Il Mulinello

37th Annual Vertical Flight Society Student Design Competition

Sponsored by Leonardo

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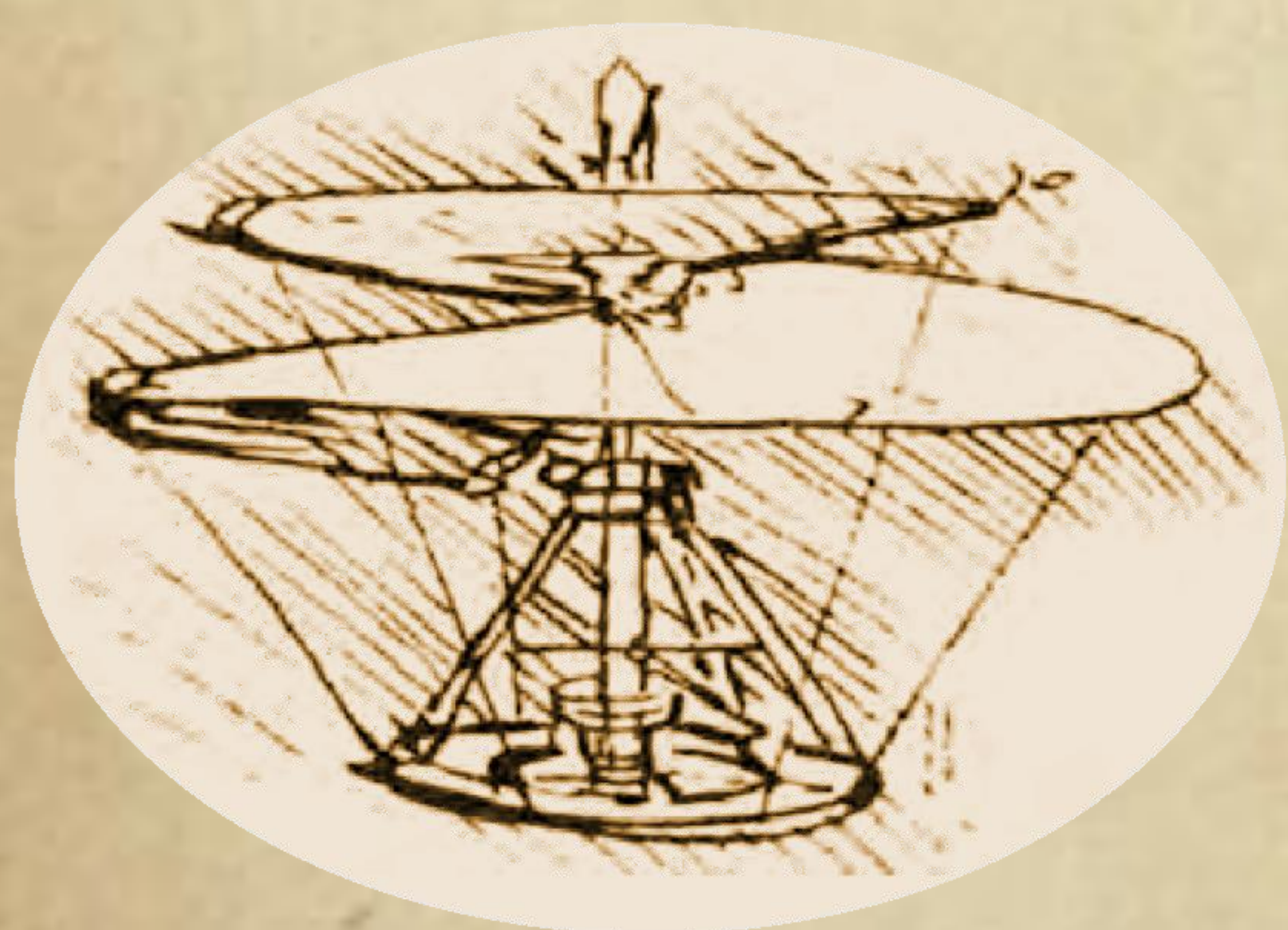
Characteristics

A Demonstrator of Innovative Ideas

Il Mulinello is intended as a demonstrator vehicle which displays the application of modern design techniques to Leonardo Da Vinci's airscrew concept. It should be capable of stable, controlled flight for a short duration and should include modern technologies which make that flight possible. This means that the flight conditions can be limited to take-off, hover, low-speed forward flight, and landing. This allows for the expensive analysis techniques of today to be applied relatively cheaply to such a novel concept and sound design can be made with a limited parameter space.

Evoking Da Vinci's Vision

Il Mulinello takes Da Vinci's vision for powered flight and makes it a reality. The key ideas behind his sketch are the iconic airscrew rotor and its human-powered rotation. Using modern design and analysis tools, these ideas formed the foundation of a design which evokes the same wonder as Da Vinci's visionary sketch.



