



Active Variable Incidence Wing System (AVIWS)

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Introduction

Aerodynamic downforce and drag management are among the most impactful performance variables in automotive engineering. While fixed aerodynamic appendages such as static rear wings and diffusers have become common in both motorsport and street performance applications, they represent a fundamental engineering compromise: a wing optimized for high-downforce cornering will induce excessive drag on straight-line acceleration, and a wing optimized for low-drag top speed provides inadequate downforce under braking or lateral loading. The Active Variable Incidence Wing System (AVIWS) was designed and built to address this compromise by dynamically adjusting the wing's angle of incidence in real time, based on the vehicle's instantaneous acceleration state.

The AVIWS project was motivated by a genuine interest in automotive engineering and performance dynamics. Inspired by two landmark engineering achievements, the Vought F-8 Crusader, the only production aircraft to implement a variable incidence wing system for carrier-based operations, and the Zenvo TSR-1 hypercar, which pioneered active lateral aero adjustment in a road-going vehicle. This project applies those same principles at an accessible scale using embedded systems and 3D-printed fabrication. The system was developed as a personal engineering project and tested on my personal car (2011 bmw e93), though the design intent was universal fitment across a range of vehicle platforms.

The AVIWS operates across three distinct aerodynamic modes driven entirely by accelerometer data from an onboard inertial measurement unit (IMU). Under deceleration, the wing pitches to a high angle of attack to act as an airbrake, generating maximum drag and downforce to supplement braking. Under acceleration, the wing flattens to minimize drag and allow the

drivetrain to perform efficiently. At steady cruise, the wing holds a neutral low-angle position to provide baseline downforce with minimal aerodynamic penalty. This behavior draws direct parallels to the Drag Reduction System (DRS) used in Formula 1 competition. In F1, DRS flattens the rear wing on designated straights to reduce drag and improve overtaking speed, the AVIWS applies the same principle, flattening the wing under acceleration to shed drag and maximize straight-line performance. Where the systems diverge is in the addition of a dedicated braking mode: rather than simply toggling between open and closed like F1 DRS, the AVIWS introduces a third high-angle airbrake position under hard deceleration, deploying the wing as an active braking aid. At constant cruise speed the wing holds a low neutral angle, mirroring the closed DRS position, providing baseline downforce for stability (Anderson, 2010).

A secondary inspiration for this project was the potential for future lateral aero control, analogous to the Zenov TSR-1's active wing that adjusts laterally during cornering to generate yaw-stabilizing aerodynamic moments. While lateral control is outside the scope of this initial build, the system architecture was designed with that future capability in mind.



Figure 1. Vought F-8 Crusader variable incidence wing system, the sole production aircraft application of this concept.



Figure 2. Zenvo TSR-1 active rear wing in lateral displacement mode.

Design Goals

Prior to fabrication, a clear set of engineering requirements was established to guide the design process and provide a measurable standard against which the final system could be evaluated.

These requirements were derived from the intended use case: a street performance vehicle operating across a range of speeds and driving conditions, as well as the practical constraints of a solo, single-week build.

Functional Requirements

- The system shall adjust wing angle of incidence dynamically and autonomously based on the vehicle's longitudinal acceleration vector, with no driver input required during operation.
- The system shall operate in three distinct modes: high drag/downforce (deceleration), low drag/flat (constant velocity), and neutral cruise angle (acceleration).

- The wing shall transition between positions with sufficient speed to be aerodynamically meaningful: target actuation time under 500ms for full range of motion.
- The system shall be entirely self-contained on the wing assembly, requiring no external electrical connection to the vehicle's wiring harness or OBD-II network.
- The design shall be mechanically compatible with a range of vehicle platforms, not exclusively the development vehicle (BMW E93).
- The wing shall maintain its commanded position under aerodynamic load without back-driving the actuator.

Design Constraints

- Total system mass shall be minimized to avoid negatively impacting vehicle dynamics through unsprung or high-mounted weight.
- All electronics shall be housed in a weatherproof or weather-resistant enclosure integrated into the wing structure.
- The system shall operate from an onboard power source capable of sustained operation without external charging mid-drive.
- All structural components shall be fabricated using accessible methods: FDM 3D printing and standard hardware, to support rapid iteration and repairability.
- The design shall leave architectural headroom for a future lateral actuation axis, consistent with the long-term vision of a multi-axis active aero system.

Performance Targets

- Acceleration threshold for wing flatten: longitudinal acceleration $> +0.2g$
- Deceleration threshold for airbrake deployment: longitudinal deceleration $> -0.2g$

- Cruise neutral band: $|\text{acceleration}| < 0.2g$
- Target servo actuation range: -5° (neutral) to 40° (airbrake) angle of incidence
- Onboard power autonomy: minimum 30 minutes continuous operation

Component Selection

The component selection process for the AVIWS was driven by three core priorities: reliability under sustained aerodynamic load, minimal system weight, and the practical constraints of a solo build with a compressed timeline. Every selection was made with a deliberate engineering rationale rather than defaulting to the most commonly available part.

Microcontroller: Arduino Nano

The Arduino Nano was selected as the primary microcontroller for this application. The Nano provides 14 digital I/O pins, six of which are PWM-capable, hardware I2C support on pins A4 and A5, and operates at 5V logic, directly compatible with both the IMU module and servo signal line without requiring level shifting (Atmel Corporation, 2015). While more capable alternatives such as the ESP32 offer dual-core processing, onboard WiFi, and significantly greater RAM, these capabilities introduce unnecessary complexity for a single-axis control loop with two inputs and one actuator output. Embedded systems design literature consistently emphasizes that system reliability scales inversely with component count and firmware complexity, a principle that guided this selection (Barr & Massa, 2006). Future iterations of the AVIWS incorporating multi-axis lateral control or real-time telemetry logging would justify migration to a more capable platform, but for the initial build the Nano's simplicity is a feature rather than a limitation.

Inertial Measurement Unit: GY-521 (MPU-6050)

The GY-521 breakout board, built around the InvenSense MPU-6050, was selected as the primary sensing element. The MPU-6050 integrates a 3-axis MEMS accelerometer and 3-axis MEMS gyroscope in a single package, communicating over I2C at up to 400kHz fast mode (InvenSense, 2013). For the AVIWS control loop, only the longitudinal accelerometer axis is required for mode switching between neutral, cruise, and airbrake states, though the full 6-DOF dataset is preserved in the architecture for future lateral aero expansion. The GY-521 breakout was preferred over the bare IC due to its onboard 3.3V LDO regulator, populated I2C pull-up resistors, and decoupling capacitors, eliminating several discrete passive components from the circuit entirely.

Raw accelerometer output from MEMS devices is inherently susceptible to high-frequency vibration noise, which in a vehicle-mounted application is compounded by engine vibration, road surface inputs, and aerodynamic buffeting of the wing structure itself. A digital low-pass filter or moving average applied in firmware is therefore necessary before the acceleration signal is used for threshold comparison (Madgwick, Harrison, & Vaidyanathan, 2011). Rodger et al. (2019) demonstrated that unfiltered IMU data in vehicle dynamics applications produces threshold crossing errors of up to 40% compared to filtered signals under real road conditions, underscoring the importance of signal conditioning even for a relatively simple bang-bang control system like the AVIWS.

Servo Actuator: DS3218

The DS3218 was selected as the primary actuator for wing angle adjustment, rated at 20 kg·cm stall torque at 6V with full metal gears and a 270° range of motion. Metal gears were treated as a

hard requirement given the sustained aerodynamic hinge moment the servo must resist at speed. The aerodynamic moment acting on a control surface about its hinge axis is a function of the surface's area, chord length, center of pressure offset from the hinge, and dynamic pressure, the latter scaling with the square of velocity (Etkin & Reid, 1996). At highway speeds, even a modest wing element generates sufficient hinge moment to back-drive or strip the plastic gears of lower-tier servos such as the SG90, which is rated at only 1.8 kg·cm. The DS3218 provides a favorable torque margin relative to the estimated hinge moment at the design operating speed, with metal gears offering both the load capacity and the fatigue life necessary for repeated actuation cycles.

