Leonardo's Aerial Screw 500 Years Later

A Review of the 37th VFS Students Design Competition

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ABSTRACT

For the last few decades, the Vertical Flight Society has organized the Student Design Competition, a challenge to design a vertical lift aircraft that meets specified requirements. This competition provides a practical exercise for engineering students at colleges and universities around the world and promotes student interest in vertical flight technology. The Student Design Competition sponsorship rotates between the main rotorcraft industry or institutions and in 2019 the 37th edition was sponsored by Leonardo Helicopters, with a subject strongly related to the new company name (recently adopted) and to the celebration of the 500th anniversary of the death of Leonardo Da Vinci. So, student teams worldwide were asked to design a VTOL vehicle based on Leonardo's Aerial Screw concept, studying and demonstrating the consistency of its physics and potential feasibility.

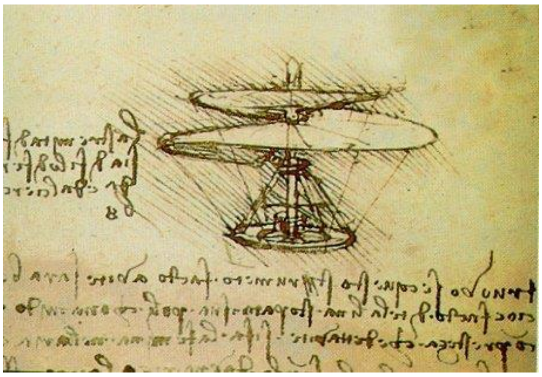


Figure 1 – the aerial screw appears only once in the Codice Atlantico, on a relatively small spot of a page which also reports a nice description of the working principle

LEONARDO DA VINCI: ENGINEERING VISION AND THE GENESIS OF VERTICAL FLIGHT

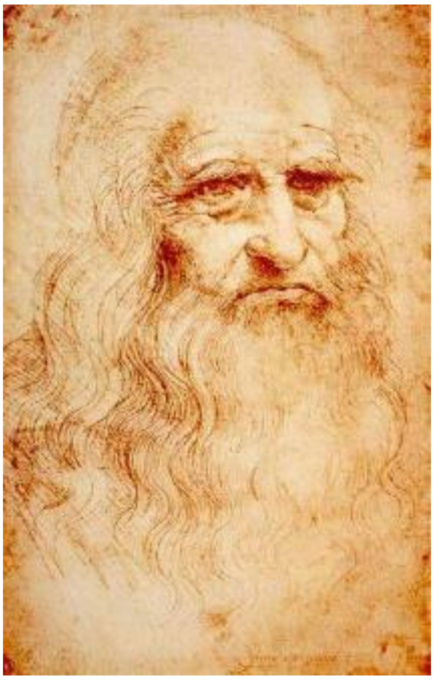


Figure 3 "Potrait of a man in red chalk". Widely accepted as a self-portrait of Leonardo da Vinci, currently in the collection of the Royal Library in Torino (Italy).

Leonardo da Vinci (1452-1519) stands as an unparalleled figure of the High Renaissance, whose genius transcended art to profoundly impact the nascent fields of science and engineering [1]. His relevance as an engineer stems not just from his inventive designs, but from his visionary approach, underpinned by an extraordinary capacity for observation and an almost preternatural ability to draw and thereby understand phenomena that were, to his contemporaries, largely invisible. This was particularly evident in his studies of fluid dynamics. Leonardo meticulously sketched the intricate patterns of water flowing around obstacles, the swirls and eddies of turbulence, and the complex interactions of air currents. His profound understanding of fluid mechanics was significantly honed during his extensive service as a military and hydraulic engineer in Milan for Ludovico Sforza. In this capacity, he worked on designing and improving the intricate network of canals (the *Navigli*) crucial for Milan's commerce, irrigation, military defense, and the transportation of heavy materials, including the marble used for the ongoing construction of the Duomo di Milano. While the major canals like the Naviglio Grande predated him, Leonardo's innovations in lock design and water management were vital. This practical experience with the behavior of water undoubtedly informed his theoretical explorations into the properties of air, which he intuited was a fluid medium subject to similar laws—a revolutionary concept for his time [2,3,4]. His notebooks, such as the *Codex on the Flight of Birds* and the *Codex Atlanticus*, are filled with detailed analyses of bird flight, wing mechanics, and the nature of air resistance and lift, demonstrating a deep, almost modern, understanding of aerodynamics.

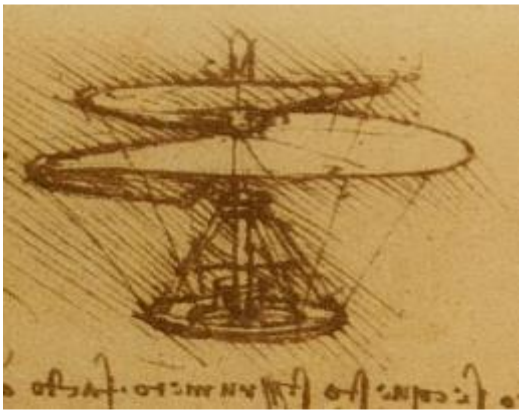


Figure 4 Leonardo da Vinci aerial screw, Folio 83v, Codex Atlanticus, Biblioteca Ambrosiana, Milano.

