R-Selected Spacecraft

V. Hunter Adams [*] and Mason Peck[†]
Cornell University, Ithaca, New York, 14850

This paper introduces R-selected spacecraft as a field of study that draws from concepts in ecology, and introduces the Monarch spacecraft as a case study for a system designed in accordance with the principles of this field. The Monarch is a 2.5-gram spacecraft that is the first to trade quantity, rather than cost, for low mission risk. By taking advantage of recent technological advancements in unrelated disciplines and taking a statistical approach to mission assurance, R-selected spacecraft open the door to an entirely new paradigm in space access and exploration. This paper describes the challenges and advantages unique to gram-scale, R-selected spacecraft. It also presents a number of use cases — involving distributed in-situ sensing and planetary science — that are unique to spacecraft of the Monarch's diminutive size and large quantity. Results from simulated lunar impact survival tests and a case-study planetary science mission are presented and discussed, suggesting one particular use case. Video demonstrations of distributed sensing, leaderless cooperation, routing, actuation, GPS acquisition, and powering are provided in the supplementary materials to illustrate the viability of some entirely new mission concepts.

I. Introduction

Spacecraft design has historically traded high-cost development and engineering for low mission risk. This successful model has changed the world. It has brought us decades of discovery and exploration, rewriting the textbooks on planetary science, heliophysics, Earth science, and astrophysics. But despite how well it has served the scientific community, this model limits the types of missions that we can perform.

There is no shortage of threats to the survival and operation of a spacecraft. Wide temperature swings, many forms of radiation damage, and impacts with micrometeoroids or larger objects are only a few that flight hardware experiences. Vast communication distances, a dearth of resources for power scavenging, and launch mass-related challenges in power storage and generation top the list of technological barriers [1]. Unlike for most everyday, terrestrial engineering problems, the cost and high stakes of spacecraft motivate a formal process, what engineering organizations know as "mission assurance." Metrics for mission assurance attempt to capture the probability of overcoming these threats and achieving mission success. For conventional missions involving a single, high-cost spacecraft, mission assurance

---

[*] PhD Candidate, Sibley School of Mechanical and Aerospace Engineering, Cornell University, 450 Upson Hall, AIAA student member.
[†] Associate Professor, Sibley School of Mechanical and Aerospace Engineering, Cornell University, 450 Upson Hall, AIAA full member.

essentially reduces to the probability of spacecraft success, which rarely exceeds about 95%. And unless the spacecraft of interest is far more valuable than a single launch — examples include the International Space Station and the Hubble Space Telescope — we never fix them when they fail. In fact, until the past decade, we gave little consideration to servicing and repair in the design of spacecraft, making them virtually impossible to fix even if we wanted to do so [2].

Conventional metrics rarely consider how confidence measures change for missions that include many identical spacecraft, since to date it has been cost prohibitive to do so except in rare cases [3–6]. If one could launch thousands of identical spacecraft, confidence in any particular one might be extremely low while confidence that some critical number remains operational could remain high. This probabilistic model is a fundamental motivation for the Monarch. Rather than trading high cost for low risk, Monarchs trade high quantity for low risk. It is an idea that would have been impossible to realize until only a few years ago.

The notion of trading quantity for risk is not without precedent in nature, and is particularly apparent in reproductive strategies. Evolution has arrived at two general solutions to the problem of maintaining a viable population from one generation to the next. Some creatures, like humans or whales, employ K-selection. K-selected species produce a relatively small number of offspring and spend a tremendous amount of time and energy to make certain that each child is successful. These animals are well suited to stable environments where they can rely on long lifespans and a low mortality rates. This strategy is clearly a successful one, as evidenced by the existence of all creatures that use it. There is, however, an alternative solution.

Other creatures, like sea turtles, produce a relatively large amount of offspring and put extremely little investment into any one of them. The probability of survival for any particular offspring can be extremely low, but as long as enough are produced then the population remains healthy. These are R-selected species. R-selected species tend to have shorter lifespans than K-selected species, faster sexual maturation rates, and larger numbers of offspring. They are far better suited to unstable environments than K-selected species [7].

This paper asserts that spacecraft engineers have something to learn from nature in this regard. Every spacecraft that humans have launched has been K-selected. Engineers produce very few spacecraft in a lifetime, and they devote an extreme amount of time, money, and energy into each of these spacecraft to be as certain as possible that it will survive for as long as intended. K-selection has been the design paradigm for spacecraft strictly out of necessity. Solving the mission assurance problem in the statistical manner of R-selection requires spacecraft that can be manufactured at much lower cost than conventional, K-selected spacecraft, launched in much greater quantity, and with a much faster development cycle. This has not been possible until only very recently when other industries (mostly cell phone and gaming industries) drove down the cost of automated circuit board manufacturing and assembly, processors, and surface-mounted sensors. The world has not yet seen R-selected spacecraft because it has never before been possible to manufacture R-selected spacecraft. The systems and programs that have come closest to this sort of architecture include Globalstar, Iridium, Orbcomm, and the Educational Launch of Nanosatellites (ELaNA). In these systems, the success of the mission or the program does not depend on the success of every individual satellite, and the system is robust to a small number of individual satellite failures [8]. These systems are best classified, however, as "failure tolerant" rather than "failure reliant." In much the same way that a pride of lions may continue to survive after the loss of a few individuals, Globalstar, Iridium, Orbcomm, and ELaNA will continue to operate after the loss of a few spacecraft. This is a different sort of risk management technique than that used by a decidedly R-selected species, like ants, where loss is a critical and expected part of the survival strategy for the colony. It is now possible to build spacecraft with this decidedly R-selected approach to mission assurance. R-selected spacecraft represent a paradigm shift away from failure-tolerant systems and toward failure-reliant systems where mission assurance is based on the statistics of survival, rather than failure rates. This ushers in an entirely new field of study within aerospace engineering.

The list of open research questions associated with building and utilizing R-selected spacecraft is nearly as extensive as the list of open research questions for conventional spacecraft was in the 1950's-60's. The open questions are fundamental ones about sending and receiving data to these systems, controlling the trajectory and orientation of each spacecraft and of the collection of spacecraft, and basic design principles. These are not issues of incremental improvement on existing technology, they are fundamental questions about construction and utilization of a new kind of space system. Answering these questions will bring space exploration and planetary science of an unprecedented variety. This paper describes the first space system designed according to this new philosophy.

The Monarch, shown in Fig. 1, is the first attempt to apply R-selection to spacecraft, and that brings with it the same advantages and disadvantages found in nature. Each satellite has a far higher probability of failure than any conventional K-selected spacecraft, but, just as in nature, that probability of failure is offset by the number of spacecraft that can be launched at a single time. Their quantity makes them well suited for unstable environments and dangerous missions, since they are not beholden to the probability of failure, like conventional spacecraft, but instead exploit the probability of failure. R-selected spacecraft have their own separate and unique set of use cases that are apart from those of conventional spacecraft. What follows is an overview of the challenges and advantages unique to gram-scale R-selected spacecraft. This paper also presents a number of use cases — involving distributed in-situ sensing and planetary science — that are unique to spacecraft of the Monarch's diminutive size and large quantity. Results from simulated lunar impact survival tests and a case-study planetary science mission are presented and discussed, suggesting one particular use case. Video demonstrations of distributed sensing, leaderless cooperation, routing, actuation, GPS acquisition, and powering are provided in the supplementary materials to illustrate the viability of some entirely new mission concepts.

II. A New Kind of Spacecraft

Designing a mission that trades high quantity for low risk rather than high cost for low risk requires a spacecraft that can be manufactured cheaply and in bulk, can launch and deploy in much greater quantities than conventional spacecraft, and can maintain the core capabilities required for them to be useful. These goals are now achievable. The economies of scale driven largely by the consumer-electronics industry (specifically, cell phones and gaming) have reduced the cost of surface-mounted processors, sensors, and radios to a tiny fraction of what they were just a decade ago [9]. This revolution has also driven down the cost and timeframe for manufacturing and assembly of printed circuit boards. The Monarch takes advantage of both of these trends. It is a spacecraft built through entirely automated processes, the same processes that build circuit boards for cell phones and other electronics. Monarchs use sensors and processors from game controllers, laptops, and other consumer-market electronics for which economies of scale have driven down component costs. The result is a 2.5 gram spacecraft that can be manufactured in bulk for less than \$50 apiece, launched and deployed by the hundreds or thousands, and can go places and do things that conventional spacecraft cannot. Fig. 2 shows the front and rear of the spacecraft. The components are labeled. Monarchs are not small versions of large spacecraft, and they do not replace conventional spacecraft. Instead, they are a new way to access and explore space, and they have their own new and unique use cases.

