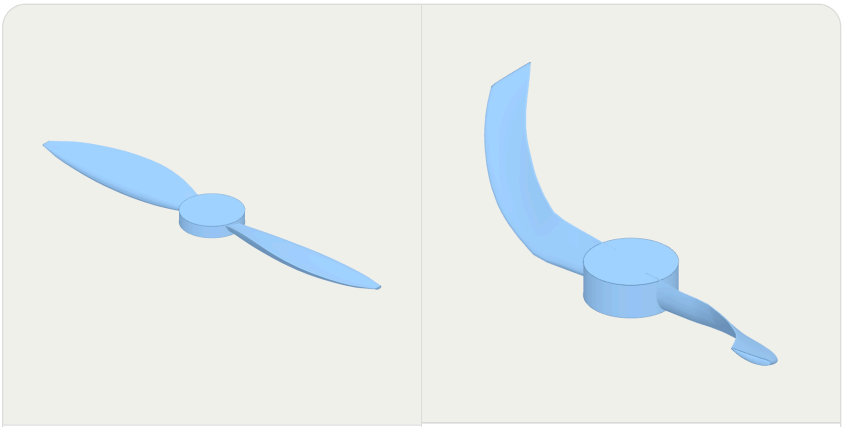
Archimedes / Drones

One propeller that flies and swims.

Water is 830 times denser than air. Put a normal drone propeller underwater and the motor stalls, wasting 97% of the battery's power. Archimedes redesigned the propeller and its gearbox together.



Stock drone prop
stalls its motor underwater

Archimedes design
swept blade, two-speed gearbox

ARCHIMEDES TECHNICAL CASE STUDY

How to interpret this report

Results apply only to the stated geometry, operating conditions, numerical models, and verification record.
They are not product certification, safety approval, or a general claim outside the documented scope.
Limitations and adverse findings are retained because they are part of the engineering result.

REPORT ID
`air-water-propeller`

CANONICAL SOURCE
`standardphysics.com/archimedes/air-water-propeller`

~90%
as good as a propeller built only for air, or only for water

20 hours
12 of agent search plus 8 of checks, about $160 of compute

1,251
designs tried by six teams of agents



The ask

One propeller for a 2 kg drone that hovers in air and cruises underwater.

Same motor in both. Score it on how much battery power turns into thrust, in air and in water.

What it found

The motor, not the blade, was failing underwater.

Water loads a drone propeller so heavily that the motor slows below its efficient speed. No blade shape fixes that on its own.

What it did

What went wrong

Added a two-speed gearbox, then evolved the blade.

A 6:1 gear and a hub that twists the blades keep the motor efficient underwater. Six teams of agents then raced different shapes, and a swept blade borrowed from marine propellers won. Underwater power fell from 47.5 W to 3.91 W.

Its first answer optimized the wrong thing.

The first search tuned the blade on its own. Checked against the real motor, its score collapsed, so Archimedes rewrote the goal around battery power and searched again.

For engineers

The full record, unedited.

The exact brief as given to the agents

The brief

Archimedes: 12 h search + 8 h verification | 1,267 3D RANS solves on 12 cloud nodes (~$160 total)

One 254 mm rotor. One motor. Hover a 2 kg drone in air, propel it underwater at 1 m/s, and optimize the complete battery-to-thrust system, not a blade in isolation.

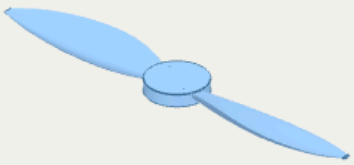
How the design came together four decisions, step by step

How it works

Four decisions turn an air propeller that barely works underwater into one co-designed flight-and-swim system.

Baseline · direct drive

recorded section rings · fixed camera



D = 254 mm · rotor axis normal to disk

373 RPM | **15.2% motor η** | **2.7% useful power**

Baseline · direct drive

The motor, not the blade, fails first.

Water torque pulls the motor down to 373 RPM. The drivetrain fails before blade geometry has room to matter.

Archimedes changed

Change the drivetrain objective from shaft efficiency to battery-to-thrust efficiency.

Reframe · gearbox + pitch

Separate motor speed from propeller speed.

A 6:1 reduction returns the motor to its efficient band. Rotating the blade +22.5° then aligns the hydrofoil with the steep underwater inflow.

Archimedes changed

Co-design gear ratio and collective pitch before searching blade shape.

Gen 264 · paddle leader

The wide blade fixes Reynolds number, then hits a vortex wall.

Full diameter and constant chord preserve low-Reynolds-number lift. The square unswept tip concentrates the pressure jump into a strong vortex core.

Archimedes changed

Keep disk area and chord, but change the stacking line at the tip.