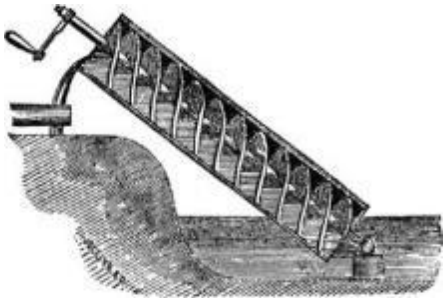


Figure 5 Archimedes' screw

Among his most iconic and forward-thinking inventions is the "aerial screw," conceived around 1487-1490. This device, depicted in a famous drawing in the *Codex Atlanticus* (folio 83v), envisioned a helical structure, likely to be constructed from reed, linen sailcloth, and wire, with a diameter of roughly 4.5 meters [5]. The conceptual leap behind the aerial screw is directly analogous to the well-established principle of the Archimedes' screw, a device known since antiquity for lifting water. The Archimedes' screw consists of a helical surface, or 'screw,' typically encased within a cylinder or trough. When its lower end is placed in water and the screw is rotated, it effectively scoops up discrete volumes of water within its threads. As rotation continues, these pockets of water are conveyed upwards along the inclined plane of the helix, eventually being discharged at a higher elevation. Leonardo, transposing this principle to the less dense medium of air, theorized that if a screw could displace and lift water, a sufficiently large and rapidly rotating helical structure could 'bite' into the air. The idea was that as the four men depicted in his drawing rotated a central shaft connected to this large helical screw, it would compress the air beneath it and, like boring into a solid, achieve vertical ascent by creating an area of higher pressure below, resulting in an upward reaction force. While the immense human power required, coupled with the weight of the materials available, rendered it impractical for actual flight, the aerial screw is a testament to Leonardo's pioneering thought. It was a direct application of his understanding of fluid compression and displacement.

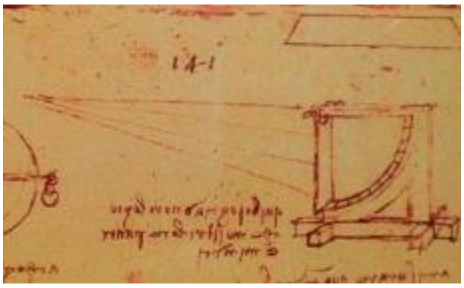


Figure 6 Leonardo's anemometer.

Leonardo's explorations into flight were not limited to the aerial screw. He designed numerous ornithopters—machines intended to fly by flapping wings like a bird—and gliders, all based on his detailed observations of avian anatomy and flight patterns. His work on parachutes, anemometers (to measure wind speed), and hygrometers (to measure humidity) further illustrates his comprehensive engagement with atmospheric phenomena and the challenges of aerial navigation [5].

Historically, Leonardo's aerial screw existed in an era devoid of lightweight engines or strong, light materials necessary for powered flight. Thus, it remained a theoretical construct, a brilliant "thought experiment." However, its conceptual significance is undeniable. While not a direct technological ancestor in a linear sense—as the development of the helicopter involved many other innovators like Igor Sikorsky, Paul Cornu, and Juan de la Cierva centuries later—Leonardo's aerial screw is widely recognized as the first known detailed design for a machine intended to achieve vertical lift through a rotating aerofoil. It prefigures the fundamental principle of the helicopter rotor, embodying the audacious human dream of ascending directly into the sky. Its legacy lies in its demonstration of Leonardo's unparalleled ability to synthesize observation, mechanical principles, and visionary engineering, laying conceptual groundwork that would inspire future generations.

THE AERIAL SCREW AS A HELICOPTER ROTOR

The design and operation of the aerial screw, while seemingly simple, involve complex geometric and aerodynamic principles that have been revisited and refined by modern research (see Refs. [6,9]). Here the geometric construction and the aerodynamic mechanisms that enable an aerial screw to generate thrust will be briefly described.

Geometric Construction of an Aerial Screw

The fundamental geometry of an aerial screw is derived from a continuous helical surface, much like an Archimedes screw. This surface winds around a central shaft, and its specific shape is a key determinant of the screw's function. The core components of an aerial screw's geometry include (see Ref. [9]):

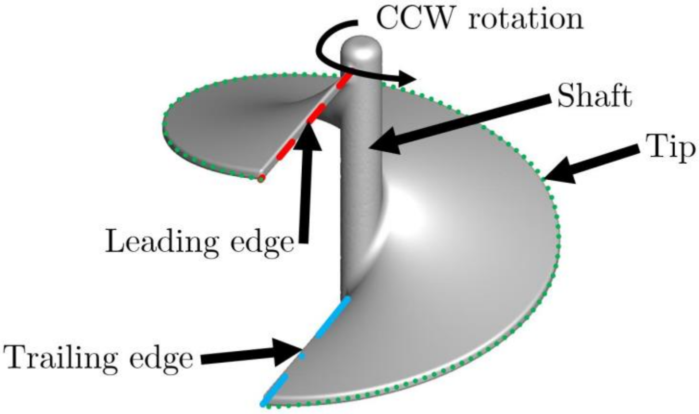


Figure 7 Illustration of the basic geometric elements of an aerial screw (figure extracted from Ref. [9]).

