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MAPLE: Marsian Autorotation Probe Lander Experiment

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MAPLE: Marsian Autorotation Probe Lander Experiment

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Abstract
The first step towards aerial planetary exploration has been made. Ingenuity shows extremely promising results, and new missions are already underway. Rotorcraft are capable of flight. This capability could be utilized to support the last stages of Entry, Descent, and Landing. Thus, mass and complexity could be scaled down. Autorotation is one method of descent. It describes unpowered descent and landing, typically performed by helicopters in case of an engine failure. MAPLE is suggested to test these procedures and understand autorotation on other planets. In this series of experiments, the Ingenuity helicopter is utilized. Ingenuity would autorotate a "mid-air-landing" before continuing with normal flight. Ultimately, the collected data shall help to understand autorotation on Mars and its utilization for interplanetary exploration.

Keywords
Autorotation, Mars, Descent, Rotorcraft

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Contents

Introduction

The current space race gives rise to increasingly creative mission designs. Ingenuity [1] is pushing the boundaries of this by being the first vehicle to perform powered flight on another planet. However, rotorcraft for space exploration are not a new idea. Autorotation is particularly interesting in this field because it could replace parachutes in several scenarios. Multiple mission proposals have been made in the past [2, 3, 4, 5, 6, 7, 8]. At JMU Würzburg, WüSpace works on the Daedalus Project series [9, 10, 11, 12]. In these projects, the so-called SpaceSeed Vehicles are being built. The current version is depicted in Figure 1. The SpaceSeeds represents the most recent development of autorotation decelerator prototypes.


Figure 1. SpaceSeed v2 flight hardware at workbench during qualification testing

MAPLE proposes an innovative experiment to take the next step for autorotation in interplanetary exploration. The Ingenuity vehicle brings all means necessary to test autorotation safely. In this work, we want to outline how such an Experiment can be conducted. The possible challenges and pathways toward solutions are also presented. Lastly, the future work, for which MAPLE is a pathfinder, is summarized shortly.

Advantages of Autorotation When compared to parachutes and propulsion, autorotation can fill a gap in between. It brings maneuverability and soft landing capability with it, while needing no fuel to operate. Combining the to biggest advantages of propulsive landings and parachutes. A number of other parameters is important as well. In Table 1, a qualitative assessment of key parameters is listed. This assessment makes it clear that autorotation is worth an investigation

-	AuroV	Parachute	Propulsion
Mass	medium	low	high
Fuel demand	no	no	yes
Controlable	yes	limited	yes
Reusable	yes	limited	yes
Atmosphere	required	required	not required
Pressurized	no	no	yes

Table 1. Qualitative comparison of Autorotation with other typical decelerators on key parameters

1. Experiment Overview

The Experiments of MAPLE aim to understand autorotation on Mars better. Ultimately, this will lead to one descent scenario that shall be the final goal of MAPLE. This Experiment shall be described in this section in a step-by-step process. An overview of the Experiment steps and an exemplary flight envelope can be seen in Figure 2. Note that horizontal motion is not necessary for MAPLE. However, it is depicted in the figure to increase readability. The presented mission envelope can only be a rough outline of what has to be implemented. Therefore, this section is aimed to create an impression of how autorotation can be implemented and tested with the Ingenuity helicopter.

Step 1: Ascent Ingenuity flies to a sufficient altitude for the Experiment (e.g., 20m above ground). The comparatively high altitude is desired to create enough clearance for a safe autorotation maneuver. This altitude will be called Maneuver Engage Altitude. The higher this altitude, the more data about autorotation can be gathered.

Step 2: Hover The helicopter goes in a short hover. This can be used as a decision threshold, checking all parameters before autorotation is engaged.

Step 3: Motor deactivation Once all systems are gone, the motors of Ingenuity will be deactivated or put into a ”friction-free” mode. This is a crucial step to test autorotation because it is a passive, unpowered mode of descent.

Step 4: Autorotation Ingenuity is now performing autorotation. In this phase, a specialized autorotation controller determines the pitch of the rotor blades. Data collection of various flight and vehicle parameters is essential in this phase. However, data will also be watched closely. Parameters will be constrained to certain boundaries. Should they violate these boundaries, the maneuver will be disengaged, and a hover followed by a landing will be performed. For this, see the following steps. They would just be engaged earlier in case of a constraint violation. These mid-air-landings will be the key element of MAPLE.