Gen 1255 · scimitar winner

Sweep unloads the tip without

surrendering disk area.

A 28° aft sweep, 3.7-4.5% outboard sections, and a final advance-ratio re-trim weaken the tip vortex while preserving attached low-Re flow.

Archimedes changed

The winning geometry combines mechanisms discovered on different evolutionary islands.

Headline numbers with the basis for each

91% / 89%
of an air-only optimum's hover efficiency and a water-only optimum's cruise efficiency, achieved by one blade
Fine-mesh 3D RANS CFD · full drive chain

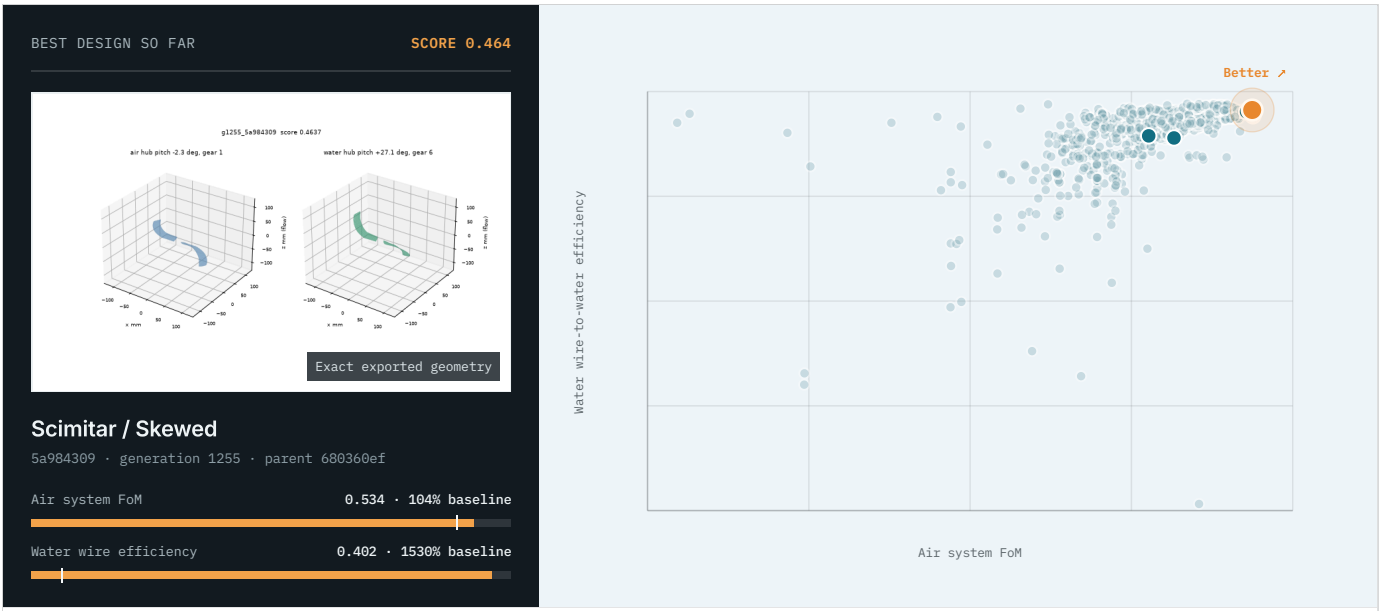
9.2x
underwater battery-to-thrust system efficiency vs a stock drone propeller on direct drive (24.6% vs 2.7%)
Fine-mesh 3D RANS CFD · 3.91 W vs 47.5 W

+10 to +14%
full-chain score over the best standard propeller (APC 10x7) given the exact same variable-pitch hub and gearbox
Like-for-like hardware benchmark

The search, replayed 1,251 designs, generation by generation

The search

Each point is a solved rotor and drivetrain, not a generated shape. The search first recovered the motor operating point, then separated air and water pitch, before comparing topology on the complete battery-to-wake objective.



1,246 scored designs shown from 1,267 evaluations · exact metrics, generation order, and parent lineage from prop-run2. “Round” is a chronological 12-design replay batch because scheduler round boundaries were not exported; 16 unsolved records and five duplicate island baselines have no independent point.

The replay places every scored campaign design at its recorded air and water metric. New 12-design chronological batches appear together; the orange marker tracks the best score available at that point.

Approaches and the physical logic *what each change bought*

Approaches tried

The breakthrough was the order of operations: fix the motor, then incidence, then shape.

01

Recover the motor

Separate motor speed from rotor speed with a 6:1 water reduction.

55.88 W → 13.36 W

02

Recover the blade

Give one rotor a different collective pitch in each fluid.

