Ingenuity of NASA: Designing the paradigm-changing Martian helicopter

Raja Roy
Assistant Professor
New Jersey Institute of Technology
rroy@njit.edu

Curba Lampert
Associate Professor
Florida International University

Minyoung Kim
Associate Professor
University of Kansas

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Abstract

We explore the process through which an organization introduces a paradigm-changing innovation. We use NASA's design of the Ingenuity helicopter—that flew on Mars for the first time on April 19, 2021, thereby creating history as the first controlled flight in the atmosphere of a celestial body in the solar system other than Earth—as our context. Our findings extend prior research on technological paradigm and paradigm-changing innovations. We uncover that the process, which starts with a trigger event, includes the organization's identification of the uncertainty that are likely to affect the innovation, identification of the components that can mitigate those uncertainties, and mitigating component interdependencies to create the paradigm-changing innovation.

Keywords: Paradigm-changing innovation; Technological paradigm; Technological change.

Introduction

In his seminal study, Dosi (1982; p. 148) epistemologically defined "technological paradigm…as a set of procedures, a definition of the relevant problems and of the specific knowledge related to their solution." Dosi and Nelson (2013; p. 5) noted that the technological paradigm includes a specific body of knowledge at the "input side," a design of a product for the "desired output," and "a specific body of understanding…… shared among professionals in a field."

More recent research extends Dosi's (1982) insights and distinguishes paradigm-changing innovations from paradigm-deepening ones (Ahuja, Lampert, and Tandon, 2014). The paradigm-changing innovations—which Fujimoto (2000; p. 268) refers to as the paradigm-shifting ones—are those that involve changes in the 'input' knowledge, changes in the design of the product, as well as changes in the body of understanding shared between the engineers and scientists in the field. Paradigm-deepening innovations, on the other hand, are those that strengthen the existing paradigm.

Despite prior research highlighting that diversified firms have an advantage when it comes to introducing paradigm-changing innovations, researchers are yet to explore an answer to the research question, "*how do organizations design paradigm-changing innovations?*" Examples of such problem solving include Ben Franklin solving problems to generate electricity (Kuhn, 1962), Nikola Tesla solving problems to develop the alternating current motor, Wright brothers making powered flight possible, Soviet Union developing the Sputnik satellite, and NASA solving problems to developing the Apollo module for lunar landing.

Continuing with the tradition of Dosi and Nelson (2013; p. 5, *italics in original*), we focus on the "*microtechnological sense*: e.g. the semiconductor paradigm, the internal combustion engine paradigm, etc. this is distinct from the more 'macro' notion of 'techno-economic paradigm' used by Perez (1983; 1985) and Freeman and Perez (1988)." As compared to this traditional focus in the technological paradigm literature, the broader notion of techno-economic paradigm "is a constellation of paradigms [as compared to] our *narrow* sense: e.g. the electricity techno-economic paradigm, ICTs, etc." Further, as Dosi and Nelson (2010) observed, the broader techno-economic paradigm overlaps with the idea of general purpose technologies (Bresnahan and Trajtenberg, 1995). By contrast, as noted by Dosi and Nelson (2013), the relatively narrow microtechnological focus on technological paradigm literature overlaps with that of 'regimes' in Nelson and Winter (1977).

We concentrate on NASA designing the first helicopter, Ingenuity, that flew in atmosphere of a planet other than the Earth, therefore becoming the first 'aircraft' to fly on a celestial body other than the Earth. Ingenuity flew in the Martian atmosphere on April 19, 2021, thereby creating a historic precedence. We relied on publicly available research papers published by the engineers who designed Ingenuity as well as their interviews to generate our data.

Our research indicates that the process of designing paradigm-changing innovation not only involves reliance on prior related knowledge as Ahuja et al. (2014) reports, but also the identification of uncertainties, identification of components to mitigate those uncertainties, and mitigation of interdependencies (Baldwin and Clark, 2000) between those components. Our finding not only builds on prior seminal contributions to the technology literature (Dosi and Nelson, 2010; 2013) but also extends the insights from that literature to uncover a process that underlies paradigm-changing innovations by government agencies such as NASA and innovative firms such as Tesla.

Literature Review

Scientific and technological paradigms

Kuhn (1962; p. 10) noted that scientific research is preceded by "one or more past scientific achievements" which act as the foundation for future advancements. Such achievements, which include "Aristotle's Physica, Ptolemy's Almagest, Newton's Principia and Opticks, Franklin's Electricity, Lavoisier's Chemistry, and Lyell's Geology" define the 'scientific paradigm'—the "problems and methods for the successive generations of researchers [that] shared two essential characteristics." These characteristics include "unprecedented" new insights and problems for "future practitioners to resolve," which "together provide models from which spring particular coherent traditions of scientific research."

Extending Kuhn's (1962) exposition, Dosi and Nelson (2018; pp. 57-58) noted that three characteristics define the "state of technology at any time." These characteristics include the body of scientific understanding "illuminating the key factors" that explain how the technology works, the "way they [technological artifacts] are used,", and an understanding of the ways to improve the technology.

Building on Dosi (1982), Cimoli and Dosi (1994; p. 244) refined the characteristics that define a technological paradigm. They noted that whereas the first characteristic defines "what is technology," the second one explains "how to do things and how to improve them." The third characteristic includes "basic models of artifacts and systems" that are innovated upon over time. Cimoli and Dosi (2015; p.245) further noted that the three characteristics of the technological paradigm describes the "inputs," "production costs," as well as the "features" of the output, "such as wing-load, take-off weight, [and] speed" of an aircraft.

Dosi and Nelson (2018; p. 57) noted that engineers and scientists within a "field of technology" share these three characteristics. They highlighted that a technological paradigm is the "the sweep and structure of what is largely shared." They further highlighted that the shared knowledge explains "why at any time there often is strong similarity among the range of artifacts produced by different firms, and why often the production processes used in the industry are very similar," indicating that the technological paradigm leads to the dominant design (Abernathy and Utterback, 1978; Henderson and Clark, 1990) in an industry.

