Landing Gear Design, Fabrication, and Testing for the Ingenuity Mars Helicopter

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Abstract—**This paper describes the development of the landing gear system for the Ingenuity Mars Helicopter. Ingenuity is a 1.8 kg co-axial helicopter which demonstrated the first powered, controlled flight at Mars on April 19, 2021. As part of the Mars 2020 mission, Ingenuity was deployed from the Perseverance Rover, which landed at Jezero Crater in February 2021. To ensure safe, autonomous landings on unfamiliar terrain in variable weather conditions without the need for an onboard obstacle avoidance system, the landing gear was designed to provide no less than 50 mm ground clearance when landing at velocities up to 2 m/s vertically, 0.5 m/s horizontally, and with angular rates up to 40 deg/s. The system consists of a composite central interface plate, spring-loaded deployment hinges, suspension spring flexures and dampers, and four hollow composite landing legs and feet, all of which were uniquely designed for conditions at Mars. Traveling with the Perseverance Rover required the landing legs to be folded into four unique positions within a compact not-to-exceed volume beneath the belly pan of the rover. During deployment from the Perseverance Rover, the helicopter's landing legs deployed passively and latched securely before Ingenuity could be released onto the Martian surface. In order to reduce bounce and angular rates upon landing, each leg employs a titanium spring flexure coupled with an annealed 1100-series aluminum damper which yields as the leg deflects by as much as 17 degrees, providing up to 80 mm of vertical travel. During the development and verification process of the landing gear system, an extensive test campaign was performed to validate structural properties, landing dynamics, and reliable actuation of the deployment mechanisms. A testbed to simulate varied Martian surface conditions was fabricated in a Vicon motion capture lab at AeroVironment's Simi Valley facility to evaluate touchdown dynamics across a wide range of landing conditions.**

In this paper, the authors will describe:

1. **The conditions and surfaces that the landing gear system was designed to withstand;**
2. **Unique design features of the composite interface plate and leg hub, carbon clevis, deployment mechanism, suspension spring and damper, hollow carbon fiber leg tubes, and feet;**
3. **The unique challenges and solutions involved in stowing the landing gear within the strict and complex constraints of the available space and reliably deploying the landing gear in preparation for release onto the Martian surface;**
4. **Test procedures and results for the landing gear system's development and verification campaigns.**

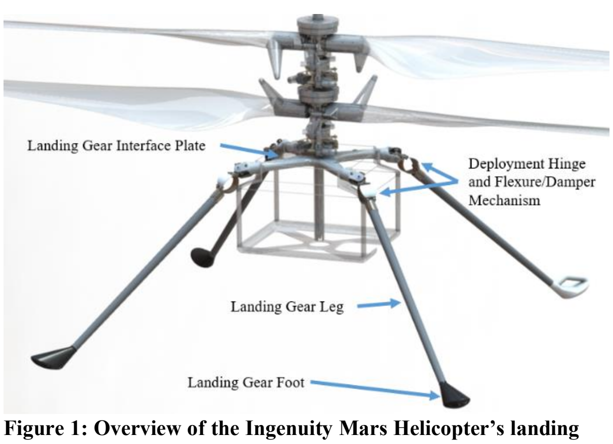

Figure 1: Overview of the Ingenuity Mars Helicopter's landing gear system

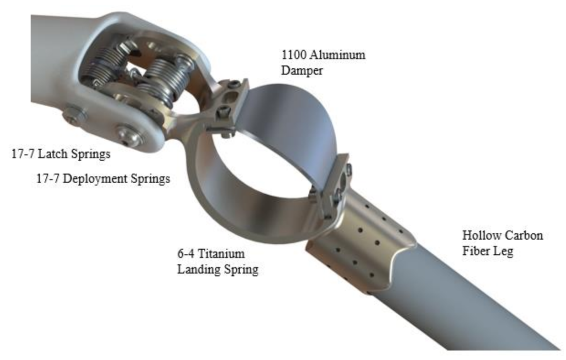

Figure 2: Detailed view of the landing gear mechanism. Carbon clevis, deployment springs and latches, landing flexure and damper, and leg tube are shown.

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1. INTRODUCTION

Ingenuity Mars Helicopter is a coaxial helicopter operating at Jezero Crater in cooperation with the Mars 2020 Perseverance Rover [1]. The program is led by NASA Jet Propulsion Laboratory (JPL) in collaboration with AeroVironment, Inc. (AV). The helicopter has a mass of 1.8kg, rotor diameter of 1.21m, and stands 0.49m tall. Ingenuity's original 30 day mission was to complete up to 5 increasingly ambitious flights to demonstrate the feasibility of flight at Mars. The success of the original mission has led to Ingenuity's role being expanded to demonstrate the value and practicality of aerial scouting support for rover mission planning and independent collection of scientifically valuable imagery. As of this writing, Ingenuity has performed thirteen flights including some over terrain too difficult for the Perseverance Rover to access in order to identify potential areas of high interest to the science community.

Ingenuity has no onboard landing site detection or obstacle avoidance capability as it was intended to operate from an ideal airfield approved by the design team after thorough evaluation of high-resolution ground-based imagery acquired by the rover. However, the newly expanded mission has since included many new landing sites, the majority of which have been found directly from satellite imagery, which cannot resolve rocks or terrain features on the scale of the helicopter (Figure 3). This places a much higher reliance upon Ingenuity's landing gear performance for survival during landings in sandy, rocky, or uneven terrain. This paper describes the details of this landing gear system and its components as well as the design and validation processes. The landing gear system consists of a central interface plate, carbon fiber clevises, deployment springs and latches, suspension springs and dampers, as well as leg tubes and feet.

Figure 3: Ingenuity at Airfield H with Perseverance 175m to the North/East as seen by HiRise imager onboard Mars Reconnaissance Orbiter September 24, 2021. Credit: NASA/JPL-Caltech/University of Arizona

2. REQUIREMENTS

Requirements for the landing gear system were derived from modeled delivery conditions during helicopter landings, environmental predictions, and functional requirements during operation. Delivery conditions during landing were derived from the impact velocities and angular rates predicted by HeliCat simulations and uncertainty in sensor noise with reasonable margins added to account for wind shear, sloping or rocky terrain, and attitude/altitude errors [2] [3] [4]. Using these conditions, the landing gear geometry was designed to maximize ground clearance while also providing extremely high tip-over resistance (Figure 4).