Da Vinci's Original Design

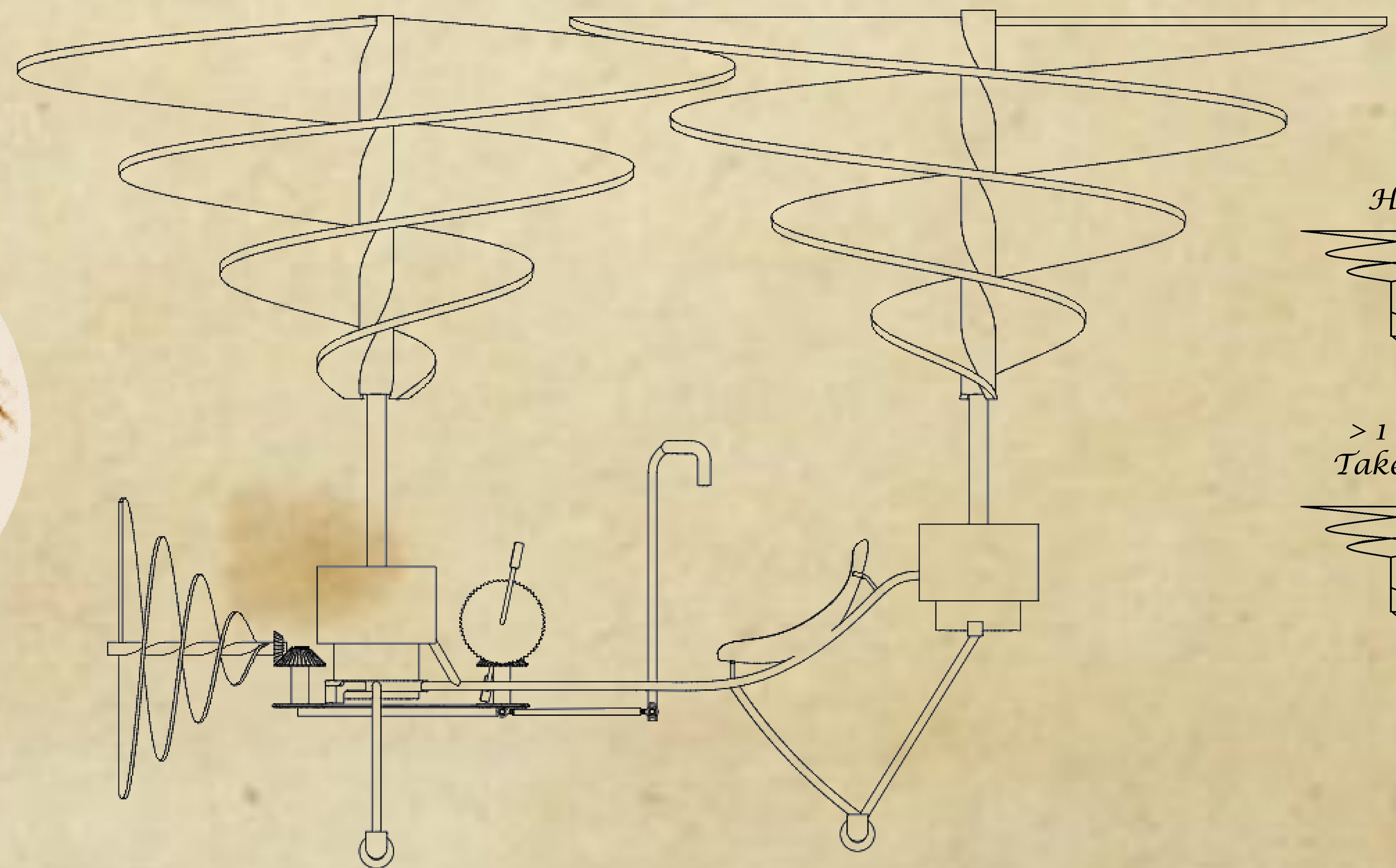
Optimized Geometric Parameters

Each of Il Mulinello's components is optimally sized using an iterative process based on detailed analysis of how each component's performance scales with its size. This process demonstrates the types tools and techniques which were unavailable to Da Vinci during his lifetime which we are now able to use to bring his sketch to life.

Vehicle Metric	Value
Total Length	3.04 m
Total Height	2.17 m
Total Width	1.72 m

Power Metric	Value
Battery Weight	43.6 kg
Powersplit Weight	0.71 kg
Motors Weight	52.4 kg

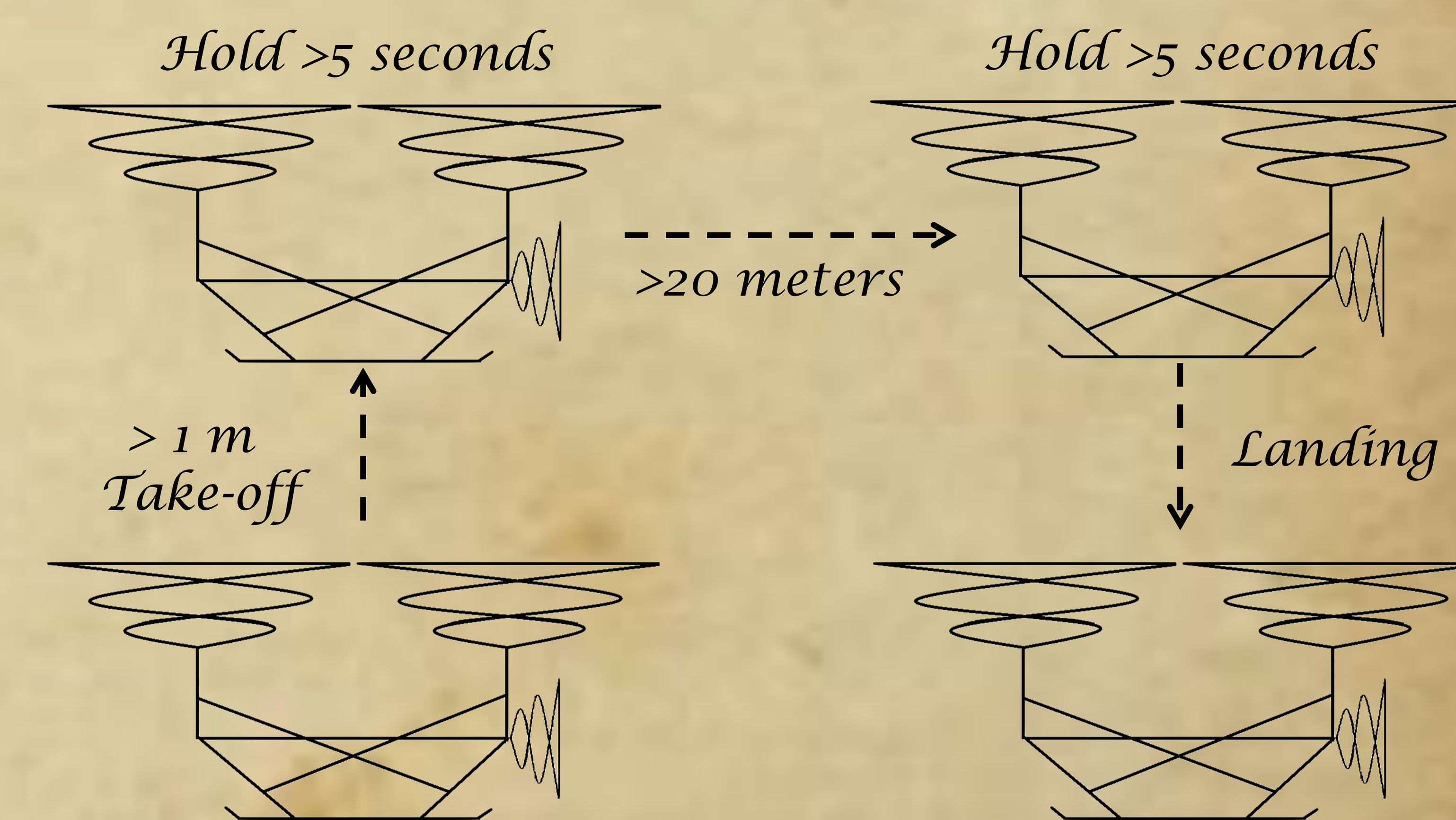
Airscrew Metric	Value
Rotor Radius	0.86 m
Propeller Radius	0.61 m
Airscrew Taper Ratio	0
Airscrew Revolutions	2
Airscrew Pitch Ratio	0.5
Airscrew Solidity	1
Airscrew Thickness	0.005 m



Exceeding Mission Requirements

Il Mulinello generates lift using two pairs of electrically powered coaxial airscrews. Each of these airscrews is a single bladed rotor of solidity 1. Thrust is generated with a human-powered coaxial airscrew. These systems provide the capability stable take-off, hover, landing, and forward flight over an estimated range of 500 meters with an endurance of almost 4 minutes. As a demonstration of Leonardo Da Vinci's vision in action, Il Mulinello excels.