20.7% → 69.0% blade efficiency

03

Recover the mission

Co-design sweep, sections, pitch, and gearing instead of optimizing a blade alone.

91% air optimum · 89% water optimum

The physical logic

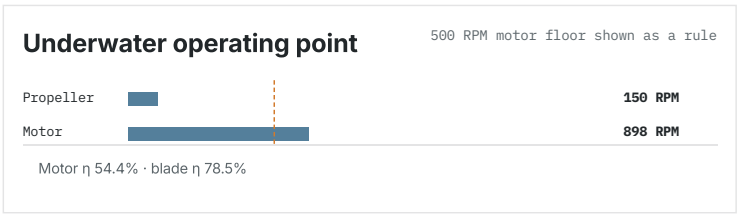
Fine-mesh CFD · full battery-to-thrust chain

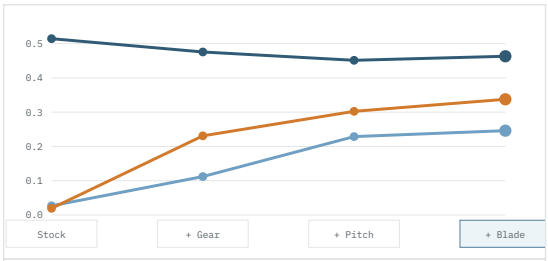
Each intervention removes a different loss. Select a step to see the measured operating point; the charts retain every earlier configuration for comparison.

Step 1 · The Failure Mode	Step 2 · Motor Impedance Match	Step 3 · Hydrofoil Pitch Unstall	Step 4 · Co-Designed Scimitar Topology
Stock APC 10x4.7 on Direct Drive (Fixed 0 deg Hub)	+ Two-Speed Gearbox (1:1 Air / 6:1 Water)	+ Variable-Pitch Hub (+4.5 deg Air / +22.5 deg Water)	+ Archimedes Gen 1255 Campaign Blade
Score 0.0194 Water 2.7%	**Score 0.2309** Water 11.2%	**Score 0.3025** Water 22.9%	**Score 0.3375** Water 24.6%

+ Archimedes Gen 1255 Campaign Blade

Only after gearing and pitch were solved did blade shape become decisive. The swept rotor preserves air performance while reducing underwater profile and vortex loss.



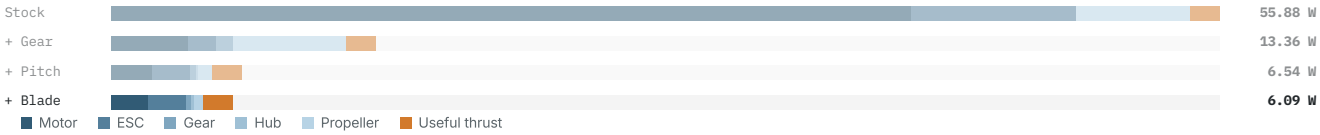


Recorded fine-mesh full-chain terms. Up is better; each step keeps the same battery-to-thrust accounting.

Air term · Water term · Full-chain score

Full-chain score	Water prop / motor RPM
0.3375	150 / 898
Air 0.463 · Water 0.246	Motor efficiency 54.4%

Water blade efficiency	Electrical power (1.5 N)
78.5%	6.09 W
Recorded at the 1.50 N cruise operating point	9.2× lower than stock



Baseline vs winner scores on the full drive chain —

Baseline vs winner

The continuation winner is the final full-chain search result. Gen 1255 remains the distinct campaign blade used by the verification studies.

Configuration	Full-chain score	Role in the campaign
Stock APC 10x4.7, direct drive	0.0194	Failure-mode baseline: fixed pitch and 1:1 drive
Archimedes Gen 1255	0.3375	Campaign blade used for the verification studies
Archimedes continuation winner	0.3504	Distinct later winner from the full-chain continuation search

Gen 1255 campaign full-chain score: 0.3375. The 0.4446 grid-convergence value is a motor-chain verification score, not a full-chain score.

3D variant explorer spin every family's best blade

Explore every variant in exact campaign geometry

Every family starts from the same comparison view and scale. Drag to inspect its recorded section-ring geometry; reset before switching back to like-for-like comparison. The CFD tabs remain the computed flow evidence.