The servo is powered directly from the regulated 5V output of the buck converter rather than through the Arduino Nano's onboard 5V pin. The Nano's internal regulator is sourced from the same linear pass element as the board's own logic supply and is not rated for the current demands of a loaded servo, which can draw in excess of 1A during actuation (Parallax Inc., 2012).

Bypassing the Nano's regulator and feeding the servo directly from the buck output eliminates this as a failure mode.

Power System: LM2596 Buck Converter

The power architecture is centered on an LM2596-based adjustable step-down converter module with an integrated LED voltage display, accepting input voltages from 4V to 40V and regulated to a 5V output for this application. The input source is a 12V portable jump-start pack, selected for its high capacity relative to its size, low internal resistance, and ability to sustain stable output voltage under the transient current demands of servo actuation, a characteristic that alkaline

battery alternatives demonstrably fail to meet due to their high internal resistance causing significant voltage sag under load (Linden & Reddy, 2011).

The LM2596 switching regulator was selected over a linear alternative such as the LM7805 on efficiency grounds. At 12V input and 5V output, a linear regulator dissipates the full 7V differential as heat across the pass transistor: at a 500mA load this represents 3.5W of thermal dissipation in a sealed enclosure, which is thermally unacceptable without active cooling. The LM2596 achieves 77–92% conversion efficiency across its operating range, reducing thermal dissipation to a manageable level (Texas Instruments, 2023). The integrated voltage display on the selected module allows direct output verification during setup without external instrumentation, which proved useful during bench calibration.

Passive Components

Two capacitors were incorporated into the power distribution network. A 100 μ F electrolytic capacitor was placed at the buck converter output to provide bulk energy storage, absorbing instantaneous current surges during servo actuation and preventing voltage droop on the 5V rail that would cause the microcontroller to reset. A 100nF ceramic capacitor was placed directly across the Nano's VIN and GND pins to suppress high-frequency switching noise generated by the servo motor's PWM commutation. The ceramic capacitor's characteristically low equivalent series resistance (ESR) enables it to respond to high-frequency transients on the order of megahertz that the electrolytic capacitor (with its comparatively high ESR), cannot attenuate effectively (Horowitz & Hill, 2015). The GY-521 module incorporates its own onboard decoupling network, making additional filtering at the IMU unnecessary.

Mechanical Design

The mechanical design of the AVIWS wing element was developed entirely in CAD prior to fabrication, with every geometric decision driven by aerodynamic function, manufacturability, and the constraints of a solo build using accessible fabrication methods. The wing assembly consists of three primary components: the main wing element, the endplates, and the printed tooling used to transfer the CAD geometry into the XPS foam fabrication process.

3.1 Airfoil Profile Selection

The airfoil cross section was the first design decision made, as it dictates the fundamental aerodynamic behavior of the entire wing. The initial profile was derived from a standard cambered airfoil geometry, selected for its ability to generate a favorable pressure differential when mounted in an inverted orientation, high pressure on the upper surface and low pressure on the lower surface which produces net downforce rather than lift (Abbott & Von Doenhoff, 1959).

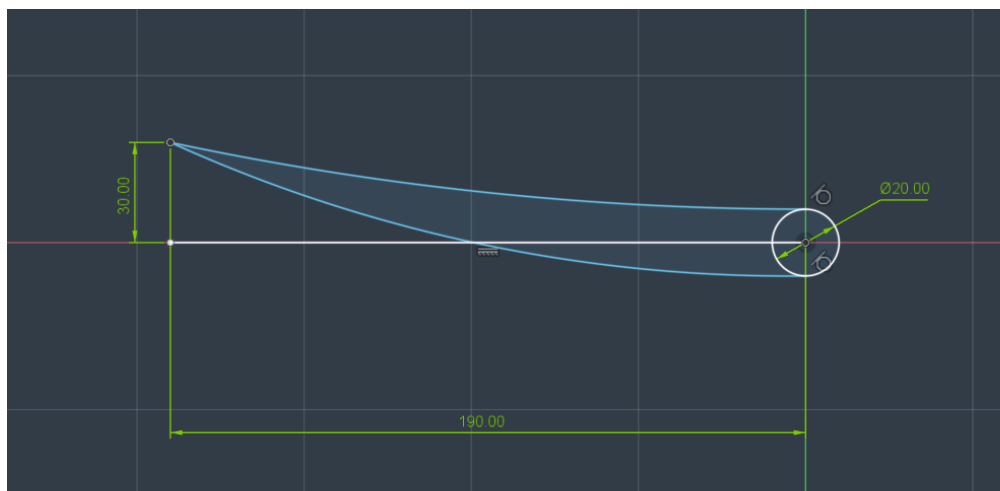


Figure 3.1. Initial airfoil cross section sketch, as modeled in CAD.

Following the initial cross section, the profile was modified to increase the pressure asymmetry between the upper and lower surfaces. The upper surface curvature was increased to accelerate airflow and reduce static pressure on top, while the lower surface was flattened slightly to maintain a higher pressure region beneath the wing. This modification increases the lift coefficient of the inverted profile, directly improving downforce generation at a given velocity and angle of incidence (Katz, 1995).

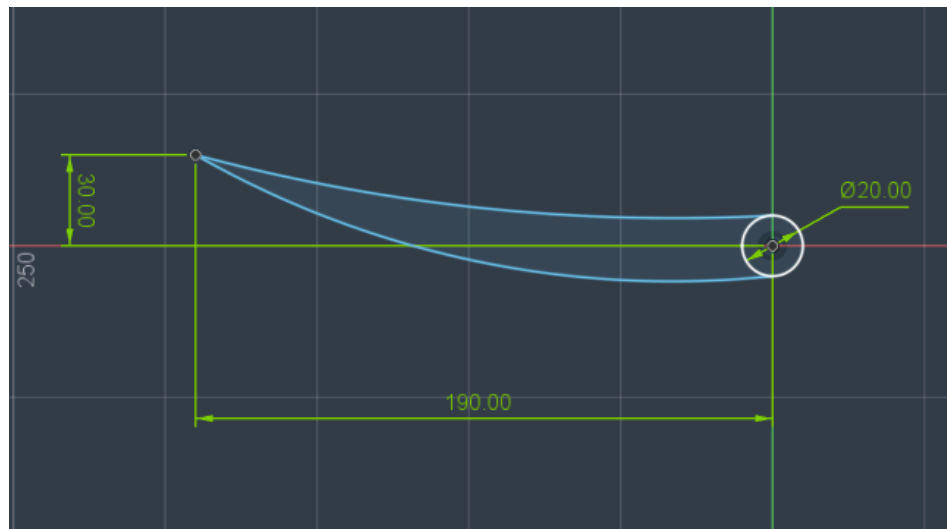


Figure 3.2. Modified airfoil cross section showing updated upper and lower surface curvature for increased downforce.

The decision to use a cambered rather than symmetric profile was deliberate. A symmetric profile such as the NACA 0012 generates zero lift or downforce at zero angle of attack, meaning all downforce in the AVIWS cruise mode would depend entirely on the servo-commanded pitch angle. A cambered inverted profile generates passive baseline downforce even at neutral incidence, providing inherent stability in the cruise mode without requiring the servo to hold a non-zero angle, reducing actuator load and power draw during the majority of driving time (Abbott & Von Doenhoff, 1959).