Requirement	Minimum	Capability
Range	12 m	500 m
Endurance	1:18	3:50



Minimum Mission Profile

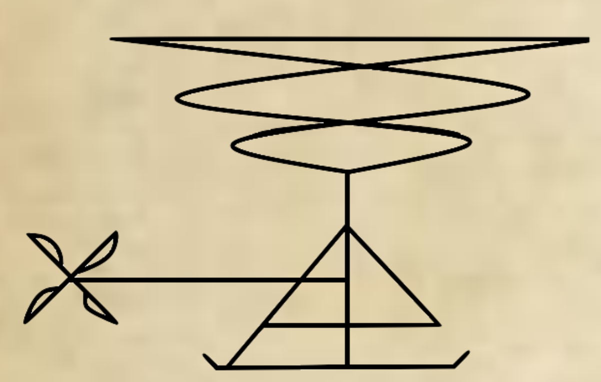
Il Mulinello's Design

Vehicle Configuration Selection

A Rigorous Trade-off analysis

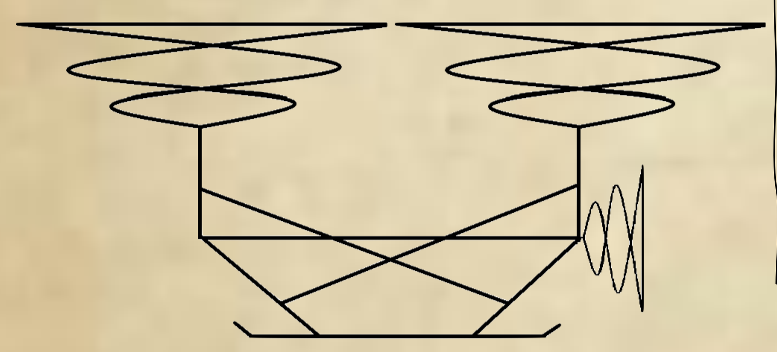
Using the mission requirements, a trade-off analysis was performed to select the optimal configuration. Five configurations were considered: conventional rotor, tandem, segue, and tilt-rotors. Five aspects were scored for each configuration in a Pugh matrix, with scores ranging from 1 to 5, 1 being the less desirable and 5 being the most desirable.

Conventional



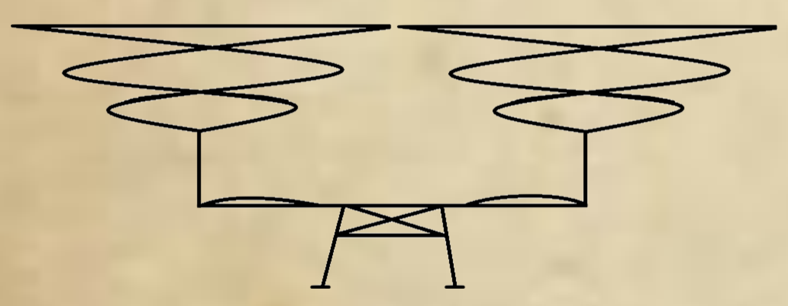
+ Simple configuration: low cost, and lowest risk
– Tail differentiate the design from Da Vinci's original one
– Tail rotor absorbs power without lift or thrust contribution
– Swash plate increases complexity of the design

Tandem



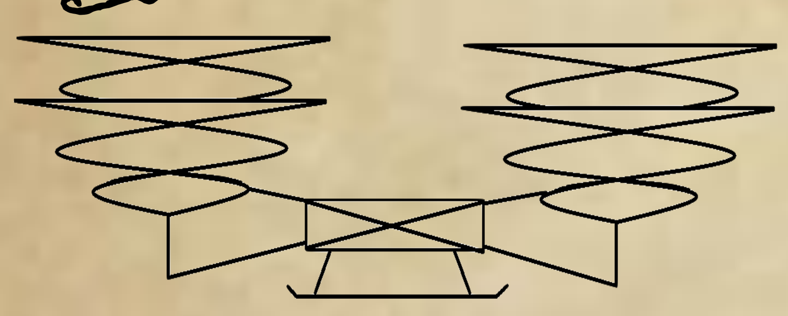
+ Less complex than other configurations
+ Torque balance is inherent to the system
– Difficult pitch and roll stability and control
– Yaw control is not possible using the main rotors, as they are needed for torque balance

Tilt



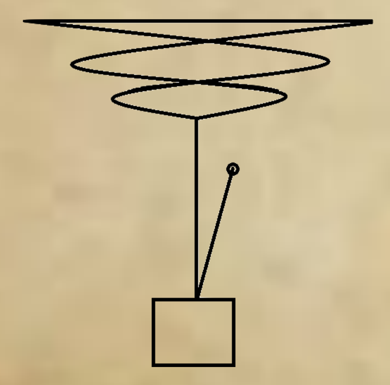
+ Higher forward speed than a conventional configuration (not needed in this mission)
– Complex aerodynamic design
– Higher disk loading than conventional configuration
– Heavy tilt mechanism

Quad



+ Unmatched control and stability provided by four rotors
– Increased complexity
– Increased power requirements

Segue



+ Innovative idea most resembling Da Vinci's design, with low footprint
+ Counter torque is obtained by using a gyroscope, also used for forward motion.
– Heavy control system challenge
– Unstable and therefore unsafe vehicle
– Completely new design requires more research and rigorous testing

Scoring system

The scores were given after careful analysis of each configuration. The aesthetics score was based on the ability to meet the spirit of Da Vinci's original design. The cost score was given using the complexity and predicted weights. The control score determined the ability to incorporate alternative control mechanisms to each configuration, and the safety score evaluated the stability and the pilot exposure.

	Weight	Tandem	Conventional	Tilt	Quad	Segue
Power Required	8	3	3	2	1	2
Cost	1	3	3	1	1	2
Aesthetics	3	4	2	4	1	4
Control	2	3	4	2	5	2
Safety	1	2	4	1	5	1
Weighted Total		**47**	45	34	27	35

Airscrew Considerations

The airscrew was expected to provide less thrust than regular low-solidity rotors while producing significantly more torque. It was therefore decided that the power required was an important aspect to consider, and it was given the most weight in the assessment of each configuration. Using airscrews in the main rotor(s) provided an additional complication for pitch, roll and yaw stability and control. Indeed, cyclic and collective control in an airscrew would cause an increase in the complexity of the design.

Final configuration

After careful consideration of each configuration, and using the Pugh matrix shown above, the tandem configuration was chosen. The team aimed to design a bicycle-like vehicle, whose lift and thrust are provided by aerial screws.