Winner **Scimitar** **0.3375** full chain · 2 blades	g48 **Toroidal Loop** **0.3008** full chain · 2 loops	g238 **Tip End-Plate** **0.3191** full chain · 3 blades	g264 **Paddle** **0.2768** full chain · 2 blades
g867 **Conventional** **0.3350** full chain · 2 blades	g30 **Ducted Kort** **0.2542** full chain · 4 blades	Baseline **Baseline APC** **0.0194** full chain · 2 blades	

Geometry Reconstruction | CFD Water Velocity | CFD Water Pressure | CFD Air Velocity | Planform & Sections

Recorded section rings · drag to inspect

Reset view



Scimitar / Skewed

g1255_5a984309 · foil section

Scimitar / Skewed (Gen 1255 Winner)

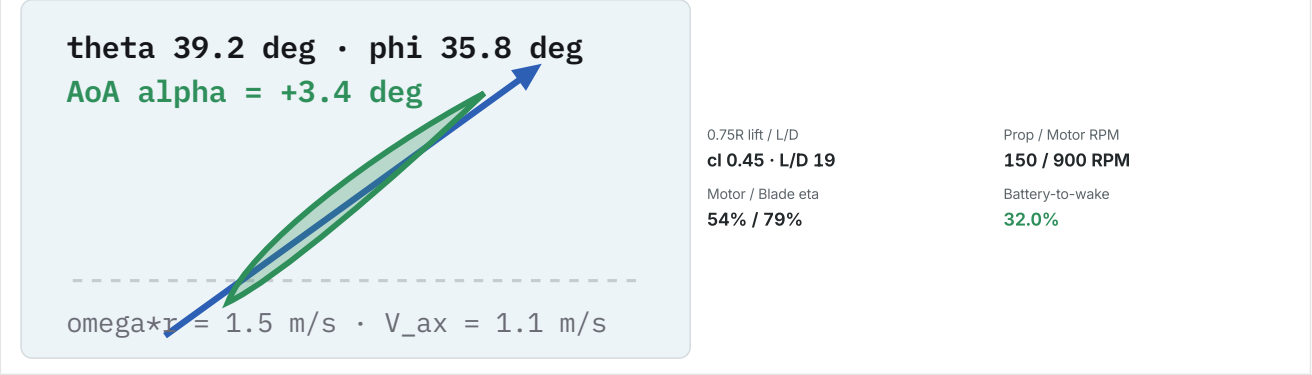
Literature anchor: Boswell (1971) highly skewed marine series + thin low-Re aero section

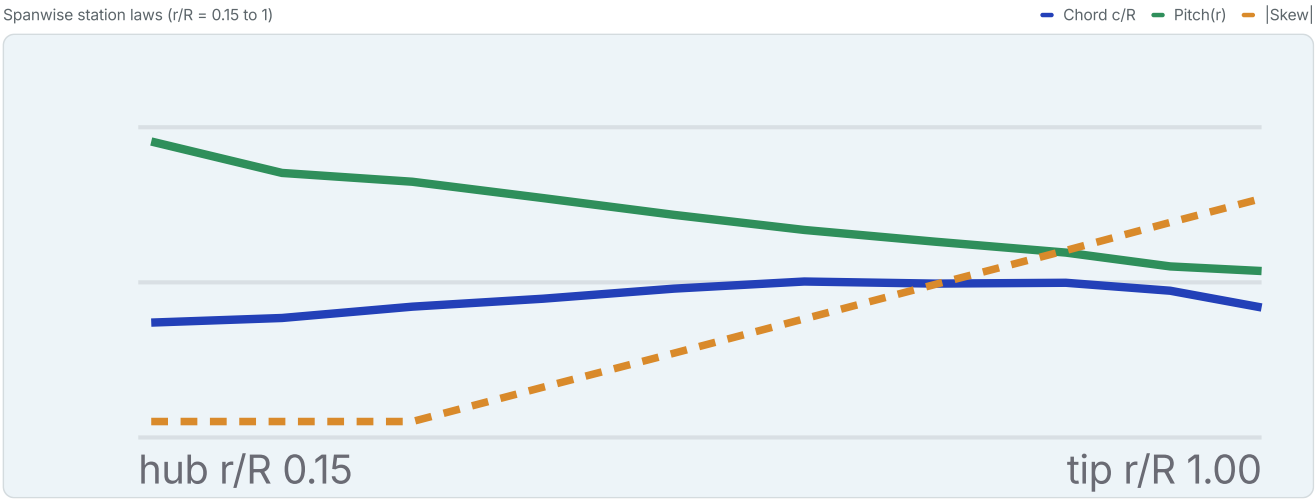
28 deg aft scimitar sweep unloads tip cavitation and shock losses while thin 3.7-4.5% outboard foil sections operate at cl 0.57 (L/D 19) underwater at +27.05 deg hub pitch and 6:1 gearing.

Spawned at Gen 286 when an Island 1 agent grafted a 22 deg aft sweep law onto the Island 2 Rectangular Paddle leader; by Gen 1255 its code evolved into a coupled two-medium advance-ratio pipeline.

