# THE CONCEPTUAL DESIGN OF AUTO-ROTARY MONO-WING DECELERATORS (ARMWIND) BASED ON THE FUNCTIONALITY OF MAPLE SEEDS AS AN ALTERNATIVE ENTRY-DECENT-LANDING SYSTEM FOR EXPLORATIONS ON MARS

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**Abstract**

Within the next years several missions will take place to land scientific payloads on Mars. Most of the upcoming missions will deploy rovers, but also other scientific payloads are to be delivered to the surface. In this regard, one essential technology to master is the Entry-Decent-Landing (EDL). The disadvantages of the existing EDL systems and the Martian environmental barriers might be avoided by the implementation of an auto-rotative descent and landing system. The intended design of auto-rotary EDL system presented in this paper (ARMWIND) is based on the geometry and dynamics of a maple seed. The advantage that this design has is that not only uses the auto rotation EDL system as a decelerator and a gliding tool for increasing the maneuverability during landing but also it takes advantage of the rotation to store energy by converting the kinetic energy of the rotation into potential energy in batteries or springs. This potential energy can later be used to generate the required extra rotational energy for the rotor to produce enough lift for decelerating the payload with near-zero impact velocity or any other possible utilization after landing.

## 1. INTRODUCTION

Within the next years more and more missions will take place to land scientific payloads on Mars. Most of the upcoming missions will deploy rovers, but also other scientific payloads are to be delivered to the surface. Mentioned by Braun et.al (2007) [1] all of the previous seven robotic systems that United State has managed to successfully land on the Martian soil have had masses below 0.6 metric tons, and landed at sites below -1.4 kilometers elevation due to the need of performing Entry-Descent-Landing (EDL) operations in an area with sufficient atmospheric density. In that regard one of the current major struggles that robotic exploration system engineers face is to increase the landing mass capability while enabling more accurate landings at sites with higher elevations. Also by the time the velocity of the payload is low enough for utilization of supersonic or subsonic decelerators, the distance of the vehicle from the ground may be too low in order to provide sufficient preparation time for landing. This problem becomes more sophisticated when the flown landing systems are not tolerant to many of the Martian surface hazards such as rock hazards. Moreover, atmospheric variability across a Martian year and various landing site elevations are big challenges that need to be overcome [1]. Therefore, one of the essential technologies to master are the EDL systems.

The typical EDL system is the utilization of parachutes deployed at supersonic speeds combined with powered soft-landing. The latest landing system that was used to land a spacecraft on Mars was the Mars Surveyor Lander (MSL) program for landing the Curiosity Mars rover [2].

The main disadvantages of the current EDL systems are lack of maneuverability and the fact that their performance is restricted by their amount of propellant, while all of their initial kinetic energy degrades during entry and the descent of the parachute. These problems besides the mentioned environmental barriers has been one the main reasons of why half of the Martian surface has been considered unsuitable for landing sites of the past spacecraft. Therefore, according to Uwe Westerholt et.al (2009) [3], the main technology drivers in this context that needs to be focused on, are the ones which help us land at higher altitudes and perform precision landings and hazard avoidance maneuvers.

Most of these mentioned environmental challenges and flaws in EDL systems can be avoided by the implementation of an auto-rotative descent and landing system. The conceptual design introduced in this study is an auto-rotary EDL system based on the geometry and dynamics of a maple seed.



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## 2. AUTO-ROTATION EDL SYSTEMS

In autorotation regimes, the rotor acts as a windmill and the lift generated is used for slowing down the descent to a safe rate. Young et.al (2004) [4] mentioned that autorotation is a condition of descending flight where the rotors blades are driven by the aerodynamic forces of the airflow through the rotor. It is a normal safety procedure after a partial or total engine failure, especially for single engine helicopter. Moreover, it also generates forces necessary to control the landing position so to avoid possible obstacles and hazards [5]. These auto-rotating rotors are capable of being slowed down by braking action as well as potentially being able to perform a collective pitch-angle step input for the final soft-flare landing maneuver and additionally having the capability to lessen the wind effects. Furthermore, a higher payload mass can be achieved with an auto-rotation system. Just like a parachute equipped system, a Martian auto-rotation EDL system decelerates after entry with having control over the rate and angle of the descent, and then glides to a dedicated landing site [3]. Examples of Auto rotational EDL systems are seen in Figures 1 (designed by NASA Ames Research center) and Figure 2 (designed by EADS Astrium).