Main Rotors

Keeping to the Aesthetics

While the technical definition of an airscrew is very open to interpretation, it was clear that under any definition, the chosen airscrew geometry would need to evoke Da Vinci's original design. The specific feature of his airscrew which is preserved in Il Mulinello's main rotors is the smooth taper function which describes how the rotor radius changes around the blade. Liberties could certainly have been taken with the taper function to improve the rotor's efficiency, but it was decided that restricting the taper function to the linear regime ensures that anyone who sees Il Mulinello's rotors instantly knows from where they drew inspiration.

Modern Analysis Techniques

Surprisingly, despite the centuries of study of fluid low, aerodynamics, and rotorcraft mechanics, we know almost as little about the performance and airflow around an airscrew as Da Vinci did in his time. This provides an excellent opportunity to demonstrate the power state-of-the-art analysis techniques which are available as a result of all that research. A parametric computational fluid dynamics study was performed to test the effect of various airscrew geometric parameters on is performance as a rotor and these results were used to design a much more efficient version of Da Vinci's classical design.

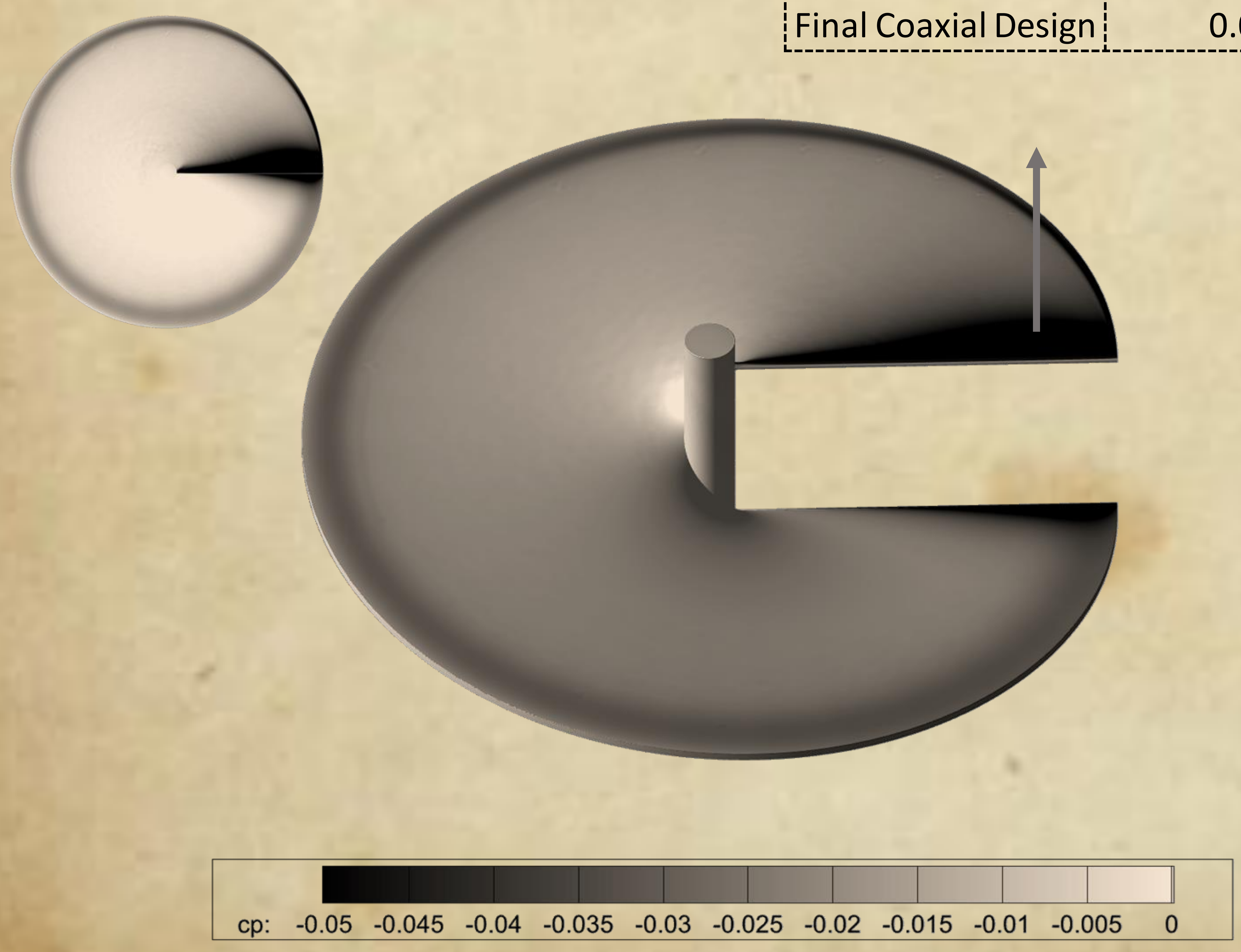
A Balanced Design

The most important result of the CFD study was the fact that the lift distribution of a single-bladed airscrew is concentrated at the leading edge, making it inherently unbalanced. As such, any rotor design which is not geometrically symmetrical about the shaft simply will not fly. Il Mulinello's rotors are therefore coaxial airscrews, i.e. two single-bladed rotors with solidity one which share a shaft. The airscrews are offset by 180 degrees so that they interlace beautifully and provide a perfectly symmetrical design, eliminating the intense vibrations which would occur if only a single airscrew was used.

