



Allen He

Scaling Analysis of Samara-Type Autorotating Seeds: Aerodynamic
Performance and Geometric Constraints Across Varying Atmospheric and
Gravitational Conditions

Faculty of Engineering and Applied Science

Aerospace Vehicle Design

MSc

Academic Year: 2024-25

Supervisor: Mr.Jack Stockford

Date May 2025



Faculty of Engineering and Applied Science
Aerospace Vehicle Design

MSc

Academic Year:2024-25

Allen He

Scaling Analysis of Samara-Type Autorotating Seeds: Aerodynamic
Performance and Geometric Constraints Across Varying Atmospheric and
Gravitational Conditions

Supervisor: Mr.Jack Stockford
May 2025

This thesis is submitted in partial fulfilment of the requirements for the degree of MSc.
© Cranfield University 2025. All rights reserved. No part of this publication may be reproduced
without permission.

Academic Integrity Declaration

I declare that:

- The thesis submitted has been written by me alone.
- The thesis submitted has not been previously submitted to this university or any other.
- All content, including primary and/or secondary data, is true to the best of my knowledge.
- All quotations and references have been duly acknowledged according to the requirements of academic research.

I understand that to knowingly submit work in violation of the above statement will be considered by examiners as academic misconduct.

Scaling Analysis of Samara-Type Autorotating Seeds: Aerodynamic Performance and Geometric Constraints Across Varying Atmospheric and Gravitational Conditions

Allen He

Abstract

The autorotation effects in descending maple seeds offer inspiration for passive payload delivery and planetary exploration. However, little research has analysed the feasibility domain of this effect across diverse planetary environments. In particular, the coupling effects of changing gravity, scale and air density. This project aims to develop a bio-inspired flying seed model with optimised scale setting for slow descent in extraterrestrial environments. A numerical blade element momentum (BEM) model was used to capture the samara autorotation, with Polhamus's method applied to model leading-edge vortices (LEVs). Results show that gravity amplifies scaling effects, and air density sets thresholds for sustained autorotation. Descent velocity follows an $\sqrt{g/\rho}$ trend in moderate densities of 1-4 kg/m³, but this breaks down beyond this region. The feasible region on Earth has air densities of 1.0–1.22 kg/m³, gravity between 9.796 and 9.834 m/s², and scales of 10–40, maintaining descent around 1.5 m/s.

Keywords: Samara seeds; Autorotation; Blade Element Momentum; Leading-edge vortex; Scaling laws; Extraterrestrial environments

NOMENCLATURE

a	2D lift curve slope
A	Reference area (projected rotor disk area)
c	Blade elemental chord length
c_{avg}	Average chord length of the blade
C_d	Sectional drag coefficient
C_{d0}	Zero-lift drag coefficient
$C_{d\alpha}, C_{d\alpha^2}, C_{d\alpha^3}$	Empirical drag coefficients from seed flight tests
C_D	Drag coefficient
C_l	Sectional lift coefficient
$C_{l,max}$	Maximum lift coefficient before stall
D	Drag force
dr	Width of each blade element
F_{loss}	Prandtl tip-loss correction factor
g	Gravitational acceleration
K_{loc}	Local thrust loading per unit annular area
K_p	Polhamus model vortex lift contribution
K_v	Polhamus model potential flow contribution
m	Mass of the samara seed
N	Number of blade elements in the model
N_b	Number of blades
Q_{BEM}	Total torque from Blade Element Theory
R	Rotor radius from blade root to tip
r	Radial distance from axis of rotation
S	Rotor disk area
Scale	Geometric scaling factor of the initial samara size
σ	Rotor solidity
T_{BEM}	Total thrust from Blade Element Theory
T_{mom}	Total thrust from Momentum Theory
T_m	Thrust from momentum theory
U	Resultant local flow velocity magnitude
U_p	Axial/perpendicular component of local velocity
U_t	Tangential component of local velocity
V_d	Descent velocity of the samara
v_i	Induced velocity generated by the spinning disk
x	Multiple of the initial samara blade area

Greek Symbol

α	Angle of attack
β	Coning angle
$\dot{\beta}$	Flapping rate of the blade
ϕ	Inflow angle between resultant velocity and rotor plane
θ	Local pitch angle of the blade element
θ_0	Datum blade pitch angle measured at 75% radius
θ_t	Local twist angle relative to datum pitch

1.0 Introduction

Autorotation is an equilibrium state reached by a rotating disk in flight, generating sustained lift without primary power coming from the engine. This phenomenon is purely caused by the moving airflow being driven through the disk, making the disk operate similarly to a parachute⁽¹⁾. Instead of a mechanical rotor, nature has also cleverly used this method in seed dispersing, allowing the seed to safely land on the ground from high without being damaged, such as the single-winged samara, shown in Fig. 3. This concept is inspiring in developing precision airdrop applications, especially in an extraterrestrial environment. These types of missions typically involve reducing payload mass while ensuring a safe, slow descent. The inspired-samara vehicle eliminates the need to carry complex reverse-thrust mechanisms, such as propellers or rocket fuel to slow down in falling, thus saving budget. Similar applications also include delivering essential supplies in areas struck by natural disasters, where large-scale parachuting is not economically feasible due to the massive drops required. Therefore, a more precise and effective descent system would allow grouped payloads to be delivered to the place where needed, reducing waste in parachutes⁽²⁾.



Figure 1: A cluster of maple samaras with wing structure for seed dispersal⁽³⁾.

The flight path of a samara seed falling is captured in Fig. 3, which is done by overlaying pictures taken from a high-speed camera. Such a path is not only beautiful, but a spiralling motion can also be noticed from a closer look. This can be explained by the gyroscopic effect during the spinning flight; Stability arises as an object spins, allowing more reliable flight by preventing tumbling. The rotational motion also spreads out the generated thrust evenly, helping

to maintain repeatable flight paths⁽⁴⁵⁾. Furthermore, the descent speed can be reduced significantly through this autorotative motion, while allowing it to land at a distance from the drop point.



Figure 2: The path of a falling samara seed⁽⁶⁾.

Each samara has a single blade, but the mass distribution is never linear. Nature has arranged this brilliantly to make sure the total torque sums up to zero, keeping a stable and effective flight performance during descent⁽¹¹⁾. From its falling path, one can also see that the angle of attack (AoA) is very high with the blade region near the seed base, while the part near the tip is relatively smaller. Conventional aerodynamic structures tend to lose flight efficiency during high AoA⁽⁷⁸⁾. Surprisingly, the change in high angle of attack still makes this descent stable; the fundamental magic behind this is due to the presence of the Leading-edge vortex (LEV), indicated in Fig. 3. At high AoA, the flow is separated at the leading edge, the LEVs help to reattach it and generate additional lift at low Reynolds numbers. Further experiments suggested that LEVs together with Trailing Edge Vortices (TEVs) are essential in producing aerodynamic forces that maintain autorotation in samaras⁽⁹⁾.

It is worth pointing out that earlier studies approach the phenomenon of the autorotating samara differently. The focus is on learning the descent properties of the seeds, including their path, descent speed, and revolution. It was

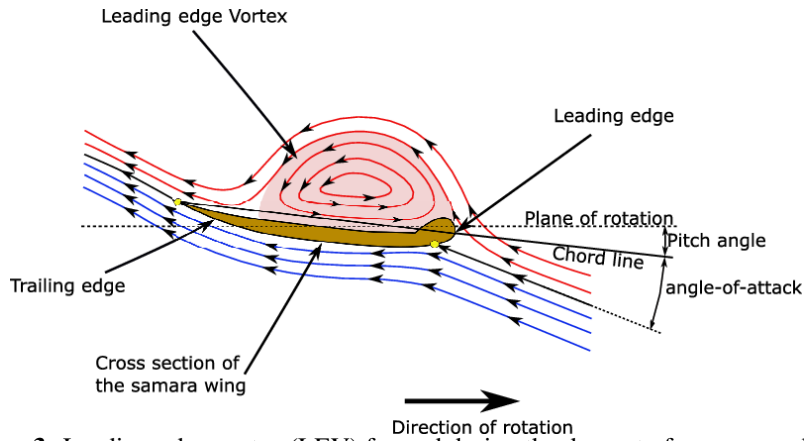


Figure 3: Leading-edge vortex (LEV) formed during the descent of samara seeds ⁽¹⁰⁾.

concluded that the descent speed is directly proportional to blade length, seed mass distribution, and angle of attack (AoA) ⁽¹¹⁾. The unexpectedly high lift produced by the samara attracted the attention of later researchers, leading to the discovery of LEVs, which form along the seed's wing during descent ⁽¹²⁾. With the help of dynamically scaled experiments and flow visualisation, they proved that the insect flight contributes to the airborne time of the seeds. The work revealed that plants, insects, and birds all use these lift-enhancing strategies ^(8,7,10).

In recent years, attention has shifted toward the physical boundaries of the the autorotating seeds. Yasuda and Azuma indicated that the stable spinning flight can only exist when the wing is longer than seed section, and the mass distribution is asymmetrical with the seed body, allowing offset from the aerodynamic centre to produce a restoring torque. Chord distribution affects the overall moment balance due to force distribution. Furthermore, With an optimal initial pitch angle set in the range of 20° – 30° , this sustains the rotation without causing a fast descent speed ⁽⁹⁾. Building on this, A serious flight modes of winged seeds are identified through the study of descent speed, which proves that they are correlated heavily to the geometry of the seed and the position of the centre of mass ⁽¹³⁾. More recently, The thrust produced from the scaled samara rotor is tested in both vertical and forward flight, showing that the rotor's performance drops when it reaches the scaling limitation ⁽¹⁴⁾. In line with these observations, Niu et al. suggested that the terminal velocity and disc loading stabilise at an equilibrium point, which occurs at a value that is inversely proportional to the lift coefficient ⁽¹⁵⁾.

Collectively, the above studies show that geometric requirements play a significant role in sustaining stable autorotation. However, there is a lack of study

on how parameters behave in isolation under Earth-like conditions. Therefore, this research project aims to develop an accurate model to capture the autorotating descent of samara seeds and to study the geometric scaling limits before the model breaks across a range of environmental conditions. These conditions include changing gravity, air density and scale. The ultimate goal is to establish a simulating model that can predict and optimise the descent behaviours of Samara seeds in safe landing on extraterrestrial environments. To achieve this aim, the specific objectives are:

1. Perform literature review to consolidate current knowledge about flight dynamics and aerodynamic properties specific to autorotating seeds, particularly from sycamore and maple species.
2. Develop a robust analysis model capable of simulating the autorotation descent of samara seeds accurately. Design a digital prototype in MATLAB for analytical investigations, using the collected seed samples.
3. Evaluate the isolated and coupling effects of parameters, including gravity, air density and scale.
4. Defining a global feasible domain for the optimised samara seeds that perform autorotating descent in extraterrestrial environments inside the solar system.

2.0 Literature Review

The foundational principle of samara aerodynamics can be explained further by experimental research. A wind tunnel is used to measure forces generated and descent speed across a range of geometric settings^{[11][2]}. This further proves that a high lift coefficient is obtained by the LEV effect, which is the key that makes the structure of the samara stand out from the conventional fixed-wing design.

This special feature of samara als lead to the advancements in renewable energy systems, espicially in wind turbine industry. Where the wind turbine blade designs inspired by samara wings can significantly improve efficiency and enhance the amount of power harnesse^[20]. These biomimetic designs use the LEV's effect to obtain additional lift, thereby increasing the overall aerodynamic efficiency. The vertical-axis wind turbines reduce the noise and vibration due to the blade curvature as shwon in Fig. 4, which smooths airflow separation.

Additionally, the autorotative descent can be used in extraterrestrial exploration. Such characteristics are beneficial in deploying payloads in challenging planetary environments^[21]. The aerodynamic similarities between

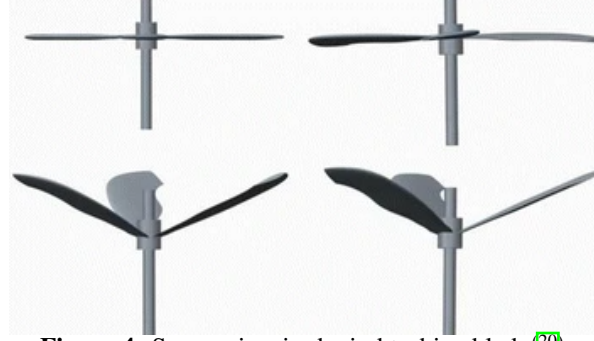


Figure 4: Samara inspired wind turbine blade ⁽²⁰⁾.

samaras and other flyers (insects, birds, bats) illustrate convergent evolution, where diverse species independently exploit LEV-based mechanisms to enhance flight performance. ⁽²²⁾. Animal flight studies also appears the use of stable LEVs, proving universal fluid-mechanical principles that can inspire biomimetic aerospace and robotic designs. ⁽²³⁾. Although recent advances have improved predictive tools, accurately modelling samara autorotation remains challenging. Techniques such as BEM, CFD, and low-order aerodynamic models have significantly enhanced understanding of samara flight dynamics ⁽²⁴⁾⁽²⁵⁾⁽²⁶⁾.

The BEM analysis discretises the rotor blade into 40 finite elements, each generating elemental lift and drag as functions of local angle of attack and inflow ratio. As scale increases, the geometric and inertial characteristics of each element change accordingly. At specific scale values, more than one element may exceed critical aerodynamic thresholds, including stall or peak lift coefficient, causing sudden changes in local lift distribution ⁽¹⁴⁾. Some assumptions are applied to the model:

1. The blade flapping rate $\dot{\beta}$ is assumed to be zero in this BEM model, because the samara wing is a rigid structure attached to the seed base; unlike a helicopter blade, which can flap up and down due to a hinged mechanism. Therefore, during free fall, the seed blade does not do the flapping motion alone and rapidly reaches the steady autorotative state, and these flapping motion terms remain zero at this equilibrium state.
2. For a real samara wing blade, the variation in elemental local twist is unique to each seed, with no general value applicable to all. Furthermore, the magnitude of this twist is typically small, so its influence on the overall angle of attack from root to tip is negligible. Therefore, setting θ_i zero makes a valid geometric simplification in the BEM model.

- For the Prandtl tip loss correction to apply in the BEM model, it is assumed that the blade wake is in the form of a helical vortex system, with inviscid and incompressible flow. And the unsteady effects such as dynamic stall and transient vortex interactions are neglected⁽³⁶⁾.

Furthermore, it is worth noting that the elemental lift δL acts perpendicular to the resultant relative velocity U , while the elemental drag δD is aligned with U . The resultant aerodynamic force δR is therefore obtained as the vector sum of the elemental lift δL and drag δD . This resultant can be resolved along two axes: firstly, the vertical axis, which is perpendicular to the flight path (or the rotor disc) plane. This makes up the thrust generated during the samara's descent; secondly, when resolved to the in-plane horizontal direction, it then produces an elemental torque when multiplying the radial distance r away from the rotation centre. Such torque would act as an accelerating or decelerating component, depending on the size of the local angle of attack α in spanwise blade direction.

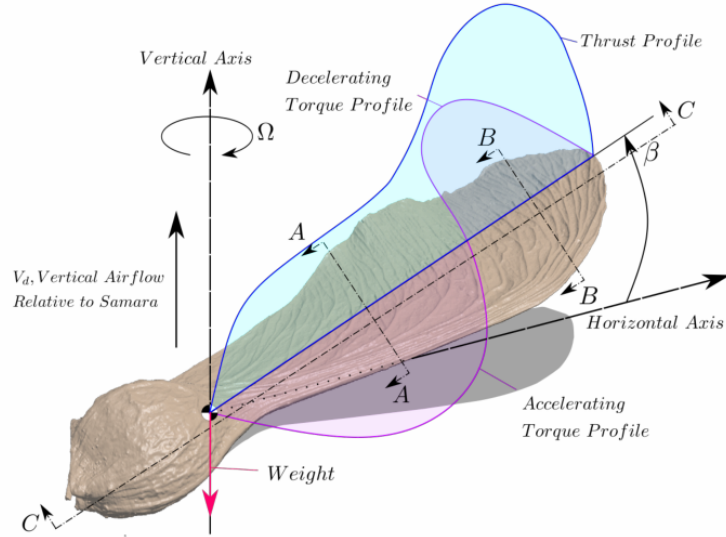


Figure 5: Torque, thrust, and geometric profiles of a samara in autorotation⁽¹⁴⁾.

From Figure 5, it is evident that two distinct regions appear on the spinning samara, generating opposing torques that together balance each other and maintain equilibrium during falling. Consequently, the net torque Q always sums up to zero about the rotation centre for samaras undergoing steady autorotative descent.

