Genetic Algorithm Optimization of Bézier-Profiled Compliant Wheel for the SWIFT-UAV

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ARTS-Lab
Adaptive Real-Time Systems Laboratory

Motivation & Design Problem

Why a Compliant PLA Wheel?
Traditional UAV landing gear wheels rely on pneumatic tires with shock-absorbing struts, adding part count, weight, and costs. A compliant wheel integrates the spring function directly into the spoke geometry. This allows for a single-piece, FDM-printable PLA part that is extremely cost-effective.

Design Requirements
- 15lbf (66.7N) of force per wheel at UAV landing
- Target Spoke Deflection: 1.0 mm per spoke under load
- Material: PLA (E = 2300 MPa, Tensile Strength = 50 MPA), safety factor of 1.6 with 31.25 MPa of allowable stress
- 25.4 mm hub diameter, 97.8 mm rim diameter, 12-spoke layout, fixed 22.4mm axial depth
- Entirely FDM printed from PLA basic, little mass as possible

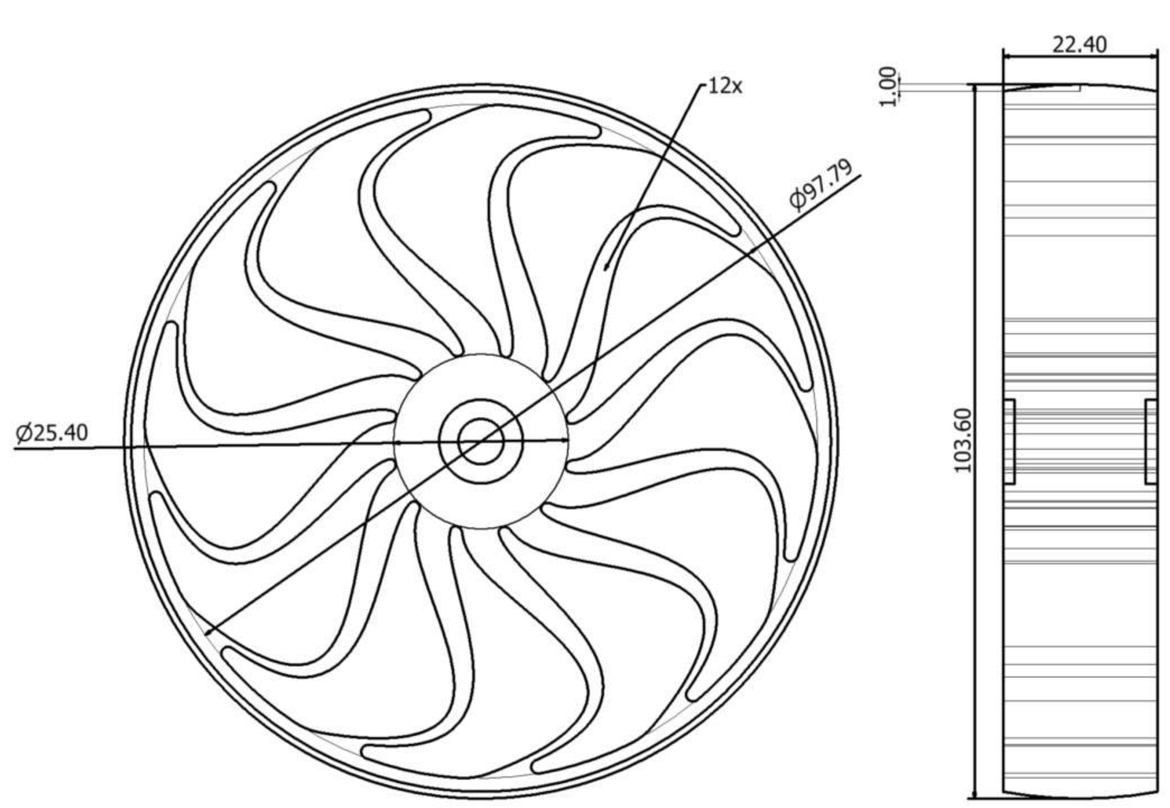


Figure 1. *Front and side view of optimized wheel showing hub, rim, transverse crown, height, and spoke count dimensions.*