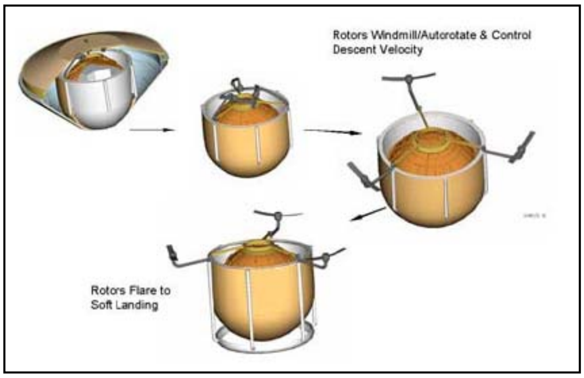


***Figure 1: Rotary-Wing Decelerator for Venus Probe [2]***

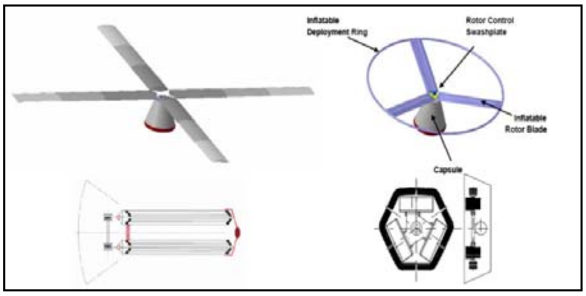


***Figure 2: On the half right is the "Rigid" rotor system with telescopic blades and on the half left is the Inflatable rotor system concept [3]***

Throughout the review over related published papers and reports it was recognized that the use of maple seeds as aero-brakes was intended to be simulated by Steve Morris et.al in Stanford University and NASA Ames research center years ago. However, it seems that it didn't lead to any publication.

Also GMV company in collaboration with the University of Bologna and EADS-Astrium and in the frame of an ESA's General Studies Program carried out a project whose main objective was to assess the feasibility of using an autorotation system, named ARMADA, as a component of the entry, descent and landing system. Even though Mars was assumed as the main planetary target, a preliminary assessment for landing on Venus or Titan was also made. ARMADA replaces all deceleration systems (parachutes, airbags, and retrorockets) except for the heat shield (Figures 3&4) [5].

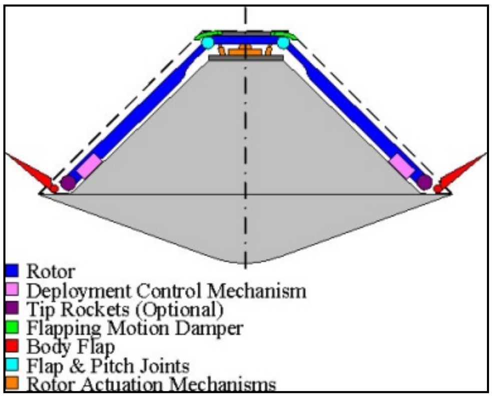


***Figure 3: ARMDA EDLS system [5]***

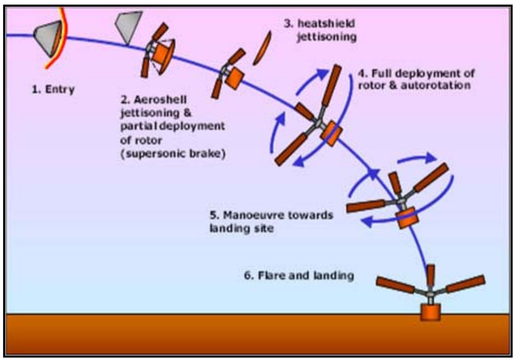


***Figure 4: ARMDA EDLS system [5]***



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The most extensive investigation of auto-rotation landing systems was done by Kaman Aircraft Corporation in the period mid-1957 to mid-1967 [6]. Kaman Aircraft Corporation performed Analytical studies on the performance, stability, and control characteristics of rotary-wing decelerators in axial descent, controlled glide flight, and flared landings to investigate the potential capabilities of stored energy rotor systems for the retardation and controlled recovery of payloads. The two models that Kaman Aircraft Corporation used for this project were KRC-6 TEST VEHICLE and ROTOCHUTE seen in Figures 5&6.