- Continuous Surface: Unlike conventional rotor blades, an aerial screw is characterized by a single, continuous winding surface. The nature of this surface, from its material to its rigidity, plays a role in its aerodynamic performance. Leonardo's original designs imagined a structure of linen, reed, and wire.
- Shaft: A central shaft forms the axis of rotation for the helical surface. The ratio of the screw's radius to the shaft's radius is a critical design parameter. A larger screw radius to shaft radius ratio is characteristic of an aerial screw designed for flight, as it aims to displace a large volume of low-density air [9].
- Leading and Trailing Edges: As with any airfoil, the aerial screw has a leading edge, which first encounters the airflow, and a trailing edge, where the airflow departs the surface. While their role may be less pronounced than in modern rotorcraft, the shape of these edges can influence performance [9].
- Tip: The outer edge of the helical blade is the tip. As will be discussed, the tip region is of paramount importance for the generation of thrust in an aerial screw [9].

- Pitch: The pitch of an aerial screw refers to the axial distance the screw would advance in one full rotation. This can be constant along the blade or can vary. Modern designs explore non-uniform pitch, such as bilinear pitch, where the pitch rate changes along the blade's length to optimize performance [8].
- Taper: Taper describes the variation in the radius of the screw along its length. A tapered design means the radius changes from the leading edge to the trailing edge. Like pitch, taper can be linear or non-linear, and it significantly impacts the aerodynamic forces generated [8].
- Anhedral and Dihedral: These terms refer to the downward (anhedral) or upward (dihedral) angle of the blades relative to the horizontal. In the context of an aerial screw, an anhedral angle can influence the lateral flow of air. While some turbine designs use dihedral to enhance efficiency, aerial screws may incorporate a slight anhedral [9].

The interplay of these geometric variables defines the overall shape and, consequently, the aerodynamic characteristics of the aerial screw. Modern analyses, such as those cited Refs. [8,9], made extensive usage of computational fluid dynamics (CFD) to explore how variations in these parameters affect performance, seeking optimal configurations for generating thrust.

How an Aerial Screw Works

The mechanism by which an aerial screw generates thrust is a fascinating area of aerodynamic study. While Leonardo's intuitive concept was that the screw would "bore" into the air, modern analysis reveals a more nuanced process centered around the generation of a powerful vortex at the tip of the blade [8]. The key to the aerial screw's operation lies in the formation of what has been termed the "da Vinci vortex," a stable, shape-conforming helical vortex that forms and remains attached to the tip of the screw as it rotates.

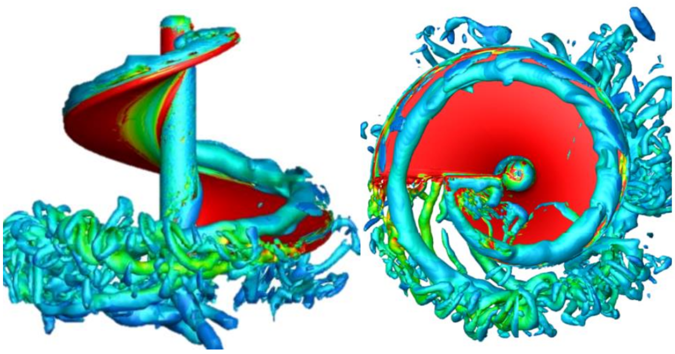


Figure 8 Iso-surfaces of vorticity Q-criterion around a notional (from Ref. [8]).

The generation of this vortex begins as the screw's rotation displaces air and creates a pressure differential between its upper and lower surfaces, with higher pressure building underneath the blade. Consequently, air from this high-pressure region flows laterally toward the low-pressure region on the upper surface. This flow is most pronounced at the blade tip, where it rolls up into a coherent and powerful vortex that adheres to the rotating tip. This bound tip vortex, the "da Vinci vortex," is the primary source of thrust for the aerial screw [9,8]. The low-pressure core of this vortex, situated directly over the blade's upper surface, creates a significant suction force, a phenomenon known as "vortex lift." This is aerodynamically analogous to the lift generated by delta-wing aircraft at high angles of attack. Research made in Ref. [8] highlights that this vortex-induced lift is responsible for a substantial portion of the aerial screw's total thrust. The geometric parameters of the screw are critical for controlling this effect. Variables such as taper and pitch are crucial for managing the development and strength of the vortex along the blade, allowing designers to optimize the balance between lift and the power required for rotation. Furthermore, the single continuous surface of the screw is advantageous for maintaining the stable and coherent vortex structure necessary for efficient thrust generation [9, 8].

In essence, the aerial screw functions not by simply pushing air downward, but by generating and harnessing a powerful, low-pressure vortex at its tip to create lift, as it has been shown in Ref. [8] that provides a modern, scientific validation of the potential of Leonardo's visionary concept.