3.1.a Computational Fluid Dynamics Analysis

Prior to fabrication, the finalized airfoil geometry was subjected to computational fluid dynamics analysis using Autodesk Fusion CFD 2027 to validate the aerodynamic behavior of the wing across all three AVIWS operating modes. Three simulations were conducted, one for each wing angle of incidence corresponding to the neutral, cruise, and airbrake positions, at a freestream velocity of 30 mph (13.4 m/s), representing a conservative urban driving condition. All simulations used a steady-state incompressible flow formulation with the k-epsilon turbulence model, which is well established for external aerodynamic flows at the Reynolds numbers encountered in automotive applications (Versteeg & Malalasekera, 2007).

The fluid domain was configured as an external flow volume surrounding the wing geometry with air at standard conditions as the working fluid. The k-epsilon turbulence model was selected for its robustness and computational efficiency in attached and mildly separated external flow regimes, with automatic mesh enhancement applied at the wing surface boundary to resolve the near-wall flow accurately (Wilcox, 2006). Reynolds numbers for the three runs ranged from 772,398 at 5° to 1,153,020 at 40°, confirming fully turbulent flow conditions across all cases consistent with real driving conditions.

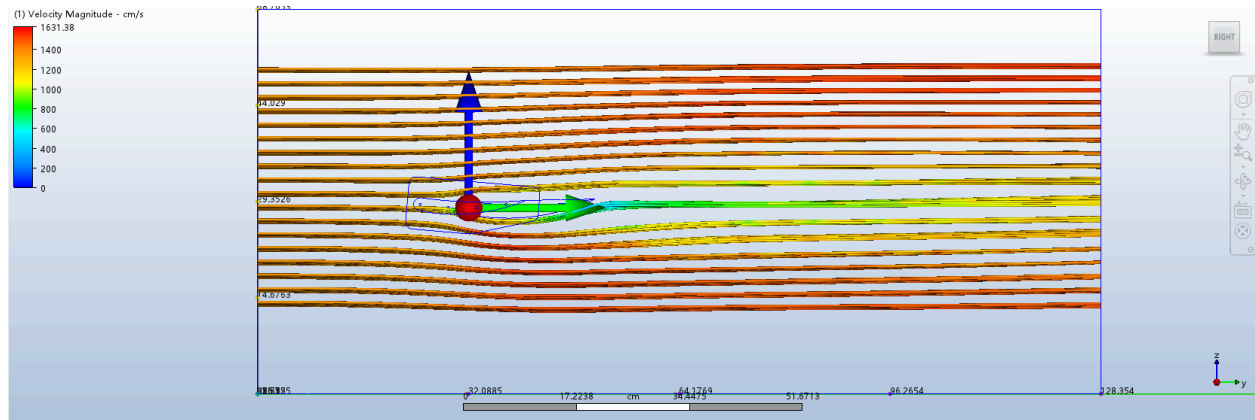


Figure 4.1. CFD pressure distribution plot, -5° neutral position.

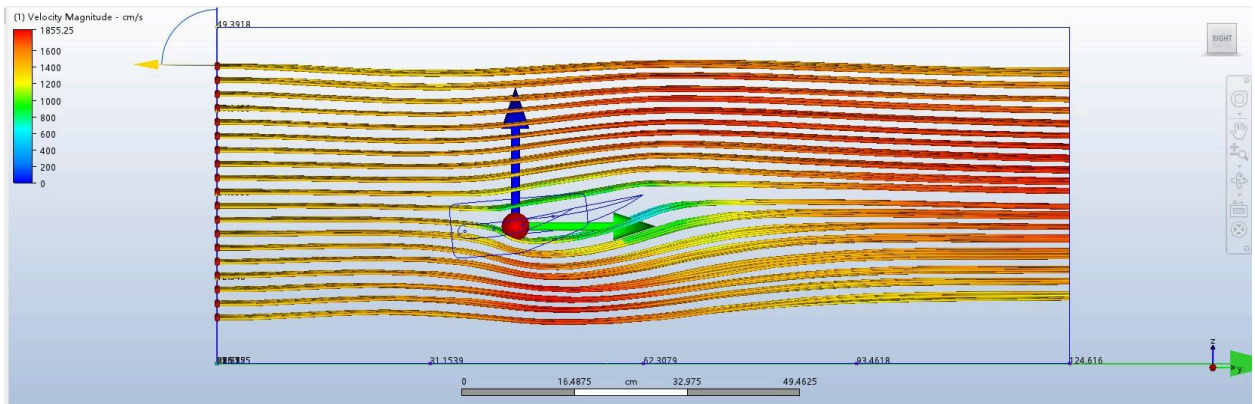


Figure 4.2. CFD pressure distribution plot, $+5^\circ$ cruise position.

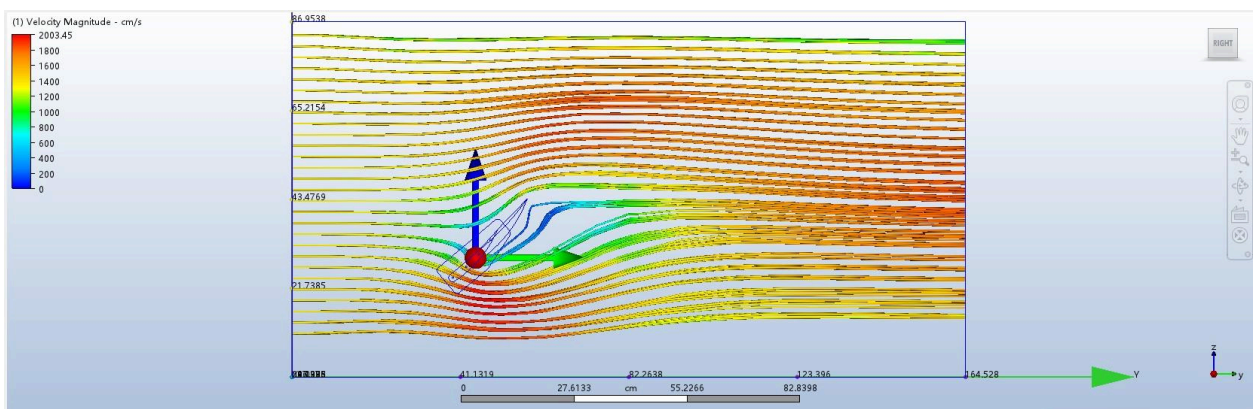


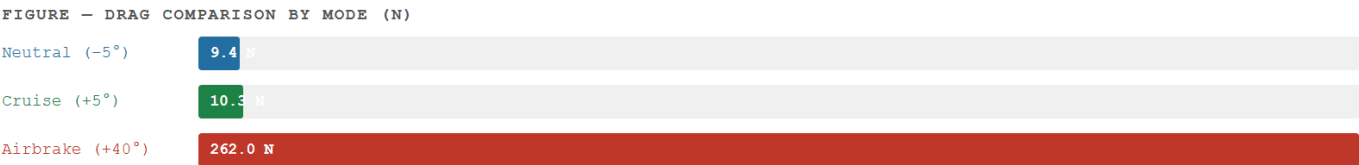
Figure 4.3. CFD pressure distribution plot, $+40^\circ$ airbrake position.

Results and Analysis

The simulation results confirmed the expected aerodynamic behavior across all three modes and validated the core design intent of the AVIWS. Full numerical results are presented in Table 1 below.

Table 1.

Wing Mode	Angle of Incidence	AVIWS State	Downforce (N)	Downforce (lbs)	Drag (N)	Drag (lbs)	D/D Ratio
Neutral	-5°	Acceleration > +0.09g	88.4	19.9	9.4	2.1	9.4 : 1
Cruise	+5°	accel < 0.07g	882.4	198.4	10.3	2.3	85.7 : 1
Airbrake	+40°	Deceleration > -0.07g	1,708.8	384.1	262.0	58.9	6.5 : 1



At the neutral position of -5° angle of incidence, the wing generated 88.4 N of downforce and 9.4 N of drag, yielding a downforce-to-drag ratio of 9.4:1. The reduced angle of incidence minimizes the wing's aerodynamic contribution during acceleration, consistent with the design goal of shedding drag to maximize drivetrain efficiency in the neutral mode.