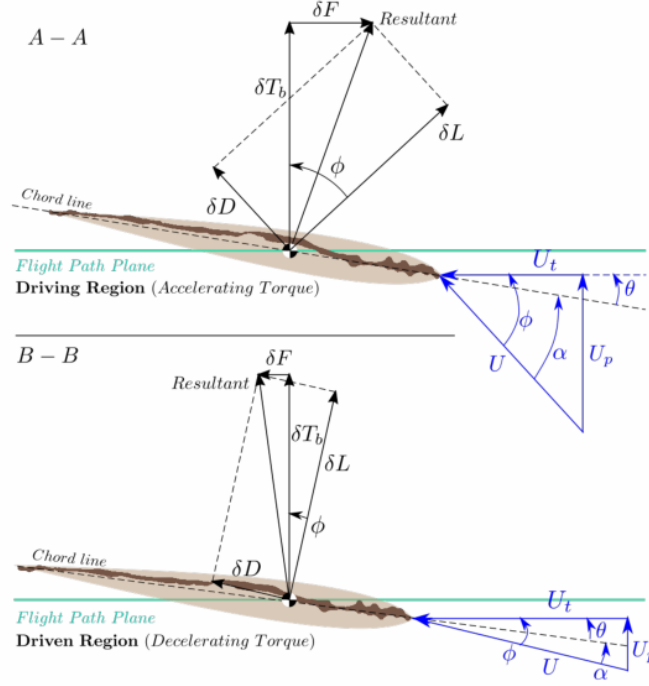


Figure 6: Section views A–A and B–B showing driving and driven regions ⁽¹⁴⁾.

For blade sections near the seed base, the perpendicular component of the relative flow dominates over the tangential component. Because the induced velocity at the root is smaller, owing to the reduced effective lifting area, and the rotational speed is lower due to the shorter radial distance from the axis of rotation. Consequently, the inflow angle ϕ becomes much larger, resulting in a higher angle of attack α , shown from Equations (5) and (6). Hence, the total resultant tilts toward the leading edge of the blade; the resolved horizontal component contributes a positive propulsive force. Therefore, the inboard region of the blade near the seed base is identified as the driving region, where accelerating torque is generated, as indicated in Figure 6.

In contrast, the outer portion of the blade corresponds to the driven region with decelerating torque. At these outboard sections, the larger radial distance from the rotation centre results in a higher tangential velocity U_t ; the induced velocity also increases before decreasing slightly near the blade tip, causing a reduction in the inflow angle ϕ . This leads to a comparatively smaller angle of attack α , making the resultant vector tilt toward the trailing-edge direction. The horizontal component of this force thereby slows down the rotation, shown in Figure 6.

3.0 Methodology

The objective of this chapter is to develop an analysis model based on the Blade Element Momentum (BEM) method. This is a conventional method widely used in modelling rotorcraft blades, which has been tested and proven to simulate the autorotational descent of a single-wing samara seed accurately. First part that made up the BEM is the momentum theory, which models the propellers as an idealised uniform actuator disk to calculate the thrust from varied axial flow velocity across the disk (27), the result is derived from the conservation of mass, energy and momentum; Since the rotor never spins as a uniform actuator disk, the blade is then divided into elements to calculate forces locally, therefore, the second part is able to couple with the local inflow angle and induced velocity along the spanwise wing direction, to account for change in lift and drag (28).

Further studies proved that a complete unsteady BEM model needs to combine these two theories to correctly solve the problems in unsteady and asymmetrical flow fields in single-blade rotation, since the unsteady vortex shedding plays a significant role in predicting the descent rate and rotational speed of monocopters (29,30).

3.1 Seed sampling and analysis

To scale the samara seed without distorting the natural relationship between its mass and size, an experimental characterisation of real seeds was conducted. Two maple species were collected, followed by analysis to establish reliable data for mass distribution between the wing and base portions. Such a procedure included collection, classification and precision weighing, seed separation for digital modelling.

Without a proper test, misuse of their proportion can produce inaccurate simulation results from the model. Thus, this dataset enabled the preservation of realistic mass-to-size scaling in subsequent BEM simulations. Special thanks are extended to Mr. Jack Stockford for collecting a substantial quantity of sycamore seeds from the Cranfield University campus.



Figure 7: Comparison of two maple seed types: (a) on the left, *Acer palmatum* var. *matsumurae* Makino and (b) on the right, *Acer palmatum* (cultivar).

There are two types of maple seeds in various sizes that were collected for analysis, including *Acer palmatum* var. *matsumurae* Makino and *Acer palmatum* (cultivar) as seen in Figure 7. A zoom-in figure for these two seeds is provided in Figure 8, where the top one is the *Acer palmatum*, which has a relatively thinner and smaller translucent wing membrane, the trailing edge is reddish^[31]; In contrast, the bottom one *Acer palmatum* var. *matsumurae* Makino has a broader wing with more deeply divided leaves, coarser teeth and more prominent lobes, often producing larger samaras^[32].



Figure 8: Closer comparison between two types of maple seeds: *Acer palmatum* (cultivar) and *Acer palmatum* var. *matsumurae* Makino.

After that, these two types of seeds are being weighed on the balance for their mass data on the whole seed, the seed base and the seed wing. This step is done by using a high-precision Sartorius electronic balance, as indicated in Fig. 9. This laboratory-grade instrument offers high sensitivity and accuracy in measuring small-scale and lightweight specimens. It contains a stainless steel weighing platform, a digital display, and a built-in tare function.

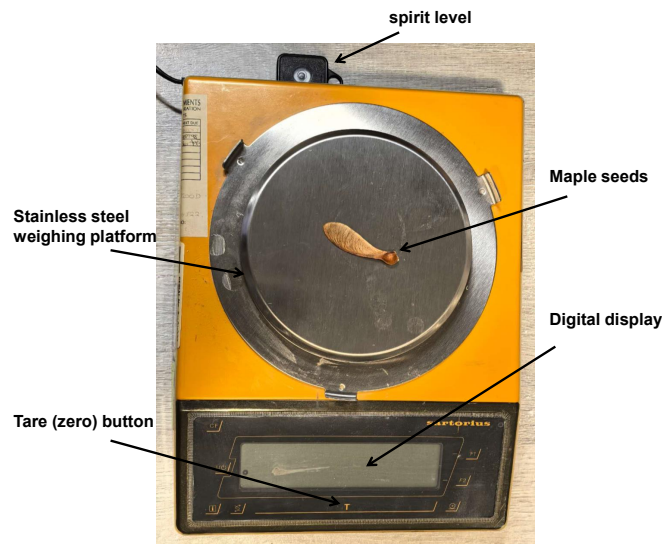


Figure 9: Digital weighing scale setup showing a maple seed placed on a stainless steel weighing platform, equipped with a spirit level, tare (zero) button, and digital display for precise mass measurement.

Prior to weighing, the balance was zeroed using the ‘Tare’ button to eliminate any residual offsets. It is important to point out that all measurements were conducted under controlled environmental conditions, ensuring stable airflow and minimal vibration. This balance has a resolution down to 0.1 milligrams, providing sufficient sensitivity to detect minor differences in sample mass. The spirit level on the balance is adjusted to centre the bubble, making sure the scale is level to prevent any potential inaccurate readings.

Next, Fig. 10 shows the preparation of the samara specimen for weighing. The pruning snip is used to carefully separate the samara into the seed base and the wing. This precise cut prevents damage to its wing structure and loss of mass from tearing off a small section of the wing. It can be seen that the safety lock and spring mechanism on the snip help ensure controlled cutting force during collection. While accurate length measurements of the radial position of the wing were taken from the ruler scale.

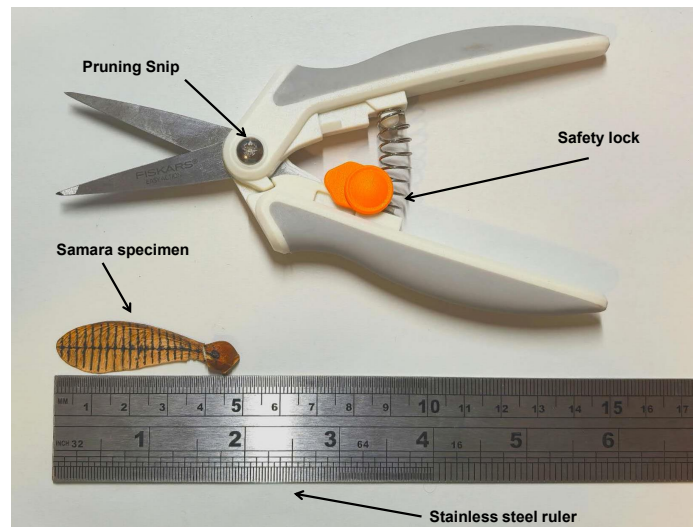


Figure 10: Selected maple seed being cut at the wing root near its centre of gravity (CG) using a pruning snip, scaling with a stainless steel ruler.



Figure 11: Selected maple seed specimen for the generalised digital model in BEM calculations, shown with ruler scales for size reference.

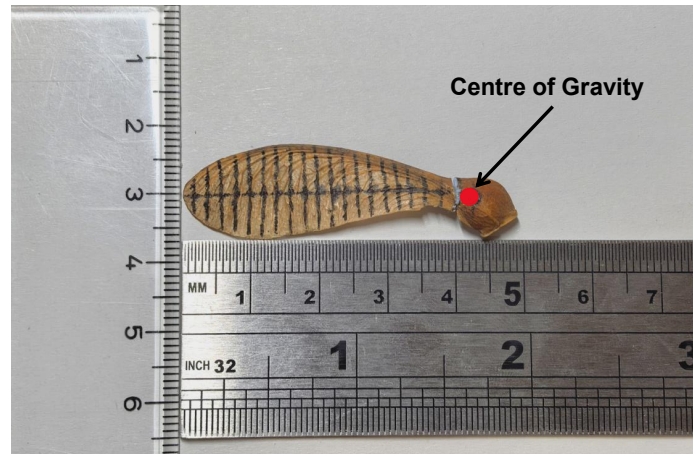
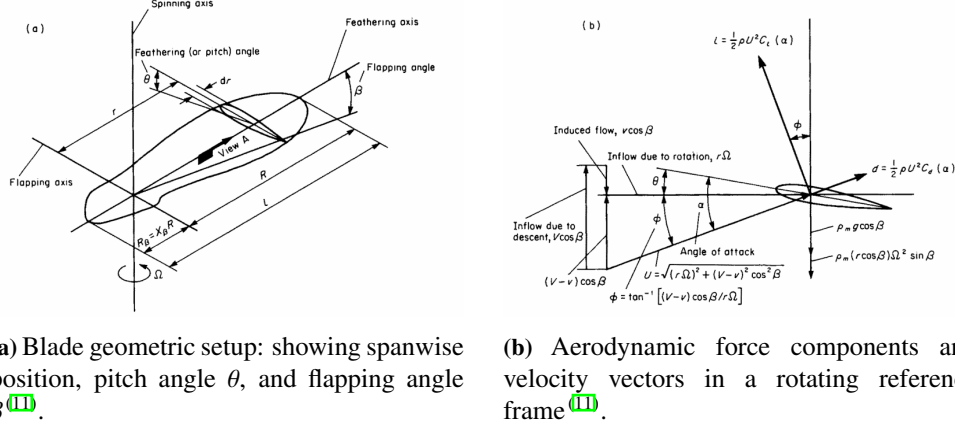


Figure 12: Sectionalised maple seeds with black line markers indicating divisions and the identified centre of gravity (CG).

Lastly, Fig. [11](#) shows a specific samara seed from *Acer palmatum* var. *matsumurae* Makino specie, which is found to have the best spinning performance and the cleanest geometry. It has been selected and handled with extra care to convert into a digital model. The detailed method was as follows: the process involves to first identify the C.G. of the seed, then a cut will be made at this location as indicated in Fig. [12](#). After that, the wing part will be equally divided into 20 sections using the ruler, with elements marked by black lines for chord references. The digital version of this seed is then made in MATLAB, with the result shown in the subsequent chapter.

The fundamental principle behind the blade element theory is to split the samara wing into multiple two-dimensional sub-sections, or so-called blade elements, each of which generates its elemental lift and drag forces corresponding to the different angles of attack from the root to the tip of the wing. For a samara seed, the angle of attack is maximum at the root and nonlinearly drops towards the tip. Therefore, the elemental resultant forces produced by each section vary relative to the incoming flow velocity.

3.2 Blade Element Theory



(a) Blade geometric setup: showing spanwise position, pitch angle θ , and flapping angle β .

(b) Aerodynamic force components and velocity vectors in a rotating reference frame.

Figure 13: Schematic representations of the samara wing: (a) geometric configuration and (b) flow and force components.

The seed blade is divided into N blade elements in the spanwise direction, for accurate simulation results while reducing the computation time, for this paper it is chosen to be 40. Each of these elements has a width dr at radial positions r away from the spin centre, i.e. the centre of gravity. And the tangential and axial components for local relative velocity are calculated from Equation (1) and (2).

$$U_t = \Omega r, \quad (1)$$

$$U_p = (V_d - v_i) \cos \beta - \dot{\beta} r \quad (2)$$

As demonstrated in Fig. 13, where Ω is the rotational speed; V_d is the vertical descent velocity; v_i is the induced velocity generated from the spinning disk, and β is the coning angle, which is the tilt between disk plane and the horizontal plane of rotation during autorotation descent; $\dot{\beta}$ shows the blade flapping rate. U_t represents the tangential velocity when the blade is doing a circumferential motion, while U_p is the component of the inflow normal to the rotor plane, which can be further broken down into the addition between the descent velocity and the induced velocity.

$$U = \sqrt{U_t^2 + U_p^2}, \quad (3)$$

Equation (3) defines the resultant flow velocity U of an elemental section on

the blade from summing its tangential and perpendicular velocity components.

$$\phi = \arctan\left(\frac{U_p}{U_t}\right) \quad (4)$$

The inflow angle ϕ is obtained from the inclination of the resultant velocity vector relative to the horizontal. Furthermore, the elemental angle of attack α for each section in the blade from root to tip is computed by adding the elemental inflow angle ϕ to the elemental pitch angle θ .

$$\alpha = \phi + \theta \quad (5)$$

This α is also the key parameter input to the sectional lift and drag coefficient models in the BEM analysis. Where θ is the local pitch angle as defined in Equation (6).

$$\theta = \theta_0 + \theta_t \quad (6)$$

Where the local elemental pitch angle θ characterises the elemental geometry at each radial position. This angle is composed of the datum blade pitch angle θ_0 relative to the plane of rotation, which is found at 75% of the radius of the blade from the spinning centre, as discussed in (33). And the local twist θ_t relative to this datum angle. However, the local twist was ignored and assumed to be zero in this BEM mode for simplicity.

3.3 Lift and drag coefficient models

$$C_l = \begin{cases} a \alpha, & \text{for } C_l < C_{l,\max} \\ C_{l,\max}, & \text{for } C_l \geq C_{l,\max} \end{cases} \quad (7)$$

where a is the 2D lift curve slope; α is the section angle of attack; and $C_{l,\max}$ is the maximum lift coefficient before stall.

$$C_d = \begin{cases} C_{d0} + C_{d\alpha}\alpha + C_{d\alpha^2}\alpha^2 + C_{d\alpha^3}\alpha^3 \\ C_{d0} - 0.008\alpha + 4.27\alpha^2 - 2.50\alpha^3 \end{cases} \quad (8)$$

Where C_d is the dimensionless drag coefficient; C_{d0} shows the zero-lift drag coefficient, accounting for parasitic drag including skin friction and form drag at $\alpha = 0^\circ$; Where these induced drag coefficients $C_{d\alpha}, C_{d\alpha^2}, C_{d\alpha^3}$ are results from the flight test of the *Acer diabolicum* Blume seeds, done by Azuma and Yasuda in 1989 (11). $C_{d\alpha}$ captures first-order changes in drag; $C_{d\alpha^2}$ shows non-linear growth of drag with angle of attack; $C_{d\alpha^3}$ introduces asymmetry in the drag when modelling stall effects at high angles.

$$C_L(\alpha) = K_p \sin \alpha \cos^2 \alpha + K_v \cos \alpha \sin^2 \alpha \quad (9)$$

In this study, another lift model is used to capture the LEV effect on the blade. Which is the Polhamus leading-edge vortex model⁽³⁴⁾, with K_p and K_v representing the vortex and potential flow contributions to lift. The values of K_p and K_v are taken to be 4.00 rad^{-1} and 3.01 rad^{-1} respectively⁽³⁵⁾.

3.4 Prandtl tip loss factor

Moreover, although the finite blade method is used to build the model, the assumptions of an actuator disk in the momentum theory with infinite blades still overestimate the induced velocity near the wing tip. To simulate the real physics, the model uses the Prandtl tip-loss factor to reduce the vortices from closer to the wing tip and reduce circulation⁽³⁶⁾.

$$F_{\text{loss}} = \frac{2}{\pi} \cos^{-1} \left[\exp \left(-\frac{1}{2} \frac{1 - \frac{r}{R}}{\frac{r}{R} \sin \phi} \right) \right] \quad (10)$$

where N_b is the number of blades and R is the rotor radius measuring from the blade root to tip; r is the elemental radial position along the blade; F_{loss} indicates the Tip-loss correction factor ($0 < F_{\text{loss}} \leq 1$), equal to 1 means ideal blade with infinite span, less than 1 represents Real blade, hence a lift reduction near the tip. This then multiplies the momentum thrust equation.

3.5 Momentum theory

The momentum Theory treats the rotor as an actuator disk and relates thrust to the induced velocity field by applying conservation of mass and momentum to a control volume encompassing the rotor. When the inflow V_d enters this stream tube, it is being pushed down by the disk formed from the falling samara, which leads to the induced velocity v_i .