Figure 4: Landing gear vertical clearance and blade strike angle measured in the virtual condition

Data analysis from satellite imagery provided information about topography, surface conditions, and rock distributions at the candidate landing sites and it was determined that a 10 m by 10 m airfield with ground slope less than 10 degrees and few rocks taller than 50mm could be located within 200 m of 90% of intended rover landing sites [5]. A minimum dynamic ground clearance of 50mm, including measured sink into soft surface substrates, was specified to ensure a very low probability of fuselage contact with the statistically common rocks at any pre-evaluated airfield. Figure 5 shows a typical rock distribution.

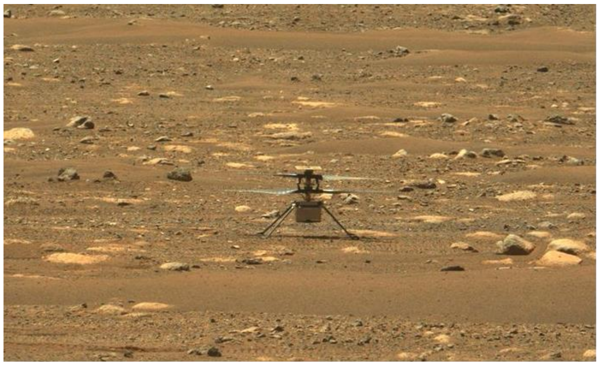

Figure 5: Ingenuity amongst rocks at Airfield H. Credit: NASA/JPL-Caltech

The overall airframe height was limited by the space available beneath the rover belly pan and Mars Helicopter Delivery System (MHDS) after deployment so great effort was made to minimize the vertical stack height of every part of the airframe from the top of the solar panel to the bottom of the fuselage to leave as much height as possible for suspension travel. This resulted in a maximum (nominal) ground clearance to the bottom of the Helicopter Warm Electronics Box (HWEB) of 130mm which, with the 50mm rock clearance minimum, allowed for 80mm of suspension travel.

To prevent structural damage to the rotor system, the suspension and damping elements of the landing gear system were designed to minimize accelerations during landing and prevent angular rates from exceeding 400 deg/s under worst-case delivery conditions. Based on the expected dynamics on touchdown, this system was iteratively designed and validated using drop tests in a simulated, Mars-like testbed described in later sections of this paper.

The landing gear system also needed to meet the harsh environments encountered during launch, cruise, entry/descent/landing, and surface operations at Jezero crater. Structural elements of the system were designed in accordance with requirements for margin and test factors outlined in NASA STD5001B, *Structural Design And Test Factors Of Safety For Spaceflight Hardware* [6]. In addition, the landing legs were designed such that the natural frequency of the cantilevered appendage modes would be outside the frequency range of the control system and away from the operating natural frequencies of the rotor system. Table 1, Table 2, and
Table 3 list the environmental requirements, expected conditions on landing, and functional requirements of the system.

Table 1: Environmental Requirements

Requirement	Value
Material and Process Compatibility	Comply with Mars 2020 planetary protection and contamination control plans
Launch Loads	60 g quasistatic (all axes) or 7.9g_{rms} input spectrum
Operational and non-operational allowable flight temperature range	-110°C to +50°C

Table 2: Delivery Conditions and Surface Requirements at Touchdown

Requirement	Value
Maximum Surface Slope	10 degrees, any direction
Maximum Aircraft Attitude (Roll/Pitch)	15 degrees
Maximum Angular Velocity	40 degrees/second
Maximum Horizontal Velocity	0.5 Meters/Second
Maximum Vertical Velocity	2.0 m/s
Additive Rock Height (for ground clearance)	5 cm Hemisphere
Surface Conditions	Soft sand to hard rock
Mars Gravity	3.721 m/sec^2

Table 3: Functional Requirements

Requirement	Value
Size/Envelope	Fit within Not-To-Exceed Volume
Deployment	Passive deployment and locking on release of restraint
Landing Leg Natural Frequency	>= 32Hz vertical; >=46Hz horizontal

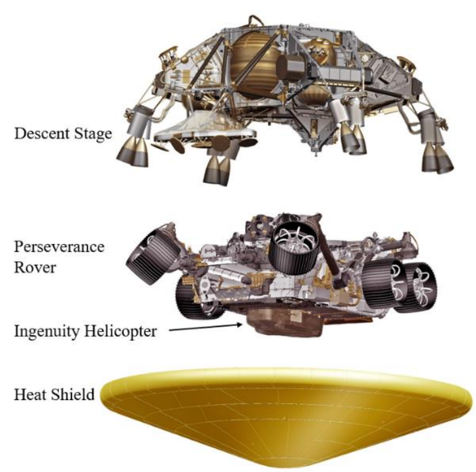

Figure 6: Ingenuity's location within the Mars 2020 spacecraft. The location of this small volume was the limiting requirement on the landing gear's size and stowed location. Credit: NASA/JPL-Caltech

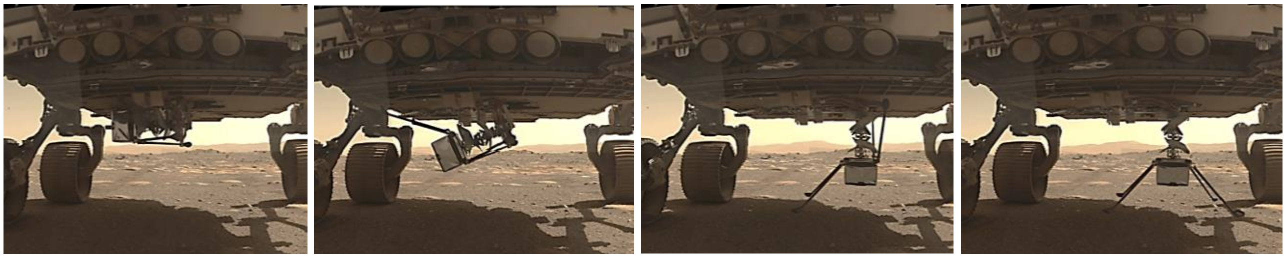

Figure 7: Deployment sequence of Ingenuity at Jezero Crater. Image 1: Helicopter stowed; Image 2: Helicopter released down and trailing legs deployed; Image 3: Helicopter brought vertical; Image 4: Leading legs deployed and ready for drop onto the surface. Credit: NASA/JPL-Caltech

Stowage and Deployment from the Perseverance

A limiting case for the design of Ingenuity's landing gear was the restrictive allowable stowed volume of the helicopter. As a technology demonstration mission, Ingenuity mounted to the belly pan of the Perseverance Rover, where it was held by the Mars Helicopter Delivery System (MHDS). MHDS supported the helicopter's primary structure, legs, and blades for launch, cruise, and entry/descent/landing (EDL), after which the system deployed the helicopter to the surface of Mars (Figure 7). The helicopter was located within the small space between the flat belly pan of the rover and the conical atmospheric entry heat shield (Figure 6) and was housed within a molded carbon honeycomb debris shield that protected the helicopter during descent to the surface (Figure 8).