At the cruise position of +5° angle of incidence, downforce increased substantially to 882.4 N, a 898% increase over the neutral position, while drag remained nearly unchanged at 10.3 N. The downforce-to-drag ratio of 85.7:1 at cruise represents the system's peak aerodynamic efficiency operating point, confirming that the cambered inverted airfoil profile generates significant

passive downforce at low angles of incidence with minimal drag penalty, consistent with classical low-angle attached-flow behavior (Abbott & Von Doenhoff, 1959).

The airbrake position at +40° angle of incidence produced the most dramatic results, generating 1,708.8 N of downforce and 262.0 N of drag, a 2,443% increase in drag over the cruise position. The substantial drag increase at 40° is attributable to flow separation off the upper surface at high angle of attack, transitioning the dominant force-generating mechanism from lift-based pressure differential to pressure drag from the separated wake, precisely the airbrake behavior the AVIWS was designed to exploit (Katz, 1995). The total aerodynamic force differential between the neutral and airbrake positions represents 1,620.4 N of additional downforce and 252.6 N of additional drag, confirming that the AVIWS actuation range produces a meaningful and measurable aerodynamic effect across its operating envelope.

Table 2.

Transition	Downforce change	Downforce % change	Drag change	Drag % change
Neutral → Cruise	+794.0 N	+898%	+0.9 N	+10%
Cruise → Airbrake	+826.4 N	+94%	+251.7 N	+2443%
Neutral → Airbrake	+1,620.4 N	+1833%	+252.6 N	+2687%

All simulations conducted at 30 mph (13.4 m/s) inlet velocity. Fluid: air at standard conditions ($\rho = 1.205 \text{ kg/m}^3$, $\mu = 1.817 \times 10^{-5} \text{ Pa}\cdot\text{s}$). Turbulence model: k-epsilon, steady state incompressible. Reynolds numbers: 772,398 (5°) · 1,153,020 (40°) · 841,675 (-5°). Force values extracted from Fluid Forces on Walls output (ShearY + PressY for downforce, |ShearX + PressX| for drag). D/D Ratio = Downforce to Drag ratio. Higher values indicate greater aerodynamic efficiency.

These results computationally validate the three-mode aerodynamic architecture of the AVIWS and confirm that the airfoil geometry, angle selections, and actuation range produce the intended force characteristics across all operating conditions.

3.2 Wing Element Geometry

The full wing element spans 1400mm tip to tip and is divided into three aerodynamic sections. The central section spans 900mm and serves as the primary downforce-generating surface, operating at a consistent cross section derived directly from the modified airfoil profile. The two outboard sections each span 250mm and feature a lofted transition geometry, the cross section at the inboard end matches the central element profile, while the outboard end transitions to a modified profile with increased angle, generating additional downforce toward the tips and improving spanwise load distribution (Hucho, 1998).

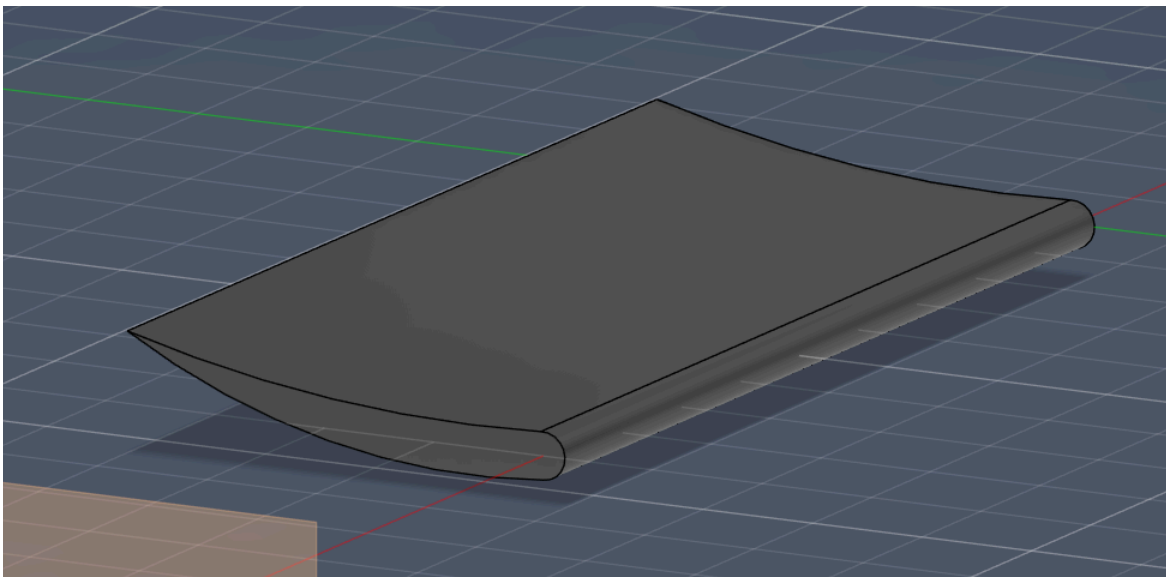


Figure 5. Central 900mm wing element, fully extruded in CAD.

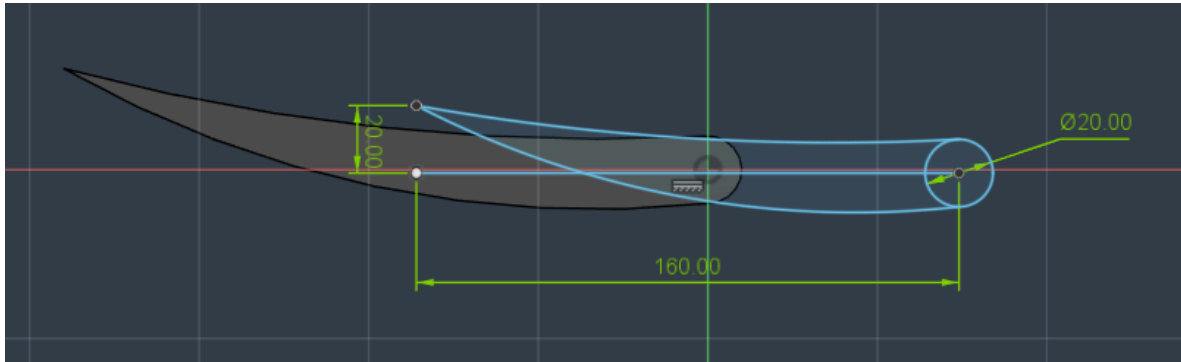


Figure 5.1. Outboard 250mm section cross section, showing lofted transition geometry.