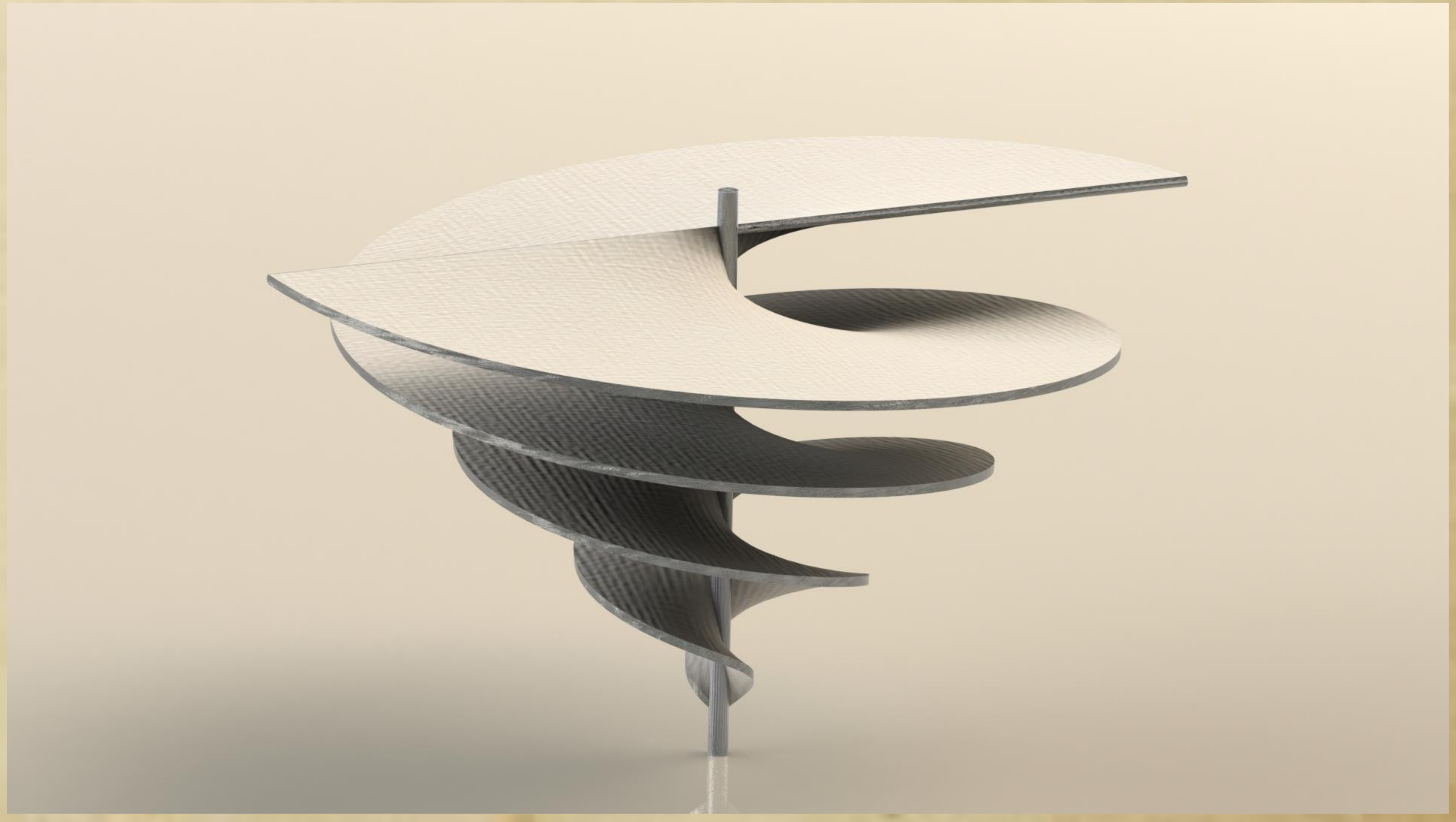
$$\sigma = \frac{revolutions}{2}(1 + taper)$$

$$taper = \frac{lower\ radius}{upper\ radius}$$

Geometry	Thrust Coefficient	Power Coefficient	Figure of Merit	Symmetrical?	Meets Requirements?
Baseline	0.0090	0.00459	0.1321	No	Yes
High RPM	0.0081	0.00540	0.0963	No	Yes
Upward Coning	0.0087	0.00459	0.1259	No	Yes
Downward Coning	0.0086	0.00455	0.1240	No	Yes
Taper	0.0056	0.00180	0.1655	No	No
Final Coaxial Design	0.0073	0.00327	0.1337	Yes	Yes



Unbalanced Single Airscrew



Balanced Coaxial Airscrew

Power System

Powertrain Description

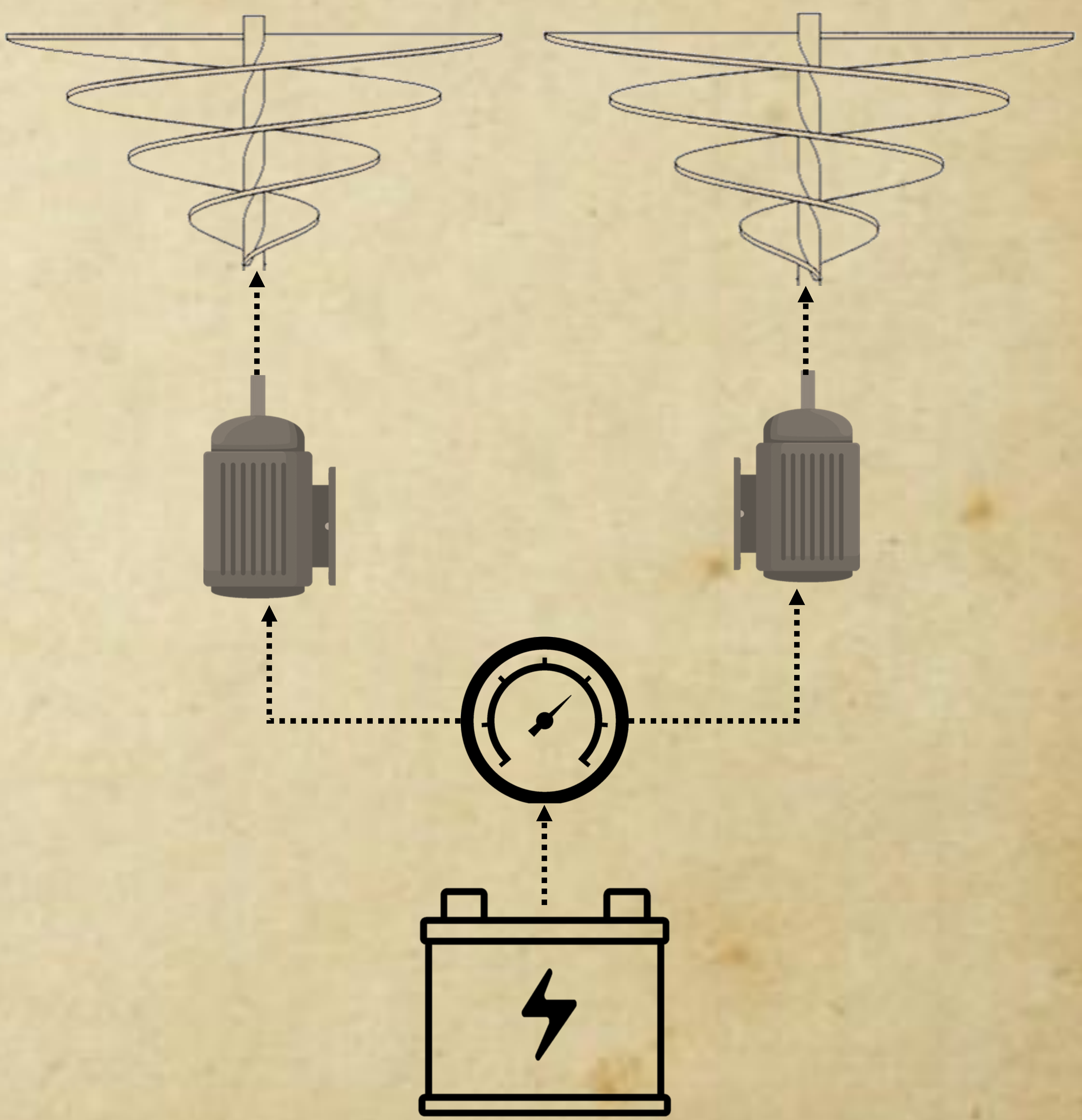
Il Mulinello is powered by an all electric powertrain which is capable of providing variable power to its two airscrews through its power split unit. The all electric propulsion system is not only environmentally friendly but also quieter than its mechanical equivalent as well as being more flexible in its positioning on the vehicle. These features embody the innovation and engineering for which Da Vinci is known and aims to go one step further and make his vision a reality.