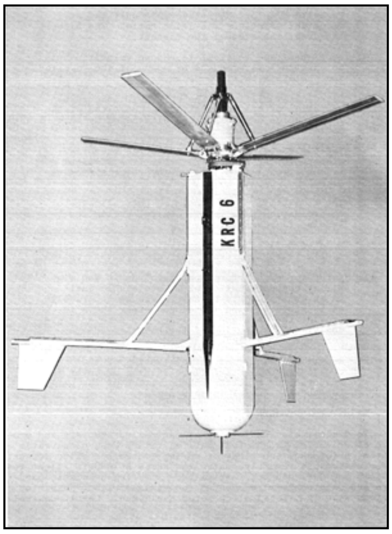


***Figure 5: On the right KRC-6 TEST VEHICLE (Original Configuration) [6]***

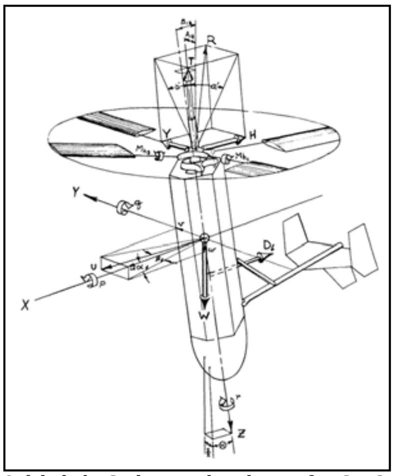

***Figure 6 (right): Schematic view of ROTOCHUTE axis system [6]***

## 3. MAPLE SEEDS AND ENERGY PRODUCTION

Lentink et.al (2009) [7] described Maples (Acer) trees as primary succession trees rely on wind, updrafts, and turbulent gusts for dispersing their seeds to distances ranging from several meters to kilometers. The "helicopter" seeds of maple trees and other similar auto-rotating seeds when detach from their parent tree, convert the potential energy while hanging on the tree into kinetic energy during its fall and once again into lift by autorotation to remain aloft. Varshney et.al (2012) [8] believe that the spiral motion of the maple samara (winged-seed) when falling appears to be stable against wind disturbance and is insensitive to the initial conditions. Slower descent leads to more maneuverability and longer dispersion under the wind condition. The seeds auto-rotate because of their heavy nut, and hence the center of gravity is located at the base of the wing-shaped seed.

***Figure 7 : Number of different types of seeds collected by the author***

There are various types of maple seeds, each with a unique geometry and shape (Fig. 7). The first author collected over 60 seed samples in a time duration of 3 years from different maple trees located at Harz national Park in Germany.



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Using Solidworks computer program, a 3D simulation of a maple seed was produced (Fig. 8). It was interesting to see that major parts of the seed such as the wing shell or the spar are also implemented in wind turbine's blades or the airplane wings.