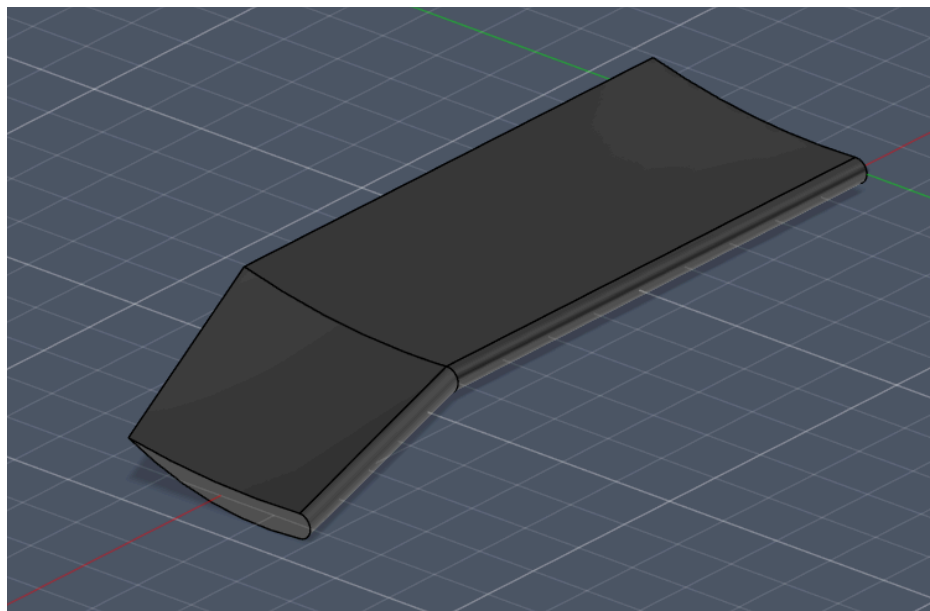


Figure 5.2. Outboard 250mm section cross section, extruded and attached to the main element.

The lofted outboard sections were generated by defining two sketch profiles at each end of the 250mm section and lofting between them in CAD, producing a smooth continuous surface transition. This approach avoids the aerodynamic discontinuity that would result from a hard geometric break between the central and outboard sections, which would produce spanwise flow separation and reduce overall wing efficiency (Katz, 1995).

3.3 Endplate Design

Endplates were designed and integrated at both wingtips. Aerodynamically, endplates function by impeding the spanwise migration of high-pressure air from the lower surface to the low-pressure upper surface around the wingtip — a phenomenon that produces induced drag and reduces the effective lift coefficient of the wing. Containing this flow with a vertical endplate reduces induced drag and improves the wing's aerodynamic efficiency, particularly at lower aspect ratios (Anderson, 2010).

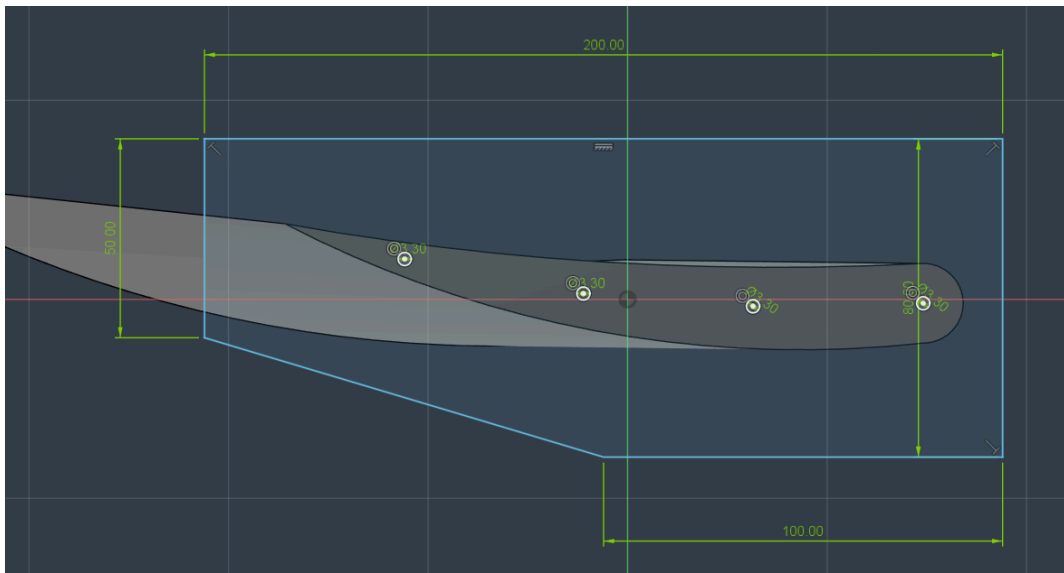


Figure 6.1. Endplate cross section sketch showing geometry and mounting hole layout.

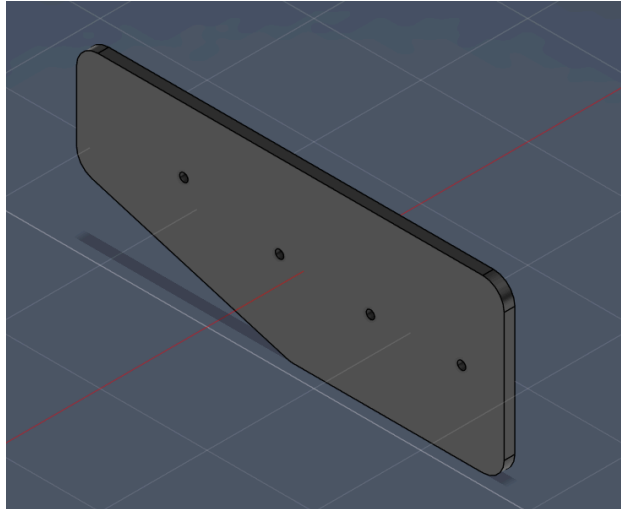


Figure 6.2. Endplate CAD

The endplates were also designed to serve as the primary structural mounting interface for the wing assembly. M3 heat set inserts were incorporated directly into the endplate geometry, with appropriately sized clearance holes on the mating face to allow M3 screws to pass through and thread into the inserts. This approach eliminates the need for nuts on the back face of the endplate and allows for clean, repeatable assembly and disassembly, a design priority given the iterative nature of the build and the likelihood of multiple assembly cycles during testing and tuning.

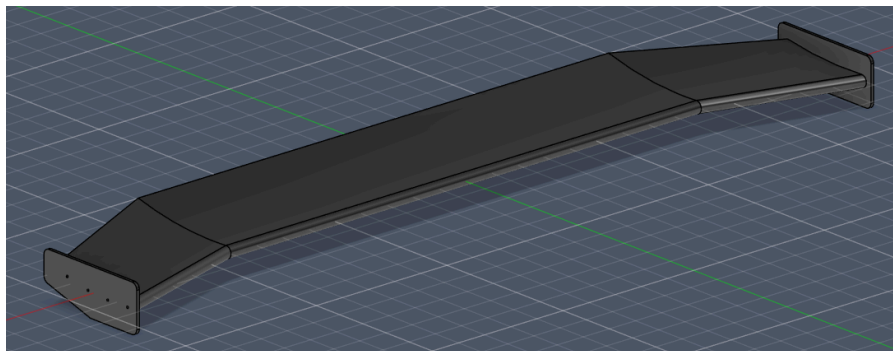


Figure 7. Finalized airfoil element assembly, complete with the endplates and the main airfoil.

3.4 Fabrication Strategy — XPS Foam and Printed Tooling

The wing element itself will be fabricated from extruded polystyrene foam (XPS), selected for its low density, ease of shaping, and compatibility with hot wire cutting and sanding processes. XPS foam offers a favorable stiffness-to-weight ratio for non-structural aerodynamic surfaces and is a well-established material in model aviation and automotive aero prototyping applications (Simons, 2002).

To transfer the CAD airfoil geometry accurately into the physical foam fabrication process, two categories of printed tooling were developed directly from the CAD model:

The first is a cross-sectional template, printed at approximately 10mm thickness, representing a true slice of the airfoil profile. This template will be used as a hot wire guide, pinned to both faces of the XPS foam block to constrain the wire path and ensure each foam slice matches the designed profile precisely.



Figure 8.1. 3d printed cross section, a template used to cut and outline xps foam

The second is a two-part female mold, printed to capture the upper and lower surface curvatures of the airfoil. Following the hot wire cutting and stacking process, the foam surface will require sanding and fairing to remove any irregularities between slices. The female mold provides a

reference surface to check the faired foam against, ensuring the final profile matches the designed geometry before the fiberglass and epoxy laminate is applied.



Figure 8.2. 3d printed cross section, upper and lower template used to match curvature.