Live 0.75R hydrofoil physics (Water 1.0 m/s)

Optimal hydrofoil L/D + motor band





Technical report benchmark, verification and limits

What this unlocks

A vehicle can cross the air-water boundary without carrying one propulsion system as dead weight in the other medium.

One propulsion system, two operating worlds

The result is not merely a better propeller. It is a practical route to smaller aerial-aquatic vehicles for inspection, coastal science, search, and infrastructure work, found by agents that could test system-level ideas across mechanics and fluids in hours instead of handing each discipline a separate optimization problem.

91% / 89%	**55.88 → 6.09 W**	**0.3375**	**0.3504**
of air-only / water-only optima	underwater battery draw	Gen 1255 campaign full-chain score	continuation winner full-chain score

Campaign record and appendices decision log, families, references

Campaign record and limitations

The brief, benchmark, decision log, population, numerical basis, verification evidence, and references, expanded in document order for human or agent review.

Same-hardware benchmark

Every standard rotor received the same variable-pitch hub and two-speed gearbox, with pitch and gear pairs retuned before fine-mesh comparison.

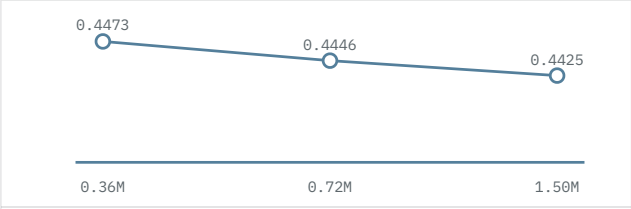
Rotor	Pitch, air / water	Gear, air / water	Full-chain score	Air FM	Water eta	Endurance, air / mixed / water
Wageningen B4-55 marine propeller (tuned on same hub & gearbox)	0.0 deg / 0.0 deg	3:1 / 6:1	0.2345	0.485	0.463	18.9 / 27.6 / 51.0 min
APC 10x4.7 SF air propeller (tuned on same hub & gearbox)	+4.5 deg / +22.5 deg	1.5:1 / 6:1	0.3025	0.701	0.690	25.8 / 45.2 / 181.2 min
APC 10x7 SF air propeller (best tuned standard propeller)	0.0 deg / +17.5 deg	1.5:1 / 6:1	0.3063	0.699	0.708	25.7 / 45.3 / 189.2 min
Archimedes Gen 1255 (scimitar / skewed, 2 blades, 254 mm)	-2.3 deg / +27.1 deg	1:1 / 6:1	0.3375	0.711	0.785	28.3 / 49.4 / 194.2 min
Archimedes Continuation Winner (full-chain search, fine-verified)	-2.0 deg / +22.7 deg	1:1 / 6:1	0.3504	0.714	0.774	28.8 / 50.6 / 208.7 min

Four-item verification

3-Grid Convergence (Celik 2008)

1.7% GCI

Three systematically refined unstructured hex-dominant meshes per medium (g3 = 0.36M, g2 = 0.72M production fine, g1 = 1.5M cells) give Gen 1255's motor-chain verification score as 0.4473 / 0.4446 / 0.4425 (GCI_fine = 1.7%, +/- 0.0073). This is not the full battery-to-wake chain score.
The lead of Gen 1255 over the next topological family (Toroidal Loop g48 at 0.3769 +/- 0.0307) is 0.0656, which is 2.1x the combined discretization uncertainty (0.0316). Hover figure of merit converges to 0.8% GCI, and enlarging the computational domain by +50% in every direction shifts thrust, torque, and efficiencies by less than 0.7%.



Motor-chain verification score · cell count per medium

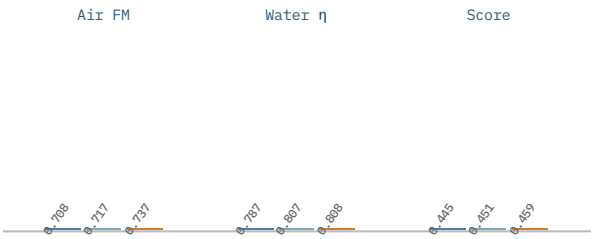
UIUC Wind-Tunnel Validation (Re ~ 25k)

4.5% RMS thrust

At underwater cruise (150 RPM), the blade chord Reynolds number is Re_0.7R ~ 22k-28k, where laminar separation bubbles can form. We validated a wall-resolved gamma-Re_theta transition model (y+ < 1) against UIUC wind-tunnel data (Deters, Ananda & Selig 2014) on DA4002 propellers at matched Re ~ 25k.
Across the advance-ratio sweep, the transition model predicts thrust within 4.5% RMS and efficiency within 5.5 points. Re-solving Archimedes' Gen 1255 blade with the wall-resolved transition model raises the motor-chain verification score from 0.4446 to 0.4593 (water blade efficiency 0.785 -> 0.824). These values are verification-chain metrics, not full-chain scores.