The Monarch is an example of what has come to be known as a chipsat, a concept whose development began in earnest at Cornell University in 2007, although earlier work at the Aerospace Corporation in 1999 offered insight into what might be possible at this scale [10]. The first publications by Atchison et al described spaceflight dynamics at the microscale. The surprising benefits of small scale, such as the importance of effects like solar pressure, drag, and the Lorentz force in Earth orbit to alter trajectories in unfamiliar ways, motivated the creation of a prototype small-scale free-flyer to verify these effects experimentally. From 2007 through 2016, Cornell's research focused on Sprite, the name Atchison gave them. Sprites were 4-gram femtosatellites or chipsats, which have now flown four times (on the International Space Station in 2011, on Kicksat-1 in 2014, Venta-1 in 2016, and KickSat-II in 2019), with an additional mission planned in the coming year. Kicksat-1 was the world's first crowd-funded spacecraft (via Kickstarter.com), almost singlehandedly designed and built by Zac Manchester, then a student at Cornell and now on the faculty at Stanford. Kicksat-1 took 104 early-generation Sprites to orbit[11]. Kicksat-2 carried 128. A Sprite on The Venta-1 mission — again, Manchester's work — established the feasibility of communicating across large distances with low power: 10 mW transmission reached over 1500 km with suitable forward-error correction, requiring only a laptop and HAM radio antenna. With their exceptionally low ballistic coefficient, atmospheric drag deorbits the chipsats in a matter of days, as shown in Section III and validated by the KickSat-2 mission. Different debris risk mitigation strategies must be employed at higher orbits. Such strategies may include building the spacecraft of a material that will sublime away, or giving them thrust capability for escaping or entering the atmosphere.

The Monarch has advanced well beyond these early efforts. Here, we describe the Monarch in terms of the subsystems associated with larger, conventional spacecraft. These subsystems include telemetry and command, power generation, attitude determination and control, navigation, and payload [5]. The size of the Monarch makes some of these subsystems different from their larger-spacecraft analogues, and it couples some subsystems that are not coupled in larger spacecraft. The fundamental concept of trading quantity for risk finds its way into each of these subsystems.

Telemetry and command takes place via a 25 mW ISM-band radio and and embedded PCB antenna [12]. With such a low-power transmitter, and without the ability to accommodate a high-gain antenna, the data rate from any particular Monarch is substantially lower than larger spacecraft with more power availability and directed, high-gain antennas. With some reasonable assumptions on the parameters associated with the communication system (500 km transmission distance, isotropic transmission antenna, 915 MHz carrier frequency, 7dB receiver antenna, 64 kHz bandwidth), it can be shown that the Shannon Limit for a Monarch in Earth orbit is approximately 84 kilobits per second [13–15]. Thus, if a line rate less than 84 kbps is used, there exists a coding technique (involving error correction) that allows the probability of error at the receiver to be made arbitrarily small.

However, these comparatively low transmission rates per Monarch are not the proper metric to consider, since many hundreds or thousands of Monarchs may be deployed simultaneously, each of which may communicate data at this comparatively low transmission rate. This is how the notion of quantity vs. cost finds its way into this subsystem. The data rate from the entire collection is competitive with large, high-power spacecraft and, furthermore, the dataset is of an entirely different sort. Rather than receiving large amounts of data from a few sensors on a single spacecraft at a single location, a dataset from a collection of Monarchs comes from many thousands of sensors distributed across vast regions of space. This distribution creates the opportunity for entirely new sorts of missions.

Trading high quantity for low risk also affects the Monarch's power subsystem. On large, conventional spacecraft, a battery keeps the spacecraft awake when it passes through the shadow of the Earth. For missions involving a single high-end spacecraft, this necessity is inescapable, since power keeps the spacecraft thermally regulated [5]. With thousands of Monarchs, power can be handled differently. At only 2.5 grams (the mass of an American penny) and with a very flat shape, Monarchs reach thermal equilibrium much faster than larger spacecraft. At their size, it costs more energy to keep a battery warm in eclipse than that battery can store when in sunlight [5]. Thus, these spacecraft have no means of thermal regulation. Instead, all sensors, processors, and components are chosen based, among other things, on their operational temperatures. This precludes the use of any battery, the operational temperatures for which are exceeded while in orbit. With a small capacitor, one that is insensitive to the thermal environment, Monarchs can continue to function at low duty cycle in eclipse. Otherwise, they sleep when in eclipse and wake when in sunlight. Networking capability ensures that a swarm or cluster of Monarchs is always on, in a generalized sense, even when a single spacecraft is unpowered. So, collecting scientific data and communicating it to Earth can continue, regardless of the local solar flux. For missions involving monolothic spacecraft, such an operations concept would be far from optimal, and likely unacceptable. For Monarchs, however, quantity makes this arrangement perfectly adequate.

Attitude determination looks very much the same on Monarchs as on large conventional spacecraft. In fact, the pointing agility (combining angular rate, acceleration, and so forth) is roughly independent of length scale. However, attitude and navigation are uniquely coupled for spacecraft of their size. Each Monarch carries a gyroscope, magnetometer, and light sensors that act as coarse Sun sensors. So, three-axis attitude determination is possible [16–19]. Each Monarch also carries a GPS receiver and a GPS antenna, with which it may determine its location, velocity, and the absolute time when operating in Earth orbit. Attitude control is a bit more subtle on the Monarch than on a conventional spacecraft. Monarchs drive electrical current through a coil of wire embedded in their interior in order to create their own local magnetic field. This magnetic moment torques against the Earth's magnetic field, thereby changing the orientation of the spacecraft. This technique is common in larger spacecraft [20–22], particularly CubeSats, but its implementation in Monarchs is unique in that the coils lie only in the plane of the printed circuit board. The inertia tensor of the Monarch is such that it is passively stable in spin about its normal axis [23]. Rather than requiring 3-axis control, Monarchs use their torque coils to induce and cease precession about the Earth's magnetic field vector during a stable spin, a 2-axis control solution. For spacecraft with area-to-mass ratios as high as that of the Monarchs, attitude and trajectory are highly coupled in low Earth orbit, where the dominant orbital perturbation is atmospheric drag [24]. As the Monarch leans its flat face into the velocity direction, drag slows it relative to other Monarchs whose thin edge faces the velocity direction. In changing their orientation, a swarm of Monarchs can both affect power generation and manage the shape of the swarm. This capability also has implications for the sorts of missions for which Monarchs are well suited.

Payloads for Monarchs are different from payloads for conventional spacecraft. Their size necessarily limits the aperture, which precludes remote-sensing payloads. Large spacecraft will always be better suited for remote sensing. Instead, Monarchs are well suited for carrying sensors that measure characteristics of the environment in the immediate vicinity of the spacecraft — quantities including temperature, pressure, electromagnetic fields, particle distribution, radiation, etc. It is best to think of a collection of Monarchs as a single radio-networked sensor, each node of which remotely reports its local in-situ measurements. Such a collection gathers data of the spatial breadth associated with remote sensors, but with the localized depth of in-situ sensors. Monarchs enable missions of two very broad types: those that involve spatially distributed in-situ measurement, and those that involve actions that pose extremely high risk to individual spacecraft. They offer in-situ measurements with remote delivery of data.