THE LEONARDO TOPIC FOR THE 37TH VFS STUDENTS DESIGN COMPETITION

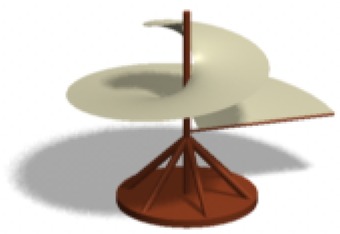
The Students Design Competition (SDC) is one of the key initiatives of the Vertical Flight Society; since 1984, teams from all over the world have been challenged with an engineering task related to the vertical flight and produce a new vehicle design carefully judged by experts from the leading rotorcraft industries and institutions.

Each year the contest is sponsored by one of the main participating industry partners, who proposes the technical design topic and is responsible for the judging awards. This request for proposal (RFP) is generally centered on some specific technical or technological challenge, often reflecting issues or trends relevant for the real-world product development. This is of course a unique opportunity for the students gain engineering design experience and also for the sponsors to raise awareness on topics of interest, in some cases also gathering original ideas or approaches. So Over the years dozens of teams of students have been tasked with projects of innovative helicopters, VTOL vehicles or tiltrotors, not to mention more recent topics for the design of drones or eVTOLs.

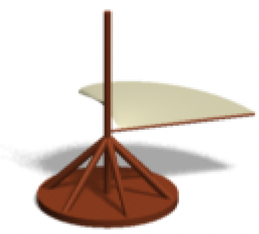
In 2019, when Leonardo Helicopters (formerly AgustaWestland, recently re-branded under the Leonardo name) ~~was~~ sponsored the competition, several possibilities were considered, ranging from drones, that were increasingly part of the product portfolios, to eVTOLs making their first steps towards the development of an actual product. Other topics of interest for Leonardo were also tiltrotors, with current AW609 certification and the NGCTR development, as well as conventional helicopters, with the first flights of the AW09 and the AW249 brand new models. At the same time, a concern of the Leonardo engineers was to avoid obvious topics and to engage students by proposing a novel, requiring some out-of-the-box thinking, following the spirit of the competition.

And -somewhat surprisingly- the help came not from the hot topics in the helicopter industry but from an old and forgotten idea, brought back to life due to an important date. Year 2019 was in fact the 500th anniversary of Leonardo da Vinci’s death and of course this was particularly important for a Company which just months before had chosen the name of the Italian inventor. The name of Leonardo is associated with many inventions and artworks, but for the rotorcraft engineers it has a special value because of a small picture with a couple of comments that the Renaissance genius wrote on the side of a page of the *Codice Atlantico*: the “aerial screw”. Although simply sketched and briefly described, the famous Leonardo~~’s~~ sketch clearly defines a rotary-wing concept and is universally considered the ancestor of all the helicopters.

The aerial screw is definitely a paper project, since no implementations nor tests by Leonardo have been documented, so the aerial screw could humorously also be considered an ancestor of the powerpoint engineering. In particular, this early helicopter idea is criticized as unfeasible because of the lack of suitable propulsion or as impractical because it does not address the torque problem. These points are valid and the aerial screw, as depicted by Leonardo, cannot take off and fly. However, the validity of the aerial screw principle has never been properly assessed. Therefore, the aerial screw seemed a very interesting and original topic for the 2019 VFS Student~~s~~ Design Competition, combining the historical value of an iconic invention, a unique possibility to celebrate the 500th anniversary of the inventor’s death and an important opportunity for the sponsoring company to underline the new Leonardo name.

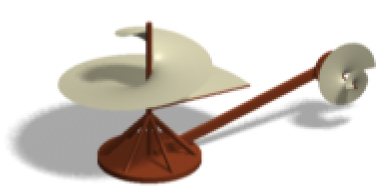


OK - Leonardo’s configuration

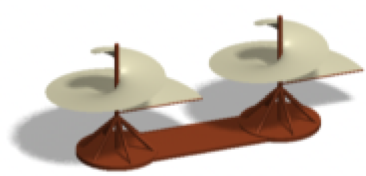


NO – Insufficient solidity

NO – Multiple blades



OK – Helicopter configuration



OK – Tandem configuration

OK – Quad-copter configuration

Once the aerial screw subject had been identified, the next step was to setup the technical RFP, with precise requirements, constraints and prescriptions to be addressed by the teams. In particular, it was necessary to preserve as closely as possible Leonardo's design, while giving to the teams a reasonable maneuvering space to develop practical design solutions. So, the first point was the definition of the aerial screw, pinpointing physical parameters reflecting the idea; this was challenging, because Leonardo produced only a single sketch, with a couple of lines of description. The aerial screw was therefore defined as a "single-bladed rotor with solidity equal or greater than one with a continuous surface". To ensure that the shape did include at least one complete helical surface, a solidity of one or more (Leonardo's sketch seems to have solidity 1.5) was defined to exclude implementations of a false screw comprised of multiple smaller blades arranged to form a helical pattern. The other important dimension of the design space left to the teams was the number of aerial screws used for the vehicle design. While Leonardo's sketch featured a single aerial screw, the SDC requirement was open to multiple devices, permitting quadcopters or conventional helicopters with main and tail rotors based on the aerial screw principle. The last key requirement was the mission, which was defined for a possible demonstration of a human flight, with a short (one minute flight) with one passenger and a minimal controllability to be demonstrated at take-off and landing.