Figure 8: Looking under Perseverance Rover after deploying the debris shield that protected Ingenuity during EDL. Credit: NASA/JPL-Caltech

The two leading legs were held in very specific locations to clear critical features on the rover's belly. The left foot visible in Figure 10 could not have been stowed any further to the left or it would interfere with critical rover hardware. As a result, when the helicopter is rotated upright, this foot protrudes into a pocket cut into the belly pan (Figure 9 and Figure 10). This foot is restrained along the 'ankle' of the leg tube. By comparison, the foot on the right would interfere with critical sections of the belly pan, in black, and therefore this foot had to be held lower so that it would not interfere when rotated vertical. The MHDS arm could not reach down far enough to grab the ankle of this leg and a hoop feature was added to only this foot to act as the restraint interface (Figure 30). The resulting geometry uses a unique deployment angle and swept volume for each leg and these angles are accommodated in the landing gear mechanisms.

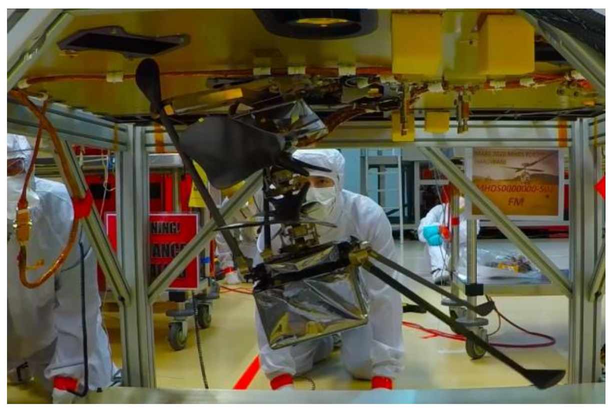

Figure 9: Ingenuity during a deployment test at Lockheed Martin Space. One leading foot protrudes into the black cup as the helicopter is brought vertical. Credit: LMS

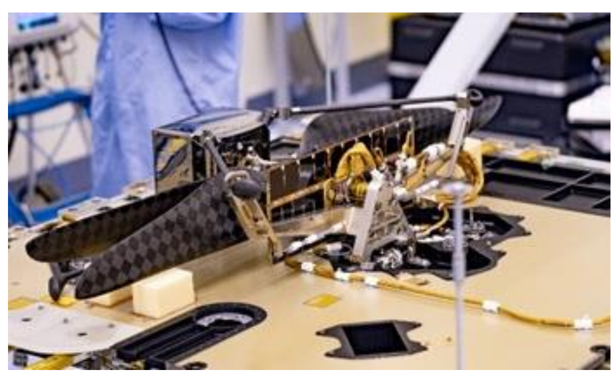

Figure 10: Ingenuity under the belly pan with stowed positions of the feet clearing critical rover hardware. Credit: NASA/JPL-Caltech

3. DESIGN APPROACH

The main purpose of Ingenuity's landing gear was to reduce landing dynamics that result in high rates on the vehicle and high impact loads on the individual components. The complexity of the leg system design and highly variable nature of the Martian surface conditions made the option of building a high-fidelity computer-based simulation of the helicopter and surface interaction impractical given the resources and schedule limitations. Once a set of satisfactory landing dynamics were obtained, those properties were used to design the landing gear system. In parallel, an analytical spreadsheet was created to ensure that the landing gear components would be able to match the stiffness qualities achieved in the testbed and be strong enough to survive landings. The use of these combined methods allowed the design process to happen efficiently and accurately, removing the need for a highly detailed and labor-intensive analytical model.

Landing Gear Testbed

A 'sandbox test' apparatus was used to iterate and validate the design of the landing leg system in sand, rocks, and simulated bedrock conditions. For environmental conditions it was critical to simulate the Mars gravity, but not the atmospheric density, wind, or temperature.

The primary goals of the sandbox tests included validation of the overall footprint dimensions, the vertical travel of the center of mass, and the conceptual design for the legs, springs, and dampers. The success of this testing heavily influenced the final landing gear design.

The basic test arrangement was to drop a helicopter model onto a representative Mars surface under simulated Mars gravity. Figure 11 shows the one-to-one scale vehicle simulator fabricated with the correct total mass, center of mass (CM), moments of inertia, and landing leg geometry used in these tests. The vehicle was supported at its center of mass such that a gravity offset system could pull upwards upon it without generating moments, allowing the vehicle to freely tumble upon landing without any artificial forces hindering the motion. The test vehicle was outfitted with an iterative series of suspension springs and dampers as the landing behavior was evaluated and optimized. Detailed design of the final spring and damper configuration is covered later in this paper.

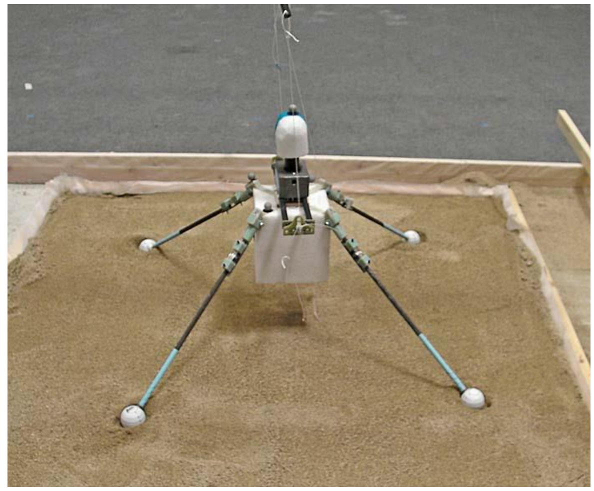

Figure 11: Simulation vehicle to match mass, inertia, landing gear geometry and conceptual spring design

To simulate the Martian surface under varying conditions, the sandbox was built from a thin layer of concrete poured to simulate a Mars bedrock surface, supported by a plywood base. Sand was placed over the concrete for some tests to simulate a deep sand surface, and individual rocks were placed over the concrete or in the sand, as desired. The entire platform was tilted to simulate 'uphill' or 'downhill' sloped landing approaches. Figure 12 and Figure 13 show the testbed setup and the simulated vehicle.