Consequently, the air surrounding the disk slows down; such an effect is exaggerated at the end of the stream tube. Noticeably, when this force generated by the samara to push down the inflow air should be the same value as the thrust generated by the samara. The momentum thrust is then obtained by finding this force T_m ⁽³⁷⁾⁽³⁶⁾.

$$T_m = 2\rho S (V_d - v_i) v_i \quad (11)$$

where S is the rotor disk area, which comes directly from the annular momentum equation⁽³⁶⁾. However, the above general equation only works for the case of constant induced velocity. This is not the case for the autorotative samara,

due to the varying angle of attack of the blade running from root to tip. Hence, the equation is adapted to give the elemental annual(ring) momentum thrust as:

$$\delta T_m = 2\rho (2\pi r \delta r) (V_d - v_i) v_i \quad (12)$$

Rearranging Equation (12) gives a quadratic form in v_i :

$$(V_d - v_i) v_i = \frac{\delta T}{4\pi r \rho \delta r} \quad (13)$$

$$K_{loc} = \frac{dT}{4\pi r \rho \delta r} \quad (14)$$

Then substituting (13) into (14).

$$v_i^2 - V_d v_i + K_{loc} = 0 \quad (15)$$

Finally, solving the quadratic (15) yields down to the following physically possible root, where it satisfies $0 \leq v_i \leq V_d$:

$$v_i = \frac{V_d - \sqrt{V_d^2 - 4K_{loc}}}{2}. \quad (16)$$

Where K_{loc} is the local thrust loading per unit annular area from momentum theory, dr is the annular element width. In the autorotation solver, K_{loc} is used to update the induced velocity v_i by matching the thrust results obtained between the blade elemental and momentum theory calculation.

3.6 Assembly and iterative solution of the BEM model

$$\delta L = \frac{1}{2} \rho U^2 c \delta r C_l F_{tip} \quad (17)$$

$$\delta D = \frac{1}{2} \rho U^2 c \delta r C_d \quad (18)$$

The elemental lift and drag forces per divided sections are obtained from (17) and (18). Where ρ is air density, c is the chord length, and U is the resultant air velocity. These can then be resolved into elemental thrust and torque:

$$\delta T = \delta L \cos(\phi) + \delta D \sin(\phi) \quad (19)$$

$$\delta Q = (\delta L \sin(\phi) - \delta D \cos(\phi)) r \quad (20)$$

Summing along the blade span yields the total thrust T and torque Q :

$$T = \sum_{j=1}^n \delta T \cos(\beta) \quad (21)$$

$$Q = \sum_{j=1}^n \delta Q \quad (22)$$

Finally, for the samara seed to sustain an autorotative state, it needs to satisfy the following algebraic expression, when all the elemental forces summing up from the root to the tip of the wing blade.

$$\begin{cases} T_{\text{BEM}} - mg = 0, & \text{(weight balance),} \\ Q_{\text{BEM}} = 0, & \text{(torque balance),} \\ T_{\text{BEM}} - T_{\text{mom}} = 0, & \text{(BEM-momentum consistency),} \end{cases} \quad (23)$$

where T_{BEM} and Q_{BEM} are the total thrust and torque from Blade Element Theory, T_{m} is the thrust from Momentum Theory, m is the mass of the samara, and g is gravitational acceleration.

3.7 BEM Model Workflow for Samara Seed Autorotation

The flowchart of the Blade Element Momentum (BEM) analysis MATLAB model can be seen in Fig. 14. Initially, it starts with introducing the fundamental parameters and autorotating conditions for the seed. Including air density, gravitational acceleration, and mass of the samara seed, the geometric characteristics of the rotor blades encompass rotor radius, wing spanwise chord length distribution, blade pitch angle, and blade flapping angle. After that, the spinning samara wing, which is often referred to as the blade, is discretised into sectional small spanwise elements, each of which has a various chord length. This helps to produce localised aerodynamic performance data, which can then be summed up to get the resultant thrust and torque acting on the seed blade when it performs the autorotating motion.

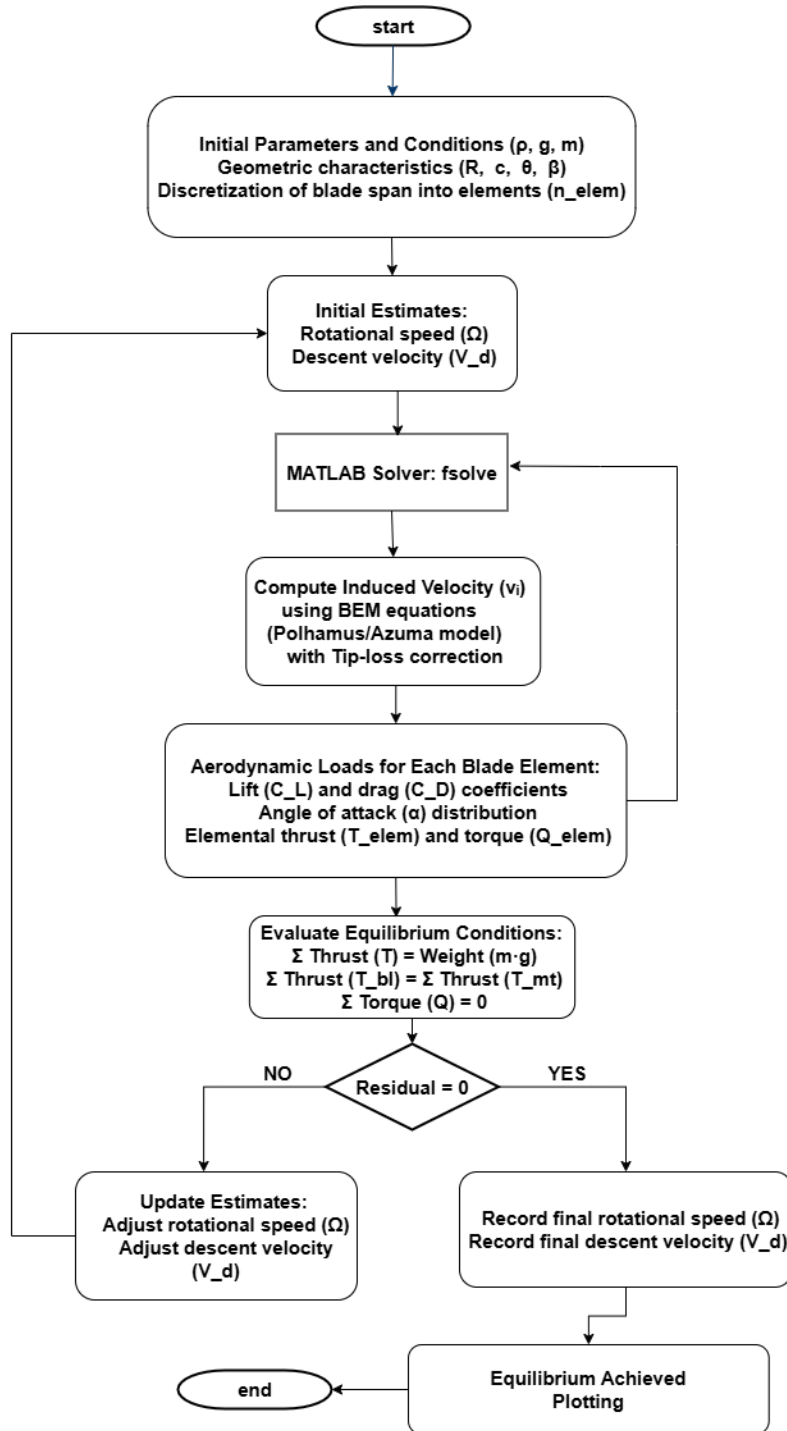


Figure 14: Schematic flowchart showing the step-by-step process of the BEM method for determining the equilibrium autorotating state, including the iterative estimation of the essential parameters Ω , V_d and v_i for a spinning samara seed.

From this model, three primary output parameters are essential to obtain during their equilibrium autorotating state:

- Rotational speed of the samara wing (Ω)
- Rate of descent (V_d)
- Induced velocity (v_i)

In order to find these values for the three interested parameters, a set of algebraic equations needs to be solved. However, not a single root of these equations is yet known. Therefore, initial guesses for rotational speed and descent velocity are made to start the iterative numerical solution process. The MATLAB solver function ‘fsolve’ is employed to iteratively find the equilibrium states for these algebraic equations in the BEM method. These loads are then integrated to evaluate if the global equilibrium conditions are satisfied.

Specifically, equilibrium is achieved when the following three conditions are met:

1. The total rotor thrust equals the total weight.
2. The sum of the blade thrust from blade element theory matches that from momentum theory.
3. The net torque about the rotational axis is approximately zero.

The model will only output results when all three conditions are satisfied. The solver examines these conditions to calculate a residual, which indicates the accuracy of the current solution.

When the residual remains nonzero, the rotational speed and descent velocity are manually adjusted to drive the solution closer to the equilibrium point. This process proceeds until the residual meets the set convergence criterion. Eventually, upon convergence, the final values of rotational speed and descent velocity are listed. The autorotational behaviour of the samara seed under varying initial conditions is then illustrated through a series of plots.

4.0 Results

This section first presents the validation results of using the BEM model, with the outcome compared against the same seed data reported in the literature. The primary performance metric for the seed under different situations is the descent velocity (V_d), which directly relates to the safe descent criteria of the Samara-inspired vehicle for extraterrestrial missions.

Next, an analysis has been done to investigate how seed mass affects the geometry and scaling parameters. The geometry of the selected seed is em-

bedded to generate 3D surface contours of valuable operating regions with parameters including gravity, air density and scale.

4.1 Validation of the BEM model

The validation process involves comparing results developed from the model to the experimental data reported by Azuma and Yasuda (11) for a variety of samara species. The dataset includes all seed species listed in Table 1a, where the relevant geometric and flight performance parameters: mass, radius of rotation, solidity, rotational speed, descent speed, coning angle, and pitch angle were used as input to the BEM simulations.

The geometric and other properties of seeds from literature are summarised in Table 1. Where the geometric parameters are shown in Table 1a, and the measured descent behaviour is given in Table 1b. Since the original work by Azuma and Yasuda did not provide detailed chord distributions along the span-wise direction, each seed was modelled as a rectangular planform. Where the length of this rectangle is obtained from the given rotation radius data, the width is obtained from an average chord length from the back calculation of the provided solidity using Equation (24).

Table 1: Geometric and aerodynamic properties of rotary seeds.

(a) Geometric properties part a.

Species	Mass (g)	Radius of rotation R (cm)	Rotational speed (RPM)	Solidity	Chord (m)
<i>Acer diabolicum</i> Blume	0.058	2.84	977.0	0.12	0.010 71
<i>Acer palmatum</i> Thunb.	0.013	1.20	1805.8	0.12	0.004 52
<i>Acer palmatum</i> var. <i>matsumurae</i> Makino	0.038	2.09	1101.5	0.12	0.007 88
<i>Carpinus tschonoskii</i> Maxim.	0.023	1.76	965.0	0.15	0.008 29
<i>Liriodendron tulipifera</i> L.	0.050	3.44	498.3	0.09	0.009 73
<i>Pinus thunbergii</i> Parl.	0.023	1.79	1472.8	0.11	0.006 19

(b) Geometric properties part b.

Species	Descent speed V_d (m/s)	Coning angle β (°)	Pitch angle θ (°)
<i>Acer diabolicum</i> Blume	0.82	23.7	−1.17
<i>Acer palmatum</i> Thunb.	1.09	15.0	−0.90
<i>Acer palmatum</i> var. <i>matsumurae</i> Makino	1.04	27.6	−1.39
<i>Carpinus tschonoskii</i> Maxim.	1.02	12.9	−2.16
<i>Liriodendron tulipifera</i> L.	1.19	34.2	−19.10
<i>Pinus thunbergii</i> Parl.	0.98	20.8	−1.43

$$\sigma = \frac{N_b \cdot c_{\text{avg}}}{\pi R} \quad (24)$$

Where σ is the dimensionless ratio of solidity, N_b is the number of blades,

c_{avg} is the average chord length, and R is the rotor radius. Hence, the resulting chord lengths for each species are then obtained and shown in Table 1a. The model simulates for each species from these parameters. Producing estimates of rotational speed (n) and descent speed (V_d) for comparison against experimental values.

Table 2: Comparison between BEM-predicted and experimental results.

Species - BEM	BEM-RPM	BEM- V_d	Difference in RPM (%)	Difference in V_d (%)
<i>Acer diabolicum</i> Blume	1086.4	0.7536	11.20	-8.10
<i>Acer palmatum</i> Thunb.	1804.8	1.0000	-0.06	-8.26
<i>Acer palmatum</i> var. <i>matsumurae</i> Makino	1098.2	1.0250	-0.30	-1.44
<i>Carpinus tschonoskii</i> Maxim.	964.5	1.0200	-0.05	0.00
<i>Liriodendron tulipifera</i> L.	567.4	1.1873	13.87	-0.23
<i>Pinus thunbergii</i> Parl.	1470.6	1.0000	-0.15	2.04

The differences between the model and existing data are summarised in Table 2. The model works well in capturing the aerodynamic behaviour of the *Acer palmatum* var. *matsumurae* Makino, with difference of less than 2 % in both rotational speed and descent velocity. These data are then turned into plots. Where the overall performance trends are illustrated in Fig. 15. Comparing with Fig. 15b, Figure 15a reproduces the classical results of Azuma and Yasuda [11], reaching a good degree. From the Fig. 15b. Many of them are of a single flat wing, only a few are multiple wings. Some even with curved wings bent to let the wing tip become horizontal. Capturing this feature can produce more accurate data, because this adds in addition airloading towards the wing tip, and so the coning angle or the flapping angle reduces. This serves to raise the effective disk area and provide more lift, hence lower descent speed.

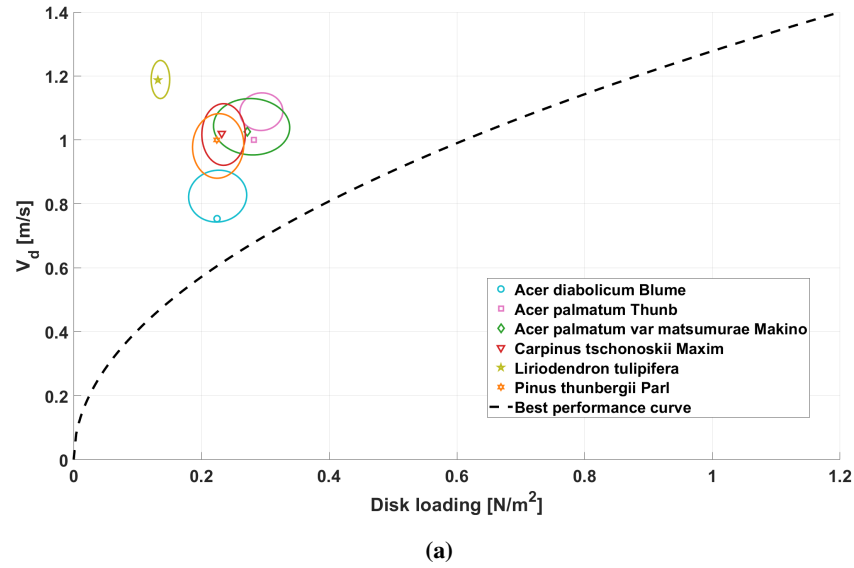
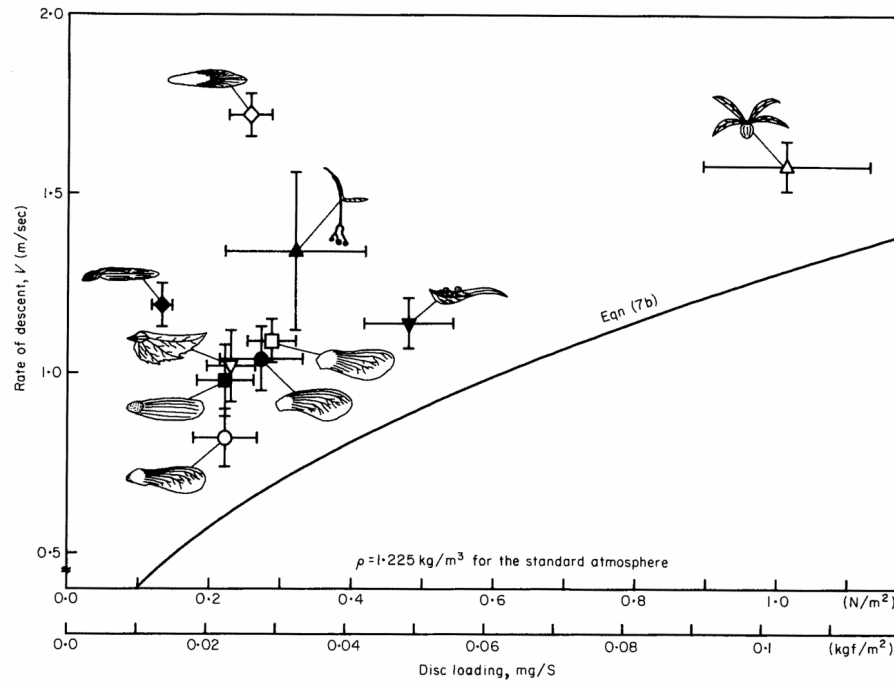


Figure 15: Comparison of model samara descent performance with literature data. (a) Rate of descent vs disc loading for various samara species from the BEM model. (b) Rate of descent vs disc loading from Azuma and Yasuda studies [\[11\]](#).