III. Statistical Mission Assurance for Distributed, In-Situ Sensing Missions

Networked collections of distributed in-situ sensors offer the opportunity to create unprecedentedly rich datasets. For the sake of comparison, consider the Ionospheric Connection Explorer (ICON), a high-cost-for-low-risk spacecraft for studying Heliophysics[25]. ICON carries a suite of instruments for measuring features of the ionosphere and thermosphere (85-575 km altitude). This region is too low for in-situ measurements with satellites and too high for aircraft. So, it is sometimes known as the ignorosphere. This little-understood region is where neutral particles from the Earth's atmosphere collide and react with ionized plasma, leading to variability that affects important space-based assets, including the GPS constellation. In an effort to understand the role that the lower atmosphere plays in driving these variations, ICON gathers both remote and in-situ measurements. Though this mission is well suited for remote sensing, it is fundamentally limited in that the 272 kg spacecraft can gather in-situ measurements only within its 575 km altitude orbit, well above the airglow and other atmospheric phenomena in question [26, 27]. A far more valuable in-situ dataset could be gathered by deploying a swarm of Monarchs to traverse the region of interest, passing information among themselves and to the ground to collectively build an understanding of the time and spatially varying phenomena that take place there.

Fig. 3 shows a physics-based simulation of this mission. In the simulation, 500 Monarchs are deployed from the International Space Station. This is approximately the number that can fit into a cubesat-sized mothership. Each has a random attitude, resulting in a range of effective surface areas to the Sun and to the incident atmosphere. Below 400 km altitude, J2 gravitational effects and atmospheric drag are, by more than an order of magnitude, the dominant sources of orbital perturbation for centimeter-scale spacecraft [24]. These perturbations cause different accelerations on each Monarch and, consequently, the Monarchs disperse. Fig. 3 shows the orbital elements and Earth-centered inertial coordinates for each of the Monarchs (individually colorized) after 0-4 days. It can be seen that the collection experiences significant in-plane dispersion and negligible dispersion out of plane, and that the first Monarchs begin to enter the atmosphere after 4 days.

Because the Monarchs contain no power storage, only those that are not in eclipse and that have their normal vectors pointing within 40 degrees to the Sun will be active. For higher-altitude deployments where the Monarchs would be in orbit for longer amounts of time, radiation damage would also reduce the expected number of active Monarchs. The 2011 chipsat experiment on the International Space Station, wherein two chipsats were exposed to space for one year and continued to operate without issue, suggest that radiation will not significantly reduce the expected number of chipsats in the timeframe of this simulation. Fig. 3 shows the range for the expected number of active Monarchs for best-case and worst-case beta angles. Only a subset of the 500 Monarchs (13-22 percent) are expected to be active at any moment in time. By controlling the Monarchs' angles to the Sun, this fraction can be increased. Even from this subset, however, the total expected data rate is in the range of 347-876 kB per second for beta angles of 0-90 degrees, which is competitive with most conventional spacecraft. Furthermore, Fig. 3 shows that connectivity among the Monarchs (nearest neighbor distances less than 25 km) is maintained for the majority of Monarchs until they deorbit. If more Monarchs are deployed, connectivity is maintained for a longer amount of time. By routing through the collection, the ground station can access data from the entire swarm of Monarchs through the relatively small number that pass within its range.

Optimal utilization of this network requires a routing policy over the collection of spacecraft. For scalability, this policy may not rely on global knowledge assumptions for any of the constituent Monarchs, and it must be robust to changing topologies as orbital perturbations change the Monarch trajectories — most significantly in the along-track direction. For collections of orbits of this sort, the provably optimal routing policy from any node in the network to a ground station is evident from a straightforward application of dynamic-programming equations. Furthermore, this optimal routing policy requires only local knowledge for each Monarch, making it scalable to an arbitrarily large number of spacecraft [28]. Fig. 4 shows an artistic representation of a low-Earth swarm of radio-networked Monarchs.

This simulated, distributed in-situ sensing mission solves the mission assurance problem statistically. The expected number of active spacecraft is less than the number of spacecraft launched. Such a mission would investigate the least understood region of the atmosphere, providing key insights for understanding and ultimately predicting space weather. Similar arguments may be made for atmospheric and gravimetry studies, even for other planetary bodies, building upon Atchison's recent work at the Johns Hopkins Applied Physics Lab [29]. The behavior of the swarm depends intimately on the physics at the place of deployment. For the low-Earth orbit simulation discussed in this section, the Monarchs deorbit before achieving a steady-state distribution. A collection of Monarchs deployed near geostationary orbit, where J2 and atmospheric drag perturbations are negligible, would be more persistent and would achieve a stable distribution, as evidenced in Fig. 5. Of course, debris is of greater concern for deployments at these altitudes and requires a risk mitigation strategy.

For years academic research into spacecraft swarms has offered the promise of new missions, but only chipsats are truly capable of putting these ideas into practice. Thanks to Monarchs, a low-Earth orbit swarm is well within the realm of possibility. Furthermore, such a swarm architecture likely would offer valuable scientific data elsewhere in the solar system, such as among Saturn's rings, around a comet or asteroid, or around Enceladus — where they could plausibly be used as distributed plume samplers. There is nothing technologically challenging about the suite of sensors with which the Monarchs are currently equipped; Monarchs can accommodate any surface-mounted sensor that meets the size and power requirements. So, for each of these destinations, a destination-specific Monarch could be constructed to answer a particular set of questions.

IV. Statistical Mission Assurance for High-Risk Missions

As with R-selected species, one of the key advantages to employing high quantity for low risk rather than high cost for low risk is that mission success does not depend on any constituent member of the group. As a consequence, Monarchs can go places and take actions that would be prohibitively dangerous for large, conventional spacecraft. And individual Monarchs are disposable. So, in addition to the favorable impact mechanics associated with their low size and mass, Monarchs are extraordinarily well suited for high-risk planetary science and atmospheric reentry missions. Monarchs can be used to descend to the surfaces and through atmospheres of celestial bodies, such as Venus, Titan, or Europa. Their small size makes entry, descent, and landing (EDL) methods significantly different for Monarchs than for conventional spacecraft. Importantly, one does not need to guarantee survival of every Monarch throughout EDL, only to guarantee the statistics of survival. This mindset is entirely new in the field of planetary exploration.

The Monarchs' size makes them better equipped for surviving impacts, turbulence, and other shock-related effects than large conventional spacecraft. Scaling benefits the robustness of small spacecraft, since mass scales with approximately the cube of length, and strength with approximately the square of length. Smaller things exhibit higher natural structural frequencies and approach crystal-lattice stiffness. They are therefore stronger and can take a greater beating. This fact is also apparent in nature, where insects have proportionally greater strength than larger creatures and are capable of withstanding shocks that larger animals could not survive [30–33]. Monarchs are the insects of spacecraft. Their resilience has significant implications for the entry, descent, and landing technology required to give Monarchs a chance of survival. There is evidence, in fact, that no such technology is required at all and that Monarchs may survive impacts with no additional protection.

A durability study in 2017 exposed 12 Monarch precursors (printed circuit board test articles) to 5000-27,000 g's of acceleration normal to the board surface via an elastically loaded drop table. The drop table is described at length in [34, 35]. Each board carried the same inertial measurement unit (IMU) as the Monarch, the internal mechanics of which make it the most shock-sensitive component on the spacecraft. Lunar regolith simulant was placed underneath each test article in order to simulate impact with the lunar surface, as shown in Fig. 6. Prior to impact, each board was placed in a static testbed and a batch of measurements was gathered from the accelerometer, magnetometer, and gyroscope. This step verified that the IMU on each board was operating to within the specifications of the datasheet, and characterized each sensor before impact. After impact, each test article was placed in the same testbed and measurements were gathered again from the same set of sensors in order to characterize degradation. As shown in Fig. 7, each IMU continued to operate to within manufacturer specifications for zero-g, zero-Gauss, and zero-rate levels after impact with the lunar regolith simulant [36]. This empirical assessment by no means guarantees that every Monarch would survive impact with a celestial body, but it suggests that they have a chance of surviving. If some number k Monarchs are required for mission success and one deploys $N > k$, then up to $\frac{N-k}{N}$ percent may fail on impact before the mission itself becomes unsuccessful. Mission assurance for Monarchs is statistical, and mission assurance equations can be derived from binomial distributions.