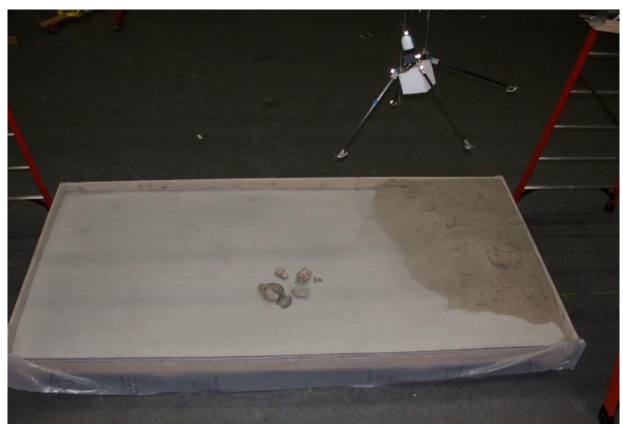

Figure 12: Testbed for landing gear testing that was capable of simulating bedrock, sand, and rocky conditions.

The gravity offset system used a large, brushed direct current (DC) motor with a pulley mounted to the output shaft. The motor was powered by a laboratory DC power supply with adjustable constant current. The constant DC current yields a constant torque on the motor shaft, which in turn yields a constant tension on a string attached to the pulley. In order to deal with motor heating that results from having the motor relatively stationary with a constant current, an oversized Maxon brand motor was used, allowing the large mass of the motor to absorb all of the waste heat without allowing the motor performance to degrade over the course of the test.

Figure 13: Adjusting drop height of the simulant vehicle before dropping into sand

The motor current was adjusted until the 1.8kg vehicle descended at 3.7 m/s^2. Because the worst-case conditions included a maximum lateral velocity of 0.5 m/s, the vehicle also needed to be set into a lateral motion while maintaining the Mars gravity force. To accommodate this, a simple gantry system was built which mounted the gravity offload motor and pulley to a linear sliding mechanism which was powered by a second large DC brushed motor, pulley, and string. The gantry drive motor drove the system at nearly a constant velocity.

The 'sandbox' landing tests were performed inside a Vicon motion capture lab to record high speed and high resolution estimates of the aircraft body angles, velocities, accelerations, suspension leg deflections, and resulting ground clearance. Vicon compatible retroreflector balls were attached to the vehicle in several places such that the motion capture system could continuously track the movement. Data from this motion capture system was used to verify that initial conditions met prescribed requirements and that the landing gear performance was sufficient. The vertical acceleration, lateral speed, pitch, roll, yaw angles, and pitch, roll, and yaw rate values were checked on the Vicon motion capture system shortly after each test drop/landing. Minor adjustments were made to the gravity offload current, the gantry drive voltage, and the hand release technique as required to achieve an acceptable test data set. High speed video of each test was captured for qualitative records.

The test campaign validated the notional design decisions for the leg springs, dampers, overall footprint spacing, and the vertical center of mass positioning. The spring-damper system was revised until acceptably low landing dynamics were achieved. The only landing gear failure was produced by testing the extreme configuration of rigidly supported legs, without any suspension, landing directly on simulated bedrock. In this case, two of the four legs catastrophically failed, confirming the fundamental design assumption that leg springs were required for vehicle safety. Similarly, without dampers, unacceptable bouncing was observed during tests on the concrete, confirming that dampers were necessary in order to reduce the likelihood of tipover. The suspension system also protects the rotor head bearings from being overloaded by gyroscopic forces by limiting angular accelerations of the airframe during impact and rebound.

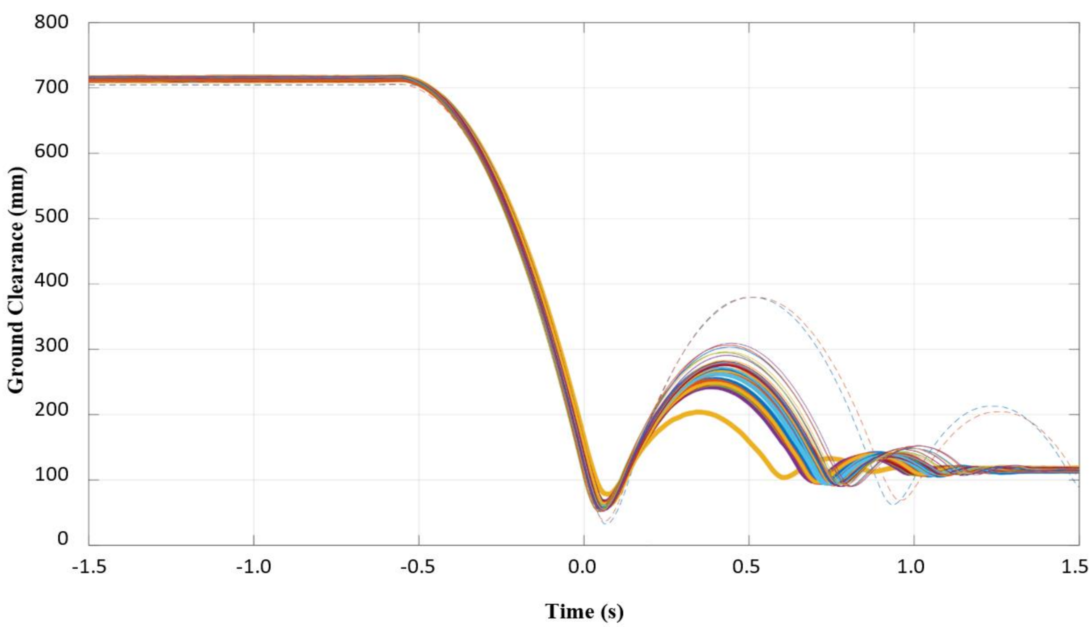

Figure 14: Damper degradation performance over 35 drops at descent rate of 2 m/s. The plot shows thinner lines later in the consecutive test series and the pattern of decreasing damping is shown in the higher rebound and longer settling time. Dashed lines are undamped tests for comparison.