Examine those seeds that lie inside the acceptable range, the most desired cases are the seeds with minimal descent speed while exhibiting larger disk loading. This is because, for future applications, when using the seed model to carry a payload for landing performance. The one that is capable of descending at a safe rate while carrying the most payload would be more economically saving. Therefore, seeds of *Acer palmatum* Thunb and *Acer palmatum* var *matsumurae* Makino would be used for the following tests.

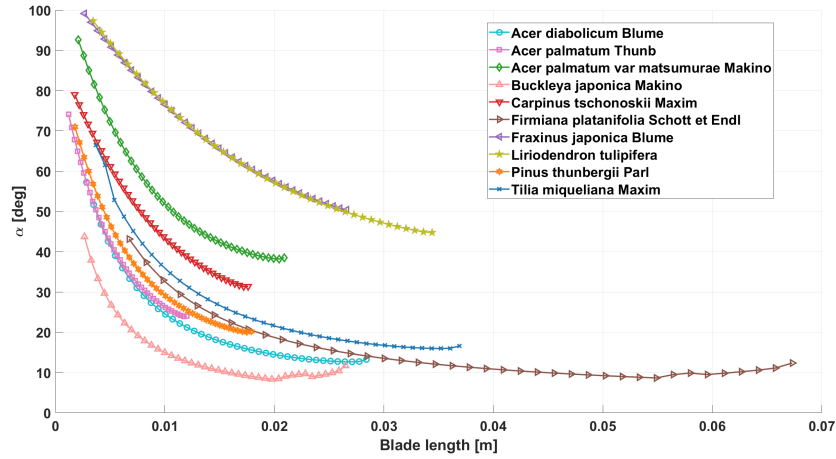


Figure 16: Variation of angle of attack α with blade length for seed species.

Next, as shown in Fig. 16, the angle of attack is highest near the seed base and gradually decreases towards the wing tip. This tendency is consistent with the observation in the literature (19), which again confirms that the BEM model is capturing the expected aerodynamic behaviour and producing reliable results.

Moreover, Figure 17 above provides the natural sampling data of two *Acer* maple seeds. This is the mass comparison data between the total seed mass and the cut wing part. The measurement has further proved that the *Acer palmatum* var. *matsumurae* Makino holds higher seed mass at comparable radial positions, while producing lower descent speed. This means a greater payload-carrying capacity. Hence, the Makino variant makes a better candidate for digital modelling and exploratory analysis in the present study.

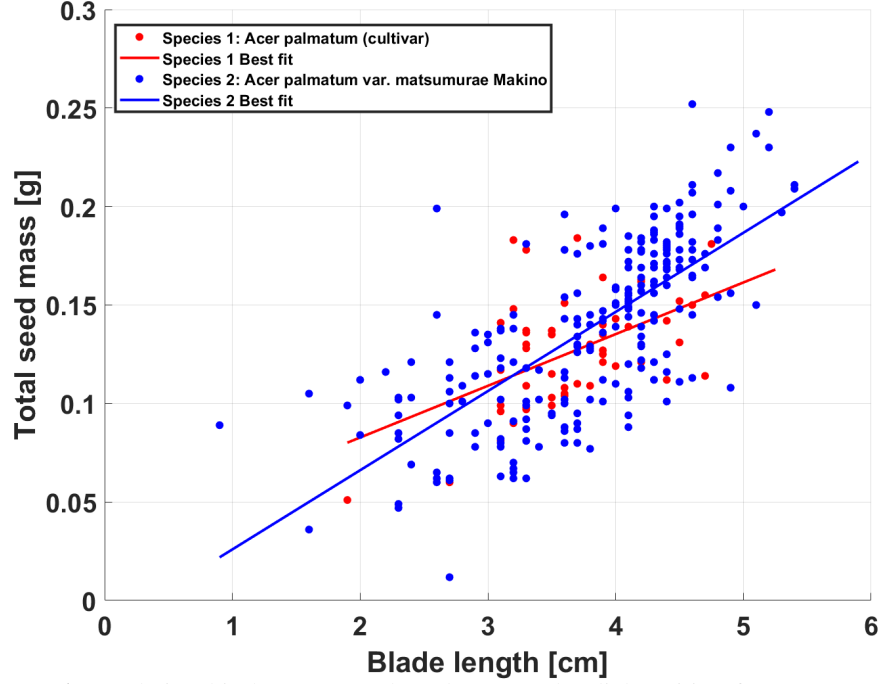


Figure 17: Relationship between total seed mass and radial position for two *Acer* species. where Red points represent *Acer palmatum* (cultivar); Blue points represent *Acer palmatum* var. *matsumurae* Makino.

4.2 Digital Samara model

The selected seed indicated in Fig. 12 is marked along both the spanwise and chordwise directions, with a cut made at the wing root. To capture its geometric characteristics in detail, the wing was divided into 20 spanwise sections. These divisions were not physically cut but rather indicated by drawn lines, with the geometric data of each strip subsequently represented in MATLAB as seen in Fig. 18.

Additionally, it is worth to point out that, only the wing section is used in the BEM model for analysis, due to this is the compoment generate must lift. The performance of this seed can be seen in Fig. A1–A5. For future physical design, a CAD model of this selected seed is also displayed in Figs. A6–A8.

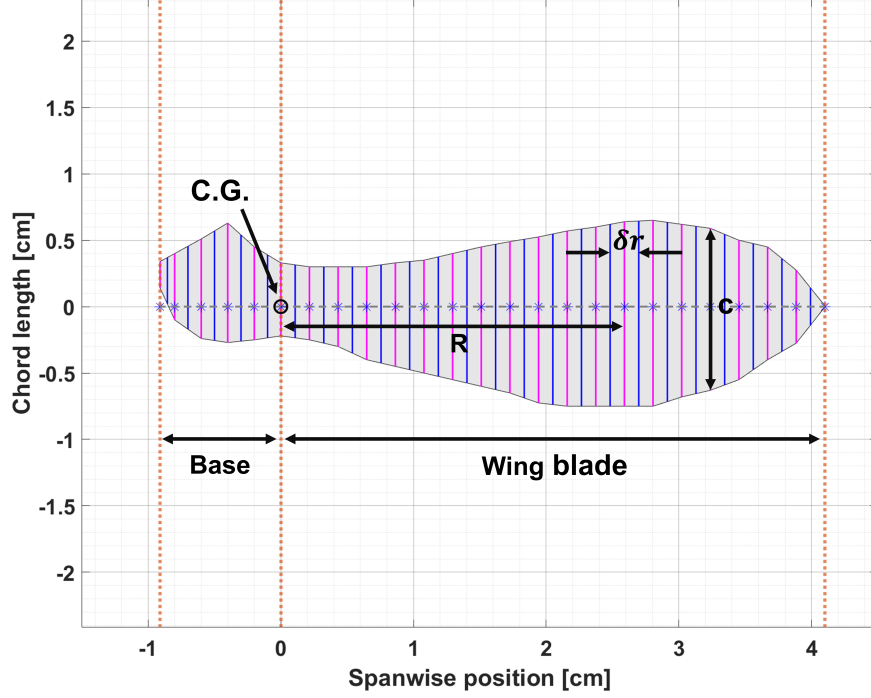


Figure 18: Digitised planform shape of the maple seed, showing radial element discretisation for BEM analysis.

In this model, the vertical axis represents the effective chord length (c) of each element of the samara seed, while the horizontal axis corresponds to the radial distance (dr) of each strip centre to the disc centre. However, only the wing portion of the seed is considered, since the seed base contributes negligibly to lift, and the actual spin centre coincides with the centre of gravity (CG) located near the root cut. For improved resolution in MATLAB, the drawn seed was further divided into 40 blade elements, as this chordwise distribution provides a finer grid that more accurately captures the natural geometry of the samara when implemented in the BEM model.

4.3 Mass scaling relations of the BEM model

Inspecting Fig. 19, it can be found that the relationship between mass and scale follows a nonlinear pattern . Such a smooth trend provides a solid foundation for comparing descent speed outcomes from various geometry settings.

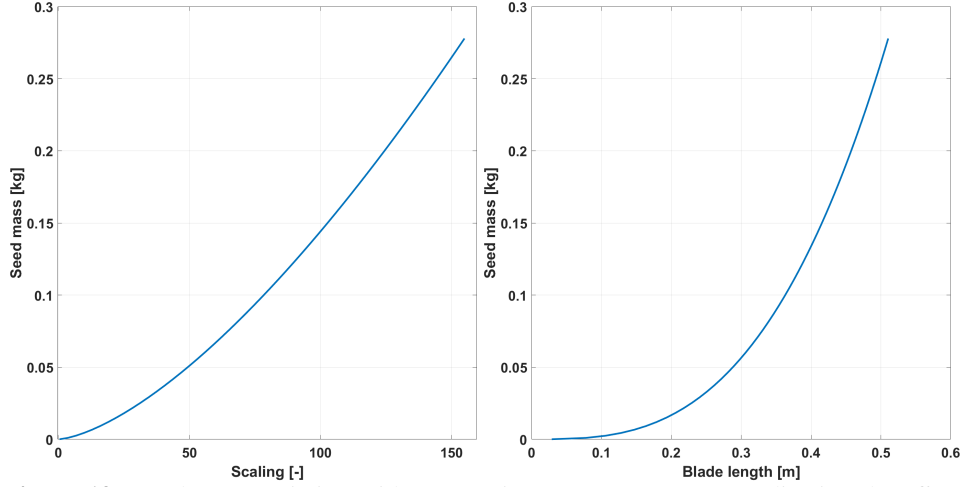


Figure 19: Seed mass variation with geometric parameters. LEFT: Indicating the effect of scaling factor on seed mass; RIGHT: Showing the effect of blade length on seed mass.

The relationship between mass and scale, as given in Equation 25, is shown in Fig. 19(LEFT). It provides a foundational link between geometric scaling and its mass. The spinning samara seed will have its mass and rotor area exhibit an upward trend with scales. Therefore, understanding this scaling divergence is essential for effective seed design optimisation 11.

$$m = 1.44 \times 10^{-4} \cdot \text{Scale}^{3/2} \quad (25)$$

Beyond scales of about 100, the increasing mass starts to significantly dominate the descent dynamics, diminishing the relative effectiveness of having additional wing surface area in lift generation.

Moreover, Fig. 19(Right) shows that seed mass scales with rotor radius (or blade). The relationship follows a cubic trend, supporting the assumption that mass grows volumetrically with size 11. Seed mass increases cubically with rotor size; this is consistent with standard volumetric scaling 16..

For a fixed blade geometry, volume increases with R^3 . When the rotor blade size increases, the mass grows faster than its surface area; this imposes a significant effect on the descent speed and autorotative stability. This disproportionate growth in weight relative to blade area can cause faster descent rates and difficulties in maintaining stable autorotation 11.

4.4 3D parametric analysis

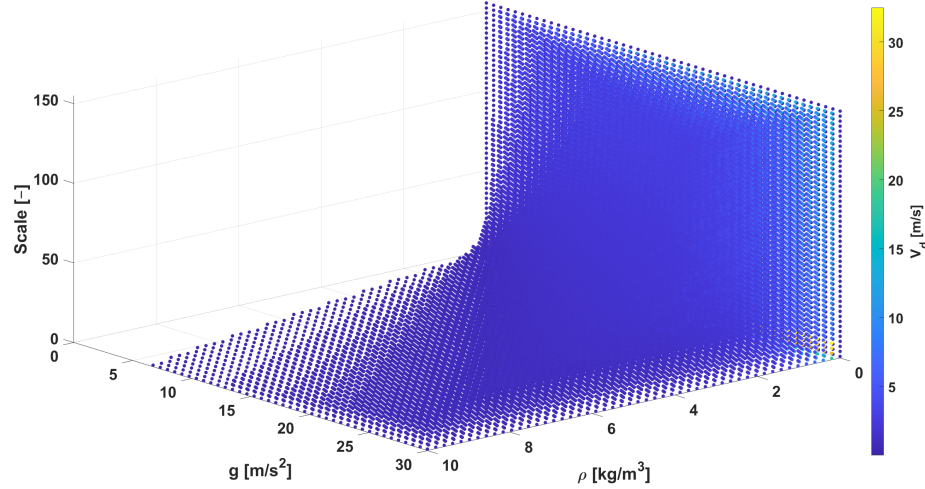


Figure 20: Initial BEM descent speed with boundaries across ρ , g , and scale; And use of colour bar to indicate size of descent rate.

Figure 20 shows a volumetric sampling of the entire 3D parameter space, with descent speed plotting for gravity, density and scale. The boundaries are defined following these reasons: Gravity set to 30 m/s^2 , due to the maximum gravitational acceleration of Jupiter is 24.8 m/s^2 ; Air density limit of 10 to give a reasonable iteration range within the solar system. The scale is restricted to 155, as this is the maximum capacity of the BEM model.

A closer look at the Figure shows that the descent speed surface is highly non-linear, exhibiting multiple minima and maxima. And within this region, a distinct ‘valley’ region emerges, representing optimal combinations of scale, gravity and air density that enable slow and stable descent.

The Fig. 21 shows the filtered output of the global BEM dataset, with only the region with decent speed equal to or below 1.5 m/s . This cutoff is made due to the assumed mission constraint, which requires the unpowered samara-inspired vehicle should carry its payload while passively landing under a certain speed. This shows a mission-feasible subspace in extraterrestrial environments such as Mars, Titan or Moons with atmospheres, outlining a smaller design envelope that this vehicle can safely descend.

Furthermore, the valid descent zone makes a triangular prism in three-dimensional space. Constrained in the following three main conditions: the gravity needs to remain moderate level, within the range of gravity less than

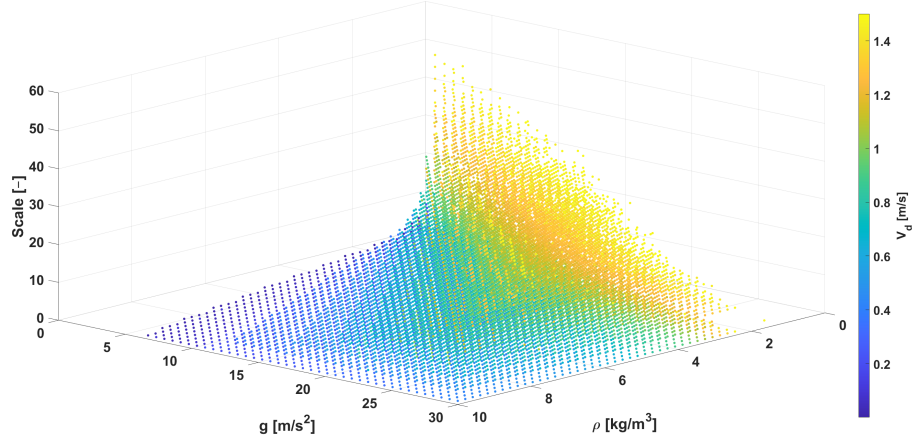


Figure 21: Filtered BEM output for maple-seed descent: cases with descent velocity cap at 1.5 m/s with colour bar indicates size of V_d .

10 m/s²; The air density should be at least larger than 0.204, smaller than this value, there is no outcome produced by the BEM model; Lastly, at scale equal to 55 is the geometric ceiling. Inside this region, the smallest descent velocities around 0.2 m/s occur under low gravity conditions with high air density, while the scale remains modest.

5.0 Discussion

The Blade Element Momentum (BEM) model overall captures the descent performance of the single-bladed samara rotor in great detail, particularly in its aerodynamic performance under changing Gravity, Air density, and Scale. All share a nonlinear coupling relationship. While each parameter independently influences the descent speed, it is essential to consider their cross-effects. This is key to uncovering the hidden physical rules of how those three parameters work together for scaling design, specifically how one parameter modulates the influence of another.

Hence, the analysis presented in this section mainly discussed three points: Analysing how individual factors influence descent velocity; Explaining parameter cross-interaction behaviours, how they link to autorotative descent in scaling seeds across varying conditions; Identifying the feasible range of descent velocity on Earth and defining a broader planetary design space for future planetary exploration applications.

5.1 Isolated parameter effects in descent velocity

To begin with, Fig. 22 illustrates the variation of descent rate with geometric scaling under constant Earth-standard conditions. Where ρ equals 1.225 kg/m^3 and g is 9.81 m/s^2 . The descent velocity V_d increases rapidly up to scale 40, showing a faster rise in mass relative to lift generation (11). However, the growth slows in the region of 40 to 100, followed by small fluctuations at larger scales.

These are not due to numerical noise. Instead, they are caused by the interaction between induced velocity and the defined finite blade section in the BEM model (36). When the blade element becomes finer, this can be removed.

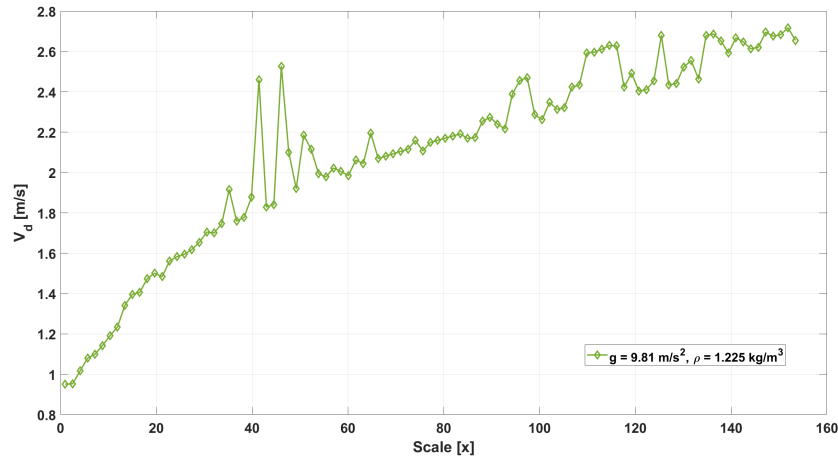


Figure 22: Effect of geometric scaling on V_d .