All of the above design requirements were synthetized in the official RFP of the SDC, reported below and published by VFS, which challenged the student teams. Two student team categories, graduate and undergraduate, were in place for the contest, where the graduate team RFP requested deeper analyses and documentation.

The competitors shall design a vehicle relying for lift and thrust from one or more "Aerial Screws," i.e. single-blade rotor with solidity equal or greater than one with a continuous surface, making use of any possible airborne powerplant/energy storage (buoyancy can be considered), capable of:

- Carrying 1 pilot or a passenger of a total of at least 60 kg (basically minimum human load of 60 kg)

- Take-off vertically, holding the position for at least 5 seconds (within 10 m radius from take-off spot, no wind)

- Flying for at least one minute, covering at least 20 m of distance at an altitude above the ground of at least 1 meter, untethered.

- Land vertically, after holding the position for 5 seconds (within 10 m radius from landing spot, no wind)

Once the topic of the contest was launched, teams from all over the world accepted the challenge and started working on their projects.

A Question and Answer (Q&A) session with Leonardo engineers was arranged clarify specific points of the requirement and a few months later, on the prescribed deadline, the proposals were submitted by the teams. A total of 12 teams met the deadline and were evaluated by the VFS design committee. There were three team in the Undergraduate category and nine teams in the graduate category.

A few examples of some of the most successful projects are reported in the following sections.

THE RESULTS BY THE TEAM: THE TUDELFT EXPERIENCE

Delft University of Technology SolidityOne - Faculty of Aerospace Engineering, Delft University of Technology (TUDelft) in The Netherlands participated for the first time to the Vertical Flight Society (VFS) Student Design Competition in 2020, section Undergraduates. A team of five aerospace students led by Dr. Pavel won the First Price Award along with Best New Entrant honours with their concept ***SolidityOne***, demonstrating the physical and potential feasibility of Leonardo's Aerial Screw.

The Challenge - The key challenge in redesigning Leonardo's aerial screw rested in the rotor configuration: it required a single-blade rotor with a continuous screw-like surface capable of generating sufficient lift to vertically take off, support a passenger weighing at least 60 kg, hover in place for a minimum of 5 seconds, and sustain flight for at least one minute while covering a distance of 20 meters at an altitude of at least 1 meter. This presented a significant engineering hurdle, as such a rotor inherently suffers from high tip losses, making efficient lift generation difficult. The design team had to demonstrate not only that this unconventional rotor configuration could achieve flight, but also that it could do so reliably and sustainably as an electric personal air vehicle.

Eighteen concepts were initially considered and reduced to three promising options: tandem, side by side and nested coaxial rotor configurations. The final concept was a tandem configuration with the key features presented in Figure 9.

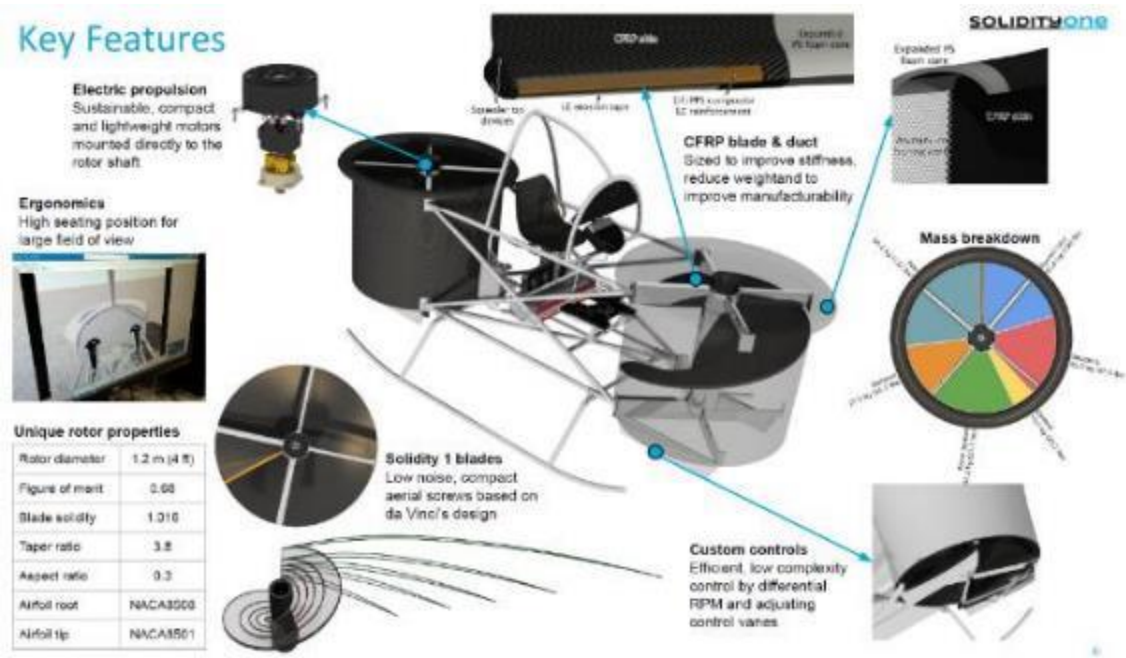


Figure 9 SolidityOne Key features: a tandem electric air vehicle with ducted aerial screw rotors capable of carrying a single pilot and designed with a focus on sustainability from lightweight materials and zero-emission propulsion