Low-Reynolds-number model sensitivity

Gen 1255 verification chain



WF / laminar / γ-Reθ transition, reconstructed from the recorded transition.json values.

3D Nonlinear FEA & Aeroelastic Sizing

SF >= 1.85 · 0.4 deg twist

Because thin outboard hydrofoils can twist under hydrodynamic load or fatigue in wet nylon, we ran 3D nonlinear CalculiX finite-element analysis using conditioned (wet) PA6-GF30 properties (E = 4.2 GPa, 10^7-cycle Goodman fatigue limit 22 MPa) and re-solved the elastically deformed shapes in CFD.
Sizing the inboard thickness schedule gives 0.4 deg of elastic twist at hover, a minimum Goodman fatigue safety factor of 1.85 across all four operating points, and first natural frequencies well clear of 1P and 2P excitation. The structurally sized blade scores 0.4363 on the fine mesh (+9.9% ahead of the best tuned standard propeller on the same chain).

0.4° elastic twist	**≥ 1.85** Goodman fatigue SF	**0.4363** sized-blade fine score

Two-Phase VOF Water-Surface Crossing

>= 4x thrust margin

Using two-phase volume-of-fluid CFD (OpenFOAM interFoam) and a time-domain vertical exit trajectory integrator from depth z = -0.5 m to +0.5 m, we tested both static submergence sensitivity and dynamic water-to-air transition.
Submerged thrust and torque remain within 1% of deep-water values until the free surface comes within 0.25 D of the rotor plane. During breach at hover RPM, the air pitch setting delivers 0.82-1.06x its in-air thrust across the interface, and vertical exit succeeds at every ascent speed from 0.5 to 2.5 m/s with a gear/pitch shift up to 0.2 s at >= 4x thrust margin.

0.5–2.5 m/s successful ascent range	**≤ 0.2 s** gear/pitch shift	**≥ 4×** thrust margin

Appendices A-E

Nothing is collapsed. The recorded campaign material is exposed as raw content.

Appendix A: Brief, operating points, and score

The frozen problem statement and objective basis

Design a single propeller rotor (D <= 254 mm) and variable-pitch / two-speed drivetrain for a 2.0 kg aerial-aquatic quadrotor on a T-Motor AIR2216 II (KV920, 4S). Must hover in air at 4.90 N per rotor, pull 2g air climb at 9.81 N (tip Mach <= 0.6), cruise underwater at 1.0 m/s (1.50 N), and dash at 1.5 m/s (3.37 N, cavitation margin >= 1.2 at 0.5 m depth, PA-GF30 root stress <= 40 MPa). Maximize the geometric mean of air and underwater wire-to-wake efficiency.

Air hover: 4.90 N per rotor.
Air climb: 9.81 N per rotor, tip Mach at or below 0.6.
Water cruise: 1.50 N at 1.0 m/s.
Water dash: 3.37 N at 1.5 m/s with cavitation margin at least 1.2.
Objective: geometric mean of air and water wire-to-wake efficiency on the full drive chain.

Score labels are intentionally distinct: Gen 1255 is 0.3375 on the campaign full chain; the continuation winner is 0.3504. The 0.4446 value used in the grid and transition studies is a motor-chain verification score and is not interchangeable with either full-chain result.