The increase in descent speed with enlarged scale initially seems counterintuitive, as larger blade area typically gives more lift to keep the seed airborne for a longer time (11). However, this can be explained by the scaling law (25), the growth of mass outpacing the lift generated by increased area alone. Mass begins to dominate the resultant falling effect, causing faster descent at larger scales. This effect will only be reversed when there are enhancements in blade efficiency for the seed. The local small-scale deviations in the curve reflect insufficient grid resolution in the BEM simulation. Such an imbalance between lift and weight is explored further in the following gravity and geometry relations.

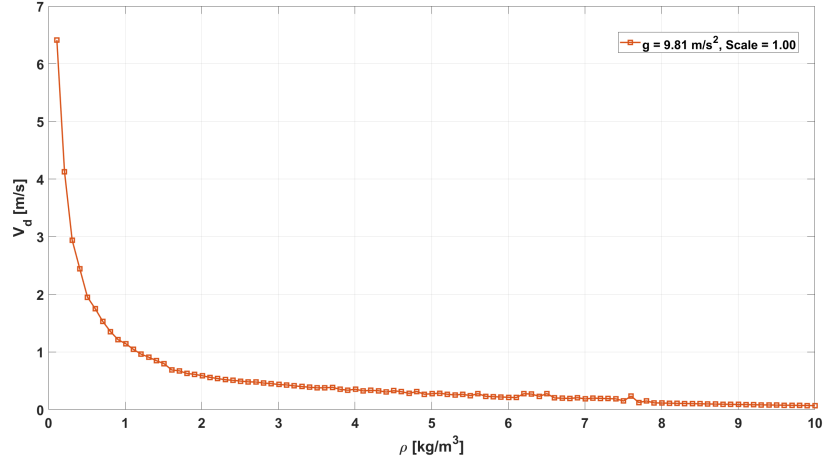


Figure 23: Influence of air density on V_d .

To complement this, Fig. 23 further isolates the role of air density. A peak appears at ρ closer to zero before it quickly drops and levels off. This is owing to the fast-falling velocity in a very low ρ condition. In a vacuum like this, there is almost zero axial velocity component, resulting in negligible aerodynamic damping. When density increases slightly above zero, a small amount of induced velocity kicks in but needs higher inflow air momentum to generate sufficient force to balance weight, producing a sharp rise in V_d . Beyond this threshold, less air inflow is needed to reach the equilibrium state, causing V_d to drop before levelling off eventually.

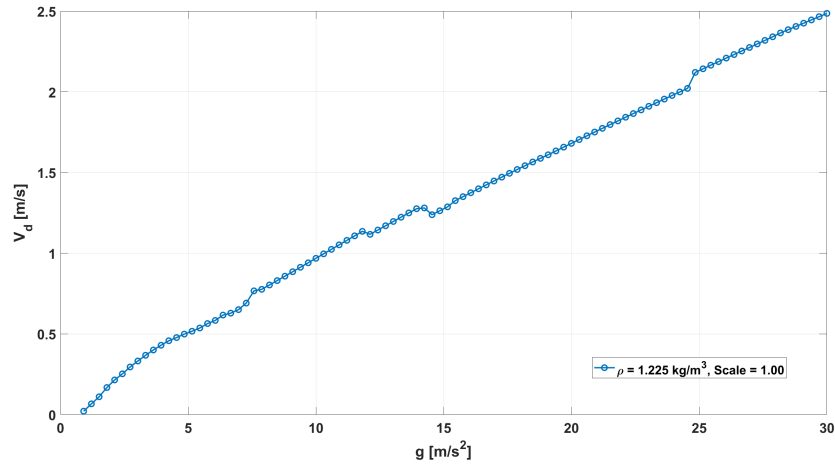


Figure 24: Variation of V_d under changing gravity.

Next, Fig. 24 isolates the role of gravity. Where V_d increases almost linearly with g , representing a direct proportionality between gravitational acceleration and the effective weight of the seed. Interestingly, gravity opposes diminishing returns as the density; instead, higher g produces faster descent.

In conclusion, the three isolating parameters analysis shows the competing influences of geometry and environment on descent performance. While larger scales and stronger gravity drive faster descent through increased weight, higher air density reduces this effect by producing a stronger axial velocity component, hence larger resultant flow velocity U as indicated in Equation (3), thus total thrust increases, meaning more aerodynamic damping.

5.2 Coupled effects of Gravity, Scale and Air density

5.2.1 Coupled effects on samara descent performance

Figure 25 shows how descent velocity varies with gravity in different air densities at the original samara size. At low density where ρ equals 0.1 kg/m^3 , the descent velocity V_d rises sharply with gravity, giving values of 14 m/s at g equals 30 m/s^2 . The samara is still autorotating but dropping fast. This results from the reduced airflow passing through the rotating disk. In contrast, at higher densities with ρ is greater than 2 kg/m^3 , V_d remains below 2 m/s even as gravity increases. This again proved that with denser atmospheres, the spinning samara are more effective at compensating for the gravity.

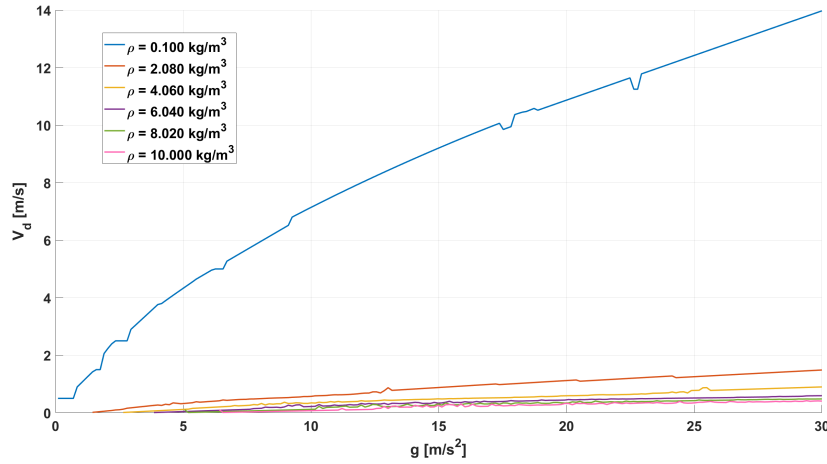


Figure 25: V_d vs g for different fluid densities (ρ). scale = 1.00, sweep ρ .

Similarly, inspecting Fig. 26, it outlines the sweeping air density with unchanged samara size at the Earth scale. Surprisingly, for all g values, V_d de-

creases exponentially with increasing ρ . This trend arises because the drag is directly proportional to air density; a larger drag force provides a stronger resisting effect, allowing the samara to remain airborne for a longer duration.

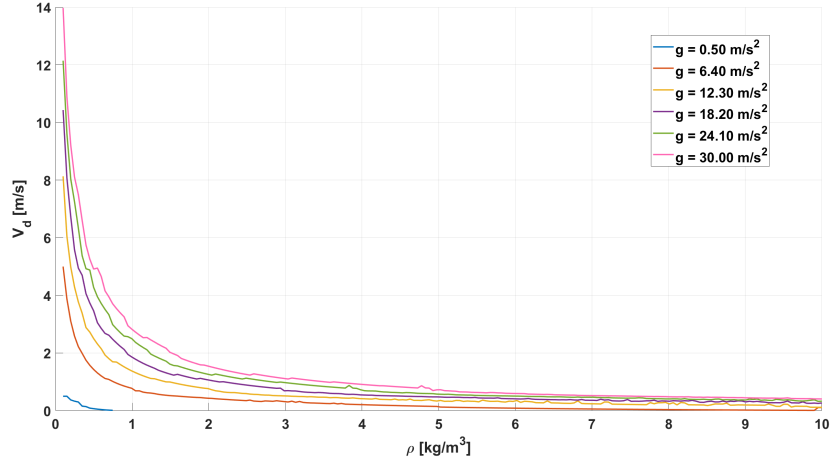


Figure 26: V_d vs ρ for different gravitational accelerations (g). Scale = 1.00, sweep g .

At higher ρ , the rotor requires a lower descent velocity to generate sufficient drag to balance the weight. Conversely, in thin atmospheres, the seed must fall faster to produce the same resisting force. This behaviour is well aligned with the drag law as shown in Equation 26, where drag increases with velocity squared, compensating for decreasing air density.

$$D = \frac{1}{2}\rho V^2 C_D A \quad (26)$$

An additional feature of Fig. 26 is that the falling rate with density is not constant across gravitational levels. At a lower g equal to 0.5m/s^2 , increasing density quickly stabilises descent speed, up to a region where the BEM model can no longer generate autorotating data, due to thrust outweighing the gravity pull. In contrast, at higher g of 20m/s^2 , the descent velocity remains below 2m/s^2 even at high density, caused by gravity increases the drag contribution. Thus, the density effect saturates, and increasing ρ further provides only small reductions in V_d .

Furthermore, Fig. 27 introduces scale as a third parameter, examining its effect under constant Earth gravity. The general inverse relation between V_d and ρ is maintained across scales, but at larger rotors, when the scale is greater than 60, this constantly provides a higher V_d than smaller ones at the same density. This is caused by the mass scaling law, where increased mass offsets

the aerodynamic gains from a larger area.

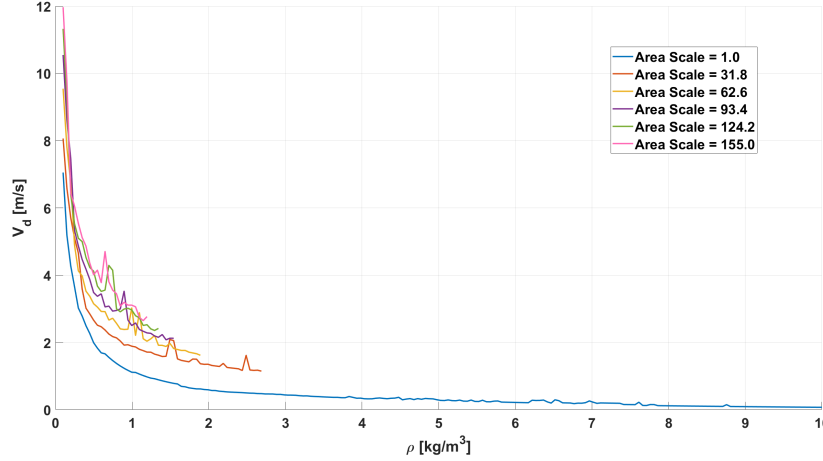


Figure 27: V_d vs ρ for different area scaling factors. Gravitational acceleration $g = 9.81 \text{ m/s}^2$, sweep scale.

Interestingly, the separation between those curves in Fig. 27 at various scale settings becomes more obvious at low-to-moderate density range, while at high densities they tend to vanish, leaving only the initial scale producing data up to the maximum density setting. This indicates that atmospheric effects can overshadow geometric differences in sufficiently dense environments.

Overall, these three plots confirm a key physical rule: where descent velocity increases approximately obey $\sqrt{g/\rho}$ in the mid-range of densities, but breaks down occur at both extremes. However, the $\sqrt{g/\rho}$ scaling is only applicable within a moderate density regime where aerodynamic and gravitational effects are comparable. Because at very low density, descent speed increases dramatically regardless of geometry; at very high density, lift saturation limits further improvement. Together with the analysis in scale has further shown that no single scale guarantees optimal performance behaviour; this has to depend on the coupled balance between mass growth, gravity, and aerodynamic drag.

5.2.2 Region of lift–gravity dominance in descent

At a constant air density of 1.225 kg/m^3 , increasing the gravitational force acting on the seed increases the descent rate as predicted. However, such an effect is not linear across the scale range: for small scales below 20, the descent speed climbs relatively slowly with gravity. This is because the relatively

light rotor keeps gravitational forces within the acceptable range of lift generation.

In contrast, at higher scale values greater than 60, there is a steeper relation between V_d and gravity. Increasing gravity causes the descent speed to rise faster than the wing area can compensate for with lift. At large scales, the extra weight from gravity significantly surpasses the amount of lift generated, leading to faster descent rates. Consequently, this creates a gravity-scale amplification effect, with rotor geometry acting as a key determinant of gravity's impact on descent.

As a result, gravity dominates at large scales, producing a rapid acceleration in descent speed. This pattern corresponds to the divergence between lift and gravity curves as illustrated in Fig. 28-30, where mass-driven gravity rises faster than lift with increasing scale.

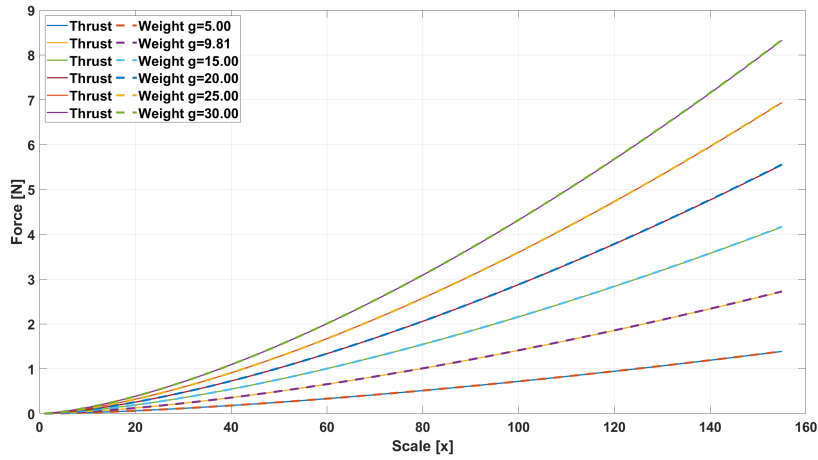


Figure 28: Comparison of thrust and gravity as a function of scale for different gravitational accelerations.

The differences between thrust and gravity is further clarified, where Fig. 28 demonstrates some selected scaling of both forces with area. It can be seen that there is a gradual divergence between them at higher gravitational accelerations. This divergence becomes stronger when comparing the net force differences across scales (Fig. 29), where the imbalance grows systematically with both g and scale. At smaller scales, however, the thrust outweighs the gravity, resulting in slower descent illustrated by the zoomed-in view in Fig. 30.

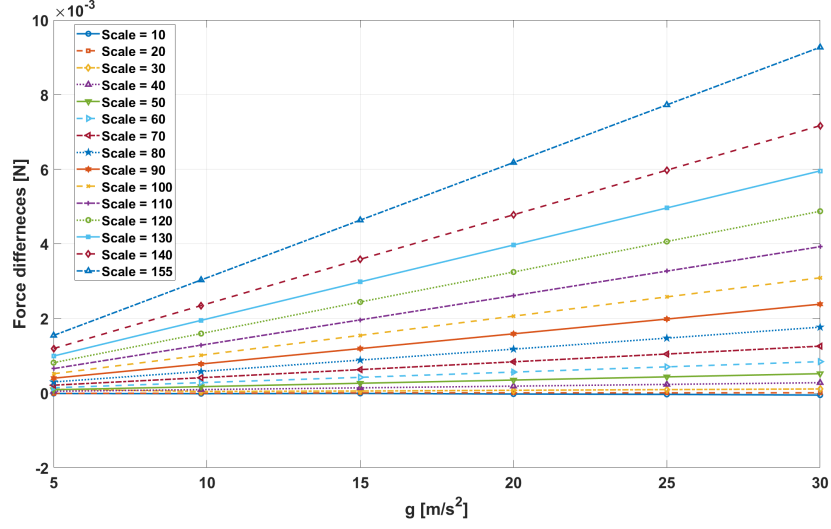


Figure 29: Force differences between thrust and gravity across a range of gravitational accelerations and scales.

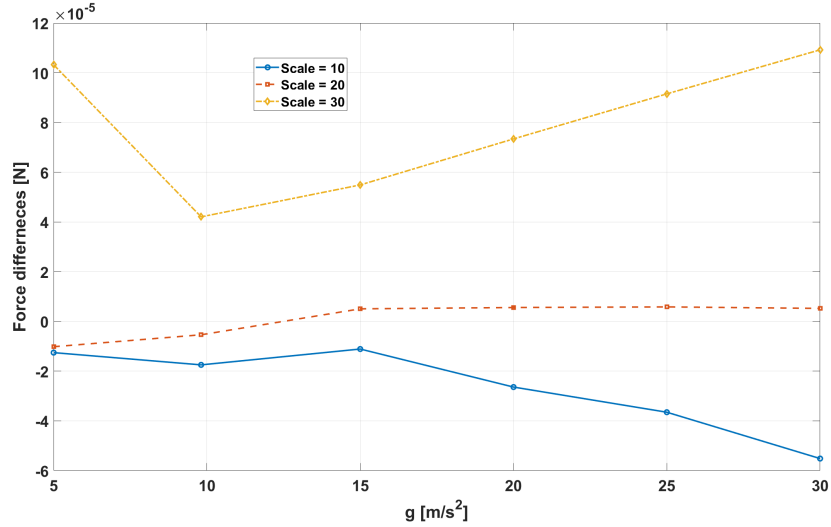


Figure 30: Force differences between thrust and gravity for $g \approx 5 \text{ m/s}^2$ at different scales.