The aerial screw achieved indeed substantial lift in a compact design due to its extensive blade surface area. However, its inverse taper ratio concentrated more surface area near the blade tips, intensifying tip losses. This issue was addressed by enclosing the screw in a duct and incorporating squealer tips. Combined with a low tip-speed, these modifications not only mitigated tip losses but also resulted in a low noise level of 64.8 dB. The duct walls were made of an aluminium honeycomb core and carbon fiber composite skin sandwich structure. This had to be stiff enough to prevent contact between the duct and rotor tip, which were only 1.2 millimetre apart. To validate the design, a scaled experiment was flown in the High Speed Lab facility of the TU Delft, see Figure 10.

Figure 10 TheSolidityOne Rotor in the wind tunnel

Finally, key design features—such as aesthetics, visibility, and overall ergonomics—were evaluated during an ergonomics test in the Virtual Reality Laboratory at TU Delft, see **Error! Reference source not found.**.

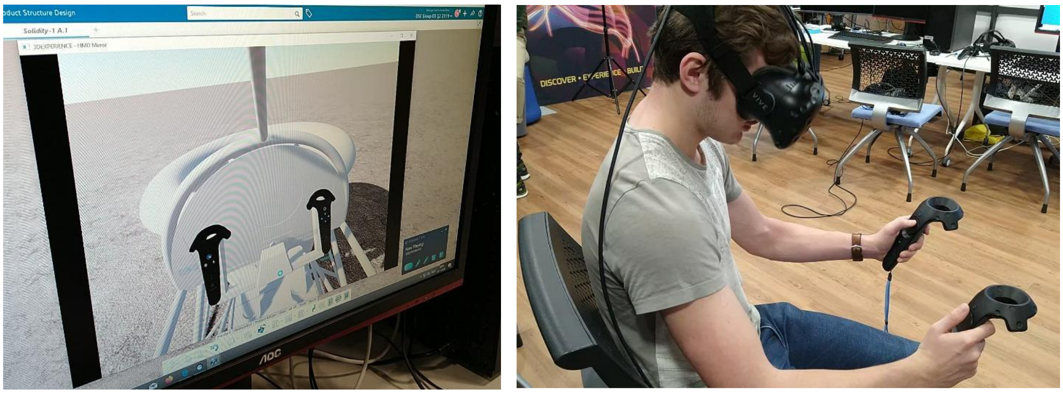


Figure 11 Flying SolidityOne in virtual reality environment

THE RESULTS BY THE TEAM: THE POLIMI EXPERIENCE

Politecnico di Milano, for the first year, participated to both the undergraduate and the graduate student design competitions in 2020 with two teams. Both were classified at the 3rd place in the two competitions.

Figure 12 Politecnico di Milano Poli'sCrew (left) and STOAT (right).

Poli' sCrew: Revitalizing Leonardo's Aerial Screw with Modern Engineering - The "Poli'sCrew" project, developed by undergraduate students from Politecnico di Milano, stands as a compelling modern reinterpretation of Leonardo da Vinci's visionary aerial screw. The students initially sought to remain as faithful as possible to Leonardo's visual concept, including the open, un-intubated screw and considering a similar number of blade rotations. The project's main innovations lie in how it addressed the inherent limitations of Leonardo's 15th-century design through contemporary engineering. A primary departure was the shift from Leonardo's single screw to a twin, counter-rotating aerial screw configuration. This was crucial for managing the significant lateral forces and torque imbalances that would have plagued a single-rotor design, thereby enhancing stability and controllability. Propulsion was another key area of modernization; where Leonardo envisioned human power, Poli'sCrew utilized three Emrax electric motors, reflecting modern advancements in power density and eco-friendly technology.

The design leveraged advanced materials unimaginable in Leonardo's time, employing high-modulus carbon fiber for the internal screw structure and fuselage, and spinnaker sailcloth for the screw surfaces, achieving a low empty weight of 130 kg. Aerodynamic design was rigorously pursued using Computational Fluid Dynamics (CFD). This allowed for detailed optimization of the screw's geometry, moving beyond a simple helix to a cylindrical screw with a single revolution, incorporating features like a modified first rib to mitigate adverse pressure spots and winglet-like structures to improve flow direction and efficiency (achieving a Figure of Merit around 0.35).

Furthermore, the Poli'sCrew incorporated a dedicated tail propeller for directional control (yaw) and pitching moments, a necessity for a practical flying vehicle not explicitly detailed in Leonardo's original concept. The students also designed a sophisticated truss structure and landing gear, and validated their concepts through 3D-printed scale models tested on CNC routers, allowing for iterative design improvements based on empirical data. While acknowledging the inherent lower efficiency of the aerial screw concept compared to modern helicopter rotors, the Poli'sCrew project successfully demonstrated how Leonardo's seminal idea could be brought closer to functional reality through the application of 21st-century technology, materials, and analytical tools, offering a tangible bridge between historical vision and modern aerospace engineering.