Methodology

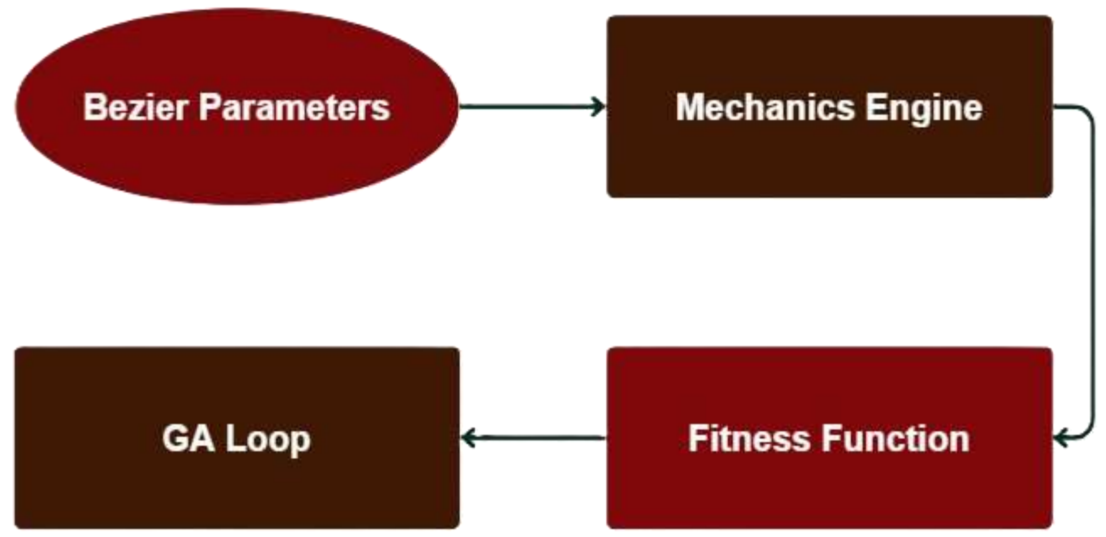


Figure 2. *Methodology flow chart of whole algorithm*

Parametric Spoke Geometry
The spoke centerline is a a cubic Bézier curve with endpoints fixed at the hub (**P_0**) and rim (**P_3**), and shaped by two control points (**P_1** and **P_2**). Spoke thickness tapers linearly from a thicker root (**t_root**) to a thinner tip (**t_tip**) connecting to the rim. Axial depth is fixed at 22.4 mm.

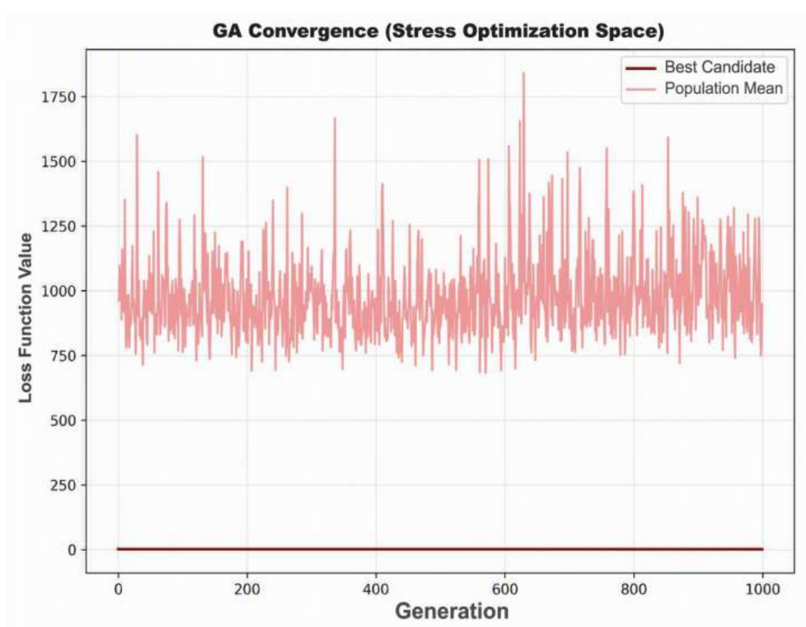
Structural Mechanics Model
The spoke is discretized along the Bézier centerline. Castigliano's method shows the total deflection from bending and axial strain energy. Then the combined stress (axial + peak bending) at each point is checked against a given allowable stress.

Genetic Algorithm Optimization
PyGAD then evolves 160 candidates over 1000 generations with 6 parameters (**x1, y1, x2, y2, t_root, t_tip**). The fitness function rewards the 1 mm deflection target, minimizes mass, and penalizes any stress violation to converge on the lightest valid spoke.

Results

The genetic algorithm optimized the spoke shape and thickness to meet a 1.0 mm deflection target while minimizing mass and stress.

Figure 3. *The best candidate's loss (dark red) stabilizes immediately, while the population mean (light red) stays elevated from mutation penalizations.*