5.3 Analysis of the feasible domain

5.3.1 3D Global parametric valley

As shown in Fig. 20, this is a densely sampled surface of descent speed across the full parametric space defined by gravity, air density and blade scale. A no-

ticeable valley of low V_d values is visible in regions of moderate scale 50-90, high density with ρ greater than 4, and mid-to-low gravity 5-15. This again confirms the existence of a sweet spot in this passive descent performance. This is the region for optimal aerodynamic and environmental conditions for the stable and slow descent using the maple-seed-inspired rotor.

The performance valley also suggests that simply maximising the blade area or minimising mass will not lead to optimal behaviour. Conversely, the sharp colour gradients at low air density and high gravitational acceleration indicate a sensitivity zone. Inside which even a minor environmental change can cause substantial performance degradation. Therefore, extra careful consideration is demanded when designing for uncertain environments.

In addition, to provide a clearer view of the 3D results, Fig. 31-33 show the separate feasibility maps of descent velocity across the parameter space. These 2D slices make clear how parametric constraints emerge in the BEM model when projecting onto specific parameter pairs.

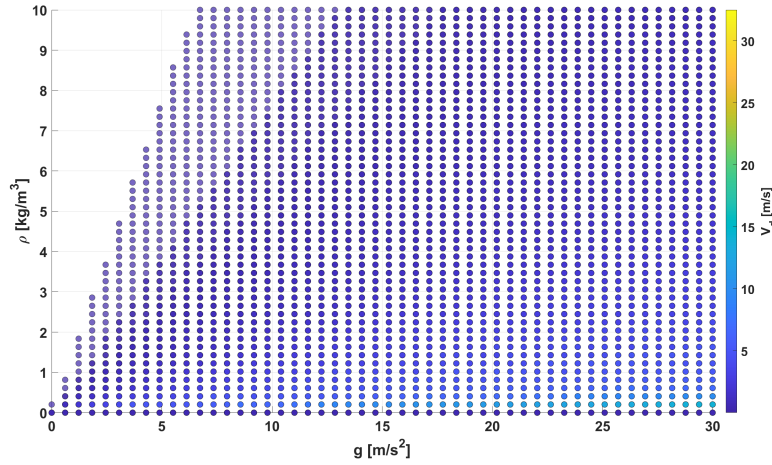


Figure 31: Gravity–Density feasible region.

To isolate the coupled effect of gravity and air density, Fig. 31 maps the gravity–density feasible region, with the descent speed V_d colored w.r.t. their values. The trapezium shape is the feasible domain, which reveals that the autorotation descent is not possible under conditions of simultaneously low gravity and high density. Because when the atmosphere is too thick, this stops the samara from reaching the equilibrium state, due to the thrust produced by the rotating blade being much larger than the gravitational pull.

However, at high gravity and low density settings, the descent Speed rises slightly, owing to less air inflow to generate the induced velocity, hence less

thrust to compensate for the gravity pull. The relatively uniform colouring across much of the domain means that the density is the dominant parameter for maintaining stable descent, while gravity primarily defines the feasibility boundary.

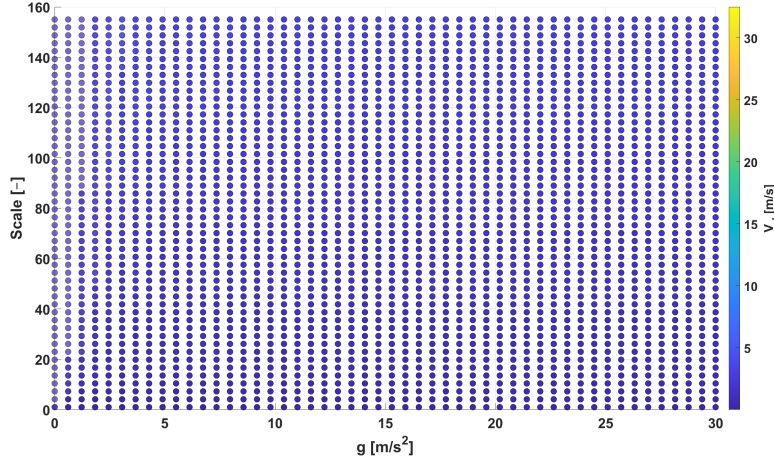


Figure 32: Gravity–Scale feasible region.

The second map considers how gravitational loading interacts with seed size. The feasible region displayed in Fig. 32 has no descent speed variation. Meaning that gravity and blade scale are not strongly coupled in determining descent speed once a feasible solution exists. However, subtle variations are visible at the lower density margins as seen in the Fig. 20. Therefore, while scale does not strongly interact with gravity, it plays a secondary role in impacting the low-density conditions.

Finally, Fig. 33 focuses on the scale versus the density feasible region. Unlike Fig. 32, there is a curved boundary seen here, which reflects a trade-off: at lower densities, larger blade areas are required to sustain autorotation, whereas at higher densities, even small scales can work without breaking the BEM model.

Two distinct regions appear at very low air density. When the scale is under 20, the descent speed is huge. The spinning blade has neither enough surface area nor enough inflow air to generate the thrust needed for autorotation. Moreover, under the same atmospheric conditions, when the scale increases to over 100, the descent rate drops a bit but remains high. Because even the area increases, the air is too thin to produce enough thrust to compensate for the additional weight gained.

In summary, the key factor for sustaining autorotation comes to air density,

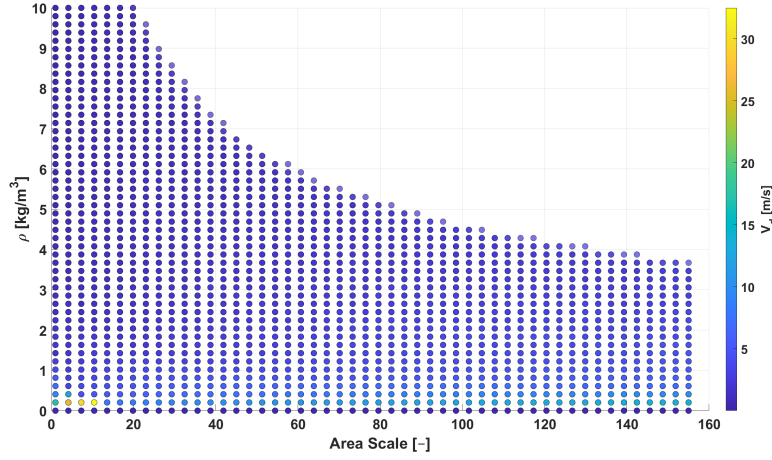


Figure 33: Scale–Density feasible region.

where gravity defines the feasibility limits, and blade scale provides compensation. Stable descent occurs only at intermediate scales with sufficient density, while extremes in low-density conditions lead to rapid fall.

5.3.2 Design space for gravity & scale

The Fig. 34 indicates a 2D surface displaying descent speed across different gravity values and scale, at constant air density with $\rho = 1.225 \text{ kg/m}^3$. Indicates the dominant influence of gravity in calculating the descent velocity of the seed.

The feasible region is the small triangle shape bounded by scale of maximum 80 and gravity below 27 kg/m^3 . Where the solid red curve is the safe descent threshold at 2 m/s , this is coming from the maximum descent speed of the natural samara. Everything below this red line is the feasible region, while the area above with V_d greater than 2 m/s is excluded, and regarded as falling too fast for a safe landing. Any white region shows that the seeds fail to reach autorotation, thus the BEM is unable to converge to an outcome.

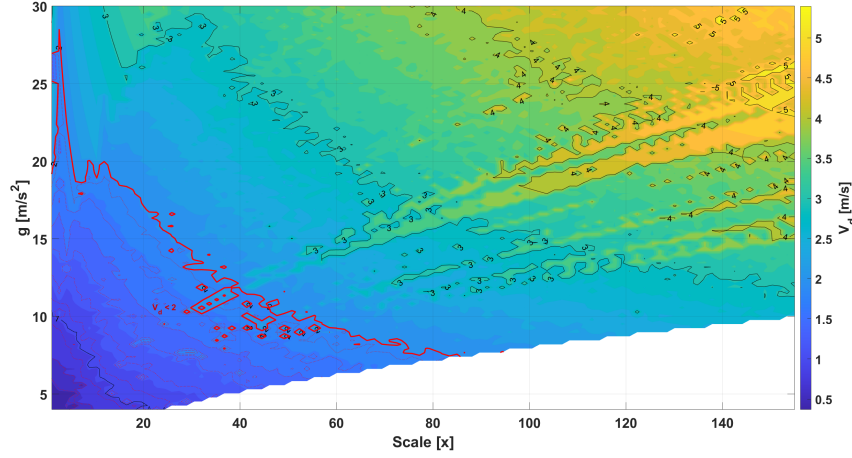


Figure 34: Feasible region for descent speed V_d across different gravitational accelerations g and scale, at constant air density ρ equals 1.225 kg/m^3 .

Furthermore, it can be seen that the descent speed increases with gravity at all scales, as expected from fundamental physics [\[36\]](#). The effect of increasing scale becomes more significant under higher gravitational acceleration. The yellow regime in the top right corners indicates the fast descents, due to the rotor failing to generate adequate lift at higher gravity levels.

5.3.3 Design space density & scale

Similarly, it comes to how density will interact with the scale to define the operational boundaries. Fig. [35](#) outlines that air density is a key factor in shaping the feasible descent range of the seed.

Similarly, the red line is the set limit of V_d equal to 2 m/s , the region above the line is the feasible region. Although the scale is able to reach 80 again, it is better to perform in a denser atmospheric environment with ρ larger than 1 kg/m^3 for optimised descent speed.

It is found that the descent velocity drops significantly with increasing air density, particularly for smaller scale [\[1\]](#). At low air density, even large rotors struggle to produce sufficient aerodynamic resistance, resulting in much higher descent speeds. Especially under low-density conditions such as those on Mars [\[28\]](#), the effectiveness of having larger blades is reduced due to diminished lift generation. As expected, this is consistent with the fundamental lift and drag equations involving air density [\[36\]](#). Notably, the feasible region shrinks when air density rises; this shows that the impact of density flattens out at higher values, implying a saturation effect in lift enhancement beyond a

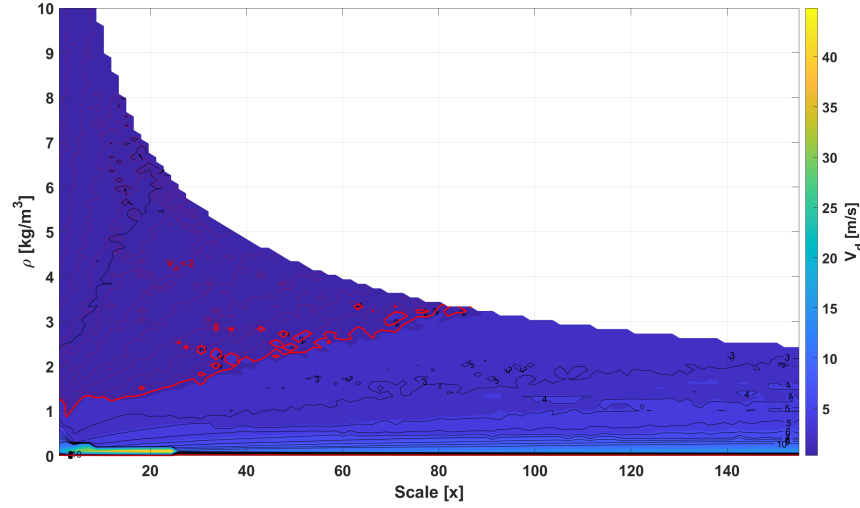


Figure 35: 2D surface of feasible range in descent speed V_d as a function of air density ρ and scale, at constant Earth gravity $g = 9.81 \text{ m/s}^2$.

certain threshold.

Thus, it can be concluded that there is a density-dependent “sweet spot” in rotor size for the slowest descent. At a moderate air density of 4 kg/m^3 , this enables the use of the largest scale while staying inside the safe descent speed region; For air density smaller or larger than this point, the allowable scales drop significantly.

5.3.4 Design space gravity & density

Figure 36 shows the design space of descent speed variation with changing gravity and air density at a constant scale of 1. The regions shaded with dotted red lines are the desired design space, which is the right of that red solid curve, beyond ρ equal to 0.6 kg/m^3 . To operate safely inside this boundary, as gravity rises, the minimum air density is also required to increase.

Moreover, a performance “dead zone” emerges, shown in yellow. This is because the largest descent speeds occur at high gravity and low density. There is a critical threshold for the density, beyond which the lift is almost negligible regardless of gravity [\[11\]](#).

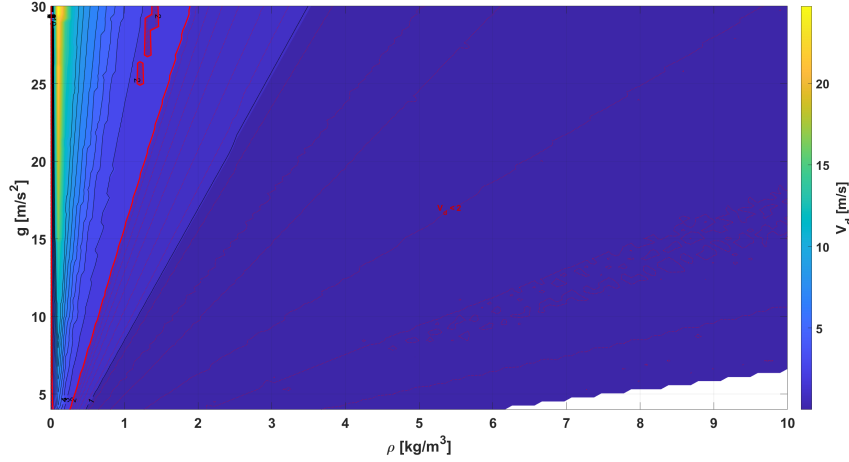


Figure 36: 2D surface of feasible range in descent speed V_d variation with gravity g and air density ρ at constant initial scale.

Inside this region, the samara falls quickly due to the lack of lift generated. In contrast, working environments characterised by moderate-to-high air density and low gravity provide slow and stable descent⁽¹¹⁾. These results have potential implications for the design of planetary descent systems⁽²⁸⁾.

Thus, optimising the ratio between atmospheric density and gravity is vital for maintaining aerodynamic functionality. The integration of these results then establishes a foundation for exploring the full parametric space.

5.3.5 3D filtered feasible regime

Next, when considering safe descent in payload carriage vehicles for extraterrestrial missions, a key requirement is to maintain sufficiently low descent speeds. To address this, the full feasible region is filtered with a descent speed under 1.5 m/s. Figure 21 represents the subsequent filtering regime for the mission-feasible descent range. This shows a strong correlation between air density and gravitational attraction. Although higher density gives more ‘supports’ to the blade to descend more slowly, such an effect works until the gravity effects become dominant.

Even when the air density increases further, this is still difficult for it to counteract the impact from the larger gravitational forces. It can be seen, once the gravity exceeds 12 m/s², the amount of data appearing on the table drops, indicating that lesser configurations can maintain lower descent velocities. At these points onwards, the gravity pull significantly overwhelms aerodynamic resistance, giving rise to a much narrower valid descent regime.

5.4 Feasibility and Performance on Earth and other Planets

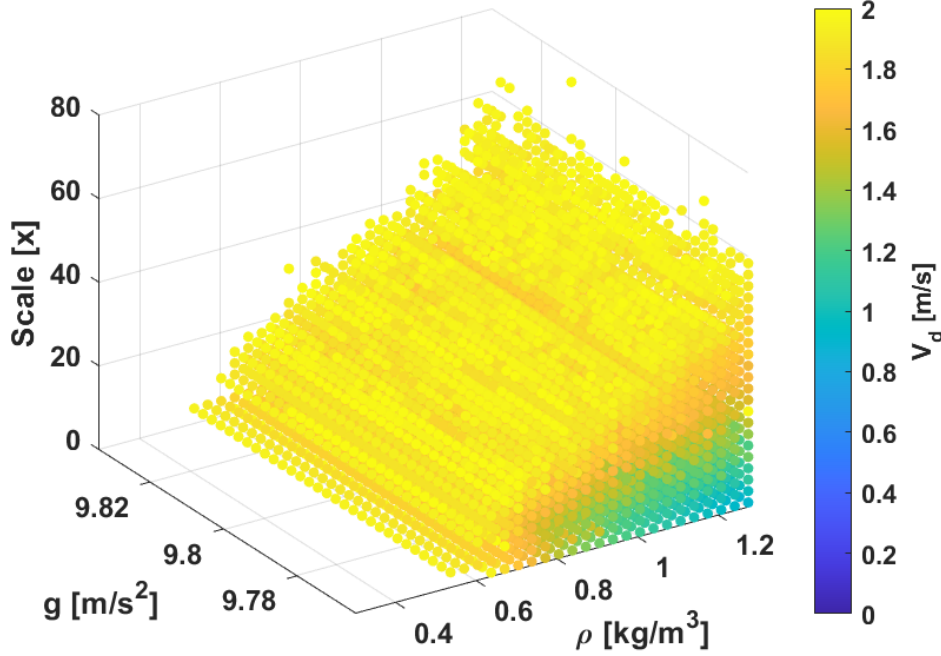


Figure 37: Feasible range of descent velocity V_d on Earth.