Appendix B: Decision log

Observation, deduction, change, and measured result

Hour 00:00 - 01:40 **Discovering why shaft-power optimization fails in water**	**Observation:** Archimedes first evolved 1,197 conventional blades using blade-element momentum theory (BEMT) scored on shaft efficiency (reaching 0.512). When it audited its own winner against the full T-Motor AIR2216 II electrical model, the combined score collapsed to 0.1569.	**Deduction:** Why did a hydrodynamically 'efficient' blade fail on the real drone? At 1:1 direct drive in 830x denser water, hydrodynamic torque forced the rotor down to 373 RPM (below the motor's 500 RPM floor, 15.2% motor efficiency, 38.7 W burned as I^2R winding heat), while the blade sections operated at cl = 0.10 (L/D = 5).	**Change and result:** Reformulated the entire optimization around wire-to-water electrical power, introduced a 2-speed gearbox (1-6:1) and 90 deg variable-pitch hub travel, and switched the evaluator to 3D OpenFOAM MRF RANS in both media.
Hour 01:40 - 02:15 **Seeding six competing geometries from aerospace & marine literature**	**Observation:** A single parametric blade template cannot simultaneously explore closed MIT toroidal loops, shrouded Kort nozzles, CLT tip barriers, and swept scimitars without collapsing onto the easiest local optimum.	**Deduction:** To prevent premature convergence, Archimedes authored six distinct geometric seed programs grounded in published literature and isolated them on six evolutionary islands for the first 200 generations (~3 hours).	**Change and result:** Calibrated all 6 seeds in 3D RANS: Rectangular Paddle (s4, 0.3876), CLT End-Plate (s6, 0.3397), Scimitar Marine (s3, 0.3389), Toroidal Loop (s2, 0.3276), Conventional BEMT (s1, 0.2948), and Ducted Kort Nozzle (s5, 0.1953).
Hour 02:15 - 04:50 **Immediate 6:1 water gear saturation & two-medium twist synthesis**	**Observation:** In Gen 1-18, CFD feedback showed water was the limiting term (0.25 vs 0.46 in air), and shrinking rotor diameter below 254 mm penalized hover figure of merit (which scales with disk area).	**Deduction:** At Gen 9, an agent replaced hard-coded station arrays with an explicit two-medium twist synthesis model: setting blade twist beta(r) as a weighted blend of hover induced inflow arctan(v_i / omega*r) and water advance ratio arctan(J / pi*r) minus the collective hub offset.	**Change and result:** Water gear locked at 6.0:1, diameter expanded to the full 254 mm limit, and water hub pitch climbed from +14 deg to +25.6 deg on the untapered Rectangular Paddle line (Gen 264, coarse score 0.4353).
Hour 05:25 **Grafting a 22 deg aft scimitar sweep onto the Rectangular Paddle leader**	**Observation:** Once cross-island migration opened after Gen 200, an agent on Island 1 inspected the Gen 264 Rectangular Paddle leader from Island 2. While its wide outboard chord (c/R = 0.16) kept water Reynolds number high, its straight squared tip shed a strong tip vortex under water loading.	**Deduction:** Drawing on Boswell (1971) marine skew theory, sweeping the outer blade path aft (progressive skew outboard of 0.35R) aligns the tip leading edge obliquely to the local inflow, unloading tip-vortex losses and widening the cavitation bucket without sacrificing disk area.	**Change and result:** Synthesized Gen 286 by grafting a 22 deg aft scimitar sweep law onto the Paddle planform, jumping the score to 0.4381 and spawning the scimitar lineage that overtook all six islands (399 of 1,251 valid designs).
Hour 09:40 - 13:50 **28 deg sweep, 3.7% thin outboard hydrofoils & advance-ratio re-trim**	**Observation:** By Gen 914 (score 0.4577), tip skew opened to 28 deg on Island 5. Inspecting the Gen 1183/1230 CFD trims, the agent noticed the trimmed water advance ratio had drifted to J = 1.643, slightly unloading the outer sections.	**Deduction:** Thinning the 0.65-0.75R hydrofoil sections to t/c = 3.7-4.1% (just above the 0.92 mm structural thickness floor) cuts profile drag at Re ~ 25k, while a -0.15 deg water-hub re-trim pulls the trimmed J back to 1.600 - placing the 0.75R section dead-center on cl = 0.57, L/D = 19.	**Change and result:** Gen 1255 reached 0.4637 coarse / 0.4448 fine motor-chain (0.3375 full battery-to-water chain, and 0.3504 in the full-chain continuation run), cutting underwater electrical power to 3.91 W vs 47.49 W for the stock APC.
Hour 14:00 - 20:00 **Proving 91% / 89% of single-medium perfection & structural/VOF sign-off**	**Observation:** How much performance did Gen 1255 sacrifice by operating in both air and water? And would a 3.7%-thick blade twist or fatigue in wet nylon or fail when breaching the water surface?	**Deduction:** Archimedes launched five dedicated follow-up campaigns (air-only, water-only, toroidal-only, ducted-only, and full-chain continuation) plus four independent physics verification suites.	**Change and result:** Proved one blade reaches 91% of the air-only optimum and 89% of the water-only optimum; confirmed 1.7% GCI across 3 grids (up to 1.5M cells), 4.5% RMS thrust match vs UIUC low-Re wind-tunnel data, 0.4 deg hover twist & SF >= 1.85 in 3D nonlinear CalculiX FEA, and >= 4x thrust margin across two-phase VOF water exit.

Appendix C: Population and families

Search breadth and topology coverage

1,267 3D RANS evaluations across 6 topological families, run on 12 cloud machines.