Because the dampers fatigue with each cycle, damper lifetime was tested in this campaign. Figure 14 shows how the damper performance degrades with use but even worn dampers perform much better than the undamped scenario. Figure 15 shows the degradation in the amount of energy absorbed by the dampers by evaluating a proxy for energy still in the system after the first ground contact. It was found that the early damper design used in this test did degrade in their damping ability over time but lasted over 100 cycles in worst-case landings before degrading to an unacceptable performance level, with the best performance in cycles 10-20. A lifetime test showed 300+ cycles could be applied to the dampers before complete failure. No tip over cases were found, including the extreme corner cases of high rotation rates, high impact angle, high ground angle, maximum lateral velocity, and worst-case foot catch condition, confirming that the tested landing gear geometry was sufficient.

The summary of the test campaign showed that the conceptual design of the landing leg system was acceptable, and that a detailed design could be undertaken to optimize the system for minimal mass, deployment requirements, and stowed packaging requirements.

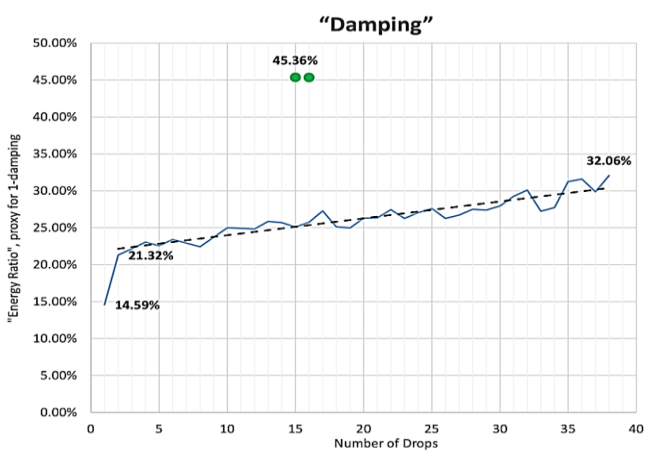

Figure 15: Degradation of damping effectiveness over the course of damper lifetime. "Damping" here is a ratio of the amount of energy in the system after the first rebound compared to before drop based on rebound height and angular rates. More energy remains in the system as the dampers degrade. The green points show undamped behavior.

Estimated Landing Loads Spreadsheet

Although the sandbox test campaign was used to iterate the initial spring and damper design, an analytical model was needed in order to properly define the spring rate characteristics that allow for safe landing of the aircraft similar to what was developed during the practical testing. To accomplish this, a spreadsheet calculator was used to tune the spring design until the landing dynamics, stroke, and resulting ground clearance were acceptable.

To calculate the optimum landing gear spring and damper rates for the maximum expected descent velocity of 2 m/s at touchdown, the aircraft's deceleration (Figure 17) due to the following forces were integrated at each step in the calculation:

- Vertical component of the load from the ground as it varies trigonometrically relative to the suspension spring as the leg sweeps thru its angular deflection range (Figure 16)
- Damper resistance as it varies through deflection angles (Figure 27).
- Complimentary varying component of the additional damping resulting from the feet scrubbing on the surface as they splay outward with an assumed friction coefficient of 0.6.

In addition to these spring forces, acceleration due to Martian gravity of 3.7 m/s^2 is applied. These calculations are performed at discretized steps through the suspension travel to build up a model of the full suspension behavior. To provide extra margin in the case of uneven terrain these calculations assume that one foot will land on a high or low spot such that only 1 diagonally opposed pair of feet will experience full travel while the other pair experiences only half travel. Ultimately, this spreadsheet was used to determine spring rates for the landing gear spring and damper system and those parts were designed to match this performance specification, which was verified through testing. Based on this analysis, the resulting loads used for part sizing within the landing gear system were 42.73 N applied vertically at the foot and 31.98 N applied laterally based on the worst-case assumption that lateral velocities are arrested by a foot snagging on a step or rock.

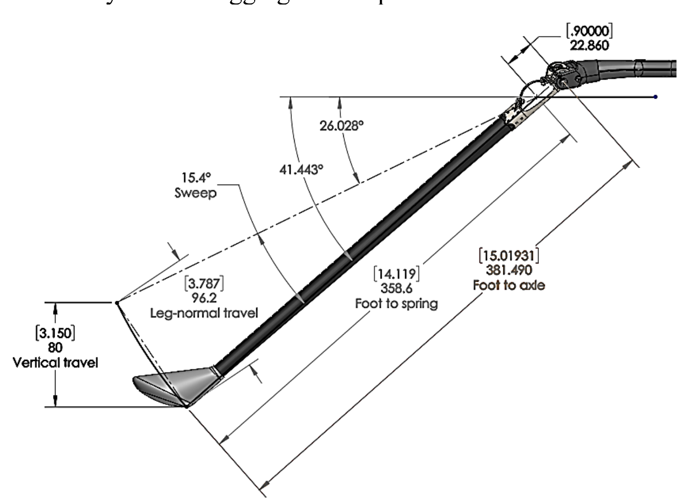

Figure 16: Landing leg geometry used to calculate spring forces and model spring-damping behavior

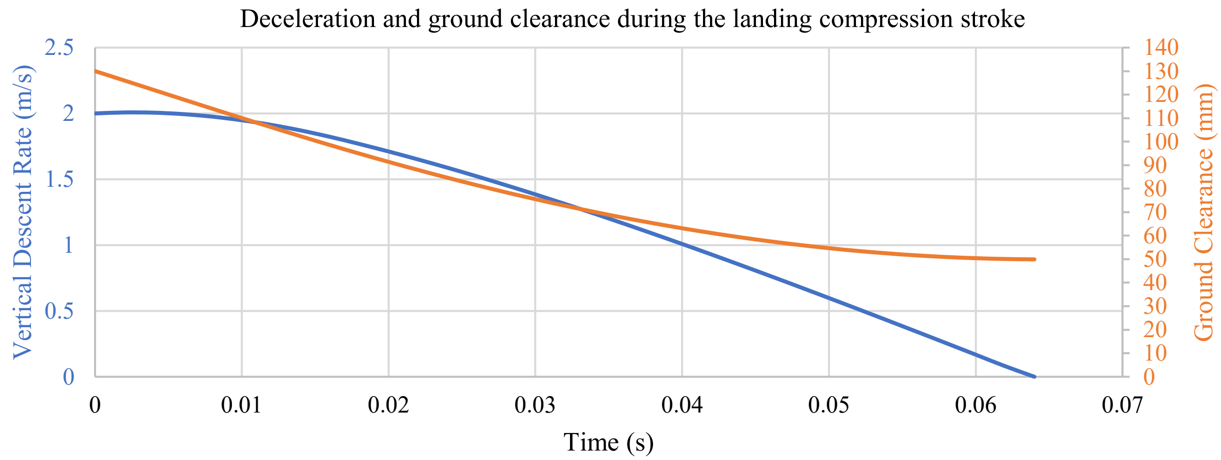

Figure 17: Ground clearance and vehicle velocity as modeled due to spring forces discretized through the stroke