Powertrain Components

The all-electric powertrain is composed of two motors which power the two airscrews used for vertical lift generation which are governed by a power split unit. The energy storage for the system is in the form of a lithium-ion battery pack located below the pilot's chair and supplies the power needed to maintain hover. The technological assumptions were chosen to be reasonable by today's state of the art capabilities and are listed in the table below.

Battery Cells

The battery cells chosen are ideal for large power requirements where power density is the driver of battery size such as a vehicle in hover. These batteries not only provide an efficient means of power supply but also provide energy which is used to complete the mission. To ensure both power and energy needs are met, the battery is sized to the most constraining of the power or energy requirements. *Il Mulinello* is sized for power which means the batteries provide enough power to hover. Inherently this means there is excess energy than needed for the baseline mission and this allows *Il Mulinello* to perform well beyond the defined mission and achieve additional capabilities.



Power System Diagram

Technological Assumptions for the Electric Powertrain

Component	Specific Power	Specific Energy	Efficiency
Battery	7 kW/kg	200 Wh/kg	93%
Electric Motor	5.2 kW/kg	-	95%
Power Split Unit	200 kW/kg	-	96%

Structural Design

Structural design for Il Mulinello involved taking inspiration not only from modern advances in vertical flight but also from the elements that inspired Da Vinci's original design. It is easy to get carried away with materials and manufacturing processes that would seem alien to the Renaissance engineers of Da Vinci's time. Keeping true to the spirit of Da Vinci's original concept will allow for a design that both showcases the modern innovations of engineering and celebrates the imagination of the past.

Airframe Material

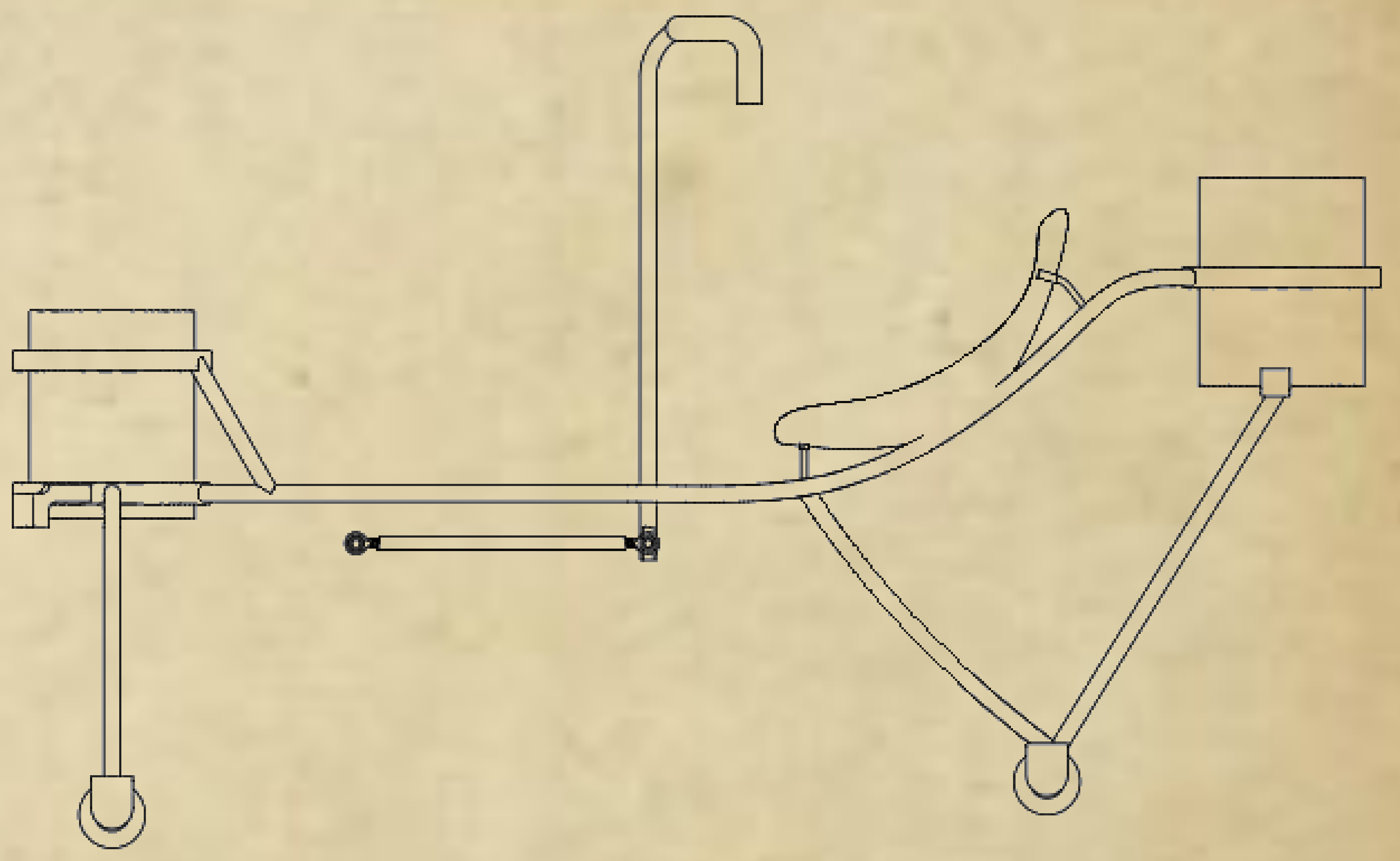
For the design of this airframe, the main material studied for usage was aluminum. Aluminum has a vast historical usage in aircraft and provides great strength to weight characteristics that have made a popular choice for use since the dawn of flight. Our particular alloy of choice here is 6061, a hardened aluminum alloy containing magnesium and silicon as its major alloying elements and is used heavily in the aerospace industry for structural applications. In particular, the T6 temper often applied to aluminum 6061 will result in a yield strength of around 240 to 270 MPa. The wide use of 6061-T6 also provides a wide variety of extrusion types and sizes that allows for flexibility in the airframe design.

Airscrew Material

Two primary classes of materials were looked at as suitable candidates for the airscrew blade design. The first of these are thermoplastics. Thermoplastics are polymers that are highly pliable at elevated temperatures and solidify upon cooling. This property of the material lends itself to a high level of versatility when it comes to manufacturing complex shapes. Types of thermoplastics include ABS, acrylic, nylon and PLA. The second category of materials studied were reinforced plastics. These typically combine epoxies, resins, or thermosetting plastics with fibers to create strong composite materials. Materials such as carbon fiber have a storied history being utilized to make lightweight aerodynamic components for automotive and aerospace applications, making them an enticing prospect for the airscrew. However, the complexity in manufacturing complex shapes, especially a helical one such as the airscrew, mean its feasibility comes into question.