Figure 37 shows the feasible range of safe descent on Earth. This is obtained in a similar way to Fig. 21, where the initial boundaries condition is set to narrow the dataset to Earth conditions:

1. Gravity: between 9.764 and 9.834 m/s^2 .
2. Air density: reaches up to 1.275 kg/m^3 .
3. Descent velocity: limited to below 2 m/s .

Inspecting the remaining data, the envelope further shrinks to air density between 0.5353 kg/m^3 and 1.275 kg/m^3 ; scale from 1 to 66 under a gravity range of 9.796 to 9.834 m/s^2 . The optimised autorotation is achieved near the maximum air density, larger than 1 kg/m^3 , with small to moderate geometric scales 10–40, where V_d is between 1.302 m/s and 1.7842 m/s . Because in this region, the air is dense enough for the rotor disk to generate strong thrust, while the blade is also large enough to allow more work done on incoming airflow, but not so large that mass dominates.

At smaller scales less than 10, because the disk area gets smaller, there is less inflow air needed to produce higher momentum thrust overcoming the mass, thus leading to slightly slower descent speed closer to 0.909 m/s; Conversely, at larger scales greater than 40, the increased mass again dominated the descent rates, driving it to almost 1.992 m/s.

Ultimately, the optimal feasible Earth conditions for stable autorotation exist in a narrow window around 1–1.22 kg/m³ density, gravity of about 9.796 to 9.834 m/s², and scale values between 10 and 40, which give the best compromise between blade area and mass to keep descent speeds around 1.5 m/s.

Table 3: Feasible range for descent speed of payload carrying vehicles in planets of the Solar System. Where scale values are calculated from the set limit, except for gas giants, which are marked with (**), where scaling is fixed at 1 due to atmospheric descent not being practically achievable.

Planet	Mass (10 ²⁴ kg)	Air Density (kg/m ³)	Gravity (m/s ²)	Scale	Descent Velocity (m/s)
Mercury	0.33010 ⁴³⁸	≈ 0 ⁴³⁸	3.70 ⁴³⁸	≈ 1.90	0.50
Venus	4.8673 ⁴³⁸	65 ⁴³⁹	8.87 ⁴³⁸	≈ 1.07	0.047
Earth	5.9722 ⁴³⁸	1.217 ⁴⁴²	9.82 ⁴³⁸	1	0.94
Mars	0.64169 ⁴³⁸	0.016 ⁴⁴⁰	3.73 ⁴³⁸	≈ 1.90	0.50
Jupiter	1 898.13 ⁴³⁸	0.16 ⁴⁴¹	25.92 ⁴³⁸	1**	13.4
Saturn	568.32 ⁴³⁸	0.19 ⁴⁴¹	11.19 ⁴³⁸	1**	7.78
Uranus	86.811 ⁴³⁸	0.42 ⁴⁴¹	9.01 ⁴³⁸	≈ 1.06	3.08
Neptune	102.409 ⁴³⁸	0.45 ⁴⁴¹	11.27 ⁴³⁸	1**	3.49

Following the same filtering method used for Earth, the optimised descent condition for each planet and selected moons inside the solar system are as shown in Table [3](#) and Table [4](#). The constrained gravitational acceleration and atmospheric density values were mainly from the NASA data sheets.

Table 4: Feasible range for descent speed of payload carrying vehicles in selected Moons in the Solar System.

Moon	Mass (10 ²¹ kg)	Air Density (kg/m ³)	Gravity (m/s ²)	Scale	Descent Velocity (m/s)
Earth's Moon	73.5 ⁴⁴³	≈ 0 ⁴⁴⁴	1.60 ⁴⁴³	3.35	-
Io	89.3 ⁴⁴³	≈ 0 ⁴⁴⁵	1.80 ⁴⁴³	3.10	-
Europa	48.0 ⁴⁴³	≈ 0 ⁴⁴⁶	1.31 ⁴⁴³	3.83	-
Ganymede	148.2 ⁴⁴³	≈ 0 ⁴⁴⁷	1.43 ⁴⁴³	3.61	-
Callisto	107.6 ⁴⁴³	≈ 0 ⁴⁴⁸	1.24 ⁴⁴³	3.97	-
Titan	134.6 ⁴⁴³	≈ 5 ⁴⁴⁹	1.35 ⁴⁴³	3.75	0.045
Triton	21.5 ⁴⁴³	≈ 0 ⁴⁵⁰	0.78 ⁴⁴³	5.41	-

It can be seen that this safe descent velocity range changes significantly across the Solar System. Bodies with thicker atmospheres, such as Venus and Titan, yield extremely low descent speeds, while thinner atmospheres, such as on Saturn and Jupiter, give much larger descent rates. For planets or

moons with almost no atmosphere, the model cannot produce results. Because autorotation requires air.

6.0 Conclusion

This study has presented a comprehensive Blade Element Momentum (BEM) analysis of maple seeds, and successfully finishes the initial set of objectives and aims. The model is validated against experimental data and further extended to planetary-scale applications. Proving accurately reproduced descent velocities and rotation rates within experimental margins, demonstrating its suitability for analysing bio-inspired passive flight.

For stable autorotation On Earth, the conditions were shown to exist only within a narrow range: air densities between 1.0 and 1.22 kg/m³, gravity close to 9.796 to 9.834 m/s², and geometric scales of roughly 10–40. Within this envelope, the compromise between blade area and mass was sufficient to keep descent speeds below 1.5 m/s. In addition, descent velocity was found to follow an approximate $\sqrt{g/\rho}$ trend in the mid-range of air densities, where gravitational and thrust balance most closely. At the extremes, however, this behaviour breaks down in fast-falling motion at very low density and becomes saturated at high density.

Finally, the results underline that air density is the key factor sustaining autorotation, gravity dictates the boundaries of feasibility, and blade scale acts as a compensating influence. Stable autorotation is therefore limited to intermediate scales in sufficiently dense atmospheres, while very low-density conditions inevitably produce rapid descent.

Future work should include CFD analysis, especially for planets with thicker atmospheric density, to examine how local flow features and leading-edge vortices change in these environmental conditions. And a closer study of Reynolds number effects to capture scale-dependent behaviour. It is also recommended to examine the impact of blade fractures or cuts, since experiments suggested that damaged wings can sometimes promote a more vertical and stable descent path.

ACKNOWLEDGEMENTS

I would like to thank Mr. Jack Stockford and Dr. Jafar Jamshidi for their guidance and support throughout this work. I am also deeply grateful to my family for their constant encouragement and belief in me.

References

1. NORBERG, R.A. Autorotation, self-stability, and structure of single-winged fruits and seeds (samaras) with comparative remarks on animal flight, *Biological Reviews*, 1973, **48**, (4), pp. 561–596. doi:10.1111/j.1469-185X.1973.tb01570.x
2. WIN, S.K.H., WIN, L.S.T., SOH, G.S., *et al.* Design, modelling and control of collaborative samara autorotating wings (SAW), *International Journal of Intelligent Robotics and Applications*, 2019, **3**, pp. 144–157. doi:10.1007/s41315-019-00091-6
3. DICKERSON, A. Maple seeds’ unique spinning motion allows them to travel far even in the rain, a new study shows, *Phys.org*, 3 March 2025. [Online]. Available: <https://phys.org/news/2025-03-maple-seeds-unique-motion.html>
4. LORENZ, R.D. *Spinning Flight: Dynamics of Frisbees, Boomerangs, Samaras, and Skipping Stones*, Springer, Berlin, 2006.
5. ALEXANDER, D.E. *Nature’s Flyers: Birds, Insects, and the Biomechanics of Flight*, Johns Hopkins University Press, Baltimore, 2002.
6. ZHOU, V. Samara Seeds, *vicszhou.com*. [Online]. Available: <https://vicszhou.com/Samara-Seeds>
7. NABAWY, M.R.A. AND CROWTHER, W.J. The role of the leading edge vortex in lift augmentation of steadily revolving wings: a change in perspective, *Journal of the Royal Society Interface*, 2017, **14**, (132), 20170159. doi:10.1098/rsif.2017.0159
8. VIDELER, J.J., STAMHUIS, E.J. AND POVEL, G.D.E. Leading-edge vortex lifts swifts, *Science*, 2004, **306**, (5703), pp. 1960–1962. doi:10.1126/science.1104682
9. YASUDA, K. AND AZUMA, A. The autorotation boundary in the flight of samaras, *Journal of Theoretical Biology*, 1997, **185**, (3), pp. 313–320. doi:10.1006/jtbi.1996.0308
10. REZGUI, D., ARROYO, I.H. AND THEUNISSEN, R. Model for sectional leading-edge vortex lift for the prediction of rotating samara seeds performance, *The Aeronautical Journal*, 2020, **124**, (1278), pp. 1236–1261. doi:10.1017/aer.2020.25
11. AZUMA, A. AND YASUDA, K. Flight performance of rotary seeds, *Journal of Theoretical Biology*, 1989, **138**, (1), pp. 23–53. doi:10.1016/S0022-5193(89)80176-6
12. LENTINK, D., DICKSON, W.B., VAN LEEUWEN, J.L. AND DICKINSON, M.H.

- Leading-edge vortices elevate lift of autorotating plant seeds, *Science*, 2009, **324**, pp. 1438–1440. doi:10.1126/science.1174196
13. MINAMI, S. AND AZUMA, A. Various flying modes of wind-dispersal seeds, *Journal of Theoretical Biology*, 2003, **225**, (1), pp. 1–14. doi:10.1016/S0022-5193(03)00216-9
 14. JUNG, B. AND REZGUI, D. Investigating the autorotational performance of scaled samara rotor in vertical and forward flight, *42nd European Rotorcraft Forum*, Association Aéronautique et Astronautique de France, 2017, pp. 1252–1266.
 15. NIU, P., ATKINS, M.D., LIU, Y., LI, M., LU, T.J. AND KIM, T. Intrinsic equilibrium of stably autorotating samaras, *Physical Review E*, 2022, **106**, (1), 014405. doi:10.1103/PhysRevE.106.014405
 16. VOGEL, S. *Life in Moving Fluids: The Physical Biology of Flow*, Revised and Expanded 2nd ed., Princeton University Press, Princeton, NJ, USA, 1994. doi:10.2307/j.ctvzsmfc6
 17. ORTEGA-JIMENEZ, V.M., MARTÍN-ALCÁNTARA, A., FERNANDEZ-FERIA, R. AND DUDLEY, R. On the autorotation of animal wings, *Journal of the Royal Society Interface*, 2017, **14**, (128), 20160870. doi:10.1098/rsif.2016.0870
 18. ULRICH, E.R., PINES, D.J. AND HUMBERT, J.S. Pitch and heave control of robotic samara micro air vehicles, *Journal of Aircraft*, 2010, **47**, (4), pp. 1290–1299. doi:10.2514/1.47026
 19. NABAWY, M.R.A. Design of insect-scale flapping wing vehicles, Ph.D. thesis, University of Manchester, UK, 2015.
 20. SEIDEL, R. Structural analysis of biologically inspired small wind turbine blades, M.Sc. thesis, Delft University of Technology, NL, 2017.
 21. PANDOLFI, C. AND IZZO, D. Biomimetics on seed dispersal: survey and insights for space exploration, *Bioinspiration & Biomimetics*, 2013, **8**, (2), 025003. doi:10.1088/1748-3182/8/2/025003
 22. ORTEGA-JIMENEZ, V.M., MARTÍN-ALCÁNTARA, A., FERNANDEZ-FERIA, R. AND DUDLEY, R. On the autorotation of animal wings, *Journal of the Royal Society Interface*, 2017, **14**, (128), 20160870. doi:10.1098/rsif.2016.0870
 23. RAO, M., HOYSALL, D.C. AND GOPALAN, J. Mahogany seed – a step forward in deciphering autorotation, *Current Science*, 2014, **106**, (8), pp. 1101–1109.
 24. NADAL-MORA, V. and SANZ-ANDRÉS, A. Stability analysis of a free-falling pararotor, *Journal of Aircraft*, vol. 52, no. 1, pp. 304–314, 2015, doi:10.2514/1.C032723.

25. REZGUI, D. Investigation into rotor blade stability in autorotation using bifurcation and continuation methods, Ph.D. thesis, University of Bristol, UK, 2009.
26. ROCCIA, B.A., VERSTRAETE, M.L., DIMITRIADIS, G., BRÜLS, O. AND PREIDIKMAN, S. Unsteady aerodynamics and nonlinear dynamics of free-falling rotating seeds, *ISMA-USD 2018 International Conference on Unmanned Systems and Aerospace*, 2018, p. 2543.
27. BRANLARD, E. The Blade Element Momentum (BEM) Method, in *Wind Turbine Aerodynamics and Vorticity-Based Methods. Research Topics in Wind Energy*, Vol. 7, Springer, Cham, Switzerland, 2017, pp. [page range]. doi:10.1007/978-3-319-55164-7-10
28. KANG, S., WANG, J. AND SHAN, J. Dynamics analysis and simulation for the invisible monowing rotorcraft, in *Proc. 27th Chinese Control and Decision Conf. (CCDC)*, Qingdao, China, May 2015, pp. 4029–4034. doi:10.1109/CCDC.2015.7162628
29. MATIČ, G., TOPIČ, M. AND JANKOVEC, M. Mathematical model of a monocopter based on unsteady blade-element momentum theory, *Journal of Aircraft*, 2015, **52**, (6), pp. 1905–1913, Nov.–Dec. doi:10.2514/1.C033098
30. BAI, S. AND CHIRARATTANANON, P. Design and take-off flight of a samara-inspired revolving-wing robot, in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS)*, Macau, China, Nov. 2019, pp. 6070–6076. doi:10.1109/IROS40897.2019.8967600
31. VAN GELDEREN, C.J. AND VAN GELDEREN, D.M. *Maples for Gardens: A Color Encyclopedia*, Timber Press, Portland, OR, USA, 1999.
32. WADA, N. AND RIBBENS, E. Japanese maple (*Acer palmatum* var. *matsumurae*, Aceraceae) recruitment patterns: seeds, seedlings, and saplings in relation to conspecific adult neighbors, *American Journal of Botany*, 1997, **84**, (9), pp. 1294–1300.
33. MERRILL, R.S. Nonlinear aerodynamic corrections to blade element momentum model with validation experiments, M.Sc. thesis, [University Name], 2011.
34. POLHAMUS, E.C. A concept of the vortex lift of sharp-edge delta wings based on a leading-edge-suction analogy, *NASA Technical Note NASA-TN-D-3767*, 1966.
35. JUNG, B.K. Investigation into the flight performance of an autorotating samara with varying flight conditions, Ph.D. dissertation, Department of Aerospace Engineering, University of Bristol, UK, 2021.

36. LEISHMAN, G.J. *Principles of Helicopter Aerodynamics*, Cambridge University Press, 2006.
37. VAN KUIK, G.A.M., SØRENSEN, J.N. AND OKULOV, V.L. Rotor theories by Professor Joukowski: momentum theories, *Progress in Aerospace Sciences*, 2015, **73**, pp. 1–18.
38. NASA Solar System Exploration: Planetary Fact Sheet - Metric, NASA, Aug. 2024. [Online]. Available: <https://nssdc.gsfc.nasa.gov/planetary/factsheet/>
39. KSANFOMALITI, L.V. Venus atmosphere, *Space Science Reviews*, 1981, **29**, pp. 445–490.
40. NASA Mars Fact Sheet, NASA, 2024. [Online]. Available: <https://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html>
41. NASA Giant Planets Overview, NASA Solar System Exploration, 2024. [Online]. Available: <https://solarsystem.nasa.gov/planets/overview/>
42. NOAA, NASA AND USAF U.S. Standard Atmosphere, 1976. [Online]. Available: <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19770009539.pdf>
43. NASA Solar System Exploration: Moons Fact Sheet - Metric, NASA, 2024. [Online]. Available: <https://nssdc.gsfc.nasa.gov/planetary/factsheet/>
44. NASA Lunar Atmosphere, NASA Solar System Exploration, 2024. [Online]. Available: <https://solarsystem.nasa.gov/moons/earths-moon/overview/>
45. NASA Io: Overview, NASA Solar System Exploration, 2024. [Online]. Available: <https://solarsystem.nasa.gov/moons/jupiter-moons/io/overview/>
46. NASA Europa: Overview, NASA Solar System Exploration, 2024. [Online]. Available: <https://solarsystem.nasa.gov/moons/jupiter-moons/europa/overview/>
47. NASA Ganymede: Overview, NASA Solar System Exploration, 2024. [Online]. Available: <https://solarsystem.nasa.gov/moons/jupiter-moons/ganymede/overview/>
48. NASA Callisto: Overview, NASA Solar System Exploration, 2024. [Online]. Available: <https://solarsystem.nasa.gov/moons/jupiter-moons/callisto/overview/>
49. JOHNS HOPKINS APL Dragonfly: Titan Mission, 2024. [Online]. Avail-

- able: <https://dragonfly.jhuapl.edu/>
50. NASA Triton: Overview, NASA Solar System Exploration, 2024. [Online]. Available: <https://solarsystem.nasa.gov/moons/neptune-moons/triton/overview/>

APPENDIX

I.0 BEM model results on the descent performance of the selected seed

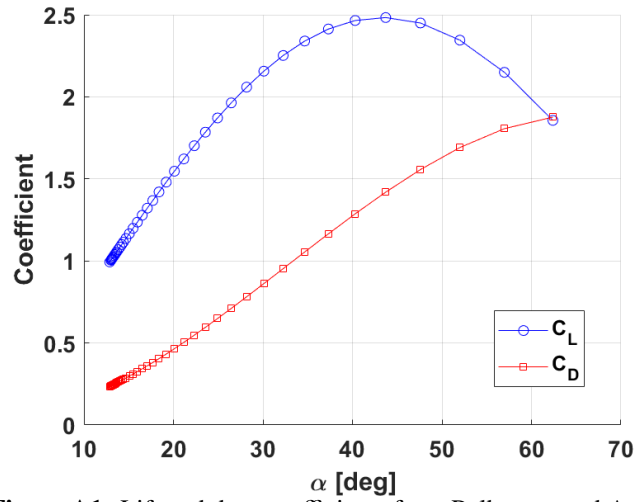


Figure A1: Lift and drag coefficients from Polhamus and Azuma.