4. LANDING GEAR ANATOMY

The landing gear system for Ingenuity consists of an interface plate, hinge clevis and deployment mechanism, suspension flexure and damper, leg tubes, and feet. Each of these components is highly optimized and purpose built. For example, the titanium flexure acts as the suspension spring, leg interface, damper interface, deployment mechanism, and latch interface. The system was analytically designed and sized to match the performance specifications seen in the simulation testbed, especially in stiffness.

Interface Plate

The interface plate provides the main structural interface between each landing leg and the main vehicle. It is an organically shaped carbon fiber part (Figure 18 and Figure 19) that allows for the unique geometry required at each leg interface for stowage and deployment. The plate is hollow molded around a silicone form and uses a separately bonded lid to close out the structure. The interface plate started as two flat plates and four carbon tubes and as the design progressed, the plate evolved into the organic shape it is today that encapsulates the benefits of both flat plate geometry and tubes for interfacing to the leg joints. The plate transfers landing loads through selectively reinforced sections along the top and bottom of the plate. Shear and torsional loads are carried through bidirectional skin plies that form the outer mold line of the plate. At the end of each leg of the plate is a cylindrical section where carbon clevises are bonded. Within the hollow area of the plate are 4 titanium threaded inserts that act as the main structural pickup for the vehicle during testing and transport and also act as a datum for the placement of all other components. These threaded inserts are mechanically captured by carbon sleeves that are bonded to the lid before closing out the plate structure. A central sleeve is also bonded inside to provide interface area to the main mast tube.

Figure 18: Interface plate that serves as the main structure for the landing gear, connecting each leg to the airframe.

Figure 19: Interface plate without the lid or interfaces installed.

Figure 20: Latches ride along the titanium surface and wedge into place once the leg is fully deployed

Carbon Clevis

In order for each landing leg to be stowed in the correct location, they each needed to fold at four unique angles. The part that allows this to occur is a carbon fiber clevis bonded to each of the ends of the interface plate. The clevises feature a 15 degree bend angle between the tube section and the forks to reduce the severity of the angle needed in both the interface plate and the lower titanium part (Figure 21). Between the forks of the clevis are the leg deployment springs and latches. The axles for the deployment are housed in bushings in each fork on the clevis. Due to the interfaces on the inner surface and the bent geometry required for deployment angles, the clevis was a very difficult part to manufacture. The part was made by wrapping thirty-five plies of carbon fiber prepreg over an aluminum male mandrel that forms all of the inner surfaces. After the carbon plies are wrapped around the mandrel, the part is encased in silicone to provide pressure to the part during curing. This results in a lower tolerance outer surface but there are no interfaces to the outer surface, so this is acceptable. The part is then cleaned up and reamed to accept bushings for the deployment axles. During final assembly of the landing gear, the bonded clevis was clocked using a large fixture to provide precise alignment of the landing gear in both the stowed and deployed configurations.

Figure 21: Carbon fiber clevis houses the deployment mechanism and carries loads into the interface plate. The 15 degree bend allows simplified geometry in adjacent parts.

Deployment Mechanism

Inside each of the four clevises is a redundant pair of 17-7 PH stainless steel torsion springs (Figure 22) to deploy each leg from its stowed position. Each spring has a mass of only 0.4 grams yet is individually capable of fully deploying the leg without the assistance of its counterpart spring or gravity. The leg assembly pivots freely about a 17-4 PH axle which also rotates freely inside the clevis bushings to provide redundancy against binding of the mechanism. Although this mechanism was mission critical, it was intentionally designed with very little excess spring force to minimize airframe stresses and risk of creep during the period of roughly a year between installation on the rover belly and deployment onto the surface of Mars. This also minimized shock loads as each leg snapped into final position upon deployment, which could have potentially damaged the dampers, latches, or other parts of the airframe.

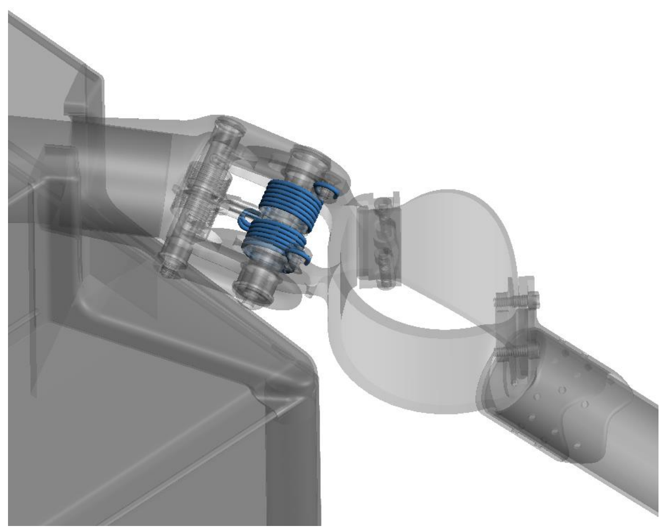

Figure 22: Redundant stainless steel springs provide deployment force to the landing legs

Each leg is latched into final position with a redundant pair of spring-loaded pawls. Figure 20 shows the pawls riding along the deployment mechanism and rotating into place once the down stop is reached. Each stainless steel pawl has a mass of 0.5 grams, is driven by a 0.14 gram 17-7 PH torsion spring and can support the entire landing load individually should its counterpart fail to engage. The pawls rotate freely and independently about a 0.7 gram anodized titanium axle, which itself rotates freely inside the clevis for redundancy (Figure 23).