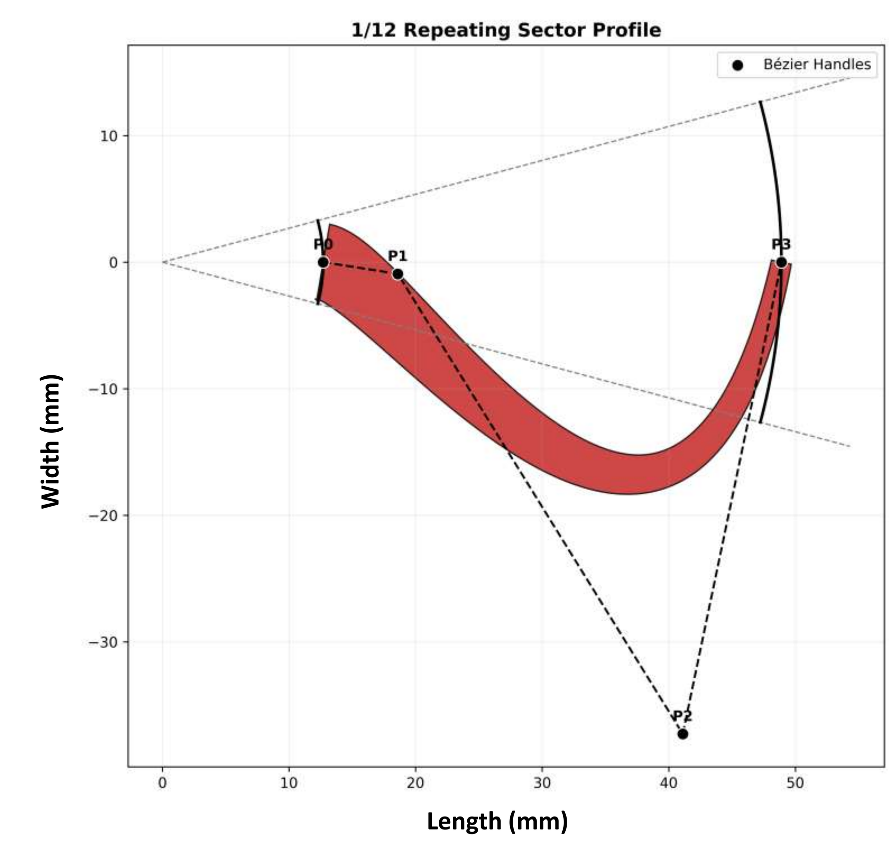
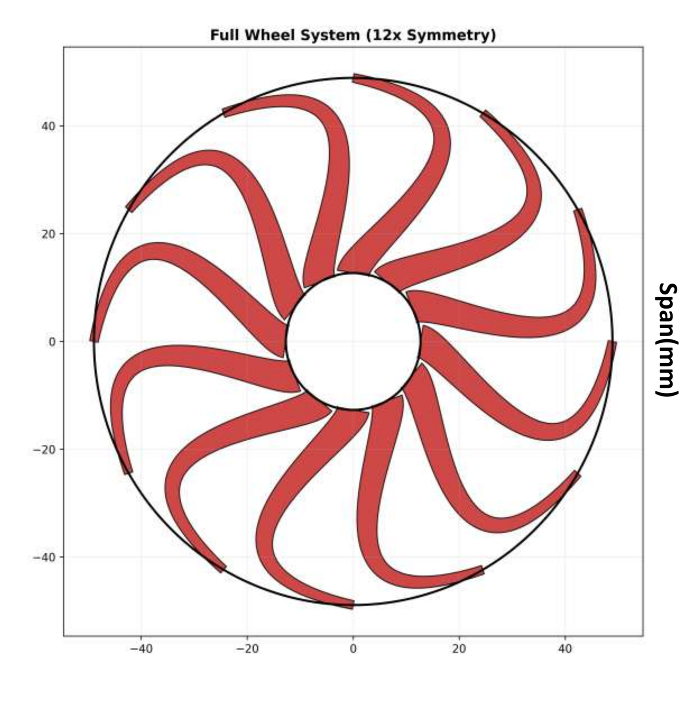


Figure 4. *Optimized 1/12 spoke sector with Bezier control points of P0 to P3. P0 is fixed at the hib and P3 at the rim: P_1 = (5.90, -0.93) mm and P_2 = (28.41, -37.28) mm, being the parameters evolved by the GA. The thickness tapers linearly from 6.07 mm at the root to 1.60 mm at the tip.*

Figure 5. *Complete wheel formed by replicating the optimized spoke with 12-fold cyclic symmetry about the hub*



The converged decision achieves the spoke deflection of 1.00 mm, a max combined stress of 10.76 MPa of an allowable 31.25 MPa, and a total wheel mass of 66.87 g.

Final Design & Conclusions

Final Design Metrics
- **Spoke deflection: 1.00 mm (target: 1.0mm)**
- **Max combined stress: 10.76 MPa (allowable: 31.25 MPa)**
- **Total wheel mass: 66.87 g**
- **Root / Tip Thickness: 6.07 mm / 1.60 mm (linearly tapers)**

Discussion & Conclusions
Though the GA converges on a mathematically correct spoke, it is not perfect in actuality, but perfect under its parameters. Furthermore, because of a lack of a direct pipeline into CAD software, the centerline Bézier curve was imported manually. The mechanical model does not penalize impossible shapes, leading to manually made fillets and geometrically feasible dimensions such as a reduced root thickness of 5.5 mm.

Future Work
Extending the structural mechanics model to include fillets. Extending the genetic algorithm to have more genes including the number of spokes and more taper points than just a linear thinning. Utilizing a servohydraulic testing machine along with a fatigue test rig to get real-life stress results that are more accurate than finite element analyses, especially with anisotropic materials like 3D-printed PLA.

Reference
Scientific Workhorse for In-flight Field Tests – UAV (SWIFT-UAV) https://github.com/ARTS-Laboratory/SWIFT-UAV

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