Paradigm-changing innovations

Researchers highlight that paradigm-changing innovations create new knowledge of inputs, outputs, and a body of understanding that, at the onset of the new paradigm, is rather narrowly shared but over time is broadly shared by scientists and engineers. For examples, Newton's laws of motion, which forms the basis of classical physics, was not available to anyone other than Newton and his close colleagues when he wrote the Principles of Mathematics. Over time, that knowledge was shared by the scholars of physics and today, it is the basis of standard physics textbooks (Kuhn, 1962). Building on the insights of Kuhn (1962) and Dosi (1982), Coccia and Wang (2015) explored the advent of new technological paradigms in anticancer treatment and Fujimoto (2000) observed Toyota's innovations in the production process used in automobile manufacturing.

Ahuja, Lampert, and Tandon (2014; p. 657) explored the challenges faced by organizations introducing paradigm-changing innovations. They uncovered that a paradigm-changing innovation is "characterized by high risk and long gestation periods" as well as "greater employment of central resources, such as basic R&D." Additionally, they observed that because of the uncertainties associated with all the three characteristics of a technological paradigm, such innovations require a "subjective" decision making, thereby making them qualitatively different from innovations that strengthen an existing paradigm.

Components and their interdependencies

Building on Simon's (1962) seminal thesis, Ethiraj and Levinthal (2004) underscored that organizations mitigate unknown interdependencies between different components as they design innovative new products. Consistently, Thomke *et al.* (1998; p. 316) observed that organizations perform a variety of tests--such as the "wind tunnel" tests by aircraft manufacturers—to mitigate the interdependencies between various components to design new products such as new aircrafts. Similar observations were reported by Thomke and Bell (2001) in the integrated circuit industry and

Kotha (2010) in his of Boeing's efforts to mitigate the interdependencies between the components in designing the Boeing 707 aircraft.

Despite the literature investigating paradigm-changing innovations on the one hand and the role of mitigating interdependencies on the other hand, researchers are yet to uncover the process that helps organizations design mitigate interdependencies between components as they strive to design paradigm-changing innovations.

Context and Method

Context

The Mars Helicopter, Ingenuity, is the first powered and controlled aircraft that flew in the atmosphere of a celestial body other than Earth. It was attached to the Perseverance rover and detached from it at an 'airfield' on Mars. It was originally designed to perform five test flights over a 30-Martian-day period (i.e., 30 sols). The historical first flight occurred on April 19, 2021, when Ingenuity took off and climbed about 10 feet (approx. 3 meters), hovered in the air, made a turn, and landed. It was a paradigm-changing innovation-- the very first powered, controlled flight in an atmosphere that is about 1% of the density of Earth, on a planet whose gravity is about 38% of that of Earth, and where the temperature drops to -90^{0}C at night. The scientific knowledge needed to design such a product, the knowledge of the production process to manufacture the product, and the performance metrics of the output—the three characteristics that form the bedrock of a technological paradigm—was non-existent and was not shared by engineers and scientists of any organization. Accordingly, a deep dive into NASA's efforts to design the Ingenuity helicopter—the context of our research— is an ideal one to explore the processes that enables organizations to introduce paradigm-changing innovations.

Method

In our pursuit to uncover NASA's efforts to design a paradigm-changing product, we took a systematic deep dive into Ingenuity's history. We followed the footsteps of Burawoy (1991), Danneels (2011), and Vinokurova (2019) to take a deep dive into a historical case study. Similar to Carton's (2018) thesis, we relied on archival data publicly available at NASA's website for our study. We used keywords 'helicopter,' 'Mars spacecraft',' and 'Ingenuity' to search for the relevant articles. We analyzed a total of 1000+ documents, totaling approximately 5000 pages available at NASA's Technical Reports Server website. This helped us create an event timeline following Van de Ven (2007) that allowed us to familiarize with the data as well as generate preliminary insights into how NASA solved problems to design the paradigm-changing innovation. The timeline is shown in Table 1.

Insert Table 1 about here

Papers published by Havard Grip (Developer, Ingenuity Flight Control System; Chief Pilot, Ingenuity; see e.g., Grip et al., 2018) acted as our primary source of information. The references listed in the publications helped us collect additional papers and data. We supplemented the archival data with videos of interviews with, and presentations by, prominent engineers, such as Bob Balaram (Ingenuity Chief Engineer), Mimi Aung (Ingenuity Project Manager), Teddy Tzanetos (Ingenuity Principle Investigator and Task Manager), Charles Elachi (ex-Director of NASA Jet Propulsion Laboratory, JPL), Larry Young (Advanced Concepts Designs for Aerial Vehicles at NASA Ames Research Center), Brian Allan (Flow Physics and Control Branch, NASA Langley Research Center), Tim Canham (Mars Helicopter Operations Lead, NASA JPL), and others. In these interviews and presentations, we followed Danneels (2011; p. 4) and, focused "on the circumstances and reasons of the events" and confirmed "the accuracy of the facts and the credibility" of our interpretations. However, because some of the interviews and presentations were "retrospective, and therefore open to potential critique regarding memory loss and retrospective rationalization" (p.4), we triangulated the information as suggested by Cardinal *et al.* (2004). For example <<>>

Additionally, similar to Burawoy (1991) and Danneels (2011), our extended case method not involved both empirical data collection and "many cycles of confrontation between data and theory in each iteration" (Danneels 2011; p.4), which was critical in collecting additional data and drawing upon additional theoretical concepts. This "emerging case history" process (Ozcan, Han, and Graebner, 2017; p.101) included two "running" exchanges (Burawoy 1991, pp. 10–11)—the former between extant literature and data analysis and the latter between data analysis and data collection (see also Danneels, 2011; p.4). The first of the exchanges involved data analysis to uncover relevant theoretical concepts and interpret the data. More specifically, in the context of our study, data analysis reinforced the relevance of technological paradigm as the keystone theoretical construct and paradigm-changing innovations as the context (e.g., Ahuja et al., 2014). Subsequently, the second 'running exchange' suggested that we had to collect additional data to understand *how* NASA introduced the paradigm-changing innovation.