Airframe Design Philosophy

Da Vinci's original concept envisioned a contraption that could utilize human power to achieve vertical flight. This original interpretation inspired many of Il Mulinello's design choices in order to stay true to Da Vinci's original vision. The primary desire of the airframe design was to take an everyday human powered vehicle and transform it into something that can achieve flight. Naturally, this inclination led to a re-imaging of a bicycle. More specifically, Il Mulinello's design revolved around a more aerodynamic version of a traditional bicycle: the recumbent bicycle. Not only does the low down seating position help provide optimum weight balance characteristics for the vehicle, allowing the airscrews to be positioned lower and reducing the overall height of the frame, but also allows for the turning system to be much more compact and provide an additional level of safety for the occupant as the distance between their head and the blades is increased greatly.



Analysis Technique

Utilizing Solidworks and the CAD models developed, the airfame and airscrew were analyzed using FEA. The airframe was analyzed by inputting the static loads described in the previous section at each of the airscrew mounting points. The airscrew was also analyzed using static loading. However, the airscrew loading had to be approached in a manner consistent with the understanding of the aerodynamic effects at play. From the CFD analysis, it is known that the vast majority of the lift is produced by a small section of the blade just after the leading edge. In addition, the forces must also taper down to zero as the they move towards the root of the blade in order to mimic the loading seen by the airscrew in the real world. With this in mind, half the total maximum static load was applied to the upper surface of the airscrew such that the forces linearly tapered down to zero with decreasing height and tapered down to zero with decreasing radius.

Criteria	Weight	ABS	Nylon	PLA	Carbon Fiber
Specific Strength	0.3	1	2	1	4
Machinability	0.1	4	2	2	1
Manufacturability	0.2	3	3	3	1
Stiffness	0.2	1	4	2	2
Durability	0.1	2	3	2	4
Aesthetics	0.1	2	3	2	1
Totals	1	1.9	2.8	1.9	2.4

Weighted Pugh matrix of airscrew material choices

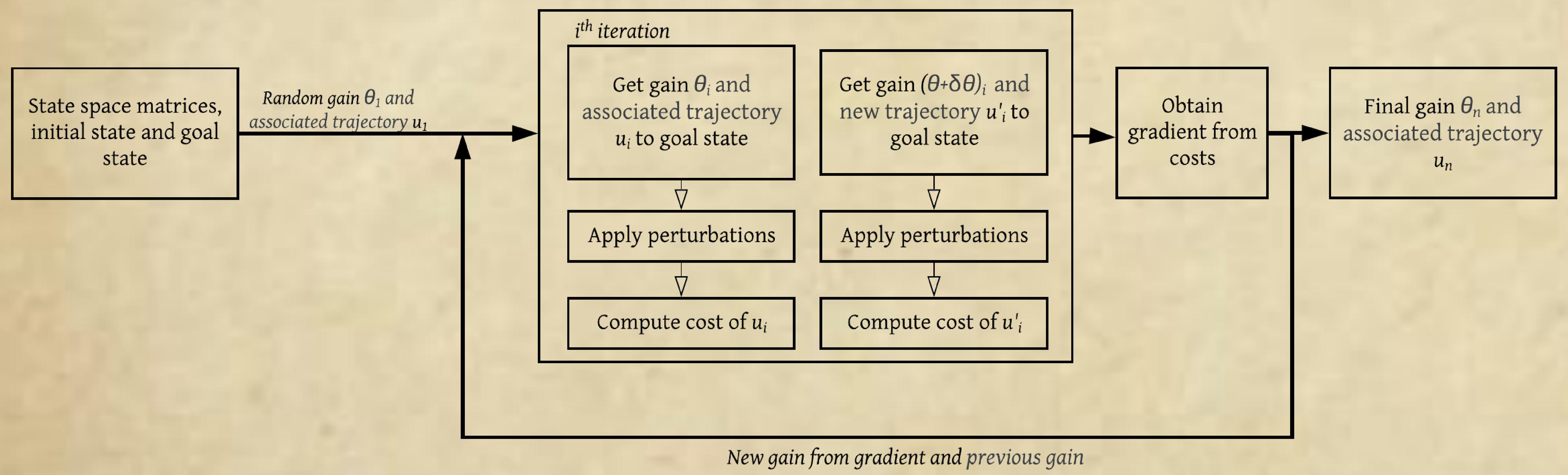
Controls and Piloting

A Difficult Control Problem

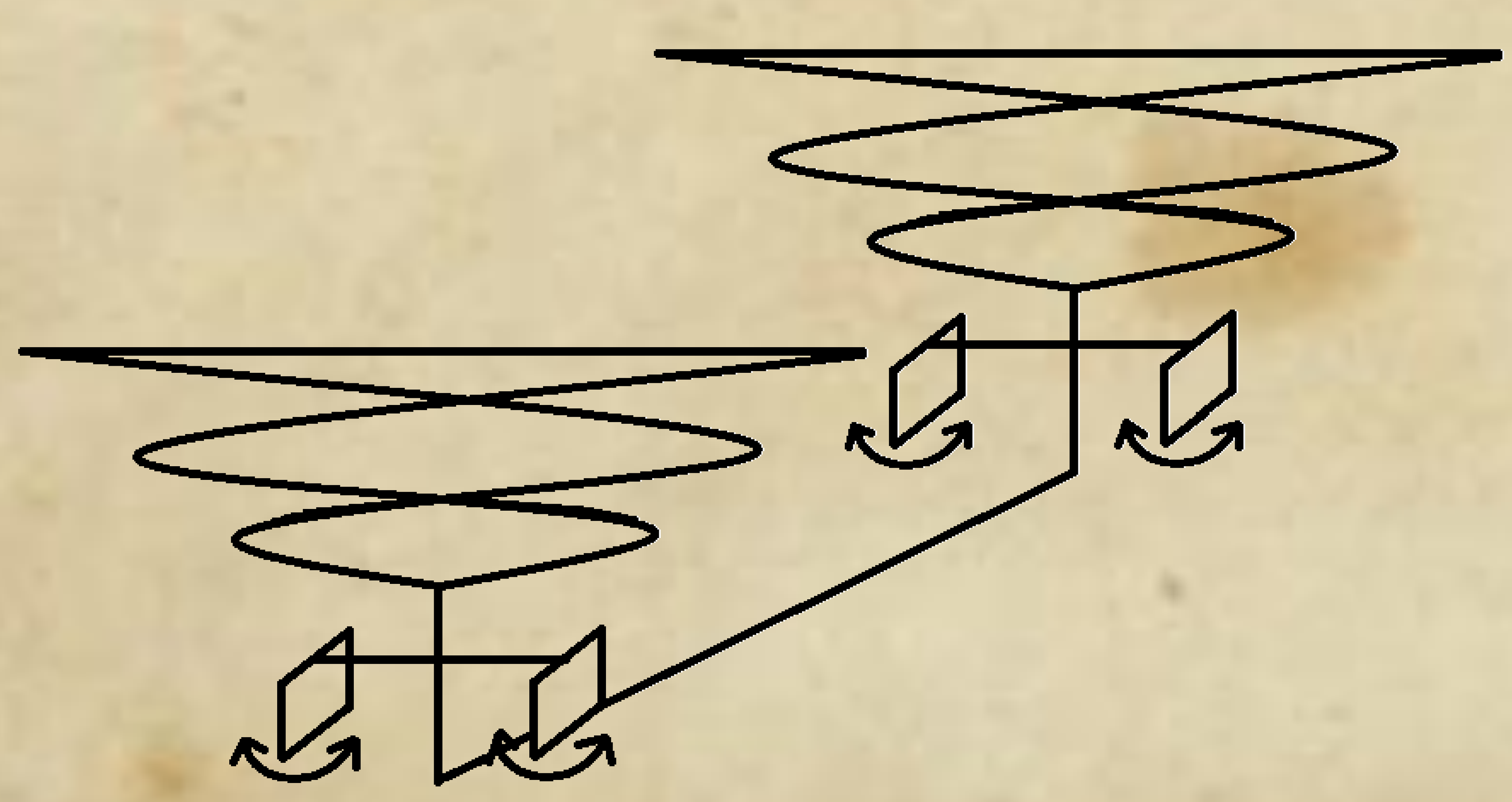
Using airscrews for the main rotors prevented the conventional use of variable blade pitch to control the pitch, roll and yaw of the vehicle. Indeed, there are no control laws to such control systems, and generating them from scratch is impossible given the current aerodynamic data on airscrews. Moreover, the complexity of such a design would be too great. Therefore, Il Mulinello needed an innovative control system.