STOAT (Team Giocondi): A Pneumatically-Powered Reimagining of Leonardo's Aerial Screw - The "STOAT" (Short TakeOff with Azimuth Thrusters) project, developed by the graduate "Team Giocondi" from Politecnico di Milano presented a highly innovative and distinct interpretation of Leonardo da Vinci's vision. While Leonardo's original concept relied on the mechanical rotation of a helical screw to "bore" into the air, the STOAT project diverged significantly in its core working principle, though it retained the iconic spiral form as a central aerodynamic element and drew structural inspiration from Leonardo's Codex Atlanticus drawings for its frame design. The name STOAT was also a tribute to the famous Leonardo Da Vinci's work of art, the Lady with an Ermine, that is currently at the Ermitage in Saint Petersburgh, Russia (since a stoat is also the animal in the hands of the painted lady). STOAT's ingenuity lay in transforming Leonardo's rotating screw into a fixed aerodynamic element, powered by an internal pneumatic jet, thus offering a unique solution to the challenge of vertical flight inspired by the Renaissance master.

The primary innovation of STOAT was its concept of static, non-rotating aerial screw surfaces. Instead of spinning the screw, lift was proposed to be generated by a high-energy airflow, provided by an onboard compressor, directed radially outwards from a central nozzle across the surfaces of these fixed spiral airfoils. The design featured two such propulsive nacelles, each housing a spiral airfoil structure. This approach necessitated a complex pneumatic system as the heart of its propulsion. An axial compressor, powered by two AC electric motors drawing from a high-performance "Energica Corsa" electric motorbike battery pack, would pressurize air. This air would then be channelled through an air reservoir, accumulators, and a system of pipes and valves (including flow control valves for thrust modulation) before being expelled through nozzles onto the spiral surfaces.

Directional control was envisioned through the independent tilting of these two propulsive nacelles, allowing them to act as azimuth thrusters for forward, backward, and yaw motion. Vertical control was to be managed by modulating the airflow to the nacelles via electronically controlled valves. The team undertook detailed design of the airframe and the propulsive units, specifying a NACA 6409 airfoil for the spiral. Their analysis relied heavily on multibody dynamics simulations, including an automatic Flight Control System to demonstrate flight capabilities. Due to pandemic-related constraints, the team focused on design and simulation development, forgoing the construction of a scaled physical model.

THE RESULTS BY THE TEAM: THE GEORGIATECH EXPERIENCE

The year for this SDC proved to be an eventful year for Vertical Lift (VL) at Georgia Tech (GT). GT's long-time design professor and SDC advisor, Prof. Dan Schrage, retired in 2019. While rotorcraft design was being taught, there were no teams competing in the SDC. However, four graduate students read the Leonardo RFP and were intrigued to see if they could design a vehicle that could fly using an aerial screw as the primary propulsion system. Commencing in January of 2020, without a formal rotorcraft design course, and an advisor who had not previously mentored a design team, this team won second place in the Graduate Division of the competition with their *Il Mulinello* (Whirlpool) design.

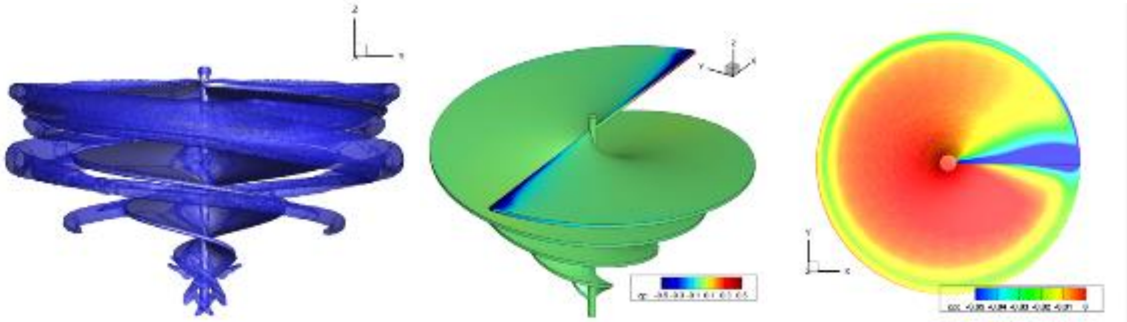
The *Il Mulinello* design is a tandem human-powered vehicle powered by two aerial screws to provide axial flight thrust and one aerial screw that acted as a forward propeller, as illustrated in **Figure 13**. A design was sought that was in keeping, as close as possible, with DaVinci's historical concept. A boost battery was needed to achieve hover, but the remainder of the mission was powered by the pilot via a pedal assist system similar to an electric bicycle. Analysis of the *Il Mulinello* confirmed its capability for stable take-off, hover, landing, and forward flight over an estimated range of 500 meters with an endurance of almost 4 minutes, exceeding the RFP requirements.