Suppose that N chipsats are deployed to the surface of a celestial body, each with a probability p_1 of surviving impact. The probability of having any $k \leq N$ survive that impact is given by eqn. 1. Put alternatively, this expression yields the probability of $k \leq N$ chipsats surviving 0 days on the surface. Each chipsat that survives impact then faces the threats associated with existing on the surface, including radiation. If one lets the probability of surviving each day be p_2 and makes the simplifying assumptions that this probability does not change with time, and that failures among chipsats are not correlated, then eqn. 2 gives the probability that $j \leq k$ chipsats survive for M days. These expressions can be used to find the probability of mission success.

$$p(k \leq N \text{ surviving impact}\Big| p_1, N) = \frac{N!}{k!\,(N-k)!} p_1^k \,(1-p_1)^{N-k} \tag{1}$$

$$p(j \leq k \text{ surviving } M \text{ days on surface} \Big| p_2, M, k) = \frac{k!}{j!\,(k-j)!} \left(p_2^M\right)^j \left(1 - p_2^M\right)^{k-j} \tag{2}$$

For a mission like the one under consideration, mission success is defined as at least specified number $j \leq N$ of chipsats remaining alive on the surface for a specified number of days, M. Eqn. 3 yields the probability of success provided the number of chipsats deployed to the surface (N), the number of days associated with the mission success criterion (M), the number of remaining chipsats associated with the success criterion (j), the probability of any individual chipsat surviving impact (p_1), and the probability of any individual chipsat surviving each day on the celestial body (p_2).

$$\begin{gathered} p(j \geq (k \leq N) \text{ surviving impact and } M \text{ days on surface} \Big| N, M, p_1, p_2) = \\ \sum_{k=j}^{N} \left[\frac{N!}{k!\,(N-k)!} p_1^k \left(1 - p_1\right)^{N-k} \cdot \sum_{i=j}^{k} \frac{k!}{i!\,(k-i)!} \left(p_2^M\right)^i \left(1 - p_2^M\right)^{k-i} \right] \end{gathered} \tag{3}$$

Eqn. 3 represents a general model for evaluating the likelihood of success for any of these high-risk planetary missions. The variables within this equation must be populated with values specific to the particular mission being performed. The values for p_1 and p_2 will vary substantially from one celestial body to the next and must be determined via testing. The values for j, M, and N will depend on mission requirements. Fig. 8 shows a heatmap for the probability of mission success for a range of impact survival probabilities and daily survival probabilities. This heatmap is generated for the particular case where success is defined as at least 5 of 100 chipsats surviving for 100 days on the surface. This paradigm in mission assurance places value on the confidence bounds, achieved by the quantity rather than quality of individual spacecraft. The nature of the data that Monarchs can gather once on the surface is best illustrated through a case study.

A case-study planetary science mission was performed in order to gather a representative dataset. 20 Monarchs were deployed to the surface of Earth for 24 hours, during which time they remotely reported in-situ data from their payload sensor suite, which included a temperature and humidity sensor. Each also reported its location, as measured by its onboard GPS. The locations of the deployed Monarchs and the data that they gathered is shown in Fig. 9. For this case study, the planet in question happens to be Earth and the sensory payload happens to include temperature and humidity sensors, but there is nothing special, from a technical perspective, about that particular celestial body or sensory payload. For other celestial bodies, the payload may include a different suite of sensors.

V. Conclusion

The Monarch applies biological principles for mission assurance to space exploration and consequently is the first spacecraft to trade high quantity for low mission risk. By taking a statistical approach to mission assurance and devaluing the importance of any particular spacecraft, Monarchs open the door to a new paradigm in space access and exploration. They are not small versions of large spacecraft, and they do not replace large spacecraft. Instead, Monarchs have an entirely new and unique set of use cases. They enable distributed, in-situ sensing, which will provide scientific datasets of an unprecedented variety. As a consequence of their size and quantity, Monarchs can perform entry, descent, and landing missions that would be far too risky for conventional spacecraft to attempt. And, perhaps just as significantly, Monarchs reduce the cost of access to space by orders of magnitude. Because they can be carried to orbit by the hundreds or thousands, the launch costs may be divided among many hundreds or thousands of Monarchs. The result is that space is no longer only accessible to governments, large companies, and universities, but also to high school classrooms and hobbyists. The Monarch is the greatest force for the democratization of space that has ever existed.

Funding Sources

Thank you to the Space Systems Design Studio at Cornell University for funding this work.

Acknowledgments

Thank you to Rob Quigley and Chris Lin of New Ascent, as well as the University of Maryland, for their assistance with impact testing the Monarch test articles. Thank you also to NASA Ames for providing lunar regolith simulant for the tests. All data and analysis from those tests can be found at https://github.com/vha3/Super-G. All of the CAD files for the Monarch spacecraft can be found at https://github.com/vha3/Monarch-Board, and all of the associated software can be found at https://github.com/vha3/Monarch-Software. Thank you to Kirstin Petersen for her help planning the lab demonstrations of the Monarchs, and thank you to Samuel Feibel and Philip Whitmarsh for their assistance in carrying out those demonstrations. Thank you to Rodrigo Taipe for his help carrying out the field demonstrations of the Monarchs, and thank you to the folks at Anthony Road Vineyard for supporting those field demonstrations. Thank you to Dmitry Savransky for reviewing this paper. Thank you to the Space Systems Design Studio at Cornell University for funding this work.

References

[1] Shimmin, R., Agasid, E., Burton, R., Carlino, R., Defouw, G., Perez, A., Karacaliglu, A., Klamm, B., Rademacher, A., Schalkwyck, J., tilles, J., and Weston, S., "Small Spacecraft Technology State of the Art," Tech. Rep. TP-2015-216648, NASA, Moffett Field, California, 2017.

[2] Roesler, G., "Robotic Servicing of Geosynchronous Satellites (RSGS)," *Defense Advanced Research Projects Agency, http://www.*

darpa. mil/program/robotic-servicing-of-geosynchronous-satellites (14 July 2017). Google Scholar, ????

[3] Crisp, J., Adler, M., Squyres, S., Arvidon, R., and Kass, D., “Mars Exploration Rover Mission,” *Journal of Geophysical Research: Planets*, , No. 108, 2003.

[4] Marshall, W., and Boshuizen, C., *Planet labs’ remote sensing satellite system*, Smallsat Conference, 2013.

[5] Wertz, J., and Larson, W., *Space Mission Analysis and Design*, 3rd ed., Microcosm, 1999.

[6] Guarro, S., Johnson-Roth, G., and Tonsey, W., “Mission Assurance Guide,” Tech. Rep. TOR-2007(8546)-6018, The Aerospace Corporation, El Segundo, California, 2012.

[7] Pianka, E. R., “On r-and K-selection,” *The American Naturalist*, Vol. 104, No. 940, 1970, pp. 592–597.

[8] Spagnulo, M., Fleeter, R., Balduccini, M., and Nasini, F., “Examples of Management Applied to Different Space Programs,” *Space Program Management*, Springer, 2013, pp. 277–330.

[9] Schaller, R. R., “Moore’s law: past, present and future,” *IEEE spectrum*, Vol. 34, No. 6, 1997, pp. 52–59.

[10] Helvajian, H., *Microengineering aerospace systems*, Aiaa, 1999.

[11] Manchester, Z., Peck, M., and Filo, A., “Kicksat: A crowd-funded mission to demonstrate the world’s smallest spacecraft,” 2013.

[12] Instruments, T., “CC1310 Simplelink™ Ultra-Low Power Sub-1GHz Wireless MCU,” *CC1310 datasheet, Sept*, 2015.

[13] Friis, H. T., “A note on a simple transmission formula,” *Proceedings of the IRE*, Vol. 34, No. 5, 1946, pp. 254–256.

[14] Shannon, C. E., “A mathematical theory of communication,” *ACM SIGMOBILE mobile computing and communications review*, Vol. 5, No. 1, 2001, pp. 3–55.

[15] Berrou, C., Glavieux, A., and Thitimajshima, P., “Near Shannon limit error-correcting coding and decoding: Turbo-codes. 1,” *Communications, 1993. ICC’93 Geneva. Technical Program, Conference Record, IEEE International Conference on*, Vol. 2, IEEE, 1993, pp. 1064–1070.