Once the foam core is shaped and verified against the mold, the wing surface will be laminated with one to two layers of 4oz fiberglass cloth wetted out with marine-grade epoxy resin. This laminate provides the structural shell necessary to resist aerodynamic pressure loading at highway speeds, protects the foam core from moisture and mechanical damage, and provides a paintable surface finish. The fiberglass laminate will be sanded back through progressive grits to a smooth finish prior to painting (Lubin, 1982).

3.5 Fabrication Strategy Revision: FDM 3D Printing

Following the initial fabrication strategy outlined in Section 3.4, the decision was made to transition away from XPS foam construction in favor of direct FDM 3D printing for all wing components. While the foam core and fiberglass laminate approach is a well-established method for producing lightweight aerodynamic surfaces, it introduces several practical limitations in the context of a solo, compressed-timeline build. Hot wire cutting is highly sensitive to operator consistency, and any deviation from the template path during a cut produces geometric error that

propagates through the entire stacked assembly. Fairing and sanding a foam core to match a precise CAD-defined airfoil profile is a time-intensive process with no guaranteed dimensional accuracy, and the subsequent fiberglass lamination introduces additional variables in surface finish and structural uniformity (Lubin, 1982).

FDM 3D printing was selected as the replacement fabrication method on the basis of geometric precision and repeatability. Every printed component is produced directly from the CAD geometry, eliminating the operator-dependent error inherent in the foam cutting and fairing process. Complex internal features such as hinge bores, dowel holes, insert pockets, and servo mounting geometry, which would be extremely difficult to incorporate into a foam and fiberglass construction, are produced automatically as part of the print with no additional machining or post-processing required (Gibson, Rosen, & Stucker, 2015). The modular architecture of the wing, described in Section 3.6, was made practical specifically by this transition: the precision and repeatability of FDM printing allows mating interfaces between modules to be held to tolerances that foam fabrication could not reliably achieve.

The primary material selected for structural wing components is PLA, chosen for its dimensional stability, ease of printing, and sufficient stiffness for aerodynamic surface loading at the intended operating speeds. For impact-critical or flexibility-dependent components, TPU was considered as a supplementary material, consistent with its application in my Humpty Dumpty antweight robot where its energy-absorbing properties proved effective under dynamic loading (Wu et al., 2026). The tradeoff accepted in this transition is a higher component mass compared to a foam and fiberglass equivalent, however, given the wing's mounting position and the relatively modest scale of the assembly, the mass penalty was deemed acceptable against the significant gains in geometric accuracy, fabrication speed, and design flexibility.

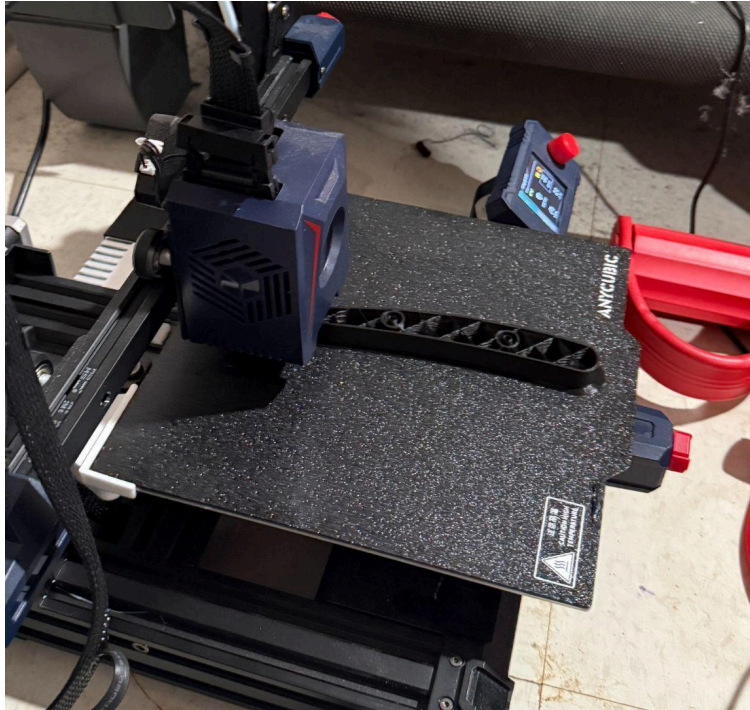


Figure 9. First of 3 wing components being 3d printed, 5% infill 3 walls.

3.6 Modular Wing Element Design

The wing element was designed as a modular assembly rather than a single monolithic component, a decision driven by both the practical limitations of consumer FDM print bed sizes and the long-term serviceability of the system. Printing the full 1400mm span as a single part is not feasible on standard FDM hardware, and a monolithic wing element would require complete replacement in the event of damage to any single section, an unacceptable outcome for a system intended to undergo iterative testing and refinement (Gibson, Rosen, & Stucker, 2015).

The central wing element is divided into discrete 200mm sections, each produced as an individual print. Adjacent sections are joined along their mating faces using 10mm diameter dowel pins inserted into precision-bored holes on each mating interface. The dowel connection serves two functions: it maintains spanwise alignment between modules, preventing angular

misalignment at the joint that would disrupt the continuity of the airfoil profile, and it transfers shear loads across the joint interface, ensuring the assembly behaves as a structurally continuous element under aerodynamic loading rather than a series of independently loaded segments (Shigley, Mischke, & Budynas, 2004).



Figure 10. 3 of the 200mm wing pieces are attached via dowels, balancing on the center of mass point of the air foil.

The outboard endplate sections, which are extruded at an angle to generate the additional tip downforce described in Section 3.2, also incorporate the same 10mm dowel hole interface, ensuring consistent alignment and load transfer at the junction between the central element and the angled tip sections. The decision to standardize the dowel diameter across all mating interfaces simplifies the fabrication and assembly process, a single drill bit or bore size is used throughout, reducing the opportunity for dimensional mismatch at any interface in the assembly.

The modular approach also provides a direct practical benefit during the active aero testing phase. Individual sections can be reprinted and swapped independently if a module is damaged during on-car testing or if a design revision is required for a specific section of the span, without requiring the full wing element to be disassembled or reprinted. This repairability was a core design constraint established in Section 2, and the modular architecture directly satisfies it.



Figure 10. Assembled wing, attached via dowels. Will be plastic welded to ensure increased rigidity

3.7 Plastic Welding and Final Wing Assembly

Following the dowel-pinned modular assembly, the individual wing sections were permanently joined using a plastic welding technique. Plastic welding is a process by which thermoplastic components are fused at their interface by locally melting the material and allowing it to resolidify as a single continuous structure, producing a bond that is structurally superior to adhesive joining for same-material interfaces (Tres, 2006). For PLA components, a soldering iron tip applied along the seam between adjacent modules generates sufficient localized heat to melt and intermix the material at the joint face, creating a fused connection that

eliminates the relative motion and potential misalignment that could occur under aerodynamic loading if the modules were retained by dowels alone.

The plastic welding was performed along all external seam lines between the 200mm center modules and at the junction between the center element and the angled outboard sections. The dowel pins provide the primary alignment and shear transfer function, while the plastic weld provides continuous spanwise rigidity along the bond line, ensuring the assembly behaves as a single structural element rather than a pinned multi-body system. This combination of mechanical and thermal joining is consistent with best practices for FDM part assembly where both positional accuracy and structural continuity are required (Gibson, Rosen, & Stucker, 2015).