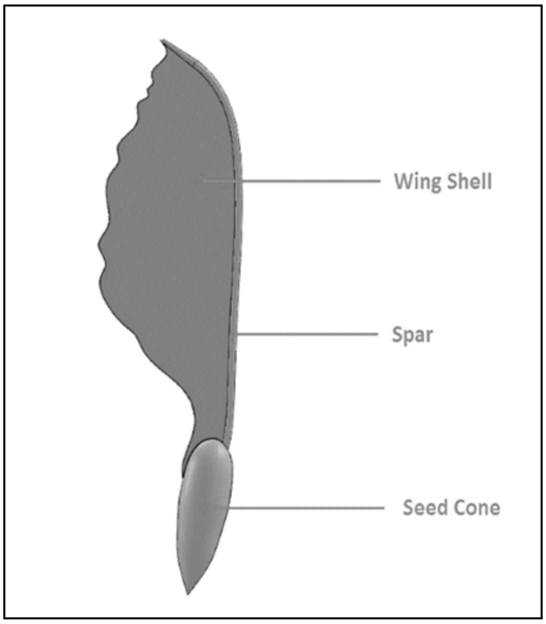


***Figure 8 : Modelling a maple seed using Solidworks***

The stable autorotation of maple and other rotary seeds depends on an interplay between their three-dimensional (3D) inertial and aerodynamic properties [7], which it can be simulated and understood by means of computational fluid dynamics. The presumed function of autorotation is that it creates a lift force resisting the gravity to prolong the descent of the seed (Fig. 9). Detailed performance studies revealed that auto-rotating seeds are able to generate unexpectedly high lift forces despite their small size and slow velocity. However, how they attain this elevated performance is unknown.

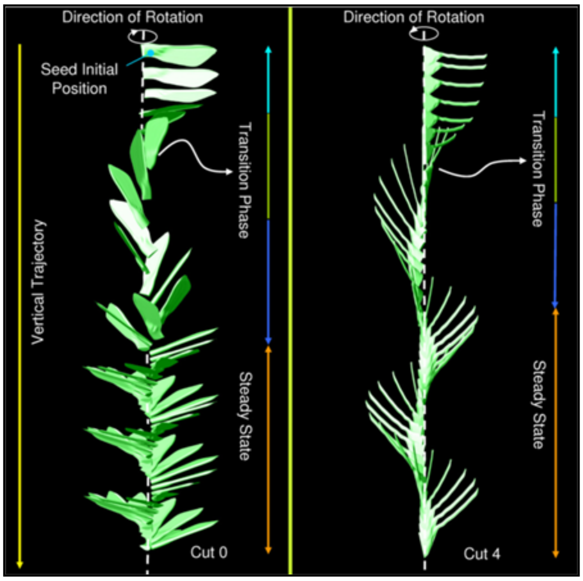


***Figure 10: Side views of typical trajectories of a falling maple seed with intact and cut wings [8]***

It is proved by Holden et.al (2015) [9] that the seed can in fact be considered as a wind turbine when falling in autorotation. A comparison of key performance quantities between the maple seed and true wind turbines has shown a potential for wind turbine design implications from the maple seed geometry. The power coefficient for the maple seed from the analysis is 0.59 which compares to a range of 0.45 to 0.48 for many wind turbines. But it is most interesting that the seed has nearly the same optimal Power Coefficient as the Betz limit which is 0.593; making the maple seed an excellent candidate for wind turbine design inspirations. A 3D model of a wind turbine blade has been generated to accurately represent a maple seed design (Fig. 10). The seed's aerodynamic promising performance shows that using its initial design could be more efficient in terms of timing and expense. In addition, because of maple seeds simple geometry and efficiency in extracting energy, the seed can also be applicable as a decelerator for items that would traditionally deploy a parachute. This also proves that maple seed designed EDL systems have promising capabilities in power generation from auto rotation while decelerating.

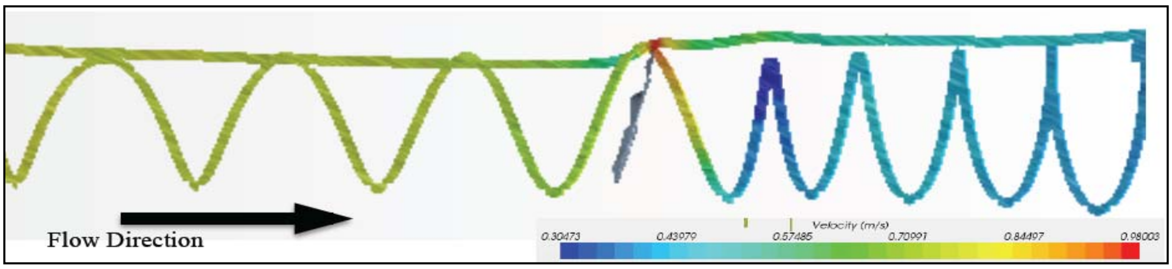


***Figure 9: Relative and absolute velocity stream tubes on the same side of the rotor [9]***



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## 4. THE CONCEPT AND DESIGN OF ARMWIND