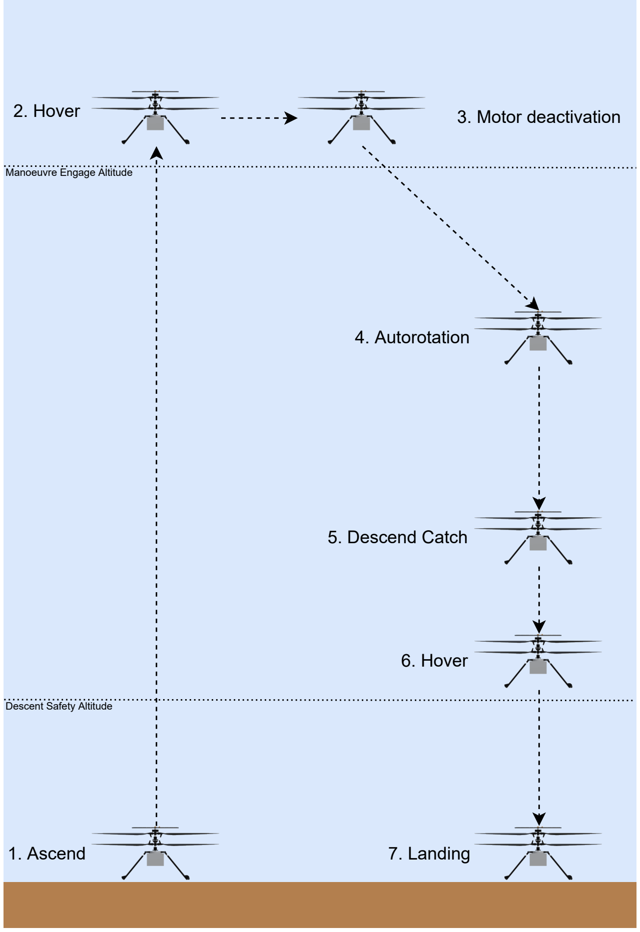

Figure 2. Exemplary flight envelope of Ingenuity performing autorotation.

Step 5: Descend Catch The helicopter shall be in a safe hover at a certain safety altitude above ground (e.g., 10m). To achieve this, Ingenuity will use its motors again to catch its descent. This descent is slow through the previously slowed autorotation landing simulation. Thus, it should be comparatively simple to go into a hover. This is where autorotation ends, and powered flight will commence again. The previously mentioned threshold will be called, Descent safety altitude.

Step 6: Hover Ingenuity will end its Descend catch in a Hover. This Hover is used as a turnover point where the helicopter will be able to perform in its typical operating range.

Step 7: Landing After the successful maneuver, Ingenuity will safely land on the ground. Now data will be transmitted for further analysis on earth.

2. Methods & Technology

This section will discuss the methods and technologies to realize MAPLE. The necessary technologies, changes, tests, and implementation works will be outlined here. Ultimately, the goal is to keep MAPLE as simple as possible, thereby protecting the integrity of Ingenuity.

2.1 Operating conditions

A key to simplicity and safety is the choice of operating conditions. Therefore, MAPLE relays on many normal functions of Ingenuity. As described in Section 1, seven key steps can be identified for the autorotation experiment. Steps 1-3 and 6-7 are within the current capabilities of Ingenuity. The Crucial Steps are 4 and 5. Autorotation and the Descend Catch are outside of the typical operation envelope. Thus two primary operation states can be identified for MAPLE. The Typical Flight State and the Autorotation Flight State. The last one needs to be tested thoroughly before actual experimentation.

2.2 Autorotation Control

The core of MAPLE is to learn more about autorotation on Mars. Therefore, an autorotation controller needs to be implemented for Ingenuity. The simplest option is vertical autorotation. Controllers for vertical autorotation where suggest by Dalamagkidis [13, 14] and Nonami et al. [15]. Most recently, a simple controller for autorotating spacecraft was Implemented during the Daedalus 2 project [11].

The least complex option is a Single Input - Single Output controller. This should also be possible for Ingenuity. The input for the controller is the rotation rate, with a certain goal rate defined. As output, the collective pitch is defined. This is in line with the previously mentioned works, which have all defined their systems like this.