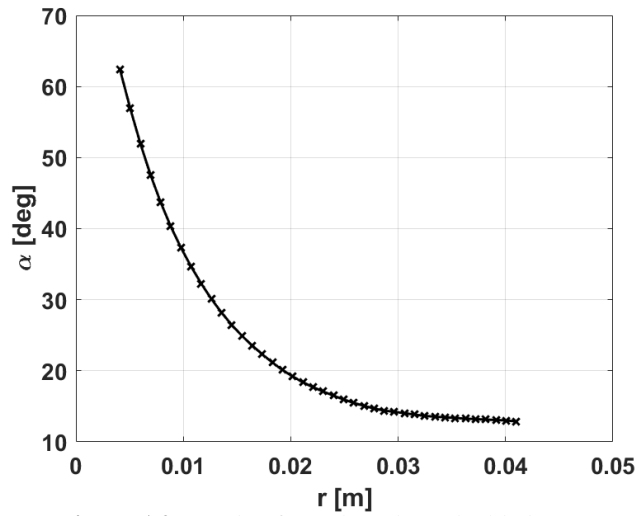


Figure A2: Angle of attack α along the blade span.

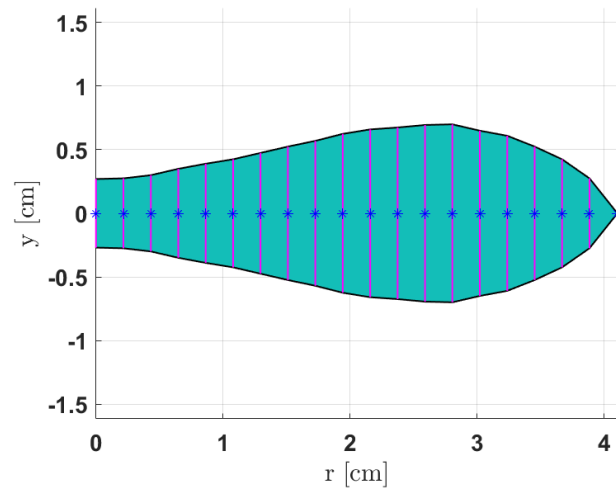


Figure A3: Blade geometry with chord distribution.

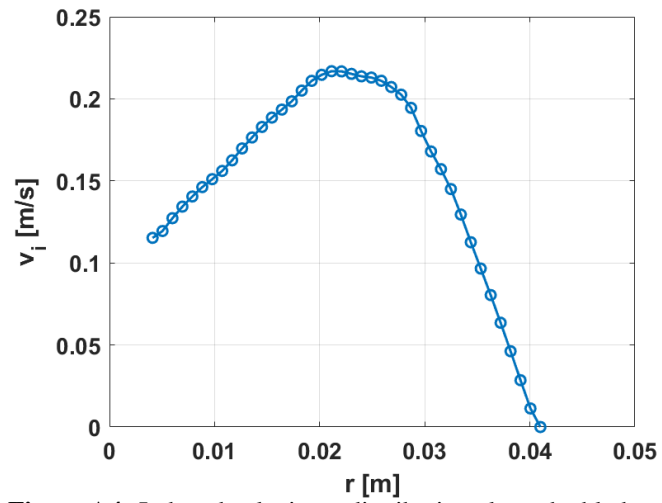


Figure A4: Induced velocity v_i distribution along the blade span.

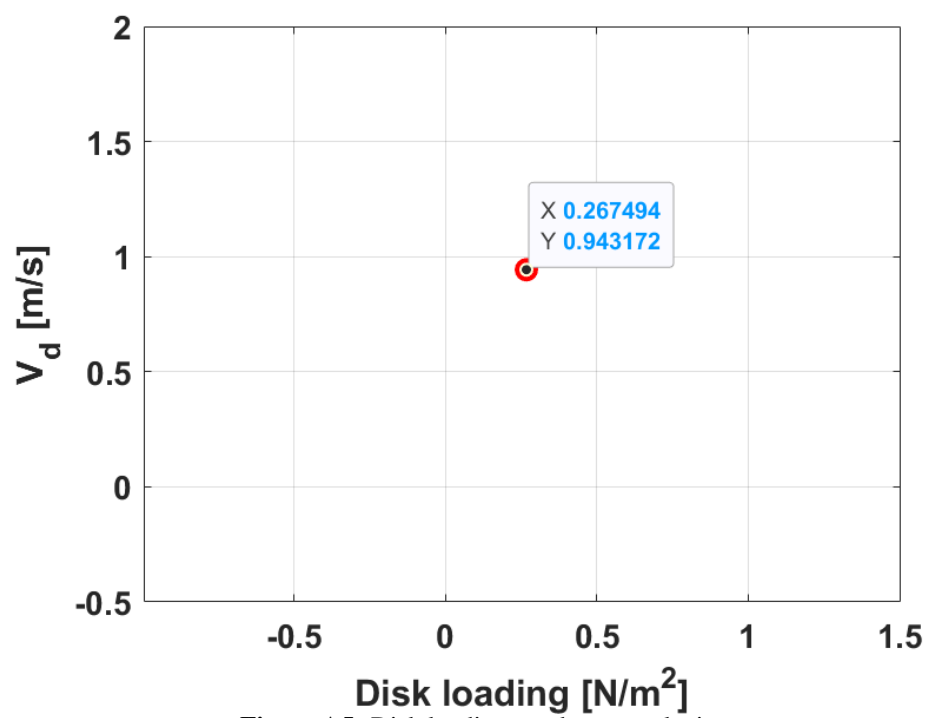


Figure A5: Disk loading vs. descent velocity v_d .

II.0 Blender-generated CAD model of the selected seed.

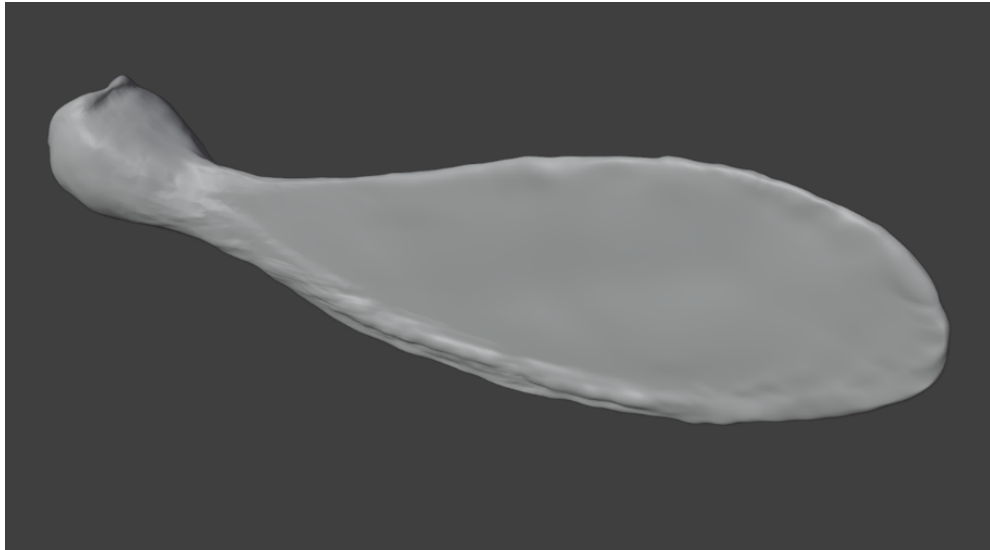


Figure A6: Side view of the 3D model of the selected maple seed.

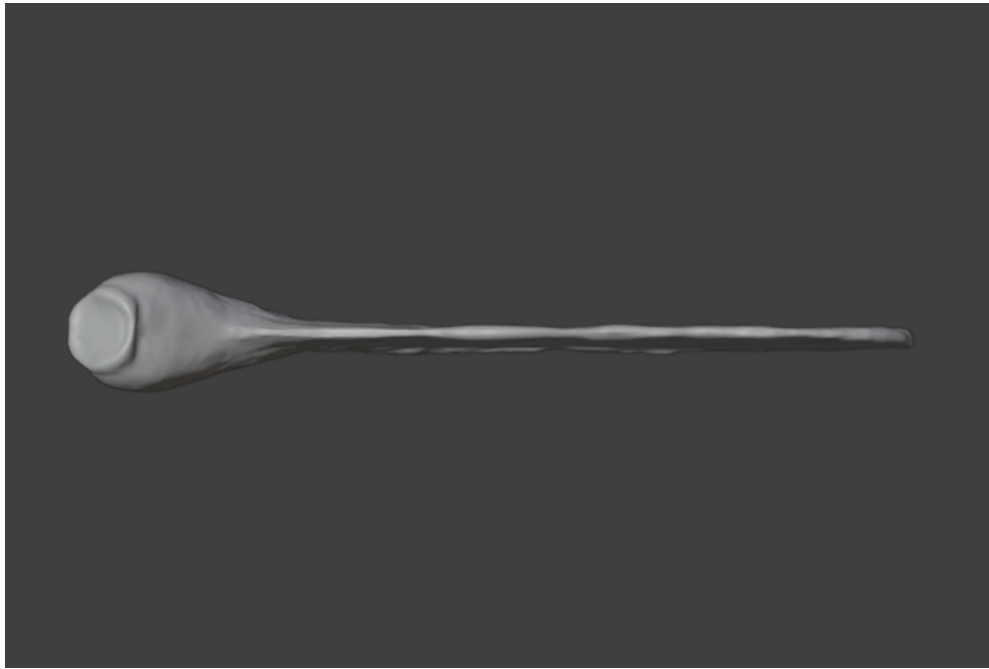


Figure A7: Top view of the maple seed.

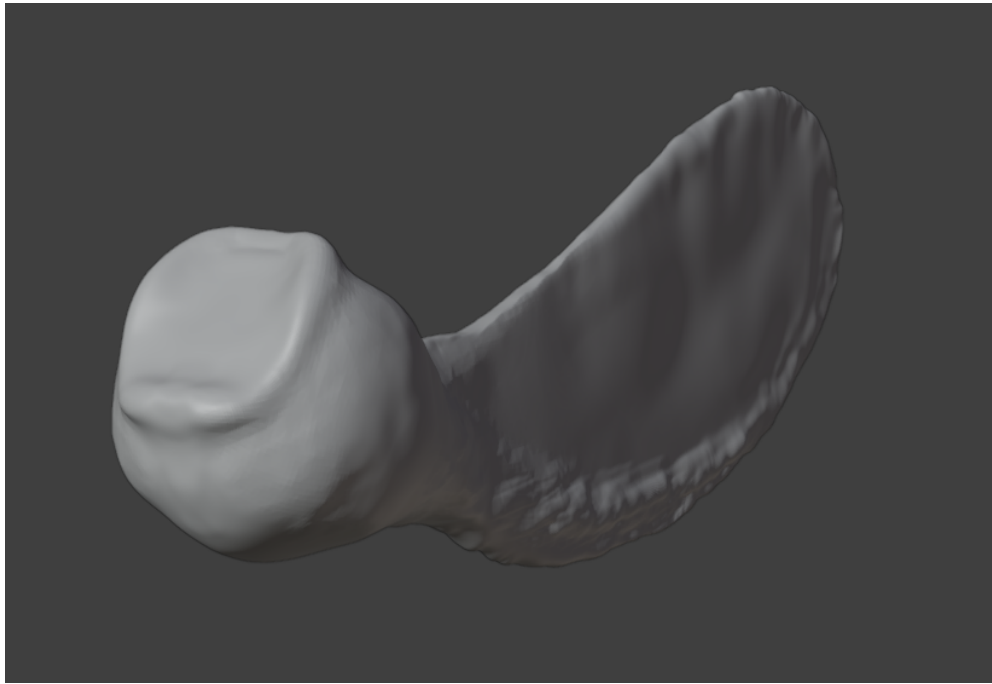
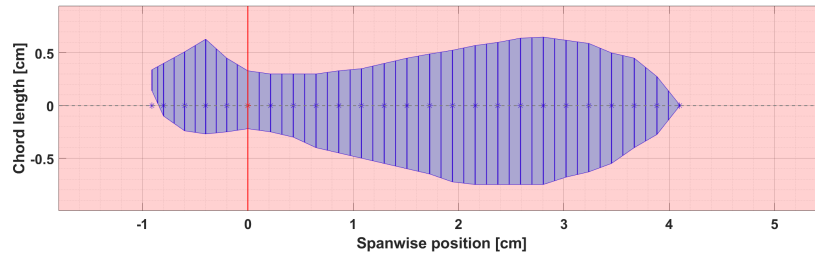
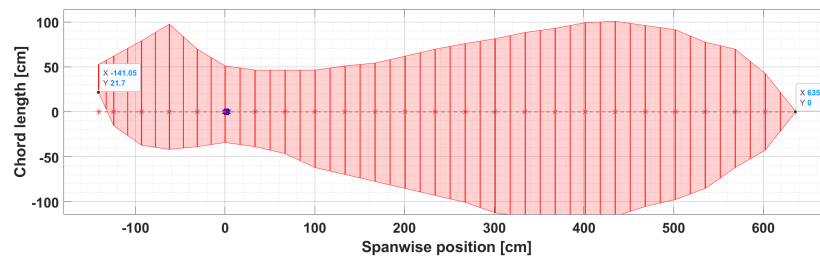


Figure A8: Back view of the maple seed.

III.0 Minimum and Maximum scale of the selected seeds



(a) Original minimum samara scale (blue).



(b) Maximum samara scale (155×, red).

Figure A9: Comparison between (a) the scale = 1 and (b) scale obtained = 155.

IV.0 The core of the BEM model in MATLAB

```

function [v_i,T_elem,Q_elem,alpha_v,CL_v,CD_v] = induced(Omega,Vd)
    v_i      = 0.5*Vd*ones(n_elem,1);
    T_elem   = zeros(n_elem,1);
    Q_elem   = zeros(n_elem,1);
    alpha_v  = zeros(n_elem,1);
    CL_v     = zeros(n_elem,1);
    CD_v     = zeros(n_elem,1);

    CLf = @(a) 4*sin(a).*cos(a).^2 + 3.01*cos(a).*sin(a).^2;
    CDf = @(a) 0.05 - 0.008*a + 4.27*a.^2 - 2.5*a.^3;

    for it=1:60
        vold = v_i;
        for j=1:n_elem
            Ut = Omega*r_vec(j);
            Up = (Vd-v_i(j))*cos(beta);
            phi = atan2(Up,Ut);
            a   = phi - theta;
            U   = hypot(Ut,Up);

            ftip = (Nb/2)*((1 - r_vec(j)/R)/((r_vec(j)/R)*sin(phi)));
            Ftip = (2/pi)*acos(exp(-ftip));

            dL = 0.5*rho*U^2*c_vec(j)*dr * CLf(a)*Ftip;
            dD = 0.5*rho*U^2*c_vec(j)*dr * CDf(a);

            T_elem(j) = dL*cos(phi) + dD*sin(phi);
            Q_elem(j) = (dL*sin(phi) - dD*cos(phi)) * r_vec(j);

            Kloc = T_elem(j)/(2*rho*2*pi*r_vec(j)*dr);
            v_i(j) = (Vd - sqrt(max(Vd^2-4*Kloc,0))) / 2;

            alpha_v(j) = a;
            CL_v(j)     = CLf(a);
            CD_v(j)     = CDf(a);
        end
        if max(abs(v_i-vold))<1e-6, break; end
    end
end

```

Figure A10: The key part of the BEM model.



28 February 2025

Dear Mr He ,

Reference: CURES/24435/2025

Project ID: 27843

Title: Flight Dynamics and Bio-Inspired Design of Auto-Rotating Seeds: Modeling, Simulation, and Applications

We are pleased to inform you that you have successfully declared that your research project is a **Literature Review – based solely on openly available literature which is in the public domain, and you are undertaking desk-based research not involving any other form of data or information.**

You have also confirmed that your project **does not meet** any of the literature review specified exceptions, listed both within the relevant section of the CURES form and below:

1) Your supervisor has requested that you apply for approval through CURES because:

- The journals or data are in a sensitive area (please discuss this with your supervisor)
- The project will be embargoed **i.e. will not be publicly available via the Cranfield library immediately or longer term**

2) Approval is/will be specifically required by another external body e.g. journal publishers

Therefore, **you do not require ethical approval** and your CURES application will be automatically closed.

Please keep a copy of this letter safe, if this exception is in relation to your thesis project, you will need to include a copy with your final thesis submission.

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team