Scimitar / skewed - Gen 1255 campaign geometry, 0.3375 full-chain

Conventional tapered - Gen 867, 0.3350 full-chain

Contracted-and-loaded tip - Gen 238, 0.3191 full-chain

Toroidal closed loop - Gen 48, 0.3008 full-chain
Rectangular paddle - Gen 264, 0.2768 full-chain
Ducted Kort nozzle - Gen 30, 0.2542 full-chain

Appendix D: Solver and uncertainty

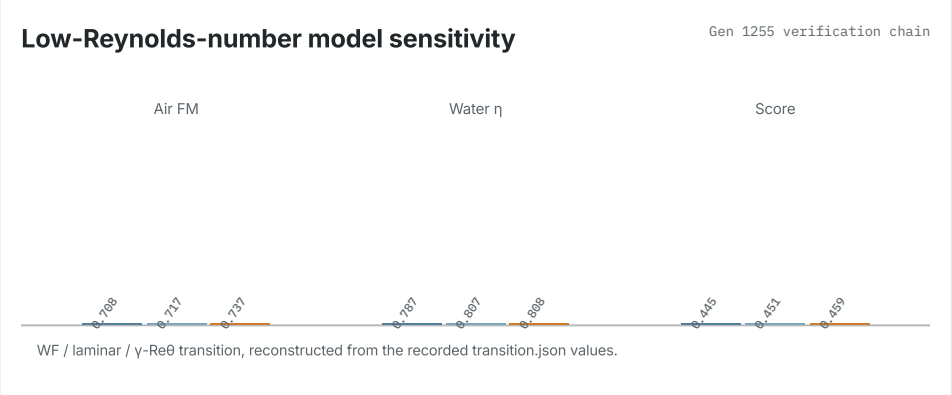
Numerical basis and independent checks

Fine-mesh 3D RANS CFD (OpenFOAM MRF, k-omega SST) + full battery-to-wake drive chain

Three-grid convergence study (0.36M to 1.5M cells per medium): score converged to 1.7% GCI; lead over the next topological family is 2.1x the combined discretization uncertainty.
Matched-Re wind-tunnel validation against UIUC data at Re ~ 25k: wall-resolved gamma-Re_theta transition CFD predicts thrust within 4.5% RMS and raises Gen 1255's score from 0.4446 to 0.4593.
3D nonlinear CalculiX FEA with wet PA6-GF30 fatigue data: 0.4 deg hover elastic twist, Goodman fatigue safety factor >= 1.85, retaining a +9.9% lead over tuned APC 10x7.
Two-phase VOF water-surface breach: vertical exit succeeds across 0.5 to 2.5 m/s ascent speeds with a <= 0.2 s gear shift at >= 4x thrust margin.

Explicit limitations

The score and family ranking converge faster than absolute loads; the recorded fine-grid water-thrust GCI is 65%.
The search tier is about 10-15% optimistic in water. Reported finalist comparisons use the fine-mesh rescoring.
No structurally sized blade has yet been built and tested as a complete aerial-aquatic vehicle.



Full-chain underwater power accounting

Configuration	Useful	Propeller loss	Hub / bearing	Gear	Motor	ESC	Battery total
Stock APC 10x4.7 on Direct Drive (Fixed 0 deg Hub)	1.497 W	5.731 W	0.001 W	0.000 W	40.272 W	8.379 W	55.879 W
+ Two-Speed Gearbox (1:1 Air / 6:1 Water)	1.497 W	5.731 W	0.001 W	0.822 W	3.889 W	1.416 W	13.356 W
+ Variable-Pitch Hub (+4.5 deg Air / +22.5 deg Water)	1.497 W	0.674 W	0.139 W	0.254 W	2.054 W	1.927 W	6.545 W
+ Archimedes Gen 1255 Campaign Blade	1.497 W	0.410 W	0.122 W	0.223 W	1.892 W	1.941 W	6.086 W

Appendix E: References

Source identifiers already present in the campaign record

Boswell (1971) - highly skewed marine-propeller series.
Celik et al. (2008) - grid-convergence method.
Brandt and Selig (2011) - UIUC APC hover measurement identifier.
Deters, Ananda, and Selig (2014) - UIUC low-Re DA4002 validation data.
Gomez and Gonzalez-Adalid - contracted-and-loaded-tip marine propeller reference.

Sebastian and Strem, MIT Lincoln Laboratory US 10,836,466 - joined-tip toroidal rotor reference.
Kort Nozzle 19A / Ka-series and Pereira and Chopra (2008) - ducted-rotor reference.
Wageningen B4-55 - marine benchmark series used in the comparison.
OpenFOAM MRF RANS, CalculiX FEA, and interFoam VOF - solver identifiers used by the verification record.