Accompanying this controller would be a set of attitude stability controllers which control selective pitch. Depending on the control architecture of Ingenuity, already implemented controllers could be utilized for this task. This would lower possible risks and build on the known system behavior of the helicopter.

2.3 Testing

Testing is a crucial aspect of MAPLE, starting early in the implementation phase. Implemented controllers and procedures are expected to run through three phases: Simulation testing, Wind tunnel testing, and experimentation.

Simulation testing evaluates controllers on available flight simulations. These can be already established simulation environments of Ingenuity. However, adapted simulations that account for autorotation can also be utilized and implemented depending on the capability of the used models.

Once simulation tests have established good behavior, wind tunnel tests shall be made. The JPL Space Simulator [16] can be utilized to conduct these tests. An engineering model can be utilized to conduct the tests and give valuable feedback for controller design.

Radius m	Mass kg	Simulation $\frac{m}{s}$	Approx. $\frac{m}{s}$
0.605	1	-25.98	-17.69
0.605	1.2	-26.07	-19.38
0.605	1.5	-26.03	-21.67
0.605	1.8	-26.39	-23.74
1	2	-21.87	-15.01
1	3	-22.32	-18.38
1	4	-23.58	-21.22
1	5	-25.22	-23.73
2	5	-14.62	-11.82
2	7	-16.45	-13.98
2	9	-17.65	-15.86
2	11	-19.41	-17.53

Table 2. Simulation [17] results compared to approximation [7] for martian autorotation descent vehicles.

Ultimately the experimentation on Mars will be conducted. However, it should be noted that smaller steps should be taken towards the final MAPLE Scenario, described in Section 1. Hover tests, shorter descends, and alike shall be performed beforehand. This has two beneficial effects. Firstly, during implementation, a lot more data will be available to help and understand possible challenges. Secondly, the integrity of Ingenuity can be protected this way by making smaller increments toward the final experiment scenario.

3. Expected Results and Future Work

MAPLE will help us to understand Autorotation better. It utilizes already available tools to create a new scientific yield capable of improving future missions. In this section, the expected outcomes and possible future works are elaborated. This will show the benefits of MAPLE and how it can improve our ways of exploring other planets.

3.1 Expected Results

MAPLE's data can have a significant effect on autorotating Spacecraft for Mars. With the Experiment Data, many conclusions are expected to be drawn. The most important is whether or not Autorotation could be viable for future missions. Descent speed is one of the critical parameters to assess. In previous simulation studies [11, 17] the steady state speed has been understood to be very high. Approximations like those used by Young et al. [7] lead to similar results when applied to Venus. A list of steady state descent speeds can be seen in Table 2. Here, the Rotor Radius and Vehicle Mass are used to calculate the steady-state descent speeds.

These results make it clear that a steady state descent experiment comes with significant risks. This is why in Section 1 an approach was chosen that simulates only the last stages of autorotation landing.

When simulating some scenarios like these, it can be seen that speeds are significantly lower. Moreover, they can be controlled by the difference of Manoeuvre Engage Altitude and Descent Safety Altitude. Figure 3 shows an example of a mid-air landing simulation. Ingenuity is given 5m of altitude to perform the maneuver.

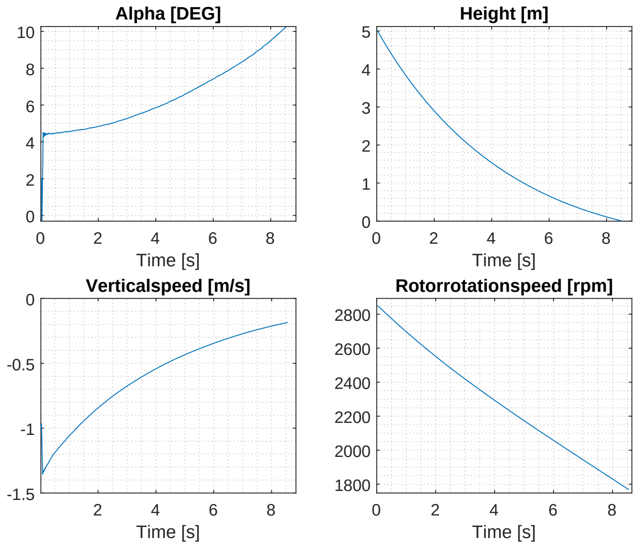

Figure 3. Simulation of a "mid air landing" maneuver performed by Ingenuity with a 5m range.