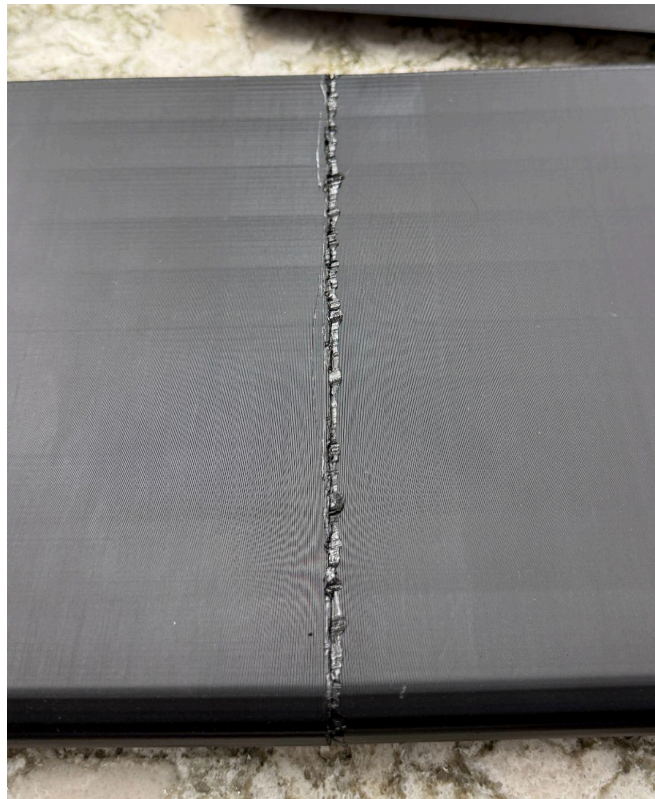


Figure 11.1 Plastic welded seam between wing modules, showing fused joint line.



Figure 11.2 Fully assembled and welded wing element prior to mounting.

3.8 Actuation Mechanism

The actuation mechanism is the critical interface between the embedded control system and the physical wing element, responsible for translating the servo's rotational output into a precise, repeatable change in wing angle of incidence. The design priority for this mechanism was mechanical simplicity, minimizing the number of moving parts between the servo output shaft and the wing hinge axis to reduce backlash, slop, and potential failure points under sustained aerodynamic loading (Shigley, Mischke, & Budynas, 2004).

The mechanism operates on a direct drive principle. The DS3218 servo is mounted rigidly within a precision pocket machined into the support bracket structure, sitting flush against the bracket face and secured with M3 fasteners through the servo's mounting ears into heat set inserts in the bracket body. The servo output shaft aligns directly with the wing's hinge axis, and a

custom-designed servo horn connects the output shaft to the rotating wing element. Rather than using a generic off-the-shelf horn, a custom horn was designed and printed specifically for this application to ensure a seamless, zero-slop fit onto the DS3218 output shaft geometry, eliminating the angular play that is commonly observed with generic horns on third-party servos and which would directly degrade positional accuracy at the wing (Barr & Massa, 2006).

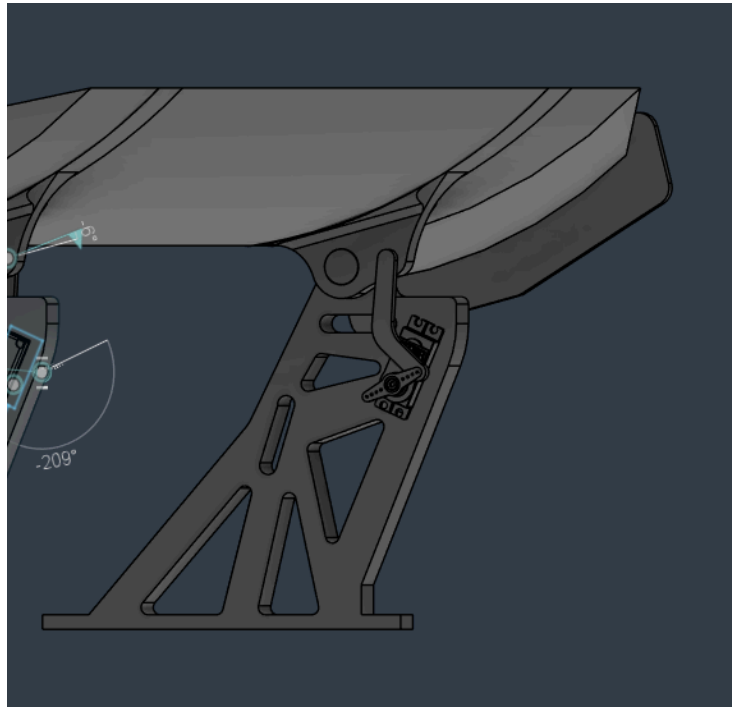


Figure 12. Actuation mechanism, arm attached to stock servo horn.



Figure 13. Custom designed servo horn to attach to the main connecting arm.

The wing element rotates about a fixed hinge axis running spanwise through the assembly, with the custom horn transmitting rotational force from the servo directly to the wing structure. This direct drive configuration was selected over a pushrod linkage arrangement because it eliminates the compliance and potential buckling risk associated with a slender pushrod resisting the aerodynamic hinge moment at speed, particularly in the airbrake position where aerodynamic loading on the wing is at its maximum (Etkin & Reid, 1996).

The servo is commanded to three discrete positions corresponding to the three aerodynamic modes of the AVIWS. In the airbrake mode, the wing pitches to a maximum angle of incidence of 40° , the upper mechanical limit of the actuation range, set by the firmware position constant and verified against the physical range of the servo horn geometry. In the acceleration mode, the wing flattens to -5° angle of incidence, reducing the wing's projected frontal area and minimizing induced drag during straight-line acceleration. At constant cruise speed, the wing

holds a $+5^\circ$ angle of incidence, maintaining a small positive angle sufficient to generate baseline downforce for stability without incurring significant drag penalty. The full actuation sweep from -5° to 40° represents a 45° range of motion, well within the 270° rated range of the DS3218, ensuring the servo operates in its highest-torque region throughout the entire actuation envelope (DS3218 datasheet, 2022).

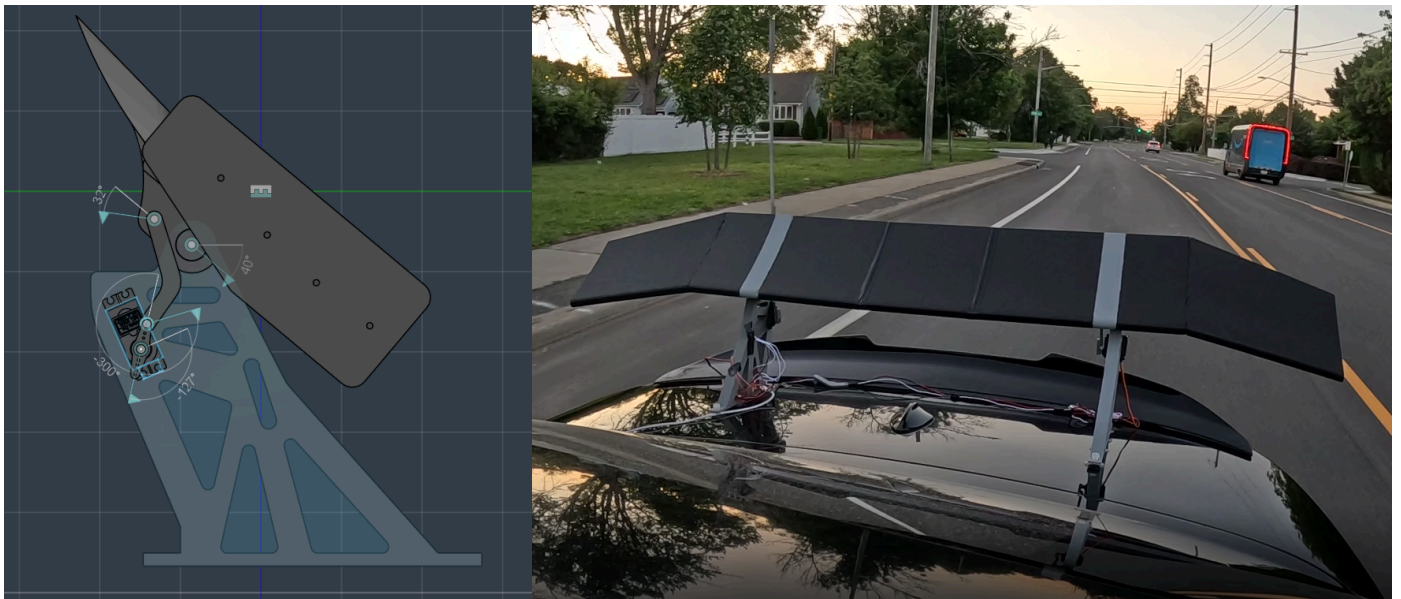


Figure 14.1. Wing element at 40° airbrake position.