Moreover, we followed Danneels (2011; p. 5) and created "memos" with insights generated during data analysis. We compared our memos with new evidence that subsequently emerged during our study. For example, in one memo we asked, "How was designing the helicopter for Mars different from that for Earth?" Subsequent data collection and analyses revealed that the atmospheric condition on Mars was unlike any other condition for which a helicopter has ever been designed. To summarize, Burawoy's (1991; p.10) extended case method—which highlights the importance of "internal" inconsistencies preceded our subsequent data collection and theory building.

Designing the paradigm-changing innovation: Trigger event

The trigger event (Agarwal et al., 2021) for Ingenuity occurred in 2013 when Charles Elachi, then director of JPL, attended the conference on drones and aerial robots[1]. He wanted JPL to design an aerial robot for use on Mars. One of his colleagues, Bob Balaram, had previous research experience on robots and Charles Elachi asked him to write a proposal for the upcoming Mars 2020 rover project. Bob Balaram and his colleagues had eight weeks to submit the proposal (JPL, 2020). The Mars helicopter, then known as Mars 2020 Rover Scout, was funded for technology development and Mimi Aung was appointed as the project's manager. Subsequently, the team worked on risk reduction and NASA decided to fund the helicopter for flight as a technology demonstration with the Mars 2020 Perseverance rover (JPL, 2020). The project eventually designed a helicopter that weighs in at little under four pounds (1.8 kilograms), with a fuselage is about the size of a softball with twin, counter-rotating blades that rotates at almost 3,000 rotations per minute (rpm; about 10 times the rate of a helicopter on Earth) and demonstrated that "big things could come in small packages" (JPL, 2018).

Highlighting that the project was a paradigm-changing one, Thomas Zurbuchen (Associate Administrator for NASA's Science Mission Directorate; JPL, 2018) recalled—

> "*Exploring the Red Planet with NASA's Mars Helicopter exemplifies a successful marriage of science and technology innovation and is a unique opportunity to advance Mars exploration for the future….. After the Wright Brothers proved 117 years ago that powered, sustained, and controlled flight was possible here on Earth, another group of American pioneers may prove the same can be done on another world*"

Similarly, Mimi Aung (JPL, 2018) also noted the paradigm-changing characteristics of the project—

[1] The first Drones and Aerial Robotics Conference was held at NYU on Oct. 11-13, 2013, and Vijay Kumar of University of Pennsylvania's Director of Robotics and Automation Laboratory and Assistant Director of Robotics and Cyber Physical Systems at the White House Office of Science and Technology Policy was one of the keynote speakers.

> "*The altitude record for a helicopter flying here on Earth is about 40,000 feet. The atmosphere of Mars is only one percent that of Earth, so when our helicopter is on the Martian surface, it's already at the Earth equivalent of 100,000 feet up…. To make it fly at that low atmospheric density, we had to scrutinize everything, make it as light as possible while being as strong and as powerful as it can possibly be."*
>
> *"We don't have a pilot and Earth will be several light minutes away, so there is no way to joystick this mission in real time. Instead, we have an autonomous capability that will be able to receive and interpret commands from the ground, and then fly the mission on its own.*"

Further, Mimi Aung (Aung, 2015; portions underscored for emphasis) also recalled—

> "*This is a <u>game-changing proposal</u>. This will be just like on Earth where we drive cars, but we have planes for faster traverse. This will be for the exploration of the surface of Mars….The proposal is to demonstrate—a new mobility technology, the first-of-a-kind science and operations utility, validate the concept and pave the way for future helicopter missions…..<u>This is a modest start of breaking the aerial dimension for exploring another planet</u>. This should be just the beginning but if we succeed, this will lead to like the little Sojourner [rover] that nobody wanted [but paved the way for bigger rovers later on]."*

Larry Young (Bluck, 2000; p. 1) noted yet another paradigm-changing characteristics of the innovation and commented—

> *"The world altitude record for a helicopter is less than 40,000 feet, and we need to produce one that would fly in very thin air, equivalent to a terrestrial altitude of over 100,000 ft. There are substantial aeronautical challenges we have to overcome to develop a Mars rotorcraft,"*

Berger (2016) reported that the U.S. Congress provide funding for the helicopter around May 2016. Eventually, the helicopter designed to fly on Mars had coaxial rotor, with two counter-rotating, hingeless, 2-bladed rotors that were 1.21m (4ft) in diameter. The rotational speed of 2800 rpm is about 10 times that of the helicopters on Earth. The helicopter would only fly in favorable weather, with wind velocities limited to 9m/s (30 ft/s) horizontally and 2m/s (6.5 ft/s) vertically, with a maximum gust component of 3.5 m/s (11.5 ft/s). Moreover, the operation requires weather forecast and the gross vehicle weight is less than 1.8kg (4lb), bulk of which are the batteries that provide energy for flights lasting up to 90 seconds. The helicopter that flew on Mars for the first time on April 19, 2021, is shown in Figure 1.

Insert Figure 1 about here

NASA completed designing the paradigm-changing product in 2018 and as we describe next, was more nuanced than what is portrayed by Ahuja et al. (2014) and Fujimoto (2000).

Prior knowledge of NASA: Helicopter technology and Martian exploration

Importance of prior knowledge in technological innovation is well documented in strategy and innovation literature (see e.g., Roy and Sarkar, 2016). The paradigm-changing innovation from NASA also relied on prior experience accumulated by NASA since at least the 1930s.

Prior knowledge of helicopter since the 1930s

NACA's (the predecessor to NASA) and NASA's research on helicopter can be traced back to the 1930s. The first helicopters—Vought-Sikorsky VS 300 and Sikorsky R-4—produced by the Sikorsky Aircraft Company of Stratford, CT, had excessive vibrations, which affected all helicopters (also called rotorcrafts) till the 1980s. In the 1950s, the frustrated engineers trying to solve the vibration problem in helicopters would comment (Kvaternik et al., 1988; p. 71)—

> "*It got to the point where, instead of calling greetings when we met in the morning, we shouted at each other: 'How is it going - still shaking?'*"

Research to reduce rotorcraft vibrations in the U.S. has been carried out in a close cooperation between NASA and the U.S. Army since the 1930s. The relationship with the Army got a boost when in 1965 Army Aeronautical Research Lab was established at NASA's Ames Research

Center followed by similar labs at other NASA research centers. One of the first major NASA program addressing vibrations was the Civil Helicopter Technology Program (Snyder and Schoultz, 1976) in the mid-1970s. The primary goal of this program was to make helicopter rides more comfortable by reducing vibrations and thereby increase the public acceptance of helicopters as a mode of transportation. Subsequently, in March 1978, NASA's Office of Aeronautics and Space Technology formed Rotorcraft Task Force to review rotorcraft technology. NASA's activities were broadly in two different areas. The first was refining existing methods of vibration analyses and the second was to develop new computational methods for such analyses. These prior activities provided the groundwork on which the Ingenuity helicopter was designed. One of the prominent development during this time was NASA's study with Bell Helicopter Textron (Alaniz, 1979). Under contract to NASA Langley Research Center, Bell Helicopter conducted vibration and reliability analysis of two helicopter, Model 206A/B and Model 212.

Prior efforts to design Martian spacecrafts since the 1970s

Young et al. (2002) reported that the U.S. Army and NASA's Rotorcraft Task Force (discussed in the previous section), in collaboration with the NASA Ames Research Center had been exploring the designs of possible Mars rotorcrafts for several years. These studies were initiated after the Viking landers touched Mars in 1976 and gave the scientists an idea of the atmospheric and geologic conditions on Mars. Early conceptual design of Martian airplanes included Reed's (1978), Mini-Sniffer for Mars (Young et al., 2021). Subsequently, in 1992, NASA organized the first Discovery program for low-cost planetary missions. John Langford of Aurora Flight Sciences put a Mars aircraft proposal similar to Dale Reed's design of the Mini-Sniffer.

Mars rotorcraft studies in the 1990s and 2000s

In the mid-1990s, Savu et al. (1993; p.2) and Savu *et al.* (1993) designed a conceptual Martian helicopter with solar panels to generate power that was stored in a pneumatic turbine. These studies, however, lacked the "structural loads and mass estimation, payload and mission requirements" (Savu et al., 1993; p. 6)—factors that are critical to designing an actual Martian helicopter. Nonetheless, as a result of these developments, NASA Ames Research Center started research into rotorcrafts in 1997 with a Center Discretionary Fund effort.

In the early 2000s, Larry Young and his colleagues at NASA Ames Research Center studied rotorcrafts for Mars (see e.g., Young, 2000) and performed rotor tests in Martian conditions (Young et al., 2000). In an interview in 2000 (Bluck, 2000; p. 1), Larry Young commented—

> "*Ours is a small project…For about 18 months we have been working on it….Engineers first made a conceptual design to predict if a helicopter could hover and fly forward satisfactorily on Mars. A good deal of our effort is to develop a proof-of-concept main rotor… It's going to be 8 ft. [~ 2.4m] in diameter. The current design is to have two of these 8 ft. rotors stacked onto one mast. The rotors will spin in opposite directions. These rotors are roughly the size we need for a 10 kilogram (roughly 22 lb.) helicopter on Earth. On Mars, the helicopter would weigh 7 to 8 lbs.[~ 3 kg] because Martian gravity is about a third that of Earth's gravity.*"

These comments indicate that the foundation of Ingenuity can be directly traced back to the efforts of the researchers at NASA Ames Research Center. Further, Bluck (2000) also quoted Larry Young and highlighted the critical steps that were being taken at NASA in the early-2000s with various universities in the U.S.—

> "*The Ames Mars helicopter project team has asked a number of universities to do 'sanity checks' on the planetary helicopter concept. 'It's something fun for students to do,' said Young. 'Many of the university proposals include the same ideas that we have in our plans,' he said.*

The university studies included studies by the students at the University of Maryland, Georgia Institute of Technology, and others, who developed conceptual Mars rotorcrafts for the 2000 American Helicopter Society student design competition. The University of Maryland students designed a rotorcraft with a 50 kg mass, 4.26m diameter coaxial rotor, and a range of 25km range (see Figure 2). This design shares several features with the Ingenuity helicopter designed 18 years later.

Yet another prior knowledge possessed by NASA was that of relevant software. Since the 2010s, the innovations in computer simulation helped NASA scientists improve the Dshell++ simulation software (Lim and Jain, 2009), which was developed at NASA's Jet Propulsion Laboratories, the precursor to the HeliCAT simulation software used in Ingenuity.

Despite the prior knowledge, Teddy Tzanetos (Tzanetos, 2020) summarized the uncertainties faced in designing Ingenuity as—

> "*There is no instruction manual for a Mars helicopter. So, what does it take to fly a helicopter on Mars? How do you convince people not just at JPL but also at the [NASA] headquarters that you are ready to go*?"

Next, we explore the steps taken by the NASA engineers since 2013 to design the paradigm-changing innovation.

Designing Ingenuity helicopter

Identification of uncertainties affecting the innovation

The design of the paradigm-changing innovation started by utilizing the prior knowledge accumulated by NASA to identify the uncertainties that would affect the Martian helicopter's performance. Bob Balaram (Balaram, 2015) noted—

> "*Challenge [of designing Ingenuity is] very low density of atmosphere [and] keeping the whole mass of the system small so as not to overwhelm the lift capability of the system. The system has to be autonomous in terms of being able to fly and maintain its stability during flight. [It] should be able to repeatedly take-off and land on natural rocky terrain. It should be able to survive the harsh environment on Mars. Because this thing will take-off everyday and land everyday, landing is the*

riskiest part of any mission. We want to make sure that we have a bulletproof landing system. EDL [of Mars Curiosity Rover] had 7 minutes of terror, we will have 7seconds of terror every day."

The uncertainties associated with landing a helicopter on a rocky terrain were elaborated by Balaram et al., 2018 (p. 5). when they noted that the challenges included--

> "*Take off and land on unprepared terrain with no helipads… navigate without external aids such as GPS…. [when] atmosphere and gravity are dramatically different from Earth [and] little prior information exists on how these differences affect the flight dynamics in the Martian environment.*"

Mimi Aung (Aung, 2015) further elaborated the challenges further and noted that --

> "*Telecommunications [challenge] is to transmit data to rover during flight but primarily when landed. [Moreover] the idea is to tuck the helicopter under the rover. It will be dropped off and then the rover will move away. From that point the helicopter will be on its own. It means the rover will have to survive on its own thermally and power-wise.*"

The telecommunications challenge with a helicopter on Mars, which is about 8 light minutes away from Earth, was also highlighted by Håvard Grip (Grip, 2020) who mentioned the importance of the helicopter making its own decisions autonomously--

> "*The system has to be fully autonomous from the moment it takes off to the moment it lands. What we do on the land is that we plan the flight. We determine from here is where we want the helicopter to go.*"

Teddy Tzanetos (Tzanetos, 2020) concurred with both Mimi Aung and Håvard Grip—

> "*It is long distance to Earth– that means you need to have autonomous flight and landing capabilities on board. We can't joystick the thing. We can't move the thing a little bit, take an imagery, and plan based on what we see. The flights are 90 seconds long, so everything needs to be done on-board.*"

Mimi Aung (Aung, 2015) also noted additional challenges due to which Earth-based helicopters could not be replicated on Mars--

> "*In an Earth-based helicopter, the torque of the main rotor is canceled by the tail rotor [which is not possible for Mars]. On Earth we have landing pads for helicopters, we don't have that on Mars. [Moreover], accurate scaling from Earth to Mars is not possible. It is not possible just to scale down from Earth's atmosphere to 1% for Mars atmosphere. Things scale nonlinearly across the parameters. So scaling is a challenge. That's why we have to do EDL techniques [entry, descent, and landing used in Martian spacecrafts earlier] of test-as-you-fly exceptions. When we land on Mars, we have many simulations, we have many hardware test, we have field test, we have test-bed test. They all have to come together and check off the different angles we want to check. So, we are employing all the EDL techniques into this.*"

In addition to the challenges of telecommunications with the helicopter and the lack of landing pads, Mimi Aung (Aung, 2015) built on prior knowledge of atmospheric conditions on Mars and highlighted additional uncertainties such as—

> "*Controlling the helicopter will have its own challenges such as robust landing in the presence of wind around 5m/s and surviving on ground at windspeed of 45m/s.*"

Building on the knowledge of the uncertainties, Teddy Tzanetos (Tzanetos, 2020) conceptualized the components that would be required to mitigate those uncertainties as follows—

> "*It's a very thin atmosphere, 1% of Earth's atmosphere. So, you need very light blades with high [rotation speed] to get enough lift to get off the surface. It's very cold with Martian nights at -90^{0}C. We are using lithium-ion batteries, which don't like being cold neither do the electronics which have different thermal coefficient of expansion. If it gets very cold, you get to have issues with your hardware. So, active temperature control is needed. That is why we have solar panels that through every sol cycle will charge the battery.*"

Mimi Aung (Aung, 2020) summarized the uncertainties, as follows--

> "*The first and foremost challenge is to make a helicopter light enough to fly on Mars. The second challenge is that to generate lift, the rotor system has to rotate very fast, somewhere between 2000-3000 rpm. It's the balance of a very light system yet having the energy that is needed to spin and lift the system, and on top of it having the autonomy [to perform].*"

Teddy Tzanetos (Tzanetos, 2020) concurred and developed the 'three commandments' for designing a helicopter for Mars as follows—

> *Those challenges distilled down to three commandments from the engineering side— mass below 2kg, rotor speed 1900-2800 rpm, and blade tip speed of <0.7 Mach. Further, the rotor speed would vary depending on where the spacecraft would land as air density varies.*"

Balaram (2021) explained why the speed of the rotor blade's tips could not be more that the speed of sound (i.e., Mach) as follows—

> "*The rotors have to spin much faster [than Earth-based helicopters] to move the air to keep thrust and spin going, but there is a limit. We do not want to get to the speed of sound at the tip of the blade [due to unnecessary vibration in helicopters]. So, we had a relatively conservative posture….we went to Mach 0.7 at the tip. But that still means that our 1.2m diameter blade rotates at about 40 times a second to bite through the air. That has been the dominant challenge.*"

Balaram (2021) further explained the other engineering uncertainties—

> "*To fly, you want to make this thing as light weight as possible to take-off. One the other hand this light-weight spacecraft has to survive the rigor to reach Mars– it has to be a spacecraft– it has to survive launch load, launch vibrations, the vacuum of space, the cold temperatures of* $–90^{0}C$ *at night on Mars. So, we had the challenge to build the first of its kind aircraft to enable powered flight but it also had to be a very durable spacecraft that could get there and function. These are two aspects of the challenge that are quite unusual.*"

To exacerbate the uncertainties, the engineering team had to design the paradigm-changing innovation within other limitations. These were, as Balaram (2021) explained--

> "*We had a certain limited space on Perseverance rover to conduct this technology experiment that determined the blade diameter– then you look at the blade diameter and you know the tip speed, we essentially we ended up knowing that we cannot be over 2kg. We ended up with 1.8kg.*"

Grip et al. (2017; p. 6) noted that in addition to the factors described above, the helicopter should be able to withstand high structural loads during launch, extreme temperature variations, high levels of radiation, operate entirely without physical intervention after launch, and overcome the instability due to 'flap dynamics.'

Component identification to mitigate the uncertainties

With the knowledge of the uncertainties facing the design of Ingenuity, NASA engineers searched for the components that could mitigate those uncertainties. They had to identify the shape, size, and other features of the components that could be used in the helicopter. For structural dynamics of the helicopter, they had to decide the helicopter blade material, the type of battery, and how the battery would be connected to other components in the system.

Aung (2015) summarized the various components that NASA engineers had to identify to design the helicopter. These included the coaxial rotors, solar cells, battery that is charged by the solar panel for flights of 2-3 minutes every sol, aerogel insulation and heater to keep the interior warm at night, camera and altimeter for navigation and hazard detection. Further Aung (2015) noted—

> "*The helicopter has to be on track autonomously. The camera will decide under a minute to land or divert the helicopter. We do a lot of these on spacecrafts for entry, descent, and land and docking, but this is the first time we are doing this on a helicopter. We need computer for flight and safe landing, science imaging camera, energy absorbing lightweight legs for landing on natural terrains, and radio*

for link to the rover. To come to a balance of a resilient and robust system and a smart system we needed onboard autonomy [whereby] the 2D images are processed [on board] to construct 3D images to keep you on planned track and to land. Moreover, all electronics, chips, batteries, gyros have to fit into a cube of 7cm [~ 2in] each side."

Consistently, Balaram (2018; p. 5) noted that the Mars helicopter would need "unusually stiff blades" to mitigate the uncertainties facing the helicopter's operations in the Martian atmosphere. Mimi Aung (2015) underscored that the existing solutions used on Earth helicopters would not work on Mars. She noted—

> "…*we are proposing is two [coaxial] rotors turning in the opposite direction. The reason for doing that is in the beginning the team traded traditional helicopter, quadrotor, and the coaxial helicopter came out the best for Mars where we need lower mass, lower power, easier accommodation, and higher performance."*

Aung (2015) further highlighted that because of the lack of landing pads for helicopters on mars, the "coaxial configuration allows for more options."

Tim Canham (Ackerman, 2021) explained the processor used in Ingenuity and noted that the Snapdragon 801 by Qualcomm was a cell phone processor and was more powerful than the processor in Perseverance rover with orders of magnitude more computing power. The fact that Ingenuity was capturing images, analyzing features, as well as tracking them from one frame to the next at 30Hz meant that the processor had to be powerful. NASA engineers used a cellphone-grade inertia measurement unit (IMU), a laser altimeter, and a downward-pointing VGA camera for feature tracking. For navigation, Ingenuity figures out its direction and speed by comparing a few dozen features in successive frames of picture.

Aung (2015) noted the constraints imposed by the Perseverance rover on the helicopter's design and explained—

"*The rotor diameter comes from rover accommodation. The bigger the rotor the better is the lift but we are limited by the what the rover can accommodate. Rotor diameter is 1.1m that means the entire mass will have to be about 1kg.*"

In addition to identifying the component, such as the Snapdragon processor, NASA engineers also tested the components. In the case of the camera, engineers had to choose a camera that was light-weight so as not to increase the mass of the system. NASA engineers tested the camera and the software's ability to generate 3D images of a location while flying at the Arroyo Canyon near Jet Propulsion Laboratory. Aung (2015) noted—

"*The helicopter's operability was tested at the Arroyo [canyon] next to JPL. We took a Scout camera [Scoutcam], a prototype of the one we are willing to fly, a low mass camera, and we wanted to show that this is feasible. The quadrotor took the camera and flew at 40m. The images were processed and put into the RSVP tool, the software tool used in Curiosity and Opportunity and those rover drivers to generate 3D terrain map that demonstrated rover blind driving.*"

Aung (2015) also explained several other testing of the components. For example, in December 2013, NASA performed the blade characteristics test to ensure that the rotor blades used could indeed lift the helicopter in a Mars-like atmosphere. Thereafter, in March 2014, NASA performed the rotor lift test. This was followed by the December 2014 test to investigate if a helicopter with coaxial rotors could indeed lead to a free flight with no added systems. Aung (2015) mentioned—

"*In parallel we have been looking at the control system. Given the thinner atmosphere, low Reynolds number, interaction between the blade and the atmosphere, how amenable is the system to control? So, there's a control analysis going on in parallel.*"

Such component tests were echoed by Balaram (2020) who explained the solar illumination test at NASA's Ames Research Center—

"*The chamber at Ames has the ability to create solar illumination on the surface of Mars. We tested the solar panels here because that's how we will be getting the power on Mars.*"

Young et al., (2021) explained that the JPL worked with NASA's Ames and Langley research centers and the work was sponsored by the NASA's Aeronautics Mission Directorate's Revolutionary Vertical Lift Technology project. This support included designing the components as well as the airfoil used on the rotor by using computational fluid dynamics (CFD) techniques. Michelle Dominguez (Young et al., 2021) mentioned—

"*Study of flow in rotor systems conducted at the JPL 25-ft Space Simulator. In winter of 2015, Ames conducted the [Rotor performance] test at the JPL simulator.*"

Mitigating component interdependencies to create the paradigm-changing innovation

Aung (2015) explained the interdependencies between the components when she noted—

"*However, when you have all the constraints and remember this is an electric vehicle that is generating its own power. You can always lift more mass by turning the rotor faster as long as you do not exceed the speed of sound. To lift more you need more power, for which you need bigger solar cells, bigger battery….. Your mass will grow.*"

Brian Allan (Young et al., 2021) provided an example of mitigating the interdependencies between solar panel and the stability of the helicopter's design. He noted—

"[Simulation tests] showed that the solar panels did not impact the helicopter's performance. Simulations did show that increasing the solar panels length [made the helicopter unsteady] but the team determined that these were within the acceptable ranges. The 10cm [approx. 4in] extension of solar arrays were within the acceptable ranges."

Similarly, Michelle Dominguez (Young et al., 2021) provided examples of migration of interdependencies between the various components such as the solar panel and the helicopter's size. She explained—

"*Solar array interaction and sizing analysis [was conducted] at NASA Ames Research Center [who] conducted the in-house Mars rotor forward flight testing at its in Mars wind tunnel in Ames N242 low pressure chamber.*"

Teddy Tzanetos (Tzanetos, 2020) explained how NASA worked through mitigating interdependencies—

"*We have a fantastic facility at JPL to simulate the environment of interest, the 25-foot space simulator. Our team put a 1/3rd scale helicopter in there [in Dec. 2014], sucked the air out to match the density of Mars and performed a couple of experiments [to conduct the tethered uncontrolled flight test]….. we learnt lessons of how to stabilize the spacecraft at Mars atmosphere. On Mars it's not exactly the same way by which you stabilize the helicopter here on Earth. [The helicopter crashed] despite being piloted by joystick by expert pilots.*"

This test highlighted the importance of the rotor-blade size and the rotor speed. Subsequently, as Tzanetos (2020) recalled, the control system was added to the rotors--

"*So, now the fundamental question is can one fly a helicopter in controlled manner in the Martian atmosphere? So now the team built some more autonomy into the system. So, we now built a full-size proof-of-concept helicopter with 1.2m diameter. But the system was still a skeleton. It had the [infrared] tracking balls to track the motion of the helicopter in the chamber but there is power system on board, no computer on board, it is only the actuator. This was still a step forward. A lot of Ingenuity has been baby-stepping forward to get ready for launch. This flight on May 31, 2016, was the big check mark of the project to say, 'Yes! we can fly controllably in Mars atmosphere. Let's move on to the next step'.*"

The above-mentioned tests involved mitigation of the interdependencies of components used in Guidance, Navigation, and Control (GNC). Next, NASA had to mitigate the interdependencies between the components used in GNC and other components. As Teddy Tzanetos (Tzanetos, 2020; underscore added for emphasis) recalled—

> "*So, now if the fun part. Up to there we had a heavily GNC-focused effort. Now comes the rest of the challenges. How do we build a helicopter that can survive the extreme cold temperatures? How do we budget the energy to survive the night and wake up with enough energy in the tank before sunrise happens and fly as designed? So we had to keep the mass below 2kg., autonomous flight, charging, and overnight heating, and communication with base station on rover. These have to be done with all computers on board.*
>
> *This is where the engineering model came in [which is] your test-bed. You want it to be as realistic as possible to the flight model. It is not the flight model, but you want to learn all your lessons. The best way to do that is to build it as close to the flight model you think it will be.*
>
> *So, we did lots of testing. In the spirit of baby-stepping our way, we first decided to spin it up. You attached something very rigid and spin the blades slowly to understand the vibrations, the <u>unintended [interdependencies] between motor control and the blades and do a system smoke test to ensure that they work</u>.*"
>
> *Then you move your way up. Before you do the free flights, you want to ensure that the spacecraft can survive crosswinds. We did not have a wind tunnel that was qualified to operate in near vacuum of space. So, you attach the spacecraft to a robot arm and swing it back and forth, side to side. That produces a little bit of cross wind so you can evaluate your controls in that scenario. Make sure you can observe those forces and can counteract.*"
>
> *Then we had to ensure stable roll and pitch. So, we had to design our own gimbal, design a way to attach the umbilicals to that gimbal, and then hook up the rotorcraft to command different pitch angles and different roll angles and <u>make sure that this is all working as expected</u> before we got ready for the free flights.*"

Teddy Tzanetos (Tzanetos, 2020) further noted that the final model for free flight occurred subsequent to the mitigation of the interdependencies between the components in the paradigm-changing innovation. According, he observed—

> *"Later when we got funding, we installed computers to the wind tunnel. Then [on Jan. 30, 2018] we had the first free flight of the engineering model [EDM]. All avionics and battery are in the system. Some of you may be wondering okay we got the pressure right, but what about gravity? The system was attached to a string [which was attached to a pulley] with a tension which would pull up the rotorcraft [and offset Earth's gravity]. With the chamber we had Nitrogen [pushed in] to simulate Mars."*

Subsequently, the final free flight model also tested if the interdependencies between the onboard vision system and other components such as rotors and battery—

> *"Then we did the experiment with the onboard vision odometry with special features on the floor so that our odometry could track some features."*

The process we identify is shown in Figure 3.

Insert Figure 3 about here

Discussion

Our research is motivated by Dosi's (1982) seminal paper on technological paradigm and the more recent extension to the theory by Ahuja et al. (2014). We asked the question, "*how do organizations design paradigm-changing innovations,"* and took a deep-dive into NASA's design of the historic Ingenuity Martian helicopter to seek the answer to our question. Using archival data and following Carton (2018), our findings uncover a unique process to design a paradigm-changing innovation. We find that the process starts with a trigger event, includes the organization's identification of the uncertainty that are likely to affect the innovation, identification of the components that can mitigate those uncertainties, and mitigation of the component interdependencies to create the paradigm-changing innovation.

Our finding builds on Dosi's (1982) thesis on technological paradigm. More specifically, our finding complements Ahuja et al.'s (2014) insights into paradigm-changing innovations. Whereas Ahuja et al. (2014) uncovered that paradigm-changing innovations differ from paradigm-deepening ones on the degree of input-relatedness across their businesses, we underscore the process through which organizations design the paradigm-changing innovative products. Our finding brings together prior research from not only the technological paradigm stream of research (e.g., Dosi and Nelson, 2010) but also the stream that explores the role of interdependencies between components in product design (Baldwin and Clark, 2000). More specifically, we uncover that the process of designing paradigm-changing innovation involves not just understanding the uncertainties that may affect the new product's performance but also the knowledge of components (Henderson and Clark, 1990) and the knowledge of interdependencies between those components.

Despite extending existing theories, our research has several limitations. Our deep-dive uncovers the process within a government agency. Anecdotal evidence of SpaceX creating the paradigm-changing reusable rocket motors (O'Connell, 2018), it is yet to be determined how generalizable our findings are. It is quite possible that the processes followed by SpaceX and Blue Origin may differ significantly and future research may explore those differences to extend the literature further. Nonetheless, our is one of the first research to explore the process of developing paradigm-changing innovations.