This can be achieved between 15 and 10 meters to ensure a sufficient safety margin. The autorotation maneuver is engaged at $-1\frac{m}{s}$ and is aimed to slow the vehicle above $-0.2\frac{m}{s}$. (Velocity is defined positively from the surface upwards) During the experiment, the simulation's autorotation controller can slow down the vehicle sufficiently. At these near hover conditions, Ingenuity is capable of restarting its motors and commence with hover and subsequent landing, thus performing steps 5-7. A similar experiment can be made with 10 meters of altitude to perform the maneuver and an initial descent speed of $-3\frac{m}{s}$. The results of this can be seen in Figure 4

MAPLE offers a pathway into autorotation by skipping the high-velocity steady-state descent zone. With the low speeds of experiments similar to those depicted in Figures 3 and 4 valuable data can be collected safely. It offers a pathway toward safe autorotation testing and data collection. This is a significant benefit of this experiment.

3.2 Future Work

With the results of MAPLE, future exploration missions can be influenced decisively. If the experimental flight yields promising results, missions like MSH [18] could use autorotation. However, Mars is not the only planet to perform autorotation on. It is easier to do so on Venus or Titan. The dense atmospheres of these two bodies would allow for very efficient utilization of autorotation, as suggested by Young et al. [7] and Steiner et al. [6] in the past. With the results of MAPLE, such a mission could become possible in the first place.

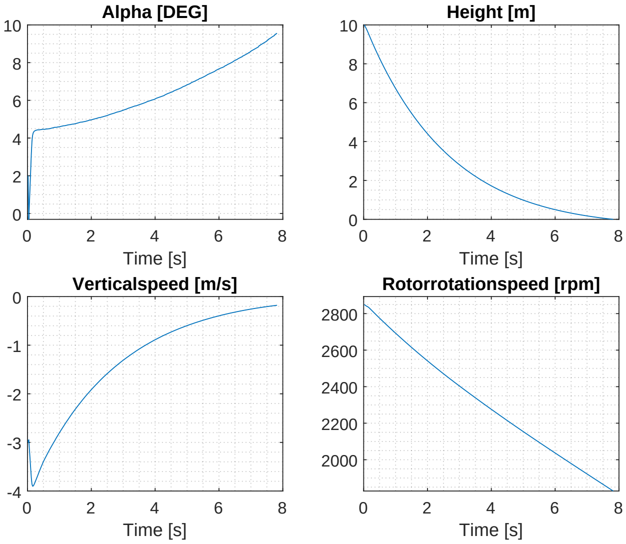

Figure 4. Simulation of a "mid air landing" maneuver performed by Ingenuity with a 10m range.

3.3 Conclusion

The first step towards autorotation can be made. Ingenuity is capable of conducting these maneuvers. The dangerously fast steady-state descent can be avoided. Important lessons of autorotation on other planets can be learned. **MAPLE will help us to dare the even mightier things.**

References

[1] J Balaram, MiMi Aung, and Matthew P Golombek. The ingenuity helicopter on the perseverance rover. *Space Science Reviews*, 217(4):1–11, 2021.

[2] Ricardo A. Diaz-Silva, Daniel Arellano, Martinus Sarigulklijn, and Nesrin Sarigul-Klijn. Rotary decelerators for spacecraft: Historical review and simulation results. In *AIAA SPACE 2013 Conference and Exposition*. American Institute of Aeronautics and Astronautics, September 2013.

[3] DW Robinson, B. A. Goodale, and J. J. Barzda. "investigation of stored energy rotors for recovery". Technical report, "Kaman Aircraft Corporation, Aeronautical Systems Division", 1963.

[4] TV Peters, R Cadenas, P Tortora, A Talamelli, F Giulietti, B Pulvirenti, G Saggiani, A Rossetti, A Corbelli, and E Kervendal. Armada: Auto-rotation in martian descend and landing. Technical report, ESA, EADS and GMV, 2009.

[5] Uwe Westerholt, Günther Börchers, Heinz, Thomas Elfers, Tobias Lutz, Peter Nöding, Herbert Schmitke, Lüder Scharringhuasen, Henning Schönbeck, and Susanne Waldwein. Amdl: Auto-rotation in martian descent and landing. *ESA Contract No. 21233/07/NL/CB*, 2009.