Automatic Roll and Pitch Control

The roll and pitch of the vehicle are controlled by four flaps, located at the front and back and on each side of the vehicle. Using Il Mulinello's dynamics, a model predictive control system was developed. This iterative process determines the optimal gain and the best "trajectory" to return to the equilibrium state after a random disturbance is input to the system. Contrary to simpler PID controller, this model's predictive nature allows for a safer and more stable flight.



Model Predictive Control System



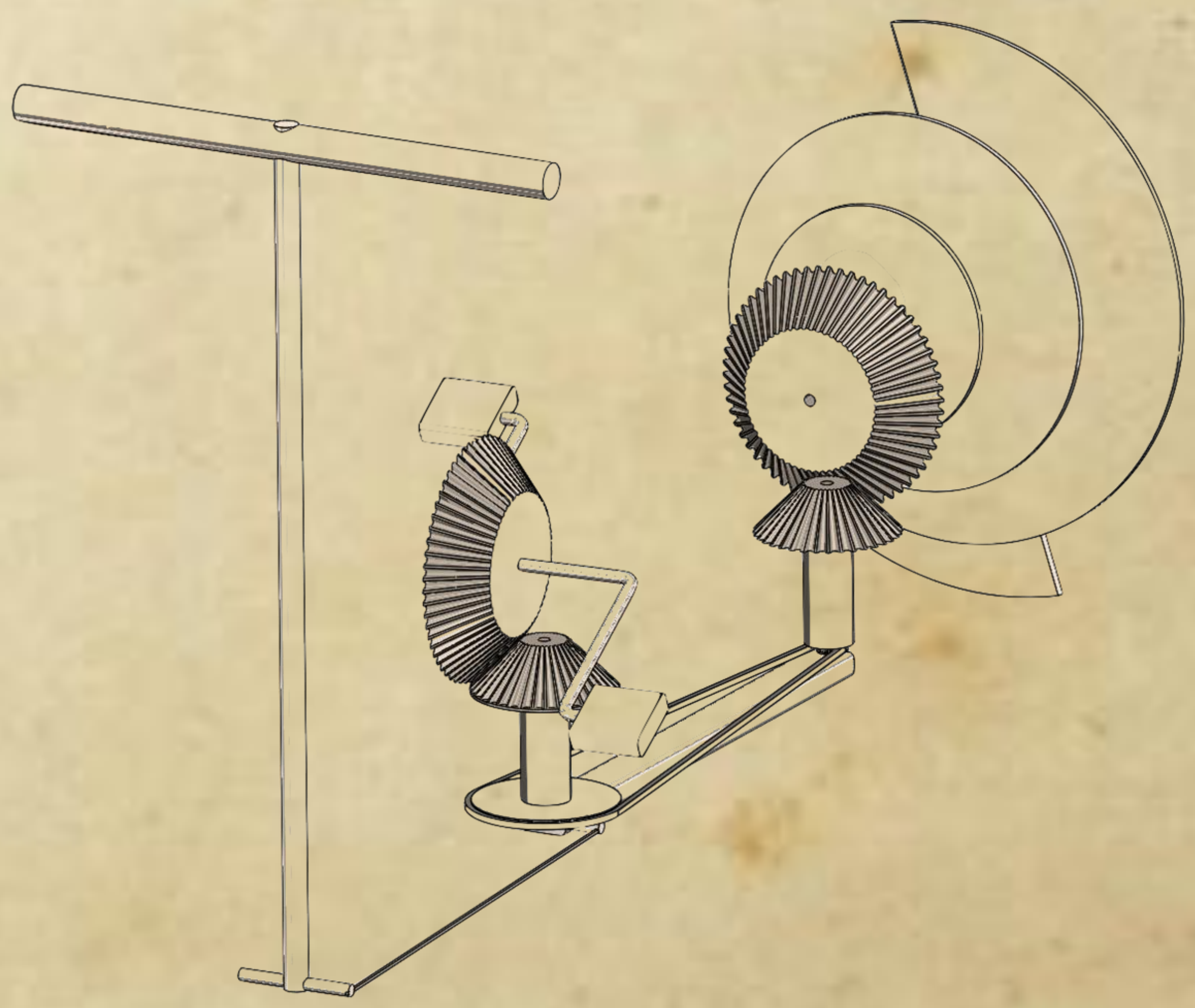
Control Flap Locations

Human-Powered Yaw Control and Throttle

Mimicking a recumbent bicycle, the pilot controls the yaw of the vehicle through a handlebar connected to the front propeller, which also provides forward thrust. The propeller, continuing the bicycle analogy, is powered by the pilot's pedaling. A gear system allows the pilot to pedal at their optimal rate while allowing the optimum rotation speed for the front propeller.

Simple Piloting and Low Workload

Il Mulinello was imagined as a flying bicycle. As such, the pilot can't be overwhelmed with many tasks, and is only required to pedal to power the front propeller and use the handlebar for directional control. Similar to a biker, the pilot can also shift their weight for an additional roll control.



Pilot Control System