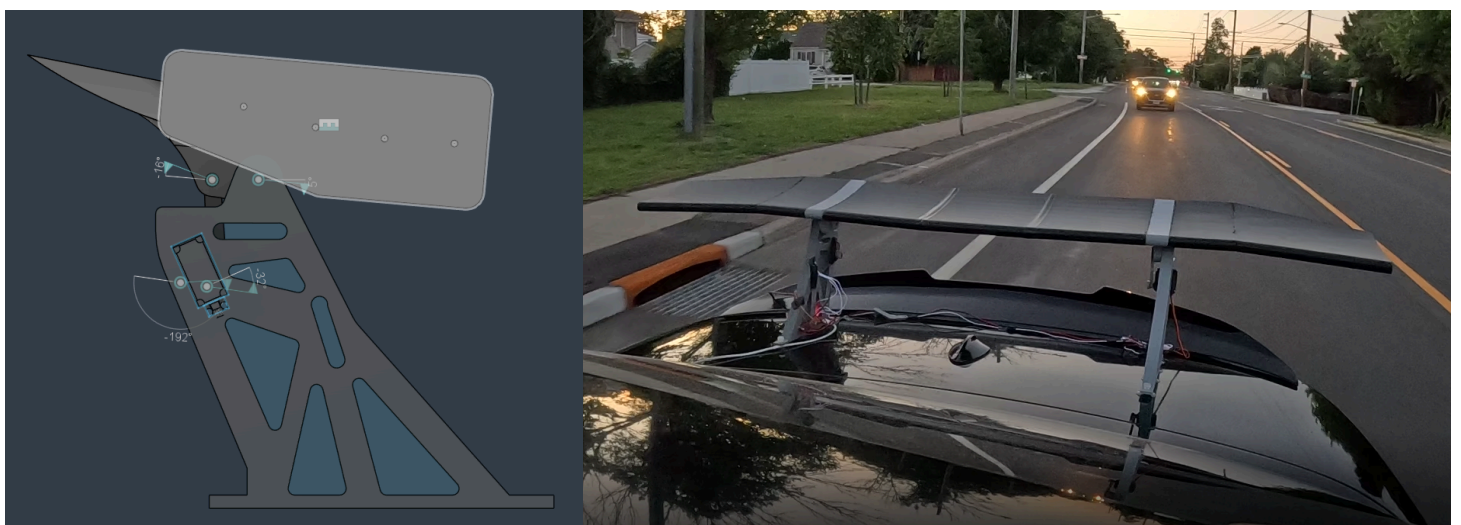


Figure 14.2. Wing element at 5° cruise position.

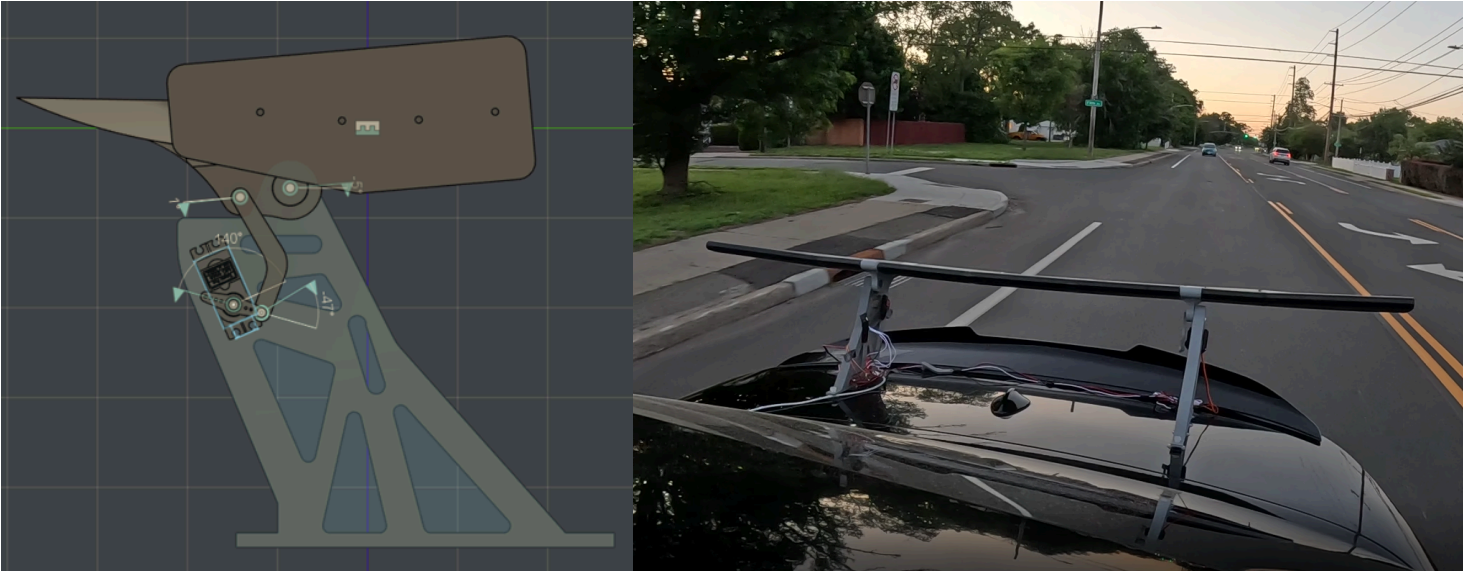


Figure 14.3. Wing element at -5° acceleration position.

3.9 Electronics and Circuit Design

The electronics assembly of the AVIWS was designed around a minimalist architecture — the fewest components necessary to achieve reliable closed-loop control of the wing actuation system. The full circuit consists of the Arduino Nano microcontroller, the GY-521 MPU-6050 IMU, two DS3218 servo motors, an LM2596 buck converter module, and a $100\mu\text{F}$ electrolytic decoupling capacitor on the 5V power rail. All components share a common ground rail, a fundamental requirement for reliable I2C communication between the Nano and the MPU-6050 and for consistent servo signal reference (Horowitz & Hill, 2015).

The power architecture separates the servo power supply from the microcontroller logic supply at the point of connection to prevent servo-induced voltage transients from propagating into the Nano's supply rail. Both DS3218 servos draw power directly from the LM2596 buck converter output at 5V, bypassing the Nano's onboard linear regulator entirely. The Nano and MPU-6050 are powered from the same 5V rail, with the MPU drawing from the Nano's regulated 5V pin

which provides sufficient current capacity for the sensor's minimal draw. The 100 μ F electrolytic capacitor is placed directly across the buck converter output terminals to buffer instantaneous current surges during servo actuation and prevent rail voltage sag (Texas Instruments, 2023).

The servo signal lines are routed from digital PWM pins D5 and D6 on the Nano to each respective servo signal wire. The IMU communicates with the Nano over the I2C bus on pins A4 (SDA) and A5 (SCL). The GY-521 module's onboard pull-up resistors and decoupling capacitors eliminate the need for any additional passive components on the I2C lines (InvenSense, 2013).