[6] Ted J Steiner and Larry A Young. Rotary wing decelerator use on titan. In *Proceedings of the International Planetary Probe Workshop*, volume 8, 2011.

[7] Larry A Young, Geoffrey Briggs, Edwin Aiken, and Greg Pisanich. Rotary-wing decelerators for probe descent through the atmosphere of venus. Technical report, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION MOFFETT FIELD CA ROTORCRAFT . . . , 2004.

[8] Dominique Valentian, Christophe Koppel, Philippe Mairet, and Loup Mairet. Venus sample return mission revisited. *Experimental Astronomy*, Apr 2022.

[9] Johanna Mehringer, Lennart Werner, Clemens Riegler, and Frederik Dunschen. Suborbital autorotation landing demonstrator on rexus 29. In *4th Symposium on Space Educational Activities*. Universitat Politècnica de Catalunya, 2022.

[10] Clemens Riegler, Ivaylo Angelov, Tim Appelt, Abdurrahman Bilican, Alexander Böhm, Babara Fischbach, Christoph Fröhlich, Jessica Gutierrez Pielucha, Alexander Hartl, Erik Hemmelmann, Kai Hofmann, Patrick Kappl, Florian Kohman, Sarah Menninger, Tobias Neumann, Jan von Pichowski, Chrsitian Plausonig, Reinhard Rath, Sebastian Seisl, Jonas Staus, Lisa Willand, Oliver Wizemann, Phillip Bergmann, Frederik Dunschen, Paul Holzer, Ulla Wagner, and Lennart Werner. Project Daedalus: Towards Autorotation based Landing and Descent. In *71st IAC Proceedings*, 2020.

[11] C Riegler, A Adler, T Appelt, B Bartho, P Bergmann, E Borschinsky, C Bös, F Dunschen, A Ettinger, L Franssen, M Gellerman, P Klaschka, N Koch, J Mehringer, J Mutter, T Neumann, J von Pichowski, M Reigl, L Richter, P Stöferle, L Werner, and J Wolf. Modeling and validation of an autorotation landing controller for reentry and descent applications. In *FAR 2022 Proceedings*, 2022.

[12] Clemens Riegler, Ivaylo Angelov, Florian Kohmann, Tobias Neumann, Abdurrahman Bilican, Kai Hofmann, Jessica Pielucha, Alexander Böhm, Barbara Fischbach, Tim Appelt, Lisa Willand, Oliver Wizemann, Sarah Menninger, Jan von Pichowski, Jonas Staus, Erik Hemmelmann, Sebastian Seisl, Christoph Fröhlich, Christian Plausonig, and Reinhard Rath. Project daedalus, rotor controlled descent and landing on rexus23. 06 2019.

[13] Konstantinos Dalamagkidis, Kimon P. Valavanis, and Les A. Piegl. Autonomous autorotation of unmanned rotorcraft using nonlinear model predictive control. In *Selected papers from the 2nd International Symposium on UAVs, Reno, Nevada, U.S.A. June 8–10, 2009*, pages 351–369. Springer Netherlands, 2009.

[14] Konstantinos Dalamagkidis. *Autonomous vertical autorotation for unmanned helicopters*. University of South Florida, 2009.

[15] Kenzo Nonami, Farid Kendoul, Satoshi Suzuki, Wei Wang, and Daisuke Nakazawa. Analysis of the autorotation maneuver in small-scale helicopters and application for emergency landing. In *Autonomous Flying Robots*, pages 133–150. Springer, 2010.

[16] Marcel Veismann, Christopher Dougherty, Jason Rabinovitch, Amelia Quon, and Morteza Gharib. Low-density multi-fan wind tunnel design and testing for the ingenuity mars helicopter. *Experiments in Fluids*, 62(9):193, Sep 2021.

[17] Clemens Riegler. Entry, descent and landing control of an autorotating spacecraft. Master’s thesis, JMU Würzburg, 10 2020. UNPUBLISHED.

[18] Wayne Johnson, Shannah Withrow-Maser, Larry Young, Carlos Malpica, Witold JF Koning, Winnie Kuang, Mireille Fehler, Allysa Tuano, Athena Chan, Anubhav Datta, et al. Mars science helicopter conceptual design. Technical report, 2020.

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