user-entrepreneurs without professional financing, and both saw the same opportunity to develop products for North American hobbyists. However, there was a striking difference in their organizational forms: 3DR began as a community, while DJI began as a "traditional" firm. By closely tracking each venture using interviews, observations, and real-time archival data from both US and Chinese sources spanning nine years (2007 through 2015), we develop an emergent theoretical framework that explains how organizational form influences the innovation process and ultimately performance.

We contribute at the nexus of organization design and entrepreneurial strategy. Our core contribution is that performance depends on fit between ventures' organizational form, innovation process, and the nature of innovation bottlenecks. Specifically, we argue that communities facilitate individual experimentation and modular problem solving, which are well-suited to ambiguous problems with simple or well-known solutions. In contrast, firms benefit from a relatively broad repertoire of experimentation and problem-solving processes and thus are better suited to uncertain or obvious problems with novel and complex solutions. We thus build on prior literature's stylized view of the innovation process by showing how organizational form influences the efficacy of specific innovation processes and the rate at which organizations can move between them. In doing so, we incorporate problem finding as well as speed and flexibility. We also contribute to entrepreneurial strategy with a more precise conceptualization of bottlenecks with ties to classic problems in entrepreneurship, including dominant design and product-market fit. Overall, our theoretical framework advances the importance of organizational form, problem-finding and problem-solving processes, and differences in bottlenecks in jointly shaping innovation in entrepreneurial settings.

BACKGROUND

Communities are groups of individuals affiliated through a common technology or use condition, who connect with each other and freely share related problems and solutions (Lakhani, 2016; Shah & Tripsas, 2007). Examples appear in contexts ranging from software to extreme sports and beyond (Franke & Shah, 2003; Lakhani et al., 2013; Shah, 2005). For example, Shah and Tripsas (2007) study find that parenting communities played a central role in catalyzing innovation in the juvenile products industry.

One stream of research examines the organizational differences between communities and traditional firms. Broadly, it highlights differences in four characteristics: membership boundaries, intellectual property (IP) rights, task assignment, and incentives (Gulati, Puranam, & Tushman, 2012; Puranam et al., 2014; Shah, 2006) (see Table 1). First, membership boundaries in communities are open. Communities simply require that individuals contribute time and effort to become members (Von Krogh, Spaeth, & Lakhani, 2003). Even firms can, and often do, join and contribute to communities. For example, in 2016, over 80% of Linux kernel developers were paid by an employer for time spent on the project (Corbet & Kroah-Hartman, 2016). However, firms themselves have closed boundaries, requiring that prospective employees pass a structured selection process (Puranam et al., 2014).

Second, communities freely reveal IP (O'Mahony, 2003). Free revealing, in turn, encourages knowledge sharing and collaboration among community members (Boudreau & Lakhani, 2015; Felin & Zenger, 2014). In contrast, firms prioritize financial gain and so often closely guard IP (Alexy, West, Klapper, & Reitzig, 2017). Nonetheless, community openness does not necessarily discourage commercialization. Rather, communities often hive off firms to compliment innovation within the community (Alexy et al., 2017; Shah & Tripsas, 2007). For example, firms often reproduce and improve products based on community IP, such as by manufacturing hardware or providing customer support (Bonaccorsi & Rossi, 2003).

Third, communities are characterized by self-selection into tasks. That is, whereas firms have managers divide and assign tasks to employees based on firm goals, community members are free to work on whatever task they find personally relevant or interesting (Puranam et al., 2014; Shah, 2006). To coordinate these efforts in lieu of formal authority, community leaders, who emerge based on their technical expertise and administrative facility, often volunteer to define goals or vet contributions (Dahlander & O'Mahony, 2011; Fleming & Waguespack, 2007; O'Mahony & Ferraro, 2007).

Finally, communities rely on a variety of non-financial incentives to motivate members. Specifically, community members are motivated to contribute by a combination of intrinsic and extrinsic factors, such as satisfying personal needs, learning new skills, or attaining status (Lakhani & Wolf, 2005; Nagle, 2018; Shah, 2006). While some receive indirect financial benefits from contributing by commercializing related products (Alexy et al., 2017), the point is that the direct financial incentives used by firms, such as salaries or pay-for-performance schemes, are absent from communities (Felin & Zenger, 2014).

Overall, research that examines the organizational differences between communities and traditional firms highlights differences in membership boundaries, IP rights, task assignment, and incentives (Gulati et al., 2012; Puranam et al., 2014; Shah, 2006). At the same time, it suggests similarities, such as the role of both forms in coordinating effort (Fleming & Waguespack, 2007) and facilitating successful commercialization (Alexy et al., 2017). However, it leaves differences in innovation outcomes unexplored.

A related stream of research looks at how organizational form influences innovation. The core argument is that choice of organizational form affects an organization’s capacity to solve different types of innovation problems (Afuah & Tucci, 2012; Baldwin & von Hippel, 2011; Felin & Zenger, 2014). Problems differ along two fundamental dimensions: complexity and hiddenness (or distance) of knowledge. *Complexity* refers to the degree to which problems are comprised of many interdependent components (Simon 1962). *Hiddenness of knowledge* refers to the degree to which the location of relevant knowledge is known or discernable with a “practical” amount of search (Fernandes and Simon, 1999: 226).

When problem solving requires hidden knowledge, research suggests that communities are more effective than firms (Afuah & Tucci, 2012; Felin & Zenger, 2014). The logic is that public IP helps broadcast problems widely, open boundaries permit joining, and self-selection into tasks motivates contributions. At the same time, without need to pay for member contributions, communities can grow to thousands without becoming financially constrained like hierarchies. The result is diverse a membership that searches broadly so that hidden knowledge reveals itself without need for costly search by managers. One is example is LEGO, which has greatly benefitted from unforeseen community innovations ranging from new brick designs to complementary software kits (Lakhani et al., 2013). In contrast, research suggests that firms are ineffective when problem solving requires hidden knowledge. Specifically, because of their closed boundaries and proprietary IP, firms (i.e., managers) must actively search for relevant knowledge, whether by hiring necessary talent or licensing new technology. However, this search process is excessively costly, even impossible, if the location of knowledge is unknown (Afuah & Tucci, 2012; Felin & Zenger, 2014).

When problems are complex, research argues that firms are more effective than communities (Afuah & Tucci, 2012; Baldwin & Clark, 2006). The logic is that formal authority in firms helps coordinate frequent interaction between individuals (Afuah & Tucci, 2012). At the same time, firms can use financial incentives to motivate individuals to work on problems that are costly and yet offer relatively little intrinsic benefit. Commercialization, in turn, allows firms to spread the costs of these financial incentives to among consumers (Baldwin & Clark, 2006). By comparison, research suggests that community members interact less and innovate using a modular process (Baldwin & Clark, 2006)—i.e., so that individual members can realize the value of their contributions independent of others' (Baldwin & Clark, 2006; Von Krogh et al., 2003).

Yet, others argue that communities are becoming increasingly effective for solving complex problems (Baldwin & von Hippel, 2011; Felin & Zenger, 2014; Lakhani et al., 2013). With recent advances in communications technology, communication costs have fallen. Consequently, communities are now characterized by rich interaction and frequent knowledge exchange, and so can manage interdependencies in complex problem solving effectively like firms (Felin & Zenger, 2014). Further, with advances in 3D printing and mass customization, modularity is increasingly becoming a strategic choice (Baldwin & von Hippel, 2011; Lakhani et al., 2013). An example is Firefox's transition to open source software. Although the software was tightly integrated at first, community members modularized the code so that it was easier for others to participate (MacCormack, Rusnak, & Baldwin, 2006). Overall, researchers argue that, will falling communication costs and modular design and production, unconstrained by the financial cost of incentivizing members, communities are increasingly well-suited to solving large-scale complex problems (Baldwin & von Hippel, 2011).

In sum, prior research argues that communities are more effective for firms when problem solving requires access to hidden knowledge (Afuah & Tucci, 2012; Felin & Zenger, 2014). At the same time, while firms have traditionally excelled relative to communities at solving complex problems (Baldwin & Clark, 2006), more recent work suggests that communities are increasingly well-suited to solving complex problems as well—i.e., with new communication and production technologies that facilitate collaboration between large "crowds" of contributors (Baldwin & von Hippel, 2011; Felin & Zenger, 2014; Lakhani et al., 2013).

Nonetheless, while communities appear increasingly useful for innovation, the choice of community versus firm is not so obvious in entrepreneurial settings—i.e., for ventures or firms in nascent markets. First, it is not always clear what problems are worth solving in entrepreneurial settings. Specifically, because market needs often change and product definitions are unclear (Santos & Eisenhardt, 2009), problem finding—i.e., the generation, evaluation, and selection of alternative problems, rather than solutions (Baer, Dirks, & Nickerson, 2013)—is highly relevant. However, prior research assumes problems are known in advance, and so provides little insight into the choice between community and firm for problem finding (Afuah & Tucci, 2012; Felin & Zenger, 2014; Lifshitz-Assaf, 2017).

Second, the specifics of the innovation process are central to success in entrepreneurial settings. Ventures often must solve novel, complex problems with few resources (Ott & Eisenhardt, 2018), and so neither modular nor integrated problem solving work well (Baumann & Siggelkow, 2013; Ott & Tidhar, 2018) (hybrid strategies, such as "decision-weaving" (Ott & Eisenhardt, 2018) perform better). Likewise, the choice between parallel versus serial experimentation entails trade-offs that significantly affect performance (Yin, Davis, & Muzyrya, 2014). Nonetheless, prior research comparing communities and firms takes a stylized view of the innovation process, referring broadly to "search" or problem solving instead of considering more nuanced processes and their implications (Afuah & Tucci, 2012; Baldwin & von Hippel, 2011; Felin & Zenger, 2014). Consequently, the relationship between these organizational forms and alternative innovation processes is left open.

Finally, speed and flexibility are import strategic considerations in entrepreneurial settings. Often, first-movers gain a significant advantage vis-à-vis rivals (Katila & Chen, 2008). Further, ventures must react quickly to adapt to change to stay relevant (Davis, Eisenhardt, & Bingham, 2009). However, prior literature evaluates the efficacy of organizational forms based on their "efficiency" (i.e., total resource expenditure) while neglecting these more dynamic considerations (Baldwin & von Hippel, 2011; Hienerth et al., 2014). As a result, it remains unclear whether and when firms or communities are effective when innovation timing or environmental change is relevant.

In sum, while communities complement and may even replace firms in many situations (Baldwin & von Hippel, 2011; Lakhani et al., 2013), extant research leaves open how the choice between these organizational forms influences innovation in entrepreneurial settings. Thus, we ask: *How does organizational form (specifically, the choice between firm and community) influence the innovation process and its performance in entrepreneurial settings?*

METHODS

Given limited theory and empirical evidence, we address our research question with an inductive, multiple case method (Eisenhardt, 1989). This method is particularly appropriate for addressing process research questions such as ours (Eisenhardt, Graebner, & Sonenshein, 2016). We use an embedded design. Specifically, we compare organizations over time in their ability to identify and resolve multiple industry bottlenecks (see "Data Collection" below)—i.e., situations with distinct characteristics and demands for innovation. In contrast to single case studies, multiple case studies use replication logic (Yin, 1984), such that each case (venture-bottleneck) is treated as an individual "experiment" to confirm or disconfirm emergent theory. This approach improves generalizability, parsimony, and robustness of emergent theory (Eisenhardt, 1989).