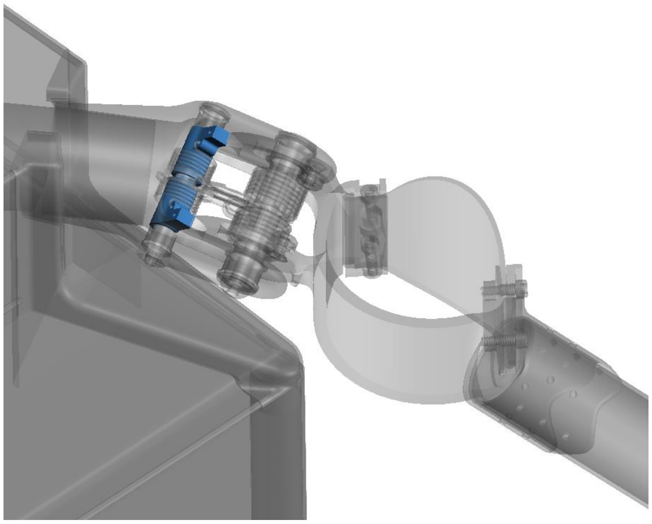

Figure 23: Latching pawls rotate freely on a titanium axle to lock the leg once deployed

Rather than locking securely within a cavity with adequate clearance, the pawls engage with a 5 degree wedging action to provide a high degree of rigidity to the joint and eliminate the possibility of any low frequency rattling that could potentially disturb the avionics. The wedging interface surfaces were installed as bare metal with no lubrication or anodization but were tested with grease to prove ample back-out resistance.

Despite the moving and latching nature of this mechanism, there is no explicit dust protection. Nearly every moving part of the aircraft utilizes a Teflon, felt, PEEK, or labyrinth seal to prevent sand or dust intrusion except for these latching mechanisms which instead were designed to be tolerant of dust. This is because the deployment mechanisms were expected to be minimally exposed to very fine 1-6 micron atmospheric dust particles during the few days between the jettison of the debris shield which protected the helicopter during the rover's landing on Mars and the one-time deployment of the landing gear. Dust tolerance was achieved thru the use of dry MoS_2 lubrication, mechanical redundancy, and careful attention to possible dust build-up locations. The system was validated by thoroughly coating and piling representative dust types (Kaolinite and Mojave Mars Simulant) into every possible part of the mechanism in different orientations and demonstrating reliable deployment and latching in all reasonable test scenarios.

Spring/Damper Flexure

Traditional fluid-based dampers were quickly eliminated from consideration due to their inherent weight, risk of fluid leakage, and contamination risk to the sensitive instruments on the Perseverance Rover. Friction-based dampers were considered but their complexity and dependence upon temperature, wear, contamination, and oxidation creates risk.

A simple expendable damper with a mass of 1.5 grams per leg was developed from ductile non-alloyed aluminum that absorbs energy thru its own plastic deformation. Damping performance decreases with each fatigue cycle (Figure 15) so extensive laboratory testing was performed in the testbed to ensure that it would still provide damping even after 100 of the assumed worst-case landings. The design began as a series of coiled aluminum wires, but this proved inefficient as the coils would quickly crack at the center of each loop before the bulk of the material could be stressed (Figure 24).

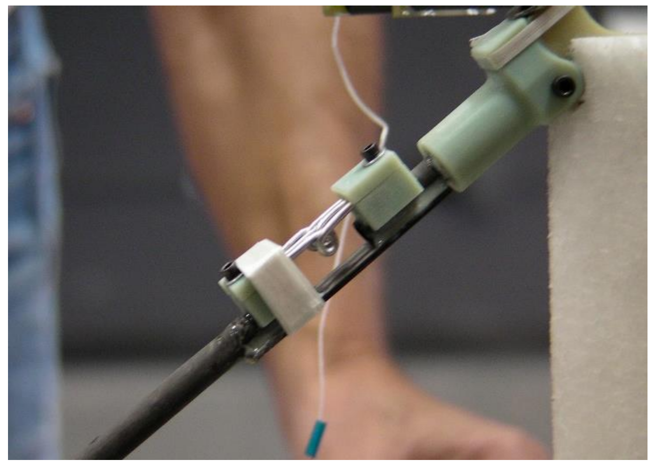

Figure 24: Initial prototype dampers using three aluminum loops

This design evolved to a flat plate and ultimately the curved oval-shaped damper in the final design as seen in Figure 25. The damper appears to be loaded in an unfavorable manner for strength, however this is intentional to maximize the stresses it is subjected to and thus the damping it provides.

Figure 25: Non-alloyed aluminum damper used to absorb energy upon landing

Each damper is paired with a 11.5 gram titanium 6Al-4V spring which also serves as the folding hinge, latch, and interface to the leg tube (Figure 26). The spring provides up to 15N arresting force at full deflection of 17 degrees while the damper provides a constant resistance of 5N throughout the travel range (Figure 27). The spring also provides restoring force to deform the damper back toward its original shape to minimize any accumulated suspension sag. The spring was designed to provide the appropriate deflections and stiffnesses required to match the performance of the testbed simulation vehicle, which was analytically modeled in a dynamics spreadsheet.

Figure 26: Titanium spring, leg tube mount, and deployment mechanism. Each of the four parts are unique in their geometry due to the four unique deployment angles required for stowage under the rover.

Landing Leg Tube

The landing leg tube is a thin-walled tapered carbon fiber tube that runs from the bottom of the titanium spring piece into the foot. These tubes are designed for both strength and stiffness, as natural frequencies interacting with the control frequencies was a main concern. The desired stiffness of the leg tubes was determined experimentally using the drop test method discussed in section 3 of this paper. After conducting these tests and iterating the design until satisfactory landing dynamics were achieved, the "ideal" running stiffness of the tubes was derived. A set of 7 different tubes were manufactured and tested to see which layup best matched the stiffness of the test vehicle and provided enough strength to survive landing loads (Figure 28). The modeled legs were then added to a NASTRAN model to simulate the resonant frequencies in flight to ensure they would not interact with the controller.

Figure 28: Load testing of a landing leg tube. Displacement measurements were taken as load was applied slowly until failure to derive a running stiffness measurement.