The ARMWIND's conceptual design of auto-rotary EDL system is based on the geometry and dynamics of a maple seed. Maple seeds convert the gravitational potential energy stored while hanging on the tree into kinetic energy during their auto-rotative fall and remain aloft due to the lift force created by the act of air against this rotation. Therefore, the advantage of this design over other comparable designs is that not only it uses the auto rotation EDL system as a decelerator and gliding tool for increasing its maneuverability during landings but also it converts the kinetic energy of the rotation into potential energy in batteries or springs. This potential energy can later be used for any possible utilization after landing or it can be used as a power source to generate more rotation for producing the extra lift needed in decelerating the payload with near-zero impact velocity.

A simple handmade model was built with a maple seed, a string and a small point mass. Interestingly the model worked and the mass landed safely on the ground (Fig. 11). However, because the attached string to the seed was fixed at the attachment point, it caused the rotation of the mass as well. In practice, a bearing can be used in the path, to decouple rotation of the wing part from the payload part. Further, a vertical vane can prevent the payload from rotations which might be induced by frictional forces of the bearing. This way the upper side can produce electricity with magnetic coils while the fix lower side can hold the object that is aimed to be landed.

***Figure 11: Illustration of the ARMWIND initial design [10]***

Following the descriptions given for ARMWIND, the EDL procedure can be as shown in Figure 12.

***Figure 12: Illustration of ARMWIND's initial proposed EDL system [10]***

### 4.1. ARMWIND-Copter

In another design, except of hanging the payload or the spacecraft to the ARMWIND and using it as a decelerator, the ARMWIND itself in much smaller scales and higher quantities can be used as an exploration tool, being released from the spacecraft at a certain height. Also the stored potential energy in ARMWIND can be a power source to generate more rotation and in the following extra lift and maneuverability; giving ARMWIND the ability to act as a mono-wing aircraft similar to the “Controllable Miniature Mono-Wing Aircraft” made by the University of Maryland in 2010 [11]. This concept of utilization which is very similar to the actual functionality of maple seeds in nature, can extend the exploration capabilities with the help various measurement and recording tools that would be installed inside the Seed-Cone section of the ARMWIND (Fig. 12)

***Figure 13: Illustration of the ARMWIND-Copter concept [10]***



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## 5. CONCLUSION AND SUGGESTIONS

Auto rotational EDL systems can be a reliably more efficient replacement for the conventional EDL systems using parachutes. Maple seed design is a new way that has not been tried till now and the author believes that it has a lot of promise and can truly make a difference. With a coefficient of power of approximately 0.59, the simple in geometry maple seed is an excellent candidate for wind turbine design inspirations; proving its capabilities in power generation from auto rotation while acting as decelerator. In order to reduce the challenges of the decelerator's wing size and also to enhance its vertical force production and load-lifting capacity, more flexible structures with folding capabilities can be designed in the wings. The folding capabilities of hindwings in ladybird beetles [12] and also the effect of wing flexibility enhancement of load-lifting capacity in bumblebees [13] can be inspirational for designing a more efficient bioengineered wing for its conceptual EDL system design. Since there are no specific equations for simulating the auto-rotation of the maple seeds, the author suggests that first and foremost the kinematics of the maple seeds must be fully understood so we can be able to simulate it under Martian conditions. In that regard, knowing the different influential factors in the rotation is very important. One for such is the gravity and the other is atmospheric density, which are very different on Mars compared to earth. In that pursuit, conducting experiments in chambers filled with gas mixtures same as the Martian atmosphere while being dropped in a micro gravity tower or being inside a free falling plane is suggested.

## 6. ACKNOWLEDGMENT

This conceptual design was an individual work based on the first author's innovative idea and the technical cooperation of the other authors. This paper is dedicated the first author's Father, Parviz Sangin, who sacrificed his dreams of becoming an aerospace engineer in order to make his son's future; enabling him to pursue his dreams in the world of academia and Dr. Firouz Naderi, former director of Solar System Explorations at NASA/JPL, which if it wasn't for his continuous utmost kind support and belief, this project could have been stopped at its early stages. We hope this article will make these two great men proud.

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## 8. BIOGRAPHIES

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