Figure 13 Il Mulinello's lift+cruise aerial screw configuration. Acknowledgements: Thanks to the Georgia Tech Il Mulinello graduate student team: Alex Moushegian (Team Lead), Carlota Bonnet, Alex Markov, and Milad Mozayyani. Team Advisors were: Marilyn Smith and Dimitri Mavris.

A primary focus in the design was an effort to assess the efficacy of the aerial screw as a viable propulsion mechanism. The team investigated the performance of an aerial screw via an experiment to evaluate the effects of the airscrew's taper ratio, coning, and total height, as illustrated in Figure 14. The pandemic shut down the test before it could be completed, so this effort moved to Computational Fluid Dynamics (CFD) analysis of different aerial screw characteristics. Figure 15 exemplifies these results, illustrating the vortical wake and the pressure coefficients of the aerial screw. Most of the thrust is generated by the leading edge of the aerial screw (Figure 15b and c), while the effect of the finite tip vortex is observed in (Figure 15c).

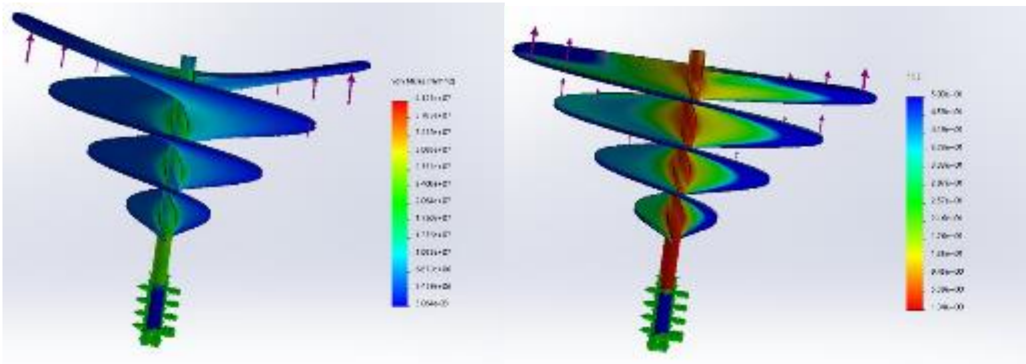
The relative inefficiency of the aerial screw had to counteracted by using materials that were lightweight but still provided an adequate margin of safety. Finite element analyses indicated that Nylon 6/10 was sufficient for the surface, but high bending moments and surface deflections required that the shaft be built of aluminum (Figure 16a) to meet acceptable margins of flight safety (Figure 16b). Stability and control analyses confirmed the ability of Il Mulinello to meet or exceed the RFP requirements.

Figure 14: Aerial screw small-scale performance test. Rig design (left) and test setup (right).



a) Q-criterion isosurfaces b) Surface pressure coefficient c) Planform surface pressure coefficient

Figure 15: Aerial Screw aerodynamic behavior as determined through CFD.



a) Stress analysis b) Figure of safety

Figure 16: Finite element analysis of an aerial screw.

LESSONS LEARNT AND OVERALL RESULTS

The participation to the contest was a first positive outcome, in spite of some initial doubts because of the unusual character of the topic. The Q&A session typically setup once the topic was issued did help in clarifying several students' questions and feedback received later did confirm that the subject did actually stimulate the participants.

The results submitted to the evaluation committee did meet in most cases high quality standards but, more important, those were actually showing interesting ways -in some cases even surprising- to implement the aerial screw idea, not to mention the inspiring names that the student gave to some of their project.

And going beyond the contest, the results did also have an historical value: the number of developed concepts, together with the feasibility outcomes obtained, did represent a first solid assessment of the Leonardo's idea, both in terms of performance and aircraft design.

In particular, the performance of the aerial screw was evaluated using both numerical methods and experimental techniques and reached fair values, perhaps beyond expectations, with figure of merit up to 0.5, addressing the typical critics about the low efficiency of Leonardo's invention. Also the various proposals were successfully considering different configurations, including tandem or multi-copter, solving in many ways the anti-torque issue, often quoted as the main shortfall of Leonardo's idea. Moreover, the analysis of some variants of the aerial screw were also showing interesting characteristics of this unusual rotor configuration. Experiments and computational analyses by several teams confirmed that while not an optimal propulsive mechanism, that the aerial screw could be used in personal aerial vehicles using both human-powered and electric motors.

Some efforts also evolved in more structured studies, adding to the simulations and tests prepared for the competition some ergonomics and piloting simulations or even the manufacturing of a real flying model. This of course required to deepen the design of the vehicle, considering actual motors and energy storage systems, flight controls, structural design etc., exploring a real overall vehicle application, although of course scaled and/or unmanned.

Possible next steps in this subject would be the completion of the evaluation of the concepts, with sensitivities on the geometrical properties and on the resulting performance of the aerial screw. Air vehicle implementations could also be further pursued, accumulating more flight experience on the existing asset or exploring other configurations.

Finally, given the historical value of the above activities, particular attention should also be placed on the dissemination of the results, making sure in the future history books will report a better historical and technical view on the aerial screw, the iconic helicopter ancestor invented by Leonardo da Vinci.

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