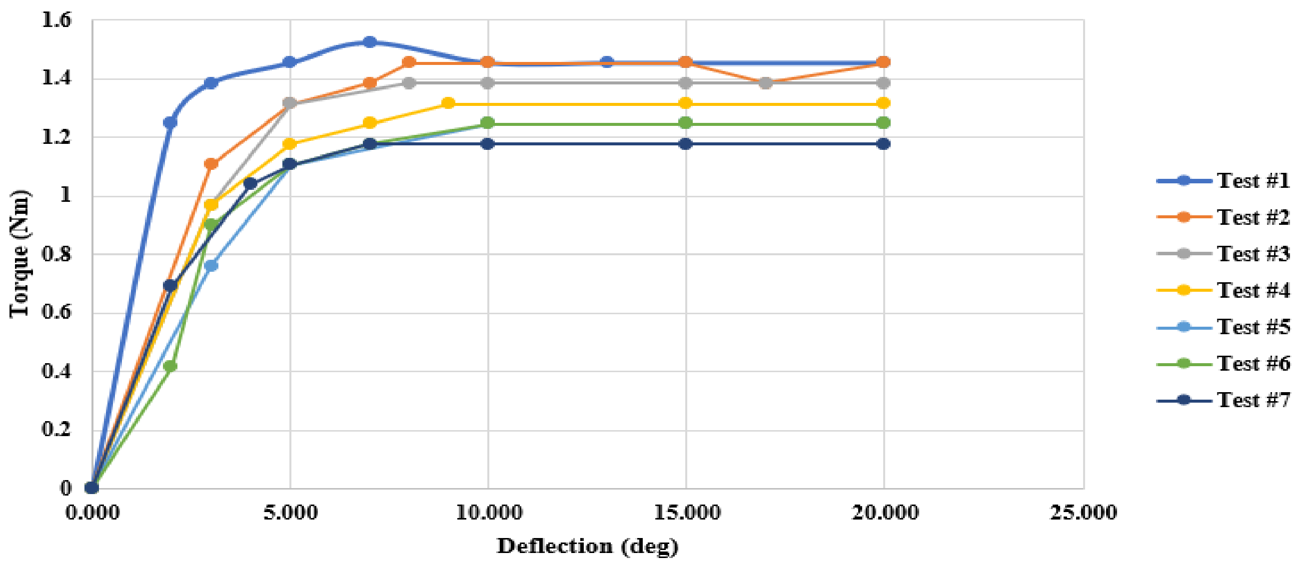

Figure 27: Damping force in terms of torque and deflection measured about the spring axis of the spring-damper system

Feet

In order to land safely on a variety of surfaces, the feet of the landing gear were designed to prevent sticking or digging into the surface of Mars. Each foot consists of a molded single ply of bidirectional carbon fiber cloth with a second ply only along the bottom of the foot for reinforcement against rubbing on the ground. These are formed in an open face mold with a silicone insert to apply pressure. The feet are formed in two halves with a joggle lip that allows the halves to be bonded together. The geometry of the foot shape was designed to not collect dust on the upper surface by ensuring all of the upper surfaces are sloped downward. The geometry of the bottom half of the foot was designed to act as a ski and skim over rocks and bumps instead of digging in as would be the case if the toe of the foot was the lowest point (Figure 29). One foot features a unique hoop which acts as an interface point to the Mars Helicopter Delivery System (MHDS) (Figure 30).

Figure 29: Landing gear foot designed to be toe up to act as a skid to skip over rocks and bumps instead of digging in.

Figure 30: Unique "hoop" foot used to restrain one of the four landing legs during stowage under the rover.

5. CONCLUSIONS

Ingenuity has already exceeded all of its original mission objectives and has proven that flight is not just possible at Mars, but that it can be valuable, practical, and reliable. The landing gear is just one subsystem helping to achieve this feat and it is now becoming one of the components pushed furthest beyond its original design limits as the mission expands into more daring terrain. We know that landings so far have been successful and have not caused damage to the vehicle. Based on imagery from Ingenuity, we have seen the feet dig into soft sand and skim over small, sharp pebbles. The optimized elegance of this landing gear system provides a lightweight, yet robust, means for absorbing energy on landing to maintain vehicle safety. Thoughtful design, creative innovation, extensive testing, and an unwavering attention to weight reduction have produced a remarkably well performing landing gear system for the first aircraft to ever fly on another planet.

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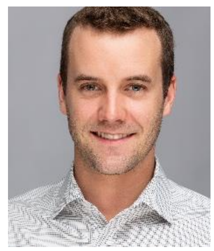
BIOGRAPHY

Sara A. Langberg is an aeromechanical engineer and one of the lead landing gear designers for Ingenuity. She received her B.S. from University of California, Davis in 2016 with degrees in Aerospace Engineering and Mechanical Engineering. After graduation, she came to AeroVironment and the Mars Helicopter team. Her work on the project includes analyses of blade loading, control linkage geometry, and servo loading, landing gear deployment and stowage geometry, and design of the composite parts in the landing gear system. Sara specializes in mechanical and composite part design and fabrication and rapid prototyping for UAS in the MacCready Works division.

Jeremy D. Tyler holds a B.S. in Aerospace Engineering from the University of Arizona and has enjoyed a lifelong hobby of designing, building, and flying model airplanes and rotorcraft. He joined AeroVironment in 2007 as a member of the R&D group tasked with the creation of new aircraft designs. Jeremy has been involved with dozens of innovative unmanned aircraft projects, ranging from fixed-wing VTOL airplanes to single and multi-rotor helicopters to giant solar-powered stratospheric airplanes, and he can now add Martian aircraft to that list. Jeremy was involved in many aspects of the Ingenuity airframe design and developed the majority of its metal mechanisms including the servos, swashplates, and landing gear components.



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Matthew T. Keennon received a B.S. in Physics from University of California, Los Angeles in 1988. He has been with AeroVironment Inc. for more than 25 years. He was the technical lead for the rotor system development for the JPL Mars Ingenuity helicopter, with particular contributions to the propulsion motor fabrication and electrical wiring. He maintains the 'Nano Lab' in the MacCready Works division of AeroVironment in Simi Valley, providing technical support for many cutting edge UAV projects that require extreme small size or extreme light weight electrical and mechanical systems. He has been the principal investigator or technical lead on many of the most challenging UAV developments at AeroVironment including the Black Widow squad level micro air vehicle system and the Nano Hummingbird miniature flapping wing, robotic hummingbird. He specializes in the conceptual design and rapid prototyping of vehicles, propulsion systems, and avionics for novel or unusual UAV systems.