Our setting is the nascent civilian drone industry. This industry is appropriate for several reasons. First, the industry has both communities and firms and thus fits our research question. Second, drones are comprised of multiple, interdependent hardware and software components. Consequently, novel complex problem solving is central to venture success. Third, the industry emerged relatively recently. We could therefore collect rich qualitative and quantitative data while avoiding left-censoring issues for each venture. See Appendix A for industry history and

Appendix B for detail on drone technology.

Our sample is two civilian drone ventures: DJI and 3DR. While accompanied by other pioneering ventures at the start of the industry, we selected these ventures because they were the most influential. Most importantly, they exemplified the prototypical firm and community organizational forms at founding: DJI began as a strictly-managed hierarchical firm, while 3DR began as an open community. Otherwise, the two ventures had many similarities at founding that served to control for alternative explanations for observed differences in growth. Specifically, both DJI and 3DR were founded by hobbyist users and first-time entrepreneurs to address the same opportunity (stabilizing flight for RC aircraft) at the same time (around 2007). To address that opportunity, each venture commercialized similar solutions (flight controllers) for the same market (North American RC hobbyists). Finally, both ventures were founded as side projects and self-financed early on and later secured venture capital financing around the same time (2012) in pursuit of growth. Table 1 summarizes each venture's founding conditions.

Data Collection

We began data collection in 2014, while the rivalry between DJI and 3DR was ongoing and the outcome thus unclear. We collected data from several sources: (1) 45- to 120-minute interviews with members of each firm, including executives and community members, (2) interviews with competitors, industry experts, users, and analysts, (3) onsite observation, and (4) archival material, including press releases, media coverage, videos, product reviews, and analyst reports from U.S. and Chinese sources. Extensive media coverage provided with a rich source of real-time data, which include in-depth interviews with the founders of each venture.

Our primary source of data was semi-structured interviews with executives in each venture. The interviews had two sections. We began with an overview of the history of the industry, competition, and the focal venture, prompting an open-ended narrative focused on major events and outcomes. We structured the second section of the interview on the major innovations identified in the preceding discussion. We then probed more deeply into relevant decisions and actions made during these periods, in addition to organizational characteristics (e.g., incentive structure). When possible, interviews were recorded and professionally transcribed. Otherwise, a second researcher took detailed notes in real-time. Where necessary, we used follow-up interviews to fill in gaps.

To address data reliability and validity, we promised all respondents anonymity to ensure that they would speak openly. We also used interview techniques, such as nondirective questioning, to minimize response bias. Further, we triangulated data with several sources (noted above), which provided richer and more reliable data (Miller, Cardinal, & Glick, 1997). Within each firm, we interviewed informants at multiple levels (e.g., executives, managers, employees, and community members) who were involved at various points through the history of each venture. We also interviewed non-focal venture industry participants, such as executives at competing ventures, partners, industry analysts, and users. Overall, these sources provided a more complete picture of events and processes than single informants could provide.

Data Analysis

Consistent with theory-building from multiple cases (Eisenhardt, 1989; Eisenhardt et al., 2016), we began by preparing detailed case histories for each venture. To do so, we triangulated data from different informants and sources. One author wrote initial drafts of the initial cases, each of which totaled approximately 80 single-spaced pages. The other reviewed the data independently. We then analyzed each case (i.e., using replication logic) in relation to our research question and subsequently compared across cases. We facilitated this comparison with tables and charts (Miles & Huberman, 1994) and formed tentative theoretical constructs and arguments based on emergent patterns. Then, we refined our theory using replication logic and revisiting the data to resolve discrepancies. We also revisited extant research when our theoretical insights became more refined. Overall, iterating between theory and data allowed us to sharpen theoretical constructs and improve the generalizability of our findings (Eisenhardt & Graebner, 2007).

Innovation

Given our research question, our focal dependent variable is *innovation*—i.e., the invention and commercialization of new products or services (Edwards & Gordon, 1984; Katila & Shane, 2005). Consistent with prior research, our data revealed that innovation in the drone industry unfolded as ventures identified and resolved a series of bottlenecks (Adner & Kapoor, 2016; Hannah & Eisenhardt, 2018). Specifically, a *bottleneck* is a component in a complex system that is fully utilized and therefore limits the system from realizing greater performance (i.e., in spite of low utilization in other, non-bottleneck components) (Baldwin, 2015; Rosenberg, 1972). Each bottleneck thus represents a critical problem that ventures needed to identify and solve to improve product performance and ultimately facilitate industry growth.

We identified bottlenecks using interviews with industry experts, analysts, and users. In our interviews, informants inevitably discussed the history of the industry in terms of a series of critical problems (e.g., low carrying capacity), each of which had to be solved for the industry to grow. Our data revealed agreement on three distinct problems: product architecture, video quality, and assembly (Table 3). Subsequently, we confirmed that these bottlenecks and their solutions were germane to innovation using data on product introductions and industry growth.

We measure innovation for each venture based on their performance identifying and resolving each bottleneck (speed and solution quality). We measured whether ventures *identified* each bottleneck based on the date it was first acknowledged by the management team (i.e., in archival materials, such as press releases and interviews). Consistent with prior research (Adner & Kapoor, 2016; Hannah & Eisenhardt, 2018), our primary indicator of whether firms successfully *resolved* each bottleneck is venture growth (Table 4). We use revenue because it is the most common indicator of growth (Gilbert, McDougall, & Audretsch, 2006; Nason & Wiklund, 2015). We also measure the annual number of employees for each venture (in addition to community members for 3DR). Finally, we supplement growth with additional measures of innovation, such as patents, expert ratings, and qualitative assessments by users.

A striking feature is the comparative performance of the two ventures (Figures 1 and 2). While they start at the same time with similar resources, they have widely divergent growth. At the end of our study, DJI's annual (2015) revenue exceeded one billion USD. In contrast, 3DR earned 45 million USD in 2015 and ultimately decided to exit the industry. We turn now to our emergent theoretical framework explains the processes that underlie this difference.

EMERGENT THEORETICAL FRAMEWORK

Our research question asks: *How does organizational form influence the innovation process and its performance in entrepreneurial settings?* Prior work points to the value of new community-based organizational forms and their increasing use for innovation (Baldwin & von Hippel, 2011; Felin & Zenger, 2014; Lakhani et al., 2013) but leaves open how these forms influence the innovation process and its outcomes for ventures in nascent markets. To address this gap, we develop a theoretical framework that outlines when and why the firm and community organizational forms are effective for innovation in entrepreneurial settings. Our principal argument is that fit between ventures' organizational form, innovation process, and the nature of innovation bottlenecks is critical for performance.

Below, we develop this emergent framework and explicate its theoretical logic through the history of innovation bottlenecks in the nascent consumer drone industry. Specifically, we detail the roles played by both DJI and 3DR, including the specific processes each venture employed to identify and resolve each bottleneck and, to that end, the central role of their organizational forms. In doing so, we show that organizational form influences the repertoire of experimentation and problem-solving processes ventures can employ to innovate. Performance, in turn, is a function of the fit of this repertoire with the different types of bottlenecks that block innovation—i.e., whether ambiguous or uncertain, or whether solutions are novel or complex.

First Bottleneck: Problematic Product Architecture

Triggered by the availability of inexpensive smartphone components, the civilian drone industry emerged around 2007. DJI and 3DR were pioneering entrants. Both founders were hobbyist-users. DJI's main founder, Frank Wang, began tinkering with radio-controlled helicopters in high school and started DJI when he left graduate school at HKUST. Chris Anderson, the primary founder of 3DR, was a physicist and journalist. Anderson started building drones using a Lego kit in his backyard as a family project.

The initial product for both was a flight controller. A flight controller combines hardware and software into a product that makes drone flying easier (much like an automatic transmission makes driving a car easier than using a manual shift). However, the two ventures focused on alternative product architectures. DJI developed its flight controller for a helicopter architecture, while 3DR did so for an airplane architecture. Each architecture had well-known tradeoffs, and so the dominant design was not obvious. Planes can fly for a long time and are safe, but they cannot carry a heavy payload or hover. In contrast, helicopters can carry more and hover, but they have limited range and are less safe. Still, despite these tradeoffs, neither entrepreneur saw product architecture as a bottleneck.

Anderson planted the seeds for 3DR in early 2007 when he launched an online community for drone hobbyists, DIY Drones. Inspired by his initial backyard success, Anderson spent his time building the community and creating hobbyist drones, working with community members to improve various flight controller designs. Given the excitement around the promise of drones, the community grew rapidly to about 1000 worldwide members in its first year, and 5000 the year after. A member described, *"It was like people who were really amazed by what they could get this software and hardware to do at such a low cost…They were all just very into that, and so it was a fun project for all these guys"*.

In response to the need for manufactured components that arose within the community, Anderson launched 3DR as a profit-making venture within the community in 2008. He saw 3DR as a new type of organization that combined open source innovation and its "long tail of talent" (i.e., leveraging talent wherever it is) with the maker movement (Anderson, 2012). Thus, 3DR was both a hardware design and manufacturing firm as well as a member of and contributor to a large community of open-source hobbyists. As one community member described, *"The idea behind 3DR was you would create the genesis of some hardware and basic software, and then put that out in the community, and other people would take it on to flesh it out."* Anderson himself described the basic premise of 3DR as "*give away the bits and sell the atoms*." Thus, 3DR's advantage was mostly free innovation provided by a large community of talented users around the world, some of whom were experts.

The community was diverse and global. Some members had PhDs in various technical fields while others were simply aviation enthusiasts. However, they were united by the community's "do-it-yourself" (DIY) and "open innovation" values—i.e., collective interest in tinkering with drones, and sharing their experiences and improvements. For its part, 3DR embraced these diverse interests, and supported the community by contributing improvements (mostly hardware), and manufacturing flight controllers and other components in its Tijuana-based factory. Community members often designed these components and were the primary customers. As a result, 3DR developed a thriving and profitable hobbyist business. The community model was working well. As an analyst observed, *"It's hard not to be innovative when you have one hundred scientists around the world, whose passion is working on the flight code, which is open source flight code… Much of it comes from the DIY Drones community contributing to this open-source copter."* Anderson also believed in the community, *"What do I know about traditional helicopters? I've never flown one, but it turns out that someone in the community does. And they figure it out."*

In 2009, several "core" 3DR community members (i.e., frequent contributors) discovered the promise of a new architecture: the quadrotor (see Appendix B). These members began working with a similar online community of drone racing enthusiasts, who had been experimenting with lesser-known product architectures to improve their results. Although not interested in racing per se, the 3DR community members quickly recognized the advantages of the quadrotor over both the plane and helicopter architectures—it was easy to maneuver, yet still safe. Consequently, several community members banded together to create a new version of the 3DR flight controller that worked with quadrotors. One member even designed and began selling a kit that included the frame itself (described below). Consistent with its role as the primary commercial and manufacturing arm of the community, 3DR was watching, noticed this shift to quadrotors, and realized the product architecture was a bottleneck and the quadrotor a solution.

DJI took a different path to identify the bottleneck. Inspired by the challenges he faced flying remote-control helicopters during childhood, Frank Wang and three other young engineers began DJI in 2006. They began by creating a flight controller for the helicopter architecture. Wang described, *“It was my dream to develop this technology”* (Wee, 2013). Wang had strong product views that he pressed onto the team. He explained, *“If I like something, I don't care about why or others' opinions. I just want to realize it.”* One co-founder noted Wang's 3 a.m. phone calls and intense and meticulous approach. Another described, *“[Wang] would tell us, for each screw, how many fingers we should use and continue turning until we felt a certain type of feeling."* Since the team saw Wang as the prototypical user, they spent little effort into thinking about the market. Wang explained, "*I didn’t know how big the market could be, I just wanted to make a product, feed 10 to 20 people, and have a team*."

By 2010, 3DR and its community had switched to the quadrotor architecture. But the DJI team remained committed to incrementally improving the flight controller for the helicopter architecture. As one early employee explained, when one engineer brought up the safety problem of helicopters, the team ignored him. Finally, in 2011, when a New Zealand distributor mentioned the simple fact that multirotors were outselling helicopters 20 to 1, the team paid attention. Wang described the shift*, “We didn’t think much of multirotors… But when the dealer told us this information, we thought seriously about multirotors.”* From this point on, adopting the quadrotor became, as a DJI executive described, “*an easy and obvious decision*.”

Solving the bottleneck: Designing a quadrotor

Although neither 3DR nor DJI initially recognized the product architecture bottleneck, each team quickly solved it. The quadrotor architecture had existed for decades but was obscure because quadrotors were so difficult to pilot entirely by hand. The new flight controllers, enabled by smartphone technology, changed this.

The community designed 3DR's first quadrotor. A U.S. member (described as a "*brilliant software engineer*") jumped in to adapt 3DR's flight controller software for quadrotors. As one member said, *"Over the space of a couple of weeks, [the community member] took the plane code and turned it into copter code."* A Thai community member took the initiative on the hardware side. He sourced generic parts from Shenzhen, designed a few components himself (e.g., the frame and motor), and bundled everything into an unassembled, DIY kit. He described relying on individual, serial experimentation,

> *"I experimented with the different materials: to find which materials were strong enough, but as light as possible… Yeah, I went through probably something like 400 different motors, choosing the best ones, then I started to work with the companies who made them, like "let's change the magnet on this one, let's change the windings to be like this one, and so on."*

His quadrotor kit worked. A community member described,

> *"John produced the first standard quadcopter frame… I'm sure he's got an "unboxing" video somewhere on his YouTube channel. It's like this clear plastic thing—it's super light, not very sturdy… John had been making quadcopters longer than anybody else. He was the one that very quickly produced two hundred… They just sold out like that."*

The 3DR team noticed, improved the design, and began manufacturing and selling kits in 2010. As Anderson proclaimed, *"That's what an open community can do."*

The DJI team also developed a quadrotor kit in a few months. They re-used their helicopter software with a few tweaks, and easily copied a 3DR open-source hardware design. Wang explained, *"Most of the stuff was the same, and we could use our software on multirotors."* Another executive summarized, *"It was easy…. We saw that somebody else had used the quadrotor design and we just copied it."* Thus, although slow to identify the bottleneck, the DJI team quickly solved it and released their first quadrotor flight controller in 2011, launching a DIY kit the following year.

How did 3DR identify and solve the bottleneck sooner and faster than DJI? One reason is that 3DR benefited from *individual experimentation*—i.e., a deliberate, individual-level process that involves independently testing alternatives to solve a self-identified problem. Individual experimentation is particularly useful for identifying ambiguous problems where the problem (or its solution) are hidden and obscure for most, or even all, people. Here, the product architecture bottleneck was a problem that was not apparent to most people (i.e., ambiguous). But 3DR community members were experimenting individually to solve whatever problems that they found to be personally interesting or otherwise worth solving, and it was apparent to a few that the product architecture was a severe limitation. At the same time, these members had diverse motives and knowledge about old aircraft product architectures.

Often, solutions that emerge from individual experimentation generate *insight*—a sudden and unexpected understanding of a problem after reframing its structure (DeYoung, Flanders, & Peterson, 2008; Weisberg, 2015). By waiting and watching for individual experimentation in the community, the 3DR team identified the product architecture bottleneck and its solution through insight. In contrast, the DJI team was using local search. The team knew a problem existed but believed it was fundamentally an issue with the flight controller, rather than the broader helicopter architecture on which they focused. Consequently, they missed the bottleneck until happening upon a diverse information source: the New Zealand-based hobby distributor.

A second reason is that the solution was not novel. Although obscure and rarely used, the quadrotor architecture had existed for decades. Even when complex, solutions that are not novel have well-understood interdependencies that can be addressed easily via design rules and thus modular problem solving. Consequently, even though the quadrotor design was comprised of multiple interdependent components (see Appendix B), it was straightforward for the 3DR community members to recreate, even working relatively independently. For example, the flight controller hardware and software, which had been optimized for airplanes through the concerted effort of many, operated on a few common principles and so could be adapted quickly.

Overall, 3DR's community form facilitated individual experimentation, which fit well with identifying the ambiguous bottleneck and solving it with a known, but hidden solution. The quadrotor went on to become the dominant design in the consumer drone industry since many preferred its combination of safety and usability. 3DR, the first venture to reintroduce the architecture, grew rapidly: revenue increased by 300% from the prior year to over one million USD. In contrast, supported by a few incremental helicopter flight controller innovations, DJI grew as well. However, in spite of the team's early start in 2006, they fell behind 3DR.

Second Bottleneck: No "Killer App"

By 2011, 3DR and DJI recognized the possibility of a larger market opportunity beyond hobbyists and began to consider VC funding to pursue it. As one executive said, "*It was super obvious that we were onto something hot.*" The two teams saw possibilities around big data, photography, and vertical markets like agriculture and construction. Thus, it became apparent to both teams (and others throughout the industry) that the new major bottleneck was the lack of a *killer app*—i.e., a compelling product(s) for a significant group of buyers that would propel the industry beyond hobbyists. However, although possibilities existed, there was significant uncertainty surrounding the specifics and ultimately the viability of each (product-market fit).

Like others, the DJI team saw the multiple possibilities for the killer app. As one of their 2011 job postings explained, "*DJI is committed to the development of autonomous flying, vertical take-off drones for rescue, disaster investigation, air monitoring, transmission line inspection… a wide range of applications.*" The DJI team briefly considered waiting for a killer app to emerge while they stayed focused on improving their drone, but instead decided to search themselves. To that end, the DJI team began experimenting with multiple vertical markets in parallel. Specifically, they organized experimentation with a few simple rules that created a flexible yet somewhat efficient "formula" for each test. One rule was "*send one or a few senior executives to tradeshows (especially in North America and Europe) in promising market verticals"*—verticals like agriculture, public safety, real estate, and sports. For example, one executive described, *"We went to a Chicago [entertainment] trade fair to come up with ideas. We also went to a toy trade show and an aerial photography show in Indianapolis."*

A second rule called for "*finding one to three show participants to be lead users*." But finding lead users was not always easy since many dismissed DJI as a "copycat" Chinese manufacturer. The CEO described one incident, *"The first time we went to an exhibition at Nuremberg, Germany we were placed in the China section, with one of those cheap and small booths, right next to stuffed animals… We were not even in the model section; we were in the toys section!"* A third rule was to *"engage with the lead users to come up with useful drone ideas."* A prototypical lead user was a German kayaker who helped DJI to explore drone applications in sports. Another was a Californian pilot and firefighter who helped DJI experiment with drones in fighting wildfires. In another instance, several farmers were enticed to help by a senior executive at an Iowa agriculture convention. As an executive described, "*We showed them how drones could show their whole fields at once...and we got them to contact their Congress representatives to help us."*

Parallel experimentation paid off when DJI executives struck up a relationship at a tradeshow with the owner of an aerial photography business. This owner used helicopters (full-size ones) to do high-quality aerial photography for clients in markets such as high-end real estate. He knew about a potentially lucrative application in Hollywood movies, where aerial photographers charged thousands of dollars per day. But a more accurate bottleneck existed, preventing drones from catching on: low-quality video. One executive enthused, *"We learned that people in the movie industry were charging really high day rates for crappy [aerial] videos… So, if we could just make the footage really, really stable, we knew directors were gonna go crazy for it."* Once the DJI team recognized the need for better video, they looked for a solution in the aerial photography industry. There, professionals achieved high-quality footage during flight by using a gimbal (i.e., a notoriously temperamental device that stabilizes a moving camera). As one executive emphasized, "*The success of the product was all about the gimbal."* Thus, the DJI team identified video quality as the bottleneck and began experimenting to design a small, lightweight gimbal in 2012. Unexpectedly, the DJI team also began to speak in terms of a new collective identity. An executive explained, *"We were flight control specialists, now we're flying camera makers."*

The 3DR team also recognized that no killer app existed for drones, as well as many possibilities. As one executive asked, "*We need to be the future of x, but what is x*? The CEO echoed, *"We created a community, then the product, and the next question is: what is it good for?*" To cope with this uncertainty, 3DR again waited for a killer app to emerge from individual experimentation in the community. While waiting, they continued building and managing the community, making and selling drone kits for hobbyists, and maintaining a supply of inexpensive drone components so that the community could continue tinkering and experimenting. As the CEO argued, "*By making drones easy, cheap and ubiquitous, we hope to put drones in the hands of regular people…maybe it will be windsurfers, maybe it will be agriculture, maybe it will be wildlife management."* The 3DR team saw no need to rush because they had both a profitable hobbyist business and confidence in the community. As an executive explained, *"We didn't have any particular urgency to find applications… We expected our users to find those."* The team believed they were uniquely well-positioned to find a killer app with their community-based, open innovation strategy. In a veiled shot at DJI, an executive noted, *"There are like a zillion verticals out there, all of them are going to be transformed by drones. And we don't know anything about any of them, but we don't have to…because we're the only open platform."*

The 3DR team complemented individual experimentation by the community with local search. For example, Anderson spoke with friends in San Francisco, including the CEO of a CAD firm and a Napa winery owner. As Anderson told us, *"We would spend our weekends just nerding out on [drones]."* Some of the team members went to drone conferences. 3DR was an often anchor participant with Anderson as a keynote speaker. Consistent with local search, the 3DR executive team also discussed possible killer apps among themselves. One executive favored inspection of infrastructure like bridges as the best application. Another saw the killer app as the "*empty space where there's lots of money and hunger for data"* such as "big data" for agriculture. In contrast, one investor favored a platform with a few vertical markets. He argued, "*You can't do everything good at once, so you have to pick a few killer applications to focus."* The team concluded that it was unwise to emphasize any one vertical just yet.

Overall, the 3DR team believed that the community would identify a killer app, and solve the problem of addressing it, as it had in the past when community members re-discovered the quadrotor. Then, 3DR would adopt the solution and scale up. An investor described,

> *"Once you let loose a bunch of hackers and the technology gets cheap enough, the hackers can go from the bottom, Burning-Man style, figure out all sorts of little applications for themselves… What happens after that is [those applications] give rise to commercially viable apps, like agricultural assessments from the sky, geospatial*

mapping, or [having] your own personal cinematographer five feet above all the time."

Over time, the community developed several components that solved less critical problems. For example, a U.S. member developed a "follow-me" feature so that the drone could follow its operator like a dog. Other community members added additional features based on personal interests, such as for racing or more precise flight control. However, the 3DR community did not immediately identify a killer app like movies or a more accurate bottleneck like low-quality video. Rather, as one community member explained, and others echoed, they believed the video quality *"looked fine."*

By 2014, the 3DR team noticed that an increasing number of community members were adding a gimbal to their drones. A Russian drone enthusiast had cobbled together software and semiconductors into a crude gimbal. He had released the designs to the community, and others around the world developed and began selling the missing hardware pieces. Although temperamental and buggy, the gimbals did improve video quality. And so community members started buying, such that over 60% of 3DR drones eventually sold with a gimbal. As the 3DR team watched, they realized the gimbal's popularity signaled that the bottleneck was, in fact, low-quality video. Finally, they had identified the problem.

Resolving the bottleneck: Designing a gimbal

Drone gimbals are moderately complex. Although comprised of only a few major components, gimbal technology integrates computer science, electrical engineering, and mechanical engineering know-how. As an engineer emphasized, "*A gimbal is a notoriously difficult thing to make work"* Another described, *"The challenge is that everything impacts everything. If you change something you shift the balance, or you shift the friction, or you shift something which causes a ripple in the software."* Further, a drone gimbal has to be small and light so that a drone can carry it during flight without a significant reduction in flight time. At the same time, it needs to be high-quality enough to compete with traditional aerial photography solutions, yet relatively inexpensive.

The DJI team briefly considered contracting the design of its first gimbal to a third-party firm but decided that the venture should design it in-house to build technical skills and intellectual property around a core component. As one executive described, the team believed the gimbal would be a "*game changer*" and therefore central to the venture's future performance. Thus, although the DJI team also occasionally got advice from an experienced third-party engineering consultant to avoid *"rookie mistakes,"* they otherwise kept the design in-house.

DJI used rapid, serial experimentation to design its first gimbal—i.e., a repeated cycle of testing a solution and updating its design to incorporate feedback (Erat & Kavadias, 2008; Thomke, 2003). The engineering team began with a basic prototype and then built, tested and improved the gimbal with as many as 3 to 4 iterations per day. As one executive explained, *"We would make literally 20 prototypes on a weekly basis."* Another described the process as *"Hardware iterations at extreme speed."* Another summarized the process best as, "*DJI knows that their first prototypes are going to be terrible and the 15th prototype is going to be terrible, but by the 20th prototype, it's going to work pretty well. They never stop iterating".*

The DJI team launched its gimbal in just under a year (by late 2012). By solving the low-quality video problem, they opened the door to growth in high-end aerial photography, especially in Hollywood for movies. It was a significant inflection point for DJI. With its innovative gimbal, the venture was no longer seen as a cheap toy company. As the CEO noted, *"People in the industry began paying attention."* A rival echoed, *"DJI was just not taken seriously until they did the gimbal."* An influential journalist perhaps best captured this inflection point, "*While* *everybody has focused on DJI being an innovative drone company, the gimbal is where we all need to focus and understand that's where the key innovation is."*

By comparison, the 3DR team was slow to identify that the killer app bottleneck was more precisely low-quality video. Even after this realization in early 2014 (following the gradual emergence of a community-designed gimbal), the team was slow in deciding whether to design an improved gimbal in-house, use a third-party design firm, or just pay a few highly-talented community members. An executive described the conflict and delay,

> *"The gimbal was a source of conflict. Some strongly believed that we needed to make our own gimbal, and I did too because I just generally thought that if you're making a product around users, you have to own the touch point… So, it was a big debate that was a huge problem because it meant that the gimbal started very late."*

Initially, the 3DR team chose to pay a select few community members to create the design. One executive recalled, *"There was this massive desire…to use the community to develop as much of the code as possible and even a lot of the mechanical design."* But, like DJI, 3DR believed they should maintain control over the intellectual property. Although it hadn't previously been an issue, the increasing popularity of its flight controllers and kits spurred new commercial rivals who were "ripping off" the community's open source designs without contributing back to the community. One executive lamented, "*the open source hardware business was cratering."* However, the most qualified community members were uncomfortable with proprietary designs, and so were reluctant to help. One noted, *"Our goals just diverged too much, and we weren't willing to go with them."* Another elaborated, *"3DR wanted to build a gimbal and they came and asked us to… So, I asked, 'Is this gonna be open source?' They just waffled back and forth. Couldn't even give the answer. And so we said, 'Okay, if we can't guarantee open source, we're not gonna do it."*

With tensions running high and pressed for time, the 3DR team settled on outsourcing the gimbal design instead. With the design of a new quadrotor underway (next section), 3DR engineers outlined detailed design specifications for the gimbal passed that to a third-party engineering firm. But this linear "waterfall" process of planning up-front was ineffective: because of the constraints imposed by size, weight and cost, designing the gimbal required tight coupling between design and manufacturing. After several setbacks manufacturing the new third-party gimbal design, in desperation, the 3DR team reached back to the community members to fix the design. This time, as one community member explained, they *"bailed 3DR out."* Still, it took 3DR nearly two years (twice as long as DJI) to produce a gimbal that outperformed the community's hacked together design. DJI's gimbal, in contrast, remained superior. As one executive summarized, "*The gimbal was a bloody disaster.*"

How did DJI identify and resolve the bottleneck sooner and faster than 3DR? One reason is DJI's astute use of parallel experimentation to identify the bottleneck—i.e., testing multiple alternatives simultaneously to resolve uncertainty (Loch, Terwiesch, & Thomke, 2001). While parallel experimentation can be expensive, it is fast and highly effective for reducing uncertainty (Ozcan & Eisenhardt, 2009). Moreover, it fits especially well when alternatives are independent, such as when identifying market needs (i.e., problems) (Yin et al., 2014). When alternatives are independent, learning about one does not inform choices made about others, and so little is gained by waiting to experiment serially. Further, simple rules improve parallel experimentation. They loosely guide the process, making it faster and lower cost (and thus more scalable) without sacrificing learning (Davis et al., 2009). In contrast, the 3DR executive team used more serial approaches, searching locally to identify a killer app and relying on individual experimentation.

A second reason is DJI's use of rapid serial experimentation to resolve the bottleneck. Serial experimentation is effective when uncertainty and interdependence are high (Erat &

Kavadias, 2008), such as when design-manufacturing integration is critical (Eisenhardt & Tabrizi, 1995). Further, rapid iterations such as DJI used further speeds learning (Thomke, Von Hippel, & Franke, 1998). By comparison, a linear "waterfall" process like the one used by 3DR can be fast and effective when uncertainty is low (Eisenhardt & Tabrizi, 1995), but not when producing a novel (and thus uncertain) design, like a drone gimbal.

Finally, DJI resolved the bottleneck sooner because its engineers were well-aligned. Because of the gimbal's complexity, serial experimentation required integrating the effort of a team of engineers. DJI's organizational form helped facilitate this joint effort despite the venture's shift in identity—i.e., to become "flying camera makers." By comparison, individual experimentation was ineffective, the 3DR team's attempt to entice skilled community members to be "paid" volunteer designers was slow as well. As one engineer explained, *"There's a gillion people that can write basic gimbal software and have basic micro-controller talents."* However, 3DR struggled to find a critical mass of qualified members willing to invest the time and effort required to produce a higher-quality proprietary design.

Overall, DJI's organizational form and innovation process was complementary, and fit well with identifying a killer app (i.e., validating product-market fit) and the more accurate bottleneck of low-quality video. With the introduction of the high-quality gimbal in 2012, DJI unlocked the lucrative high-end aerial photography market and grew dramatically—by over 500%. In contrast, while 3DR continued to grow within the hobbyist market, without a high-quality gimbal to move into the aerial photography market, the venture fell significantly behind DJI. As a 3DR executive explained, *"It was something that really only DJI had—a gimbal that really worked."*

Third Bottleneck: Assembly Hassle

In 2012, the hassle of assembling a drone emerged as the major innovation bottleneck. At that time, DJI, 3DR, and other firms sold DIY kits that required assembly. However, assembling drones was challenging for all but the savviest users. As one industry expert explained, it required "*tribal knowledge*." Executives at each venture recognized this bottleneck. For example, one DJI executive noted, "*Probably 80% of our leads would drop off…trying to learn how to put this thing together, and potentially having it not work out.*" A 3DR executive echoed, "*The marketplace has spoken clearly on this—not everyone wants to have to use a soldering iron or load code to use a UAV [unmanned aerial vehicle].*" Further, the solution was obvious: a ready-to-fly (RTF) drone—i.e., one that is fully integrated for users "out of the box", thus eliminating the need to do any assembly after the purchase.

Resolving the bottleneck: Designing a ready-to-fly drone

Although it was easy to spot the assembly bottleneck and its solution, designing an RTF drone that worked was a highly complex and novel problem. Like a gimbal, an RTF drone combines several technical disciplines—from computer science and telecommunications to mechanical, electrical, and aeronautical engineering. But, while a gimbal has relatively few components, an RTF drone design is complicated by a large number of components involved. Further, these components have numerous interactions, exacerbated by constraints such as size and weight. For example, magnetic interference from the motors and wiring can affect the flight controller. The first RTF drones also required that engineers overhaul the design the components that had were previously used in DIY kits—i.e., so that the drone was fully enclosed (no exposed parts). In short, as many informants told us, "*Designing a drone is hard*."

To design an RTF drone, DJI changed its problem-solving approach to a "modular yet integrative" one. The engineering team began by using low-quality generic components to build a very rough working drone. The engineers then re-designed the components one by one, deliberately and successively focusing on what they considered to be the most critical remaining component. After iteratively designing a component, they would prototype and test the entire system to ensure it worked, repeating this process with additional components until the entire design was proprietary. As a DJI executive described, *"We start with off the shelf parts and prototype the whole design. Then gradually we replace key modules one by one, and design and make them ourselves."* Another described the approach more colorfully, *"We duct tape and zip tie the thing together to show it kind of works, and then just make literally 20 prototypes on a weekly basis, constantly building a new prototype, constantly replacing the zip ties with better parts, replacing some crappy brace with a better brace, and so on."*

DJI also maintained its pace of rapid serial experimentation. A DJI engineer described a typical example of this process, "*We'll have a meeting to discuss the design or features, and we'll come up with an idea or a change. An hour or two later, we'll have a fresh prototype, just off the factory floor, still warm to the touch."* Another executive similarly described the engineering team's process,

> *"They [the engineering team] would crank out iterations of hardware, very quickly… It was just extreme brute force and extreme focus on what they were trying to do. They would just crank out stuff at extreme speed. If it wasn't working specifically, then crank another version out. Test that and just fly the living crap out of it. That was the strategy."*

Thus, DJI rapidly and continually experimented to improve their design. As a rival described, *"When you live at the smartphone metabolic rate, you're instinctively fast."* An engineer summarized for us, "*We're always looking to do things better than the conventional way… We're questioning the whole time… We're constantly iterating."*

Another aspect of designing the RTF drone was parallel experimentation with competing teams. For example, an engineer described, *"Pitting teams against each other and having one win is how product development works inside of DJI."* Although costly, DJI's success with the gimbal helped provide resources. Further, the DJI engineers loosely guided their parallel experimentation with simple rules for when to use these teams like "use competing teams for critical components". An engineering manager elaborated, "*We use competitions between product design teams in-house. We especially do this with critical components. The teams compete, and then we see who wins… We don't do that all of the time, but we do for critical components, and then we always compete at the product level to cannibalize successive products."* These and other simple rules provided a rough "formula" for parallel experimentation. For example, they used rules to guide how the competitions would work like "use two competing teams" and "disband the losing team." Another engineering manager described,

> *"There would be a team anywhere from 3-8 engineers working on a given subsystem [e.g., the gimbal, airframe, or mainboard design]…two different teams of engineers working in silos to create the mainboard or whatever. And then by the time they got to prototype number two or three, then it was decision time about which team had a better working model… And that team got to stay together… The other team was disbanded into the pool of people who would make up the challenger teams on the next project."*

The DJI team launched its first RTF drone in just under a year (by early 2013), which opened the door to growth in the mass market for drones. Like the gimbal before it, DJI's RTF drone became a significant inflection point for the venture. In a typical comment, an industry expert said, *"DJI took drones from something you could just fly around for fun to something you could do something with. DJI had a great system—camera, safety, transfer to your phone. It was a pretty compelling package."* The CEO summarized DJI's accomplishment, "*This drone is representative of all of our products. It is a collection of our camera technology, stabilizing [gimbal] technology, and automatic flight control technology."*

Unlike DJI, 3DR took a modular problem-solving approach to the overall RTF design. 3DR’s community members were often quite skilled at modular designs. As one engineer recalled, *"We had gotten really good at building autopilots and GPS and the various ancillary bits that you need to put into a drone."* There was also a lot of talent in the community. Echoing others, an informant told us, *“The community members were actually incredibly qualified.”* Similarly, an executive who worked at both companies praised 3DR’s talent saying, “*I would say that 3DR level of domain knowledge and engineering maybe was even higher than DJI”.* The community had also been able to self-organize product development effectively in the past. For example, many observers agreed that 3DR's community-developed flight controller was the best in the industry.

However, although a modular approach can be effective for optimizing individual components, it neglects their integration into an overall system. So, interactions between components (like magnetic interference, heat build-up, and weight restrictions) will cause issues if not recognized and accounted for in advance. However, because RTF drones were novel, nobody on the 3DR team fully understood these interactions. Consequently, community members and 3DR engineers often created individual components that were very well-designed for DIY kits but did not always work well together once integrated into an enclosed RTF drone. As one executive said, *“They [3DR and the community] really didn't have a lot of vehicle [system] development experience.”* For example, the 3DR team sometimes used simulation to test the entire system, but simulation testing misses unknown interactions. Thus, as one engineer noted, even after simulation, *“We’d have these lurking bugs.”* Likewise, as an executive lamented, *“Then we recognized, of course, there's no substitute for flight hours.”*

Like DJI, the 3DR team valued rapid serial experimentation. So, the venture maintained a tight link between engineering and manufacturing. A community member described, *"That's the one thing that 3DR has: good prototyping capability. You could run a small batch of boards readily."* He went on to observe, *"The manufacturing side of things and the design side of things and the software development side of things. It was all very tightly coupled."* Nonetheless, relative to DJI, the pace of experimentation was slow. Instead of prototyping designs as much as three to four times per day, the CEO explained, 3DR would *"wait for the [community] designs to come in"* and prototype designs about once per week.

3DR also engaged in parallel experimentation, but compared to DJI's competing teams, 3DR's received less direction. As a new engineer noted, *"All they [3DR] did was experiments. But it wasn't like a team-oriented engineering team; it was just people doing little experiments here and there—one guy working on open source, one guy working on a mapping thing."* While some of these experiments furthered 3DR's vision to become a top RTF drone manufacturer, such as the discovery of a superior long-distance communications technology, others were less applicable. Community members were often not very interested in contributing to an RTF drone. As an engineering leader explained, *"It took 'missionary work' to find community members to work on the drone."*

3DR introduced its first attempt at an RTF drone by the fall of 2013, almost a year after DJI. However, 3DR's drone still required some assembly, which an industry analyst described as *"anything but easy."* It also lacked major features like an integrated camera. As an executive noted, "*3DR as a kind of DIY, maker company was getting left behind… We needed to get our act together."* With Series A financing, 3DR supplemented the community by hiring experienced engineers and paying key community members with critical expertise to dedicate more time. As a result, there was a blurring between the commercial organization and the community. One 3DR manager mused, *“Are they 3DR people or are they community people? It’s kind of a grey area.”*

However, the mix of paid community members and full-time 3DR engineers did not always work well. For example, the remote community members worked at a different pace than the local engineers, and so had difficulty staying up-to-date. As a 3DR engineer noted, “*If you just bring them in once every two weeks or once a month… They don't know the product goals and they don't know what we're trying to do.”* Another described that complex manufactured products like drones were hard to design with the community members because they only worked part-time. *“It [part-time] just doesn’t work… You need to be closer to manufacturing.”* Finally, many members strongly identified with 3DR’s original DIY and open-source values, making a sharp distinction in discussions between 3DR and “3DR 2.0.” Often, this led to conflict. As a former community member and later lead 3DR engineer described, *“So, basically, the engineering leadership and the community battled constantly. The community was like ‘You guys should be making hobbyist stuff, you can get the parts and glue it together with bolts exposed and whatnot.’ And we're like, ‘We wanna be able to sell this thing at BestBuy.’”*

In 2015, 3DR finally launched an RTF drone that was regarded by many as excellent, and that included several features that DJI drones lacked. Early press celebrated the product as *“the smartest drone ever”* (Newton, 2015). However, like all first products, the drone had bugs. As an executive said, *“It’s like any first product, better than most, actually”.* Racing alongside DJI, the launch was also very late. 3DR executives gambled to catch up with DJI’s market share by producing significant inventory. A well-regarded journalist told us, “*They were rushing to market… They were trying to get everything out the door to get a sales bump.”* But, unfortunately, the 3DR team miscalculated. DJI added several new products with added features, including one that resolved another innovation bottleneck: land-drone communication.

Consequently, 3DR ended up with excessive inventory and ceded the market to DJI. As one 3DR executive lamented, *"Fundamentally, we made an error."*

How did DJI resolve the assembly bottleneck sooner and faster than 3DR? One reason is DJI's "modular yet integrative" problem-solving strategy. RTF drones are a novel, complex product. As one observer noted, "*They're so hard to build. You think you have it figured out, but there are so many moving parts and software pieces and components."* So, a modular approach like 3DR's does not work well, nor does a purely integrated approach (Baumann & Siggelkow, 2013; Ott & Tidhar, 2018). Rather, DJI's combining (a) successive modular focus on designing the most critical component with (b) integration across components is most effective for a novel, complex product like an RTF drone. In contrast, 3DR's modular approach works well for software, such as when coding a flight controller, but not for a novel product with many different types of components, like an RTF drone.

A second reason is superior experimentation. One element is speed. DJI was much faster than 3DR when experimenting serially. DJI engineers sometimes time-paced three or even four experiments per day (i.e., building prototypes with "*parts still warm to the touch*"), while 3DR's pace was much slower at one test per week (i.e., testing prototypes whenever community designs came in). Consistent with past research (Eisenhardt & Tabrizi, 1995), DJI also used other elements of effective experimentation like strong leadership and tight integration with manufacturing. For example, DJI focused narrowly on a single component (e.g., a camera) when experimenting in parallel. However, while 3DR attempted parallel experimentation as well, there was less focus. Consequently, the venture spent time optimizing components that were less critical and sometimes never used at all.

More subtly, a third reason is focus. DJI was organized as a firm, using high-powered incentives (e.g., team competition, high pay, and BMW giveaways) to align teams on a common vision. One 3DR executive described the DJI advantage, *"DJI had the upper hand with a whole bunch of engineers, that are really good engineers, and they know about drones, and they work 70 hours a week—only for one company. There is no other company like that."* By comparison, 3DR's community form granted members autonomy that made alignment difficult. Rather than aligning on the new RTF vision, the venture's collective DIY identity and open source values stuck. A 3DR executive described, *"It wasn't about growing a business or making money and talking to customers and trying to figure out what the market actually wanted, it was just people who thought it was cool to make drones do autonomous behavior for cheap."* In describing some 3DR engineers, an engineering leader said, "*All you need to do is make a product that enough people love. That is just not language the open source guys understand."*

Overall, DJI's organizational form enabled the organization to adapt its approach to experimentation and problem-solving in a way that was well-suited to the assembly bottleneck. Then, with the introduction of the RTF drone in early 2013, DJI grew by about 400% as its sales reached almost $200 million. In 2014, the venture grew to $400 million in sales after it introduced new drones and resolved another bottleneck. A well-known analyst sharply indicated the inflection point that DJI achieved with the RTF drone and its link to innovation in the industry, *"DJI re-invented the industry. The Phantom [DJI's first RTF drone] really bridged the gap between a toy and tool. They became the 800-pound gorilla."* By comparison, 3DR grew to about $30 million in sales in 2013 after the introduction of its first RTF drone. But the venture didn't fully resolve the assembly and low-quality video bottlenecks until 2015, once DJI was far ahead. As a result, 3DR's growth rate dropped in subsequent years, and by 2016, the venture exited the drone hardware industry altogether. An executive summarized to us, *"We thought we* *were competing against a traditional 20th-century Chinese company, but instead we encountered a true 21st-century Chinese thoroughbred."*

DISCUSSION

We began by asking, *how does organizational form influence the innovation process and its performance in entrepreneurial settings?* Prior work points to the value of communities and their increasing use for innovation (Baldwin & von Hippel, 2011; Felin & Zenger, 2014; Lakhani et al., 2013) but leaves open how these forms influence the innovation process and its outcomes for ventures in nascent markets. In this paper, we address this gap. Grounded in an inductive multiple case study of two pioneering rivals in the nascent civilian drone industry over nine years, we propose a theoretical framework that outlines when and why firms and communities are effective for innovation in entrepreneurial settings. Specifically, we argue that fit between ventures' organizational form, innovation process, and the nature of innovation bottlenecks is critical for performance. In doing so, we blend and contribute novel insight to the organization design and entrepreneurial strategy literatures.

Emergent Theoretical Framework

Our central contribution is an empirically grounded theoretical framework that outlines the conditions under which organizational form and innovation process fit to identify and solve different types of problems (i.e., bottlenecks) (Table 5). This framework has three main insights. First, communities excel at finding ambiguous problems, so long as they can be solved with simple or well-known solutions. Prior research assumes problems are known in advance (Afuah & Tucci, 2012; Felin & Zenger, 2014; Lifshitz-Assaf, 2017) and so provides little insight into problem finding. Yet, while relevant problems (bottlenecks) often appear well-understood in entrepreneurial settings (since they reflect common phenomena in like dominant design and product-market fit), often they are triggered by less obvious, context-specific problems like low-quality video in drones.

Communities are effective at finding ambiguous problems because they facilitate low-cost individual experimentation. In communities, members join and self-select into solving whatever problems interest them for free. Thus, even if a problem and its solution is ambiguous to leaders, given sufficiently diverse community member interests, there is a high chance that a valuable problem-solution pair will emerge. By comparison, firms are constrained by the vision of managers. Like in problem solving (Afuah & Tucci, 2012; Felin & Zenger, 2014), the knowledge required for identifying ambiguous problems is hidden, and so firms are likely to miss them altogether. Even though individual experimentation may be possible, its efficacy in firms is limited: the scale of individual experimentation is bound by the need to provide financial incentives to employees and, furthermore, managerial vision may limit its breadth.

Second, firms excel at finding uncertain problems, particularly when solutions are novel and complex. Firms are effective at finding uncertain problems because they can organize experimentation in parallel, systematically testing problems when several alternatives are known, but their value is not. Although prior literature suggests that parallel experimentation is costly (Loch et al., 2001), firms can use simple rules to reduce cost and speed the process. Firms can further save resources by narrowing focus over time as information becomes available over time, such as in multi-armed bandit problems (Katehakis & Veinott, 1987). In contrast, communities can find uncertain problems effectively when solutions are simple (i.e., by doing everything at once) (Franke & Von Hippel, 2003), but when solutions are novel and complex, problem finding through communities is slow. Managers need to wait until a critical mass of community members converge on a problem and piece together a solution. But, for reasons described below, this process unfolds slowly when solutions are novel and complex. Even then, diffusion of the innovation may not even occur. Thus, managers might miss signals in the community, such as when 3DR executives missed early signs of the video quality bottleneck.

Finally, firms excel at solving complex, novel problems. Prior literature suggests that communities can increasingly solve complex problems through modular problem solving and, more broadly, that modularizing problems is a strategic choice (Baldwin & von Hippel, 2011; Lakhani et al., 2013). Although theoretically possible, this perspective neglects the challenge of modularizing novel complex problems. Novel complex problems have multiple, unknown interdependencies. Thus, while modularity is fast and effective when they are simple or familiar (e.g., flight controller software, quadrotor), pre-specified design rules will miss key interdependencies when solutions are novel. The result is a slow trial-and-error process as unforeseen issues arise when integrating components over time.

In contrast, firms excel at solving novel, complex problems because they can organize modular yet integrative problem solving. Maintaining a holistic perspective (e.g., through serial experimentation) as well as a modular focus helps solvers identify and exploit key interdependencies quickly and accurately (Ott & Eisenhardt, 2018). Firms are better suited to modular yet integrative problem solving because they can use high-powered incentives to align members and sustain focus. While lower communication costs may also play a role (e.g., Afuah & Tucci, 2012), communication and knowledge sharing is often rich in communities as well (Felin & Zenger, 2014). Rather, we argue that sustained focus is the critical differentiator. Focus is critical because interdependencies are often tacit and thus difficult to communicate (e.g., gimbal). Yet, intrinsic rewards in communities do not afford this level of focus and commitment.

Overall, we propose that organizational form influences the repertoire of experimentation and problem-solving processes available to ventures, and innovation (problem finding and solving) performance is a function of the fit of this repertoire with the various types of bottlenecks that block innovation. Communities facilitate low-cost individual experimentation and modular problem solving, which works well when problems are ambiguous, and solutions are simple or well-known. In contrast, firms facilitate collective (parallel and serial) experimentation and (semi-)integrative problem solving, which works well when problems are uncertain, and solutions are novel and complex.

Organization Design: A Process View of Innovation in Firms and Communities

We contribute to the resurgent organizational design literature with insight based on a rare empirical comparison of a community-based organization with a traditional firm. While stylized comparisons of these two organizational forms exist in extant theory (Afuah & Tucci, 2012; Baldwin & Clark, 2006; Casadesus-Masanell & Ghemawat, 2006), to the best of our knowledge, empirical work has yet to provide a comparison—particularly in the context of entrepreneurial settings. In doing so, our study makes several contributions.

First, we add an *empirically grounded view of the innovation process*, thereby providing a better tie between organizational form and problem-finding and problem-solving processes. Prior research takes a stylized view of the innovation process as “search”—i.e., without considering problem finding or different strategies for problem solving (Afuah & Tucci, 2012; Baldwin & Clark, 2006; Felin & Zenger, 2014). It thus leaves the relationship between organizational form and the innovation processes largely unexplored. In contrast, a more realistic view reveals that firms fit a relatively *broad repertoire of processes* for problem finding and solving. To find problems, firms can coordinate parallel experiments or give employees autonomy to experimentation individually. Firms can also wait and watch for competitors to find problems (McDonald & Eisenhardt, 2018). To solve problems, firms can use a modular approach when strategically advantageous, but they can also use integrative and hybrid approaches, such as by using competing teams for components and serial experimentation for entire systems.

Communities, by comparison, fit a relatively *narrow repertoire of processes* for problem finding and solution. To find problems, communities rely exclusively on individual experimentation. Problems are discovered through insight—i.e., when problem-solution pairs emerge—rather than through structured evaluation as in firms. To solve problems, communities are restricted to a modular approach. They cannot motivate or direct effort like firms by using high-powered financial incentives, such as stock options. Overall, this narrow repertoire leads to difficulty finding and solving problems when solutions are novel and complex.

Second, we contribute a more *holistic view of innovation performance,* thus highlighting additional advantages and boundary conditions of firms and communities in dynamic environments. Prior literature evaluates the performance of organizational forms based on efficiency (Afuah & Tucci, 2012; Baldwin & von Hippel, 2011; Hienerth et al., 2014), thereby neglecting two important considerations: innovation speed and strategic change. In contrast, we show that firms have an advantage for *speed* in both problem finding and solving, so long as problems are not ambiguous. Firms can use shortcuts like simple rules to resolve uncertainty in problem finding before shifting to problem solving. Communities, by comparison, step through the problem-solving process first before the value of the problem itself becomes clear. Firms can also use time-pacing and competition to motivate employees to hit deadlines solving problems. But with communities, pace depends on whenever "the designs come in." Finally, with more complex problems, communities are slowed by the need for a critical mass of members to join and piece together a solution over time.

We also show the boundary conditions of communities (and likewise, the advantage of firms) for *strategic change*. Prior research promotes communities as a source of innovation to catalyze strategic change (Gambardella, Raasch, & von Hippel, 2016; Lakhani et al., 2013). However, while potentially valuable in stable markets, communities may become a liability in entrepreneurial settings. Self-selection into communities reinforces their founding identity, which becomes rigid over time and thus prevents change. In contrast, firms can use incentives to shift the focus of innovation and martial new, diverse resources as necessary. This was most obvious when DJI made an easy transition from helicopter specialists to flying camera makers. In contrast, 3DR struggled to transition from hobbyists to the mass market given its founding focus on DIY and open-source enthusiasts.

Entrepreneurial Strategy: Identifying and Resolving Innovation Bottlenecks

We also contribute to the literature on entrepreneurial strategy with greater insight into innovation bottlenecks (Adner & Kapoor, 2016; Baldwin, 2015; Hannah & Eisenhardt, 2018) and strategies for managing them (Jacobides, Knudsen, & Augier, 2006; Jacobides & Tae, 2015). First, we *tie bottlenecks to classic problems in entrepreneurship*, including dominant design (Suarez & Utterback, 1995), product-market fit (Shane, 2001), and ease of use (Rogers, 2010). Like technology bottlenecks (e.g., Adner & Kapoor 2016), these problems constrain the diffusion of innovations in entrepreneurial settings and thus must be addressed for ventures to grow.

Second, we contribute a *more precise and detailed conceptualization of bottlenecks*. While prior literature that views bottlenecks solely as artifacts of technological systems (Adner & Kapoor, 2010; Rosenberg, 1972), we take multi-level view of bottlenecks to show their hierarchical character. Specifically, we propose that, even if bottlenecks are obvious at higher levels of a hierarchical system, such as in a value chain or ecosystem (e.g., Hannah &

Eisenhardt, 2018), additional, less-obvious bottlenecks exist within these components. For example, while it was obvious to all that the lack of a killer app was a bottleneck to growth in the drone industry, only DJI successfully identified the more accurate bottleneck of shaky video and its solution, the gimbal. Yet, by identifying the bottleneck more accurately, DJI could focus its resources on a single component, avoiding expensive and unnecessary system redesign.

Third, we show the *strategic value of resolving bottlenecks quickly and completely*. Prior literature suggests that ventures may benefit from maintaining, or even creating industry bottlenecks to capture value from rivals (Baldwin, 2015; Jacobides et al., 2006; Jacobides & Tae, 2015). However, we propose that, at least in nascent industries, resolving bottlenecks *quickly* (i.e., sooner than rivals) is helpful because it leads to a compounding resource advantage, increasing the odds of identifying and resolving subsequent bottlenecks sooner than rivals. For instance, DJI's advantages began to compound over time after it resolved the killer app and assembly bottlenecks. As DJI grew, its engineers greatly outnumbered the active members of the 3DR community, and the company went on to identify and resolve a fourth bottleneck (land-drone communication). As one observer summarized,

> "*You might have gotten better performance out of the community than DJI. In terms of accuracy, speed, position, whatever. The range of social development that was available made it very competitive. However, with DJI gaining more and more market share, they quickly had more developers on their products. So that technology advantage completely flipped with the first Phantom [DJI's first RTF drone]... Ever since then, DJI had the technological lead.*"

Likewise, resolving bottlenecks *completely* (i.e., such that the bottleneck no longer constrains the system) is advantageous because improvements in the bottleneck domain by competitors are less likely to erode the focal organization's market share. For example, after DJI resolved the killer app and assembly bottlenecks and moved on to others, 3DR put significant time and effort into developing an RTF drone and gimbal to match and even exceed DJI's solutions. However, these solutions had become table stakes for competing in the industry and so beating DJI resulted in only incremental growth for 3DR. As one industry analyst explained, *“3DR’s ready-to-fly drone wasn’t much better than DJI’s, so people just continued buying [DJI’s RTF drone].”*

CONCLUSION

Our aim was to shed light on how organizational form influences the innovation process and performance in entrepreneurial settings. Based on a rare empirical comparison of a firm- and community-based venture competing in the nascent global civilian drone industry, we presented a theoretical framework that outlines when and why firms and communities are effective. Specifically, we argue that fit between ventures’ organizational form, innovation process, and the nature of innovation bottlenecks is critical for performance. In doing so, we contributed an empirically grounded and specific view of the innovation process in firms and communities that that blends novel insights in organization design and entrepreneurial strategy.

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TABLES AND FIGURES

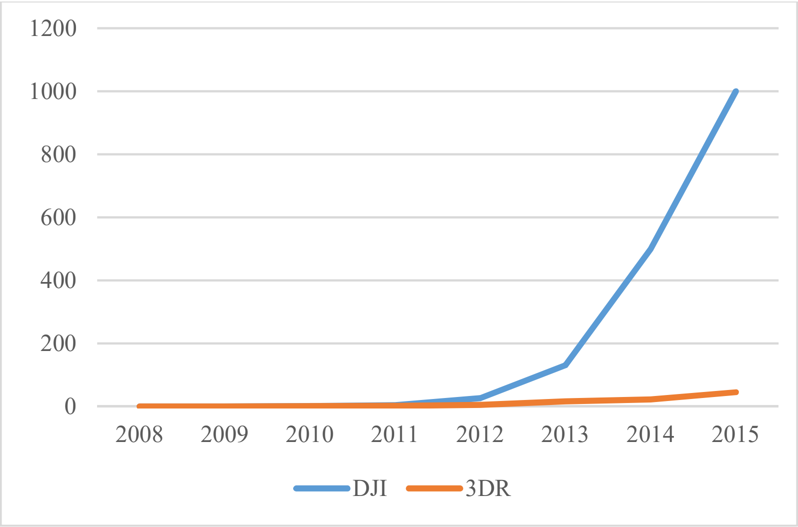

Figure 1: Annual Revenue by Firm (millions USD)

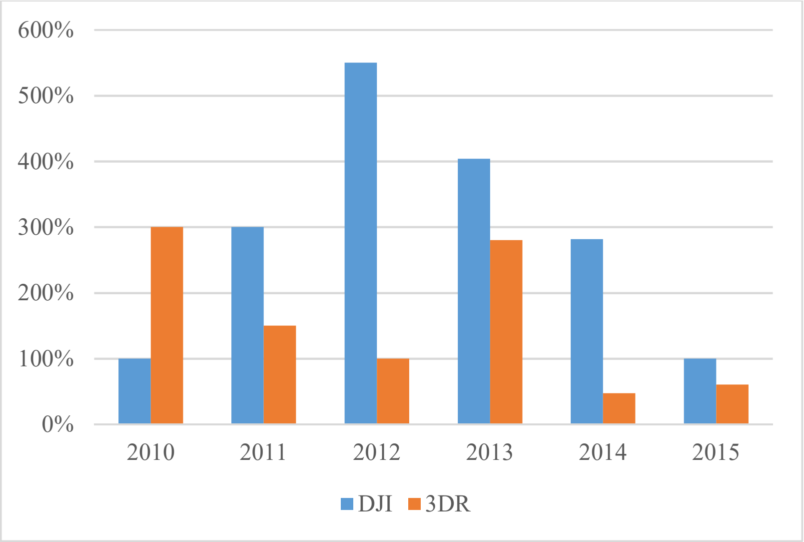

Figure 2: Annual Revenue Growth by Firm

Table 1: Characteristics of Communities and Firms

	Community	Firm
Membership boundaries	Open	Closed
Property rights	Public	Proprietary
Task assignment	Self-selection by members	Selection by authority
Reward distribution	Non-pecuniary	Pecuniary

Table 2: Sample and Data Summary

	Founding Team Characteristics	Initial Conditions	Data
DJI	**Frank Wang** *Age:* 26 *Education:* BS, electrical engineering *Industry Experience:* None *Entrepreneurial experience:* None	**Location:** Shenzhen, CN **Organizational form:** Firm **Product:** Flight controller for RC helicopters **Market:** North American hobbyists **Commercialization date:** 2008 **Venture financing:** $100,000 from family and friends; $800,000 venture round led by Maison Capital in 2012	17 internal interviews 16 external interviews 2 public talks 1950 articles (219 internal press releases) Observation 153 employee reviews (glassdoor.com, kanzhun.com)
3DR	**Chris Anderson** *Age:* 46 *Education:* BS, computational physics *Industry Experience:* Journalism *Entrepreneurial experience:* None **Jordi Muñoz** *Age:* 20 *Education:* High school *Industry Experience:* None *Entrepreneurial experience:* None	**Location:** Berkeley & San Diego, CA **Organizational form:** Community **Product:** Flight controller for RC airplanes **Market:** North American hobbyists **Commercialization date:** 2008 **Venture financing:** Undisclosed amount of personal funds; $5 million series A round led by True Ventures in 2012	34 internal interviews 12 external interviews 15 public talks 392 articles (58 internal press releases) 28 employee reviews (glassdoor.com) 1 book, 1 business case

Table 3: Bottleneck Summary

Bottleneck (Solution)	**Description**	**Representative quote**	**Characteristics**	**Resolution: DJI**	**Resolution: 3DR**
Product architecture (Quadrotor)	Airplanes were impractical, helicopters were too expensive and dangerous	*"For consumers, moving to the quadrotor was unbelievably, extremely important decision. Safety and all this other stuff being very important." (Industry analyst)*	***Ambiguity:*** High ***Uncertainty:*** Low ***Complexity:*** Low ***Novelty:*** Low	***Identified:*** early 2011 ***Resolved:*** mid 2011 ***Growth:*** 300% (1 to 4 million USD)	***Identified:*** early 2010 ***Resolved:*** early 2010 ***Growth:*** 300% (0.25 to 1 million USD)
Video quality (Gimbal)	Videos shot with drones were unusable because of vibration	*"While everybody has focused on [DJI] being an innovative drone company, the gimbal is where we really need to focus and understand that's where the key innovation is." (Journalist)*	***Ambiguity:*** Low ***Uncertainty:*** High ***Complexity:*** Moderate ***Novelty:*** High	***Identified:*** mid 2011 ***Resolved:*** mid 2012 ***Growth:*** 550% (4 to 26 million USD)	***Identified:*** early 2014 ***Resolved:*** late 2015 ***Growth:*** 60% (28 to 45 million USD)
Assembly (Ready-to-fly)	Drones were too difficult for users to assemble	*"80% of our leads would drop off because of the risk trying to learn how to put the drone together and potentially having that not work out… But they all wanted it." (DJI executive)*	***Ambiguity:*** Low ***Uncertainty:*** Low ***Complexity:*** High ***Novelty:*** High	***Identified:*** mid 2012 ***Resolved:*** early 2013 ***Growth:*** 400% (26 to 131 million USD)	***Identified:*** early 2012 ***Resolved:*** late 2013 ***Growth:*** 280% (5 to 19 million USD)

Table 4: Venture Growth

	Revenue (millions USD)		**# of employees/members**			**Disclosed financing** (millions USD)	
Year	**DJI**	**3DR**	**DJI**	**3DR**	**3DR community**	**DJI**	**3DR**
2008	<0.5	<0.25	<10	<6	1,000	0.1	0
2009	0.5	0.25	25	6	5,000	0.1	0
2010	1	1	50	10	12,000	0.4	0
2011	4	2.5	75	30	20,000	0.4	0
2012	26	5	150	50	27,000	1.2	5
2013	131	19	600	125	46,000	1.2	35
2014	500	28	2,800	250	62,000	31	35
2015	1,000	45	4,000	350	73,000	606	99

Table 5: Fit in Organizational Form, Process, and Bottleneck

		Community	**Firm**
Process	***Experimentation***	Individual	Parallel or sequential
	Problem solving	Modular	Integrated or hybrid
Bottleneck	***Problem type***	Ambiguous	Obvious or uncertain
	Solution type	Known or simple	Novel and complex
	Example(s)	Quadrotor	Gimbal, RTF drone

APPENDIX A: HISTORY OF THE GLOBAL CIVILIAN DRONE INDUSTRY

2007 – 2009

Drones (more formally known as unmanned aerial systems, or UASs) originated as a tool for military operations, the history of which can be traced back to as early as 1849. However, the *civilian* drone industry emerged around 2007. The technology itself developed from the confluence of radio-controlled (RC) aircraft technology and more recent advances in consumer electronics. Smartphones and other mass-manufactured consumer products, like Nintendo's Wii controller, significantly lowered the cost of micro-electromechanical systems (MEMS) sensors necessary to create early drone flight controllers. As one industry expert explained, *"The innovation part was the sensors—making them small enough and cheap enough. Before that, you had to have these $10,000 gyros, and they were huge, maybe the size of a sugar cube. They were all military spec, but they became smartphone spec."* Smartphones also contained light and powerful computer processors, cameras, and lithium polymer batteries—each of which was critical to driving down the cost of drone flight controllers and thus kick-starting the industry (see Appendix B for a more detailed description of drone technology and the various subsystems, including the flight controller).

The few drone industry players that got their start in these early years were manufacturers scattered around the world, including DJI in China, 3DR in the US, and a handful of others (approximately five) across North America, Europe, and Asia. See Figure A1 for the total number of civilian drone manufacturers by year. Nonetheless, most players, including DJI and 3DR, focused their efforts on selling to US consumers from the beginning. Others focused on the public sector, selling tools to law enforcement or research institutions. However, in contrast to DJI and 3DR's products, these drones typically sold for tens of thousands of dollars.

In particular, the DJI founding team believed that US hobbyists would be more receptive to drone technology, and thus demand in the country would be stronger than other parts of the world. In turn, they thought widespread adoption in the US would provide the company visibility in other countries. As one DJI executive noted, *"I believed that DJI should start selling its products in the US first because that's where people are tech-centric. People are too slow to adapt in China."* Further, although commercial drone use in the US required that pilots apply for an exemption with the FAA until 2016, smaller drones (those less than 55lbs) used for recreation were free from FAA regulation.

Drone technology promised exciting recreational and even practical applications outside of the public sector (photography-related in particular), but the architecture initially constrained it. Initially, DJI and 3DR manufactured and sold flight controllers for traditional RC helicopters or airplanes (fixed wing) vehicles. Similarly, other low-cost manufacturers, such as Zerotech in China, designed and sold entire systems based on one of these architectures. However, the fixed wing and helicopter architectures have several flaws. Airplanes are impractical. They need to maintain a certain speed and so can't hover, they require space to take off and land, and are difficult to maneuver in tight spaces, even with the aid of a flight controller. Helicopters are unappealing for different reasons. They are complex and were thus relatively expensive. As one early adopter recalled, *"It took 10 hours of tinkering for 10 seconds of flight time, and they [helicopters] were easily three times the price of airplanes."* Because of the size and weight of the blade, helicopters were also dangerous.

Given these deficiencies, adoption of drone technology was limited to skilled hobbyists who were either willing to spend the additional money for a helicopter, or who merely enjoyed tinkering with new technology as an end in itself. As a result, the civilian drone industry remained small and relatively unknown, with most analysts estimating that industry sales totaled a few million USD in 2009. Figure A2 provides a summary of total industry sales (in addition to disclosed VC financing) by year.

2010 – 2011

In 2010, 3DR and (later) Parrot, a large European consumer electronics company, released the first low-cost quadcopter drones and kick-start growth in the drone industry.[1] Quadcopters, and the multirotor design more broadly, had existed for decades. But until the advent of drone flight controllers, the multirotor design was infrequently used because of how difficult it was to control manually. As one industry analyst explained, *"Without the correct gyroscopes, without the prices of these components coming down, you could not build a quadrotor."* Otherwise, the quadcopter design offers many advantages over the fixed wing and helicopter designs: they are less complicated than helicopters and far safer. Moreover, unlike fixed-wing designs, they can hover and navigate tight spaces. So when quadcopters were introduced into the consumer market, the industry—including the firms that sold them—began to grow. Following the success of the quadrotor, other manufacturers like DJI followed suit and adopted multirotor designs. In less than two years, the multirotor became the dominant design in the drone industry, which grew from a few million US dollars to an estimated 50 million by the end of 2011.

By the end of 2011, many manufacturers chose to focus on creating and selling toy drones (e.g., Parrot's flagship quadrotor was developed to be a virtual reality game). But others like 3DR and DJI began to search for a compelling application for drone technology for the general public so that the industry would continue to grow. Drone photography appeared promising, but to what end and to whom remained unclear. Industry evangelists and thought leaders envisioned a number of applications, including agriculture, utility inspection, real estate, and disaster recovery, among others. Venture capital began to take interest (see Figure A1). A small number of drone "service providers" also began to appear—individuals who purchased flight controllers and integrated them into custom RC vehicles, usually to take aerial photos for whoever would pay, such as real estate companies.[2] Instead, further growth was limited because the quality of drone photos and videos remained poor. As an industry analyst described, the footage was *"Shaky, jittery, and overall unusable."* So, the drone photography market remained small, and drone makers continued to search for a "killer app."

2012

DJI's management team was the first to recognize that stable video was a bottleneck to using drones for aerial photography. In mid-2012, after a year of development, the company released its first gimbal. Intended for "Hollywood," as an executive described, the gimbal sold for $3,500 and required a large and powerful (and thus equally expensive) drone to operate. But because filmmakers in the US would spend as much as $20,000 per hour (plus additional fuel and photographer fees) to hire full-sized helicopters to film high-quality aerial footage, the cost was negligible. After identifying a potential killer app and launching the gimbal, DJI spurred additional growth in the drone industry. By the end of 2012, industry sales doubled to approximately 100 million dollars. DJI led the new market for photography drones, Parrot led the "toy" market, and

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[1] At least two drone manufacturers, Aeryon Labs and Draganfly Innovations, designed and sold quadcopters to the public sector beginning in prior years. However, their products were hand assembled, sold for tens of thousands of dollars each, and remained relatively obscure.

[2] Although these commercial operators often violated FAA regulations in the US, regulation was rarely enforced (Ungerleider, 2012).

3DR led the relatively smaller hobbyist segment. Others in the industry followed but were relatively far behind.

Additional industry growth was limited because low cost, high-performance drones were only available as kits. Although toy drones were ready to fly, drones with higher levels of autonomy, more carrying capacity, and further range required assembly.[3] For all but passionate hobbyists and similarly enthusiastic drone service providers, assembling these kits was too time-consuming and difficult. One expert explained that building a drone using either a DJI or 3DR flight controller required *"*tribal knowledge*"* learned only by frequenting online communities. This learning curve prevented many from purchasing.

2013 – 2016

In 2013, both DJI and 3DR released ready-to-fly (RTF) drones for the consumer market for less than $1000 each. DJI's RTF drone, the Phantom, was released in January and exploded in popularity. 3DR's RTF drone, the Iris, started shipping later that year. However, because it was late and offered relatively little advantage over DJI's drone, it was less successful (although 3DR continued to grow modestly). Others in the industry fell far behind; for example, Parrot's drone sales fell by 14% in 2013. In total, analysts estimated that DJI held approximately 60% of the consumer market, which doubled to an estimated 200 million US dollars.

Midway through the year, DJI recognized and began resolving another bottleneck: land-drone communication. Drone manufacturers had begun to incorporate third-party first-person-view (FPV) systems into their drones so that users could view the images captured from the drone camera in real-time. This technology pre-dated drones and thus had yet to constrain industry growth. However, as drone performance improved along dimensions such as flight time (from less than 10 minutes to as long as 25 minutes), the range and quality of existing low-cost transmission technologies emerged as a constraint. To that end, the following year, DJI introduced Lightbridge, a high-definition video downlink with a range of several miles—much further than competing solutions.

DJI’s Lightbridge became an industry referent for high-quality data transmission technology. With Lightbridge, users could fly their drones to capture images and videos that were previously impossible. As one DJI executive explained, *“If you can envision a shot or if you want to experience flying like a bird, you can do it… You get to fly around and have an out-of-body experience which releases a ton adrenaline and gets people into a flow state.”* Similarly, an industry analyst noted, *“Most of these people aren’t flying these drones just for the sake of flying them. They want to see the perspectives.”* After relieving the bottleneck, DJI earned 500 million in revenue in 2014 (300% growth), driving industry sales to over 750 million.

Meanwhile, other manufacturers struggled to match DJI's technology developed the prior year. Chinese-based manufacturers, such as Yuneec, began to copy DJI's products relentlessly but failed to match the design quality—particularly the gimbal. 3DR began developing its "Phantom-killer," the Solo, in 2014 and similarly struggled to develop a gimbal of similar quality to that of DJI's, let alone a video downlink. Consequently, DJI successfully maintained its near-monopoly on the drone industry in the following years, with market share estimates as high as 80%.

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[3] For example, Parrot's drones were ready to fly, but users criticized the products because of their insufficient range. Rather than use a standard RC controller, users controlled Parrot drones using a smartphone, which was a significant bottleneck. Smartphone transmission technology led to many issues, such as users suddenly losing control due to poor connectivity.

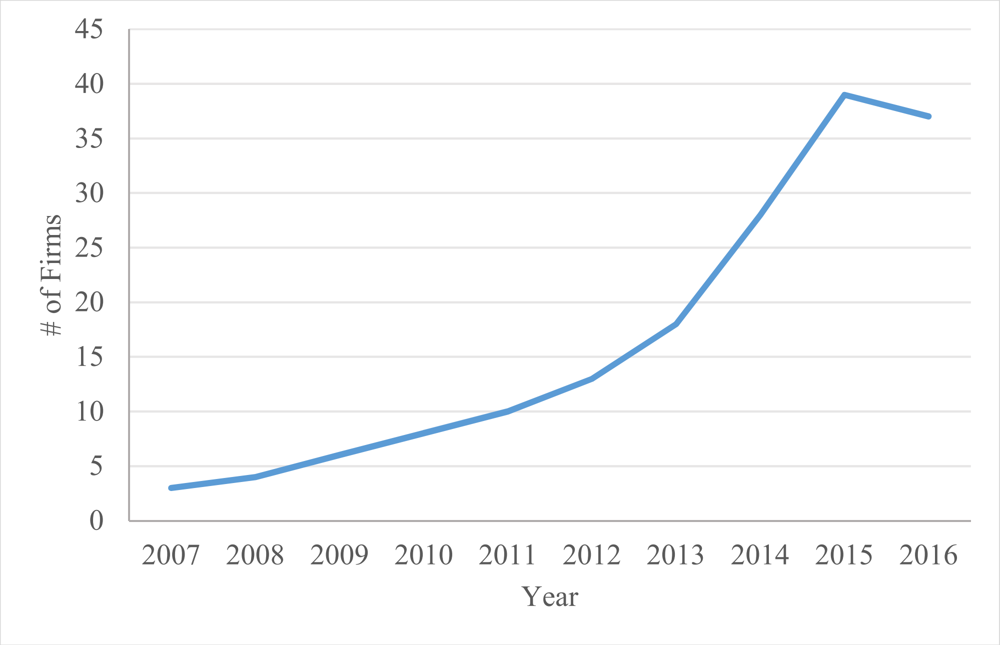

Figure A1: Number of Civilian Drone Manufacturers by Year

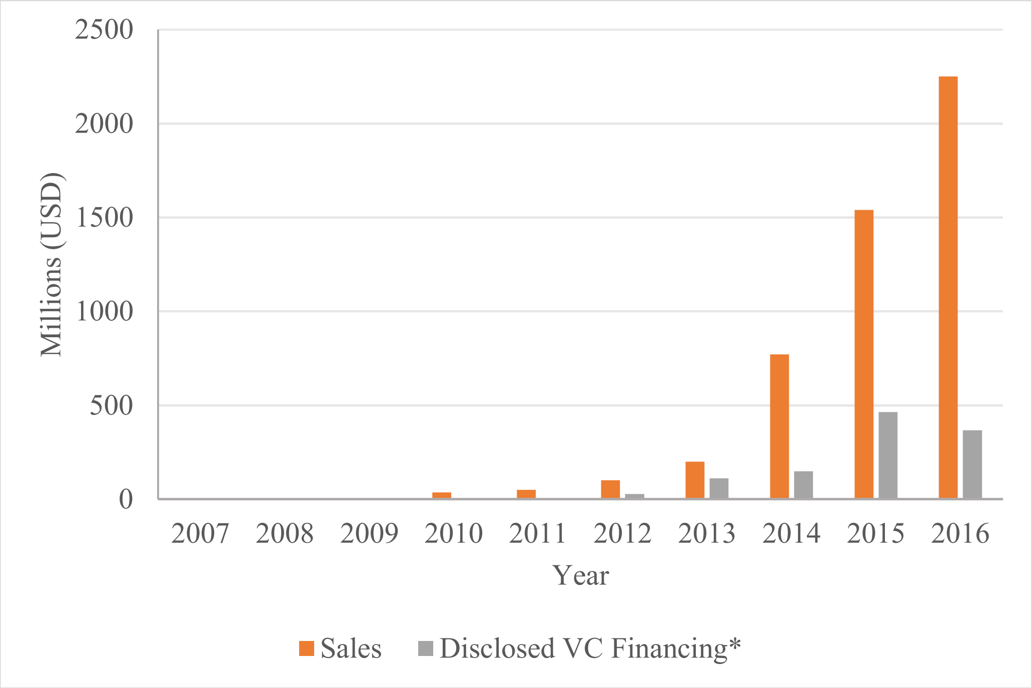

Figure A2: Industry Size by Year

**Includes financing for drone software ventures*

APPENDIX B: CIVILIAN DRONE TECHNOLOGY

Civilian drones are comprised of multiple, highly interdependent hardware and software subsystems (see Figure B1 for one example). The drone architecture and various subsystems have evolved since the emergence of civilian drone technology in 2007. However, in 2016, the typical drone included some configuration of the following: airframe, powertrain, autopilot (which includes a flight controller), communication system, and payload. We describe each of these subsystems below.

Airframe

The airframe is the mechanical structure of the drone. Drone airframes differ in their architecture. Common alternatives include fixed-wing aircraft (airplanes), helicopters, and various multirotor configurations. Unlike helicopters and airplanes, multirotors use the same set of rotors to control all types of movement, whether for hovering, directional flight (by applying greater power to the rear rotors to lean the craft forward and begin movement), or rotation. Multirotors can be configured using four rotors in an “X” shape (a quadrotor, which is most common), but additional rotor configurations are also possible. For example, airframes might have 6 or 8 rotors configured in various ways.

Powertrain

The powertrain enables lift, directional flight, and rotation. The components of this subsystem depend on the type of airframe (e.g., fixed-wing versus multi-rotor), but generally include the following: (1) a power source, which is typically Lithium-Ion Polymer batteries, (2) one or more motors, which are typically brushless electric motors, (3) electronic speed controllers (ESCs), which convert the current required to operate the flight control systems to power for the motors, and (4) propellers, which vary in size and pitch.

Autopilot

The autopilot is the “brain” of the drone. Basic autopilots include a flight controller board and control software (together, a flight controller). The flight controller board is a small computer system that includes a processor and sensor chips integrated onto a printed circuit board (PCB). Flight controller boards typically have interfaces that allow users to attach additional, external sensors. Basic sensors (those that are essential to achieving any degree of autonomy) include accelerometers, which provide data on changes in velocity and position, and gyroscopes, which provide data on orientation or rotational velocity. Additional, now commonplace sensors include barometric pressure sensors (provides altitude data), magnetometers (provides orientation data), GPS (used for position hold) and airspeed sensors (to maintain flight in airplanes only). The flight control software converts the various input data from sensors and the user to control the aircraft. The architecture of autopilot software varies, but typically includes vehicle-specific flight code, shared sensor libraries, firmware to interface with the control board, and a communications layer to interface with the user.

More advanced autopilots integrate additional hardware and software to achieve more robust forms of autonomy, with features like object tracking, obstacle avoidance or indoor position hold. Sensors that enable these features include optical flow smart cameras (used for motion tracking or position hold without GPS) and rangefinders such as LIDAR or SONAR (used to measure distance). Unlike more basic sensors, these sensors are typically integrated into the airframe (e.g., downward- versus forward-facing smart cameras) rather than the flight controller. They also require additional computing power and thus sometimes operate through a second onboard computer that communicates directly with the flight controller.

Communication System

The communication system is comprised of a user interface and data transmission technology so that individuals can interact with the drone. Alternative communication systems include radio control (RC) systems, ground control stations, and first-person view (FPV) systems, although these technologies are often used in conjunction with one another. *RC systems* include handheld devices that allow users to control the drone directly via joysticks and radio transmission technology. *Ground control stations* are software programs used to control drones from other consumer electronics devices, such as tablets or smartphones. The features included vary, but typically allow users to specify coordinates for the drone to follow via a map-like interface. Finally, *FPV systems* allow users to view a live video feed transmitted directly from an onboard camera to either the ground control station or separate FPV viewing device, such as goggles. Unlike RC systems, ground control stations and FPV systems rely on alternative transmission technologies, such as Wi-Fi or 3G.

Payload

Payloads are application-focused auxiliary systems. Often, they are tightly integrated into other drone subsystems. Aerial photography systems are now most common, but alternative systems include those used for package delivery, pesticide application for agriculture, or thermal sensors, among others. Drone aerial photography systems include a camera and (usually) a gimbal. Cameras are typically lightweight, like those used in smartphones, and integrated into the drone directly, although some adopt a more modular architecture so that users can choose their own (however, even with a modular architecture, the weight and size of the camera limit modularity). Gimbals provide image stabilization so that users can capture smooth video footage and higher quality photos from their drone during flight. Often tightly integrated with the autopilot system to avoid redundancy and reduce power consumption, gimbals use MEM sensors like those in flight controllers to detect small movements and several small electric motors to adjust the position of the camera in real time.

Figure B1: Example Civilian Drone (3D Robotics)