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Table 1: Timeline of Ingenuity design

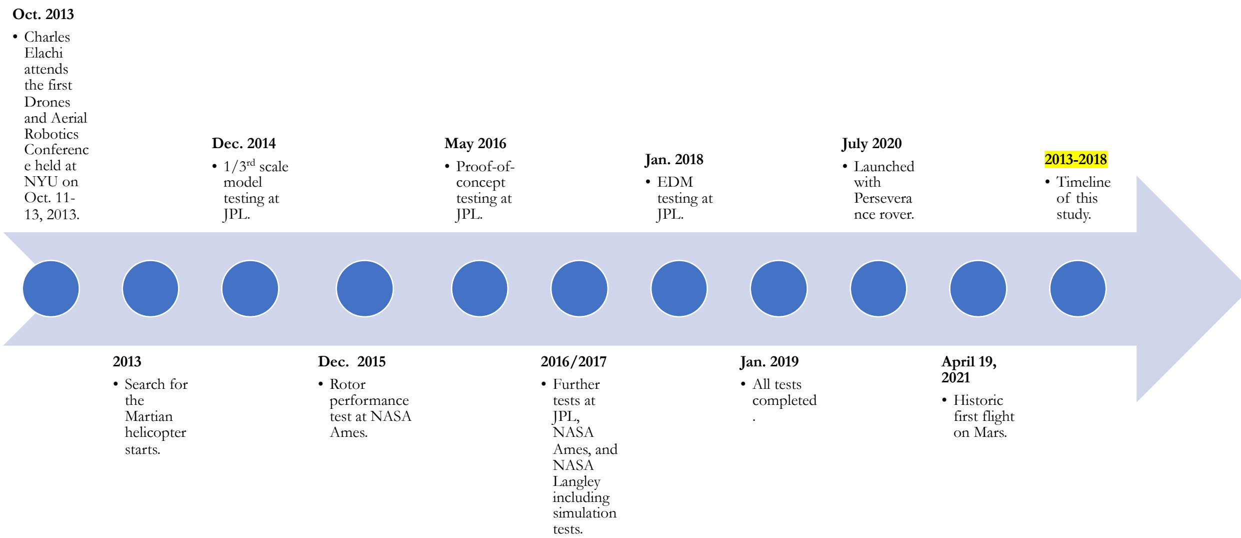

Figure 1: The final Ingenuity helicopter design
(Source: Balaram, 2018; p. 9)

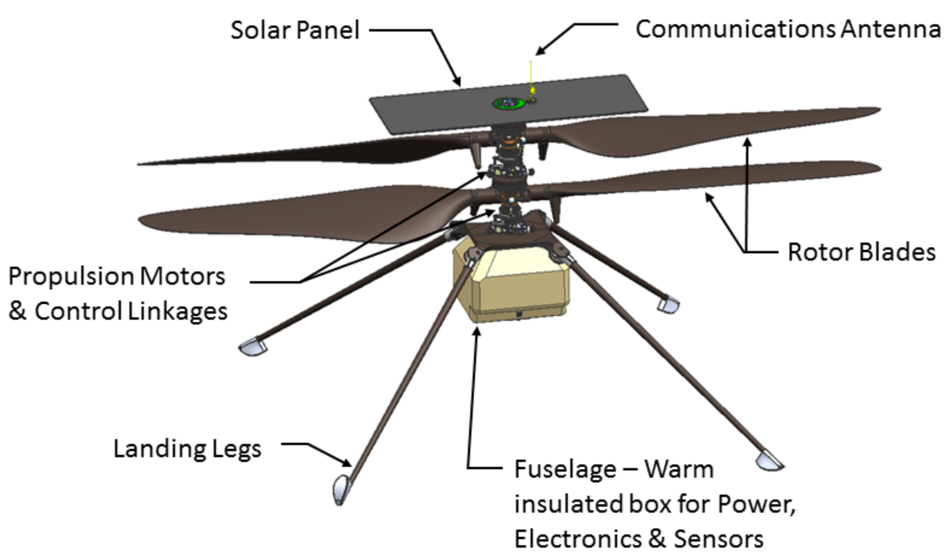

Figure 2: The University of Maryland Mars rotorcraft design in 2000.
(Source: https://vtol.org/files/dmfile/2000SDC_1stPlaceGraduateProposal_UMD_MARC.pdf)

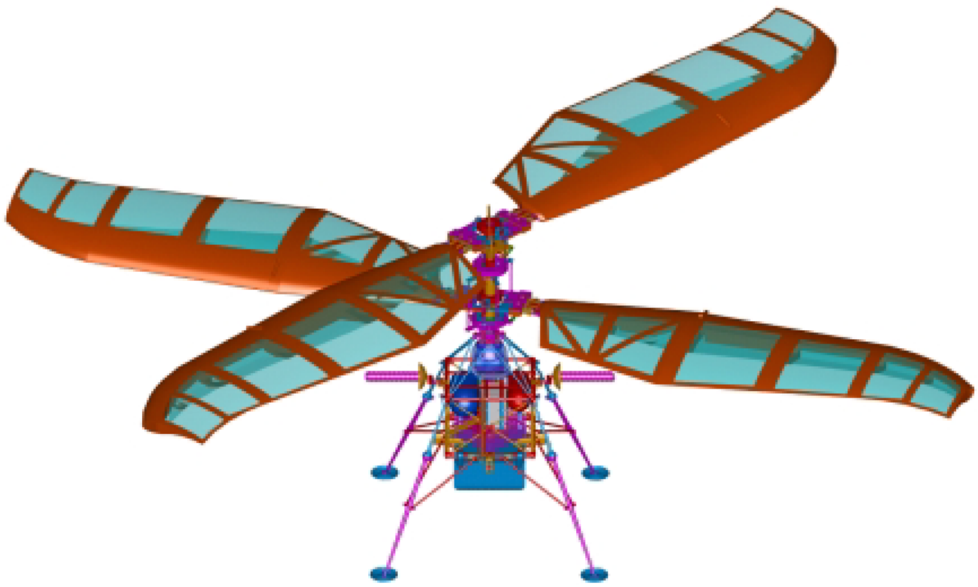

Figure 3: Process diagram of designing a paradigm-changing innovation.