[16] Markley, F. L., and Crassidis, J. L., *Fundamentals of spacecraft attitude determination and control*, Vol. 33, Springer, 2014.

[17] Shuster, M. D., and Oh, S. D., “Three-axis attitude determination from vector observations,” *Journal of Guidance, Control, and Dynamics*, Vol. 4, No. 1, 1981, pp. 70–77.

[18] Wahba, G., “A least squares estimate of satellite attitude,” *SIAM review*, Vol. 7, No. 3, 1965, pp. 409–409.

[19] Markley, F. L., “Attitude determination using two vector measurements,” Tech. rep., NASA, 1998.

[20] Silani, E., and Lovera, M., “Magnetic spacecraft attitude control: a survey and some new results,” *Control Engineering Practice*, Vol. 13, No. 3, 2005, pp. 357–371.

[21] Lovera, M., and Astolfi, A., “Spacecraft attitude control using magnetic actuators,” *Automatica*, Vol. 40, No. 8, 2004, pp. 1405–1414.

[22] Wertz, J. R., *Spacecraft attitude determination and control*, Vol. 73, Springer Science & Business Media, 2012.

[23] Likins, P. W., “Effects of energy dissipation on the free body motions of spacecraft,” Tech. Rep. 32-860, NASA JPL, 1966.

[24] Atchison, J. A., and Peck, M. A., “Length scaling in spacecraft dynamics,” *Journal of guidance, control, and dynamics*, Vol. 34, No. 1, 2011, pp. 231–246.

[25] Immel, T., England, S., Mende, S., Heelis, R., Englert, C., Edelstein, J., Frey, H., Korpela, E., Taylor, E., Craig, W., et al., “The Ionospheric Connection Explorer mission: mission goals and design,” *Space Science Reviews*, Vol. 214, No. 1, 2018, p. 13.

[26] Maute, A., “Thermosphere-ionosphere-electrodynamics general circulation model for the ionospheric connection explorer: TIEGCM-ICON,” *Space Science Reviews*, Vol. 212, No. 1-2, 2017, pp. 523–551.

[27] Englert, C. R., Harlander, J. M., Brown, C. M., Stephan, A. W., Makela, J. J., Marr, K. D., and Immel, T. J., “The Michelson interferometer for global high-resolution thermospheric imaging (MIGHTI): wind and temperature observations from the ionospheric connection explorer (ICON),” *Fourier Transform Spectroscopy*, Optical Society of America, 2013, pp. FW1D–3.

[28] Adams, V. H., and Peck, M. A., “A Probabilistic Network Formulation for Satellite Swarm Communications,” *2018 AIAA Information Systems-AIAA Infotech@ Aerospace*, 2018, p. 1802.

[29] Atchison, J. A., Mitch, R. H., and Mazarico, E., “Optical Gravimetry for Flyby Missions: Parametric Study and Validation,” *Lunar and Planetary Science Conference*, Vol. 48, 2017.

[30] Shimoyama, I., “Scaling in microrobots.” *IROS (2)*, 1995, pp. 208–211.

[31] Schmidt-Nielsen, K., *Scaling: why is animal size so important?*, Cambridge University Press, 1984.

[32] Pedley, T. J., “Scale effects in animal locomotion,” *International Symposium on Scale Effects in Animal Locomotion (1975: Cambridge University)*, Academic Press, 1977.

[33] McMahon, T. A., and Bonner, J. T., *On size and life*, Scientific American Library, 1983.

[34] Meng, J., “Multi-Scale Dynamic Study of Secondary Impact During Drop Testing of Surface Mount Packages,” Ph.D. thesis, 2016.

[35] Douglas, S. T., “High accelerations produced through secondary impact and its effect on reliability of printed wiring assemblies,” Ph.D. thesis, 2010.

[36] Microelectronics, S., “LSM9DS1 iNEMO inertial module,” *Product Datasheet*, 2013.

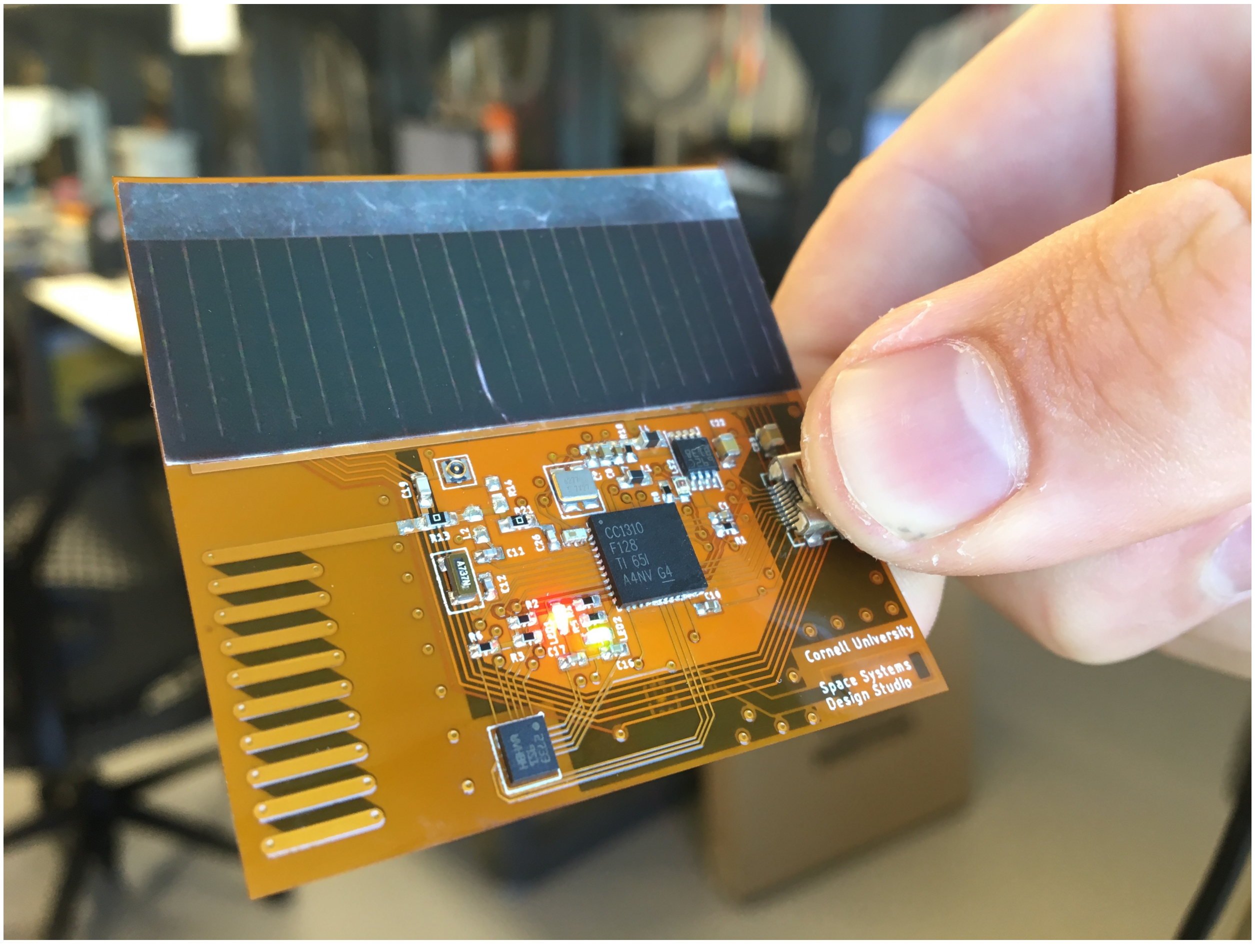

Fig. 1 A biologically-inspired Monarch spacecraft, capable of in-situ sensing and radio networking with other Monarchs and with ground-based receiver stations.

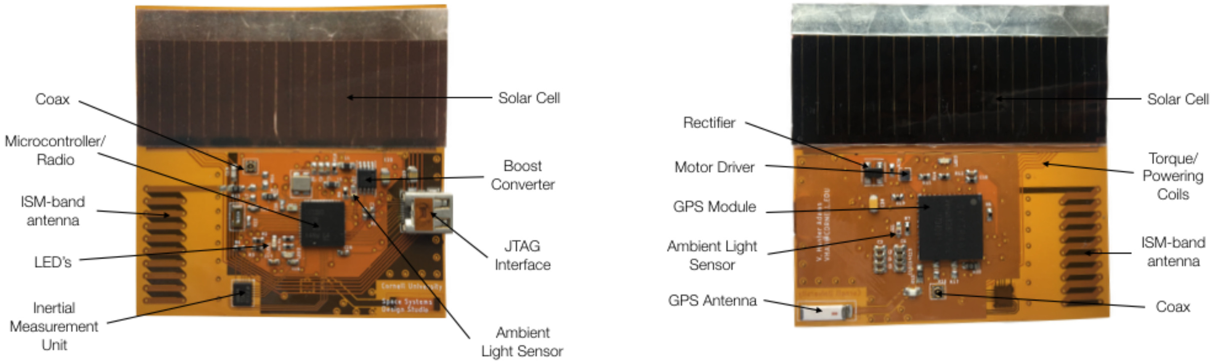

Fig. 2 Monarch spacecraft with consumer-market electronics components labeled.

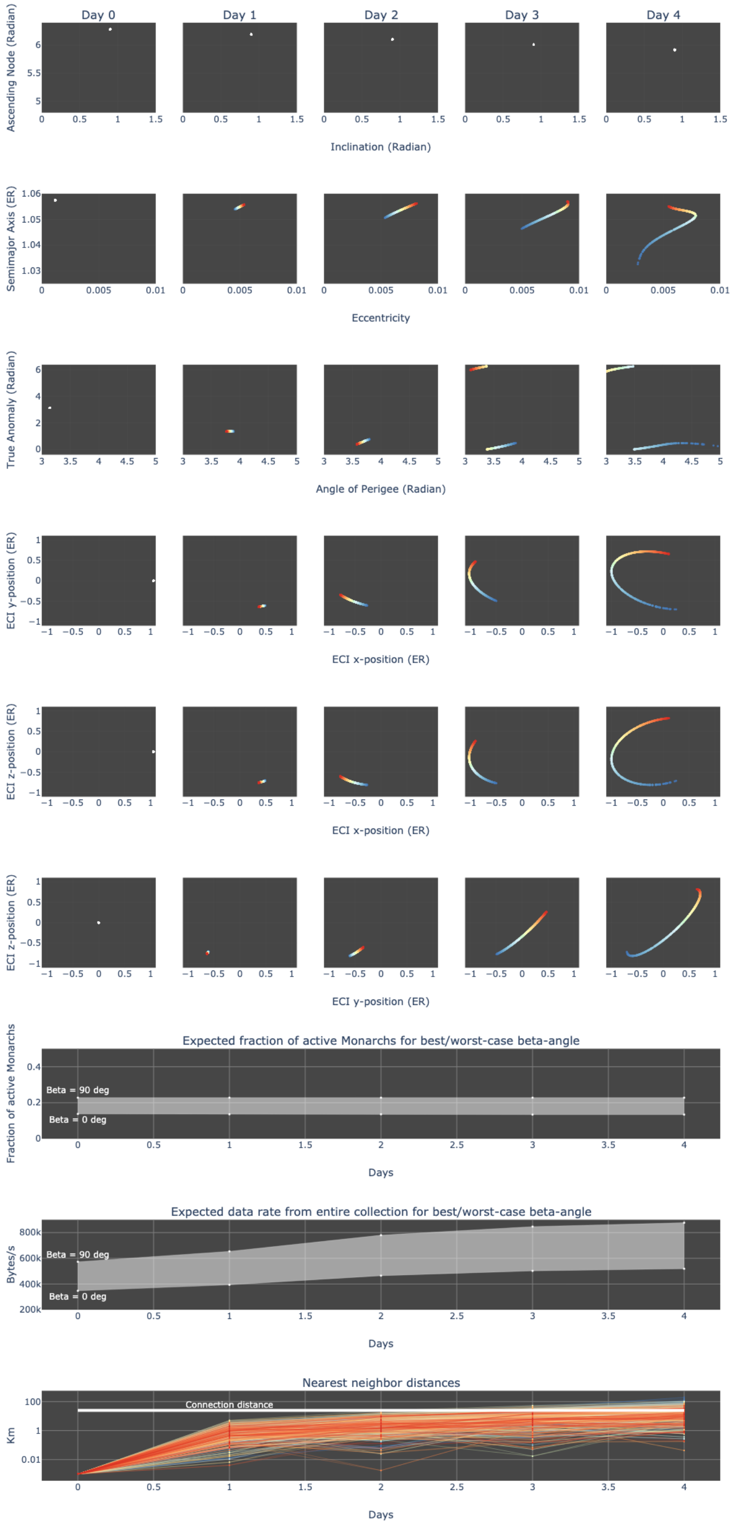

Fig. 3 500 Monarchs deployed from the International Space Station. Plots of each Monarch's orbital elements, Earth-centered inertial position, and distance to nearest neighbor (individually colorized). Plots of range of expected fraction of active Monarchs and expected range of datarates from the collection.

Fig. 4 Artistic representation of a swarm of networked Monarchs performing a distributed in-situ sensing mission in low-Earth orbit.

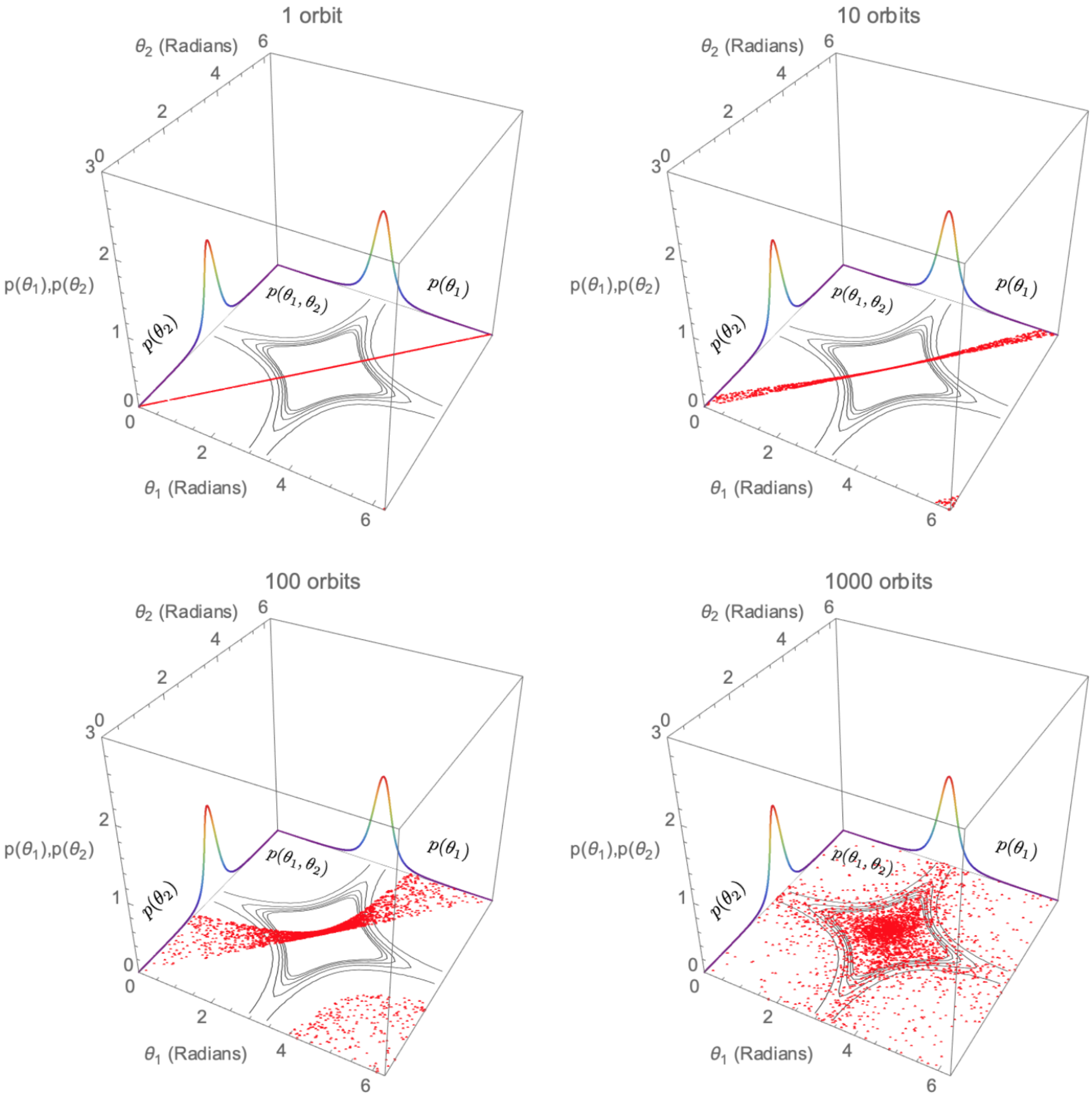

Fig. 5 True anomalies of two Monarchs deployed on orbits at geostationary altitude and inclination, after varying numbers of orbits. Their orbits are identical except of a variation in eccentricity by one tenth of a percent.

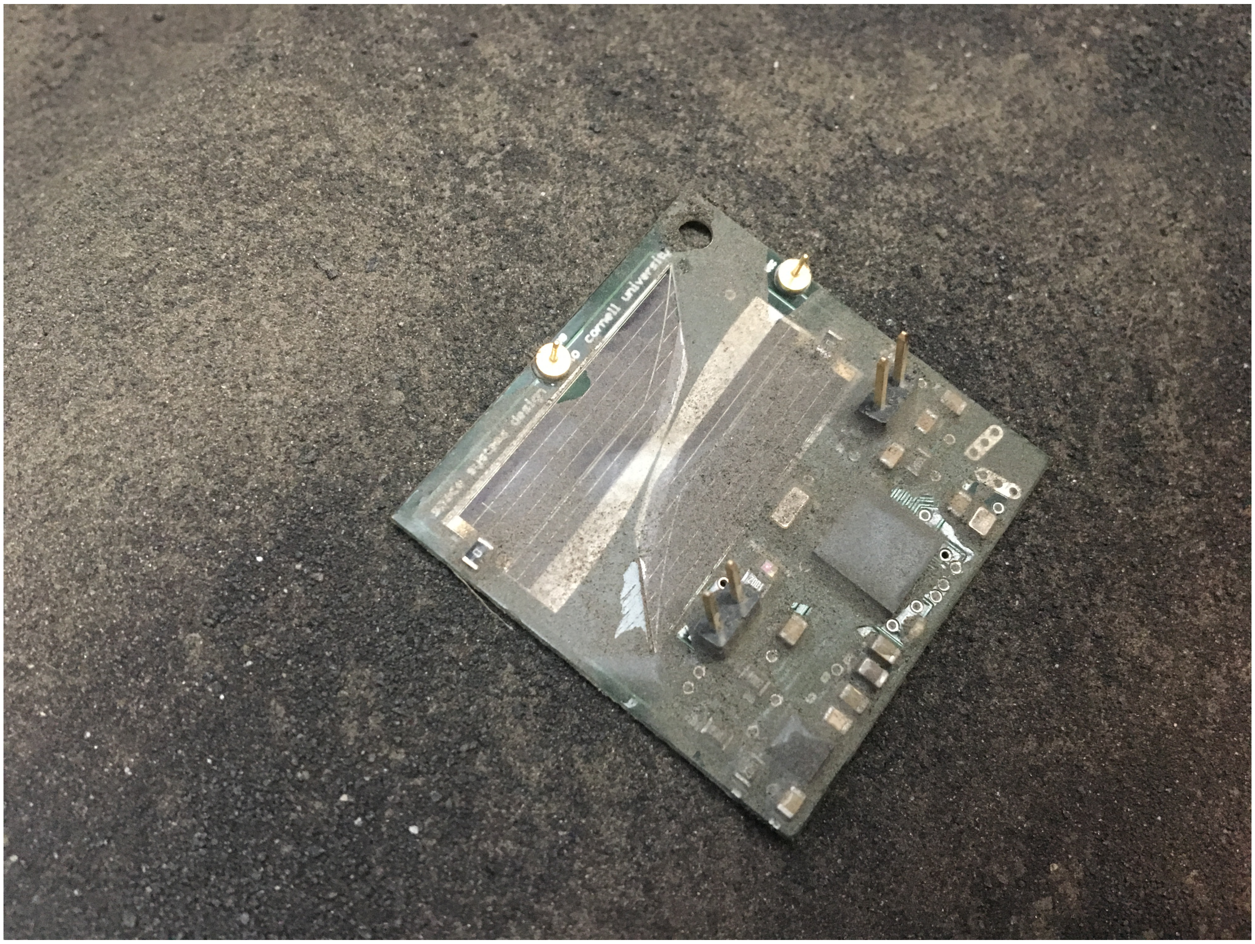

Fig. 6 Impact test article on bed of lunar regolith simulant after exposure to 27,000 g's of acceleration to simulate impact with the lunar surface.

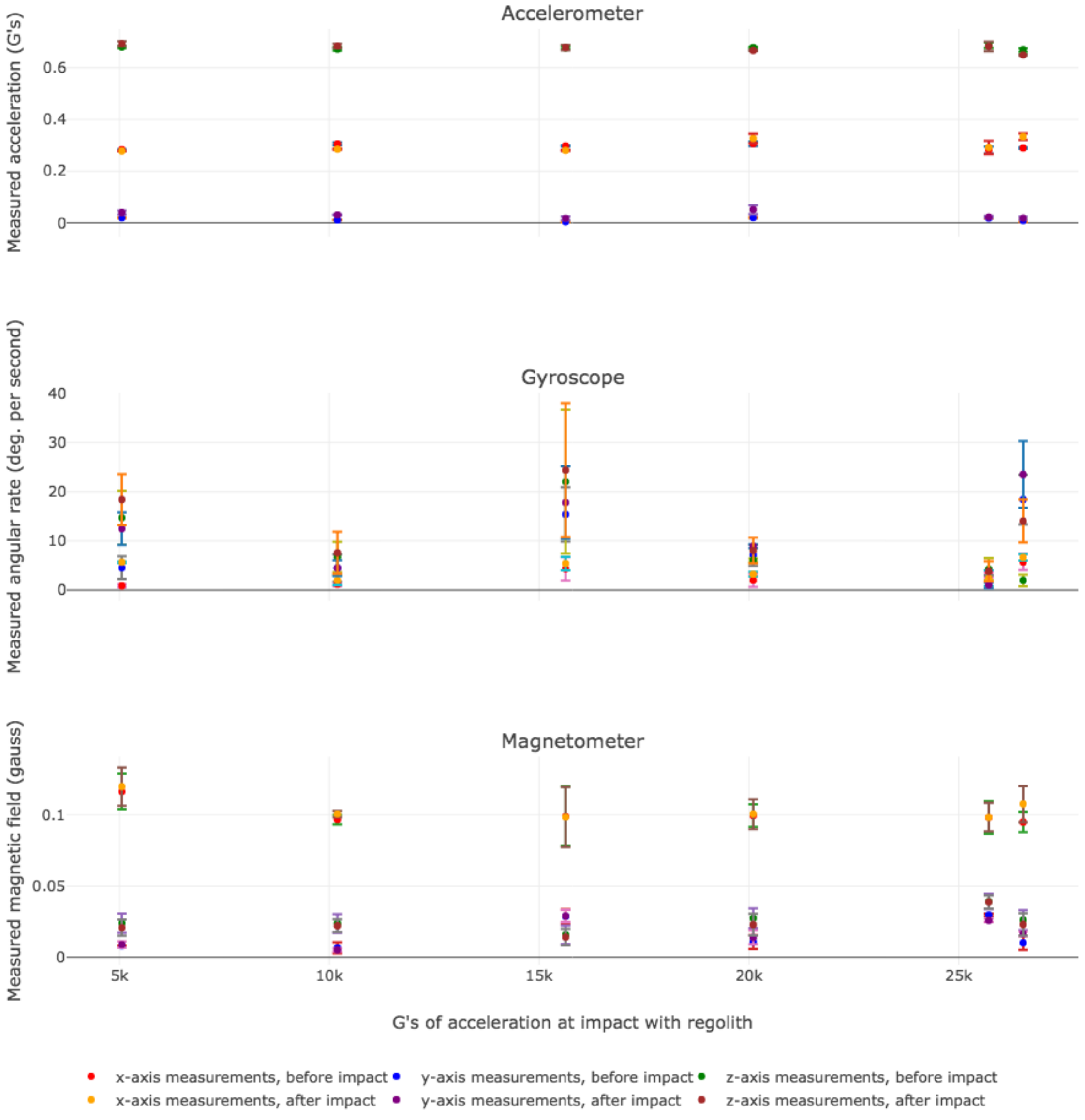

Fig. 7 IMU measurements before and after impact with lunar regolith simulant, showing that the MEM's sensor survives and continues to operate to within the specifications of the datasheet. [36]

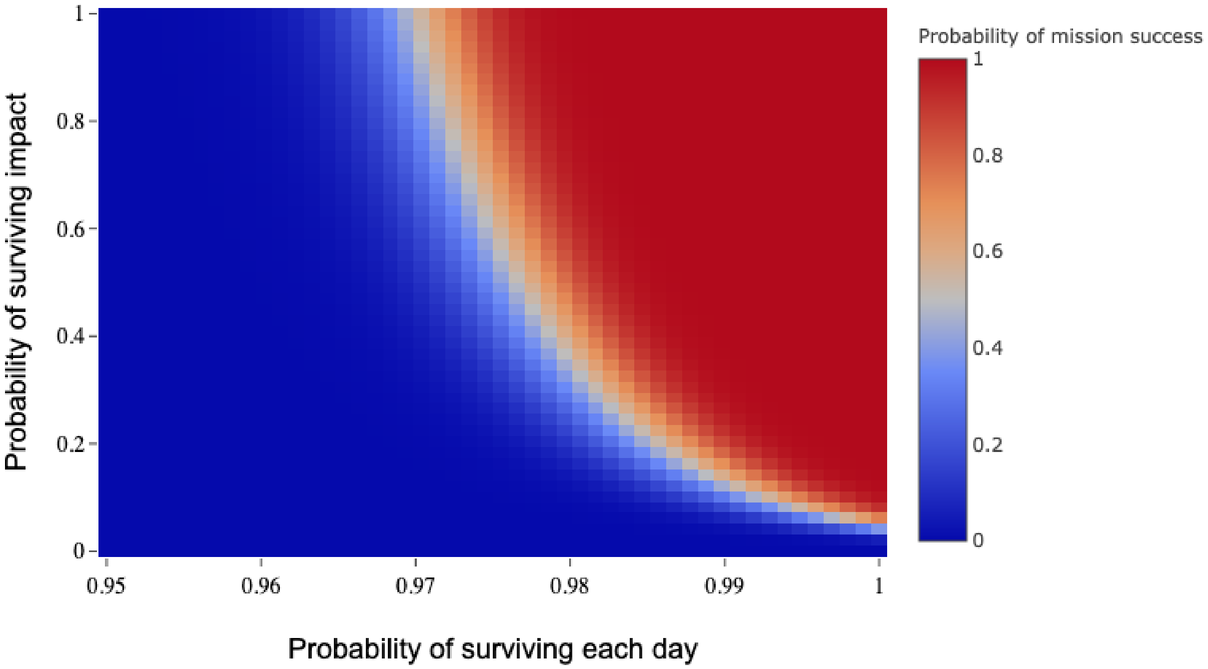

Fig. 8 The probability of mission success, defined as 5 of 100 chipsats surviving on the the surface of a celestial body for 100 days, for a range of impact survival probabilities and daily survival probabilities.

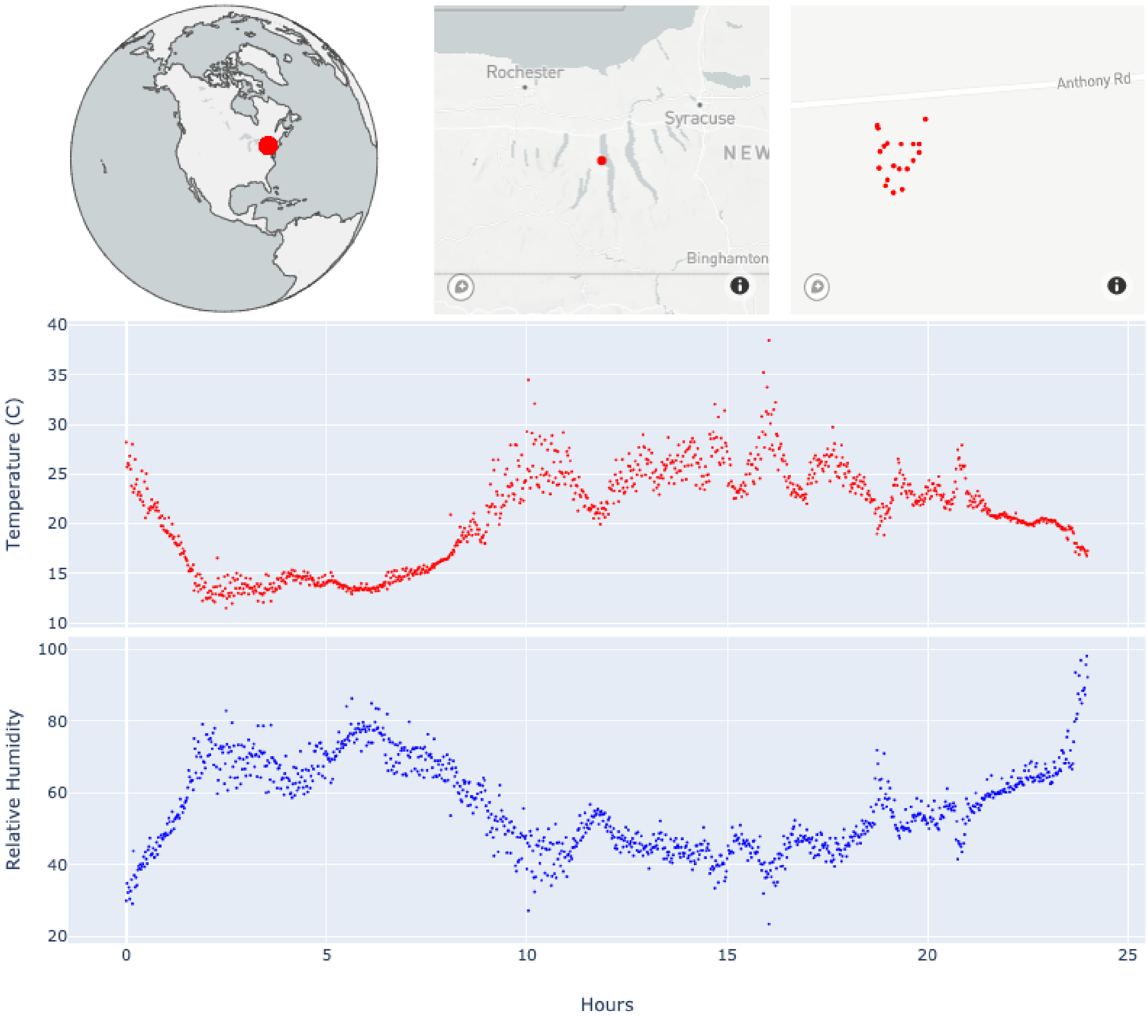

Fig. 9 **Dataset collected from a collection of Monarchs in a case-study planetary science mission on Earth. Monarchs were distributed on the surface of the planet, where they gathered in-situ environmental data for 24 hours.**

Supplementary materials

Movie S1 contains video demonstrations of distributed sensing, leaderless cooperation, routing, torque coils, inductive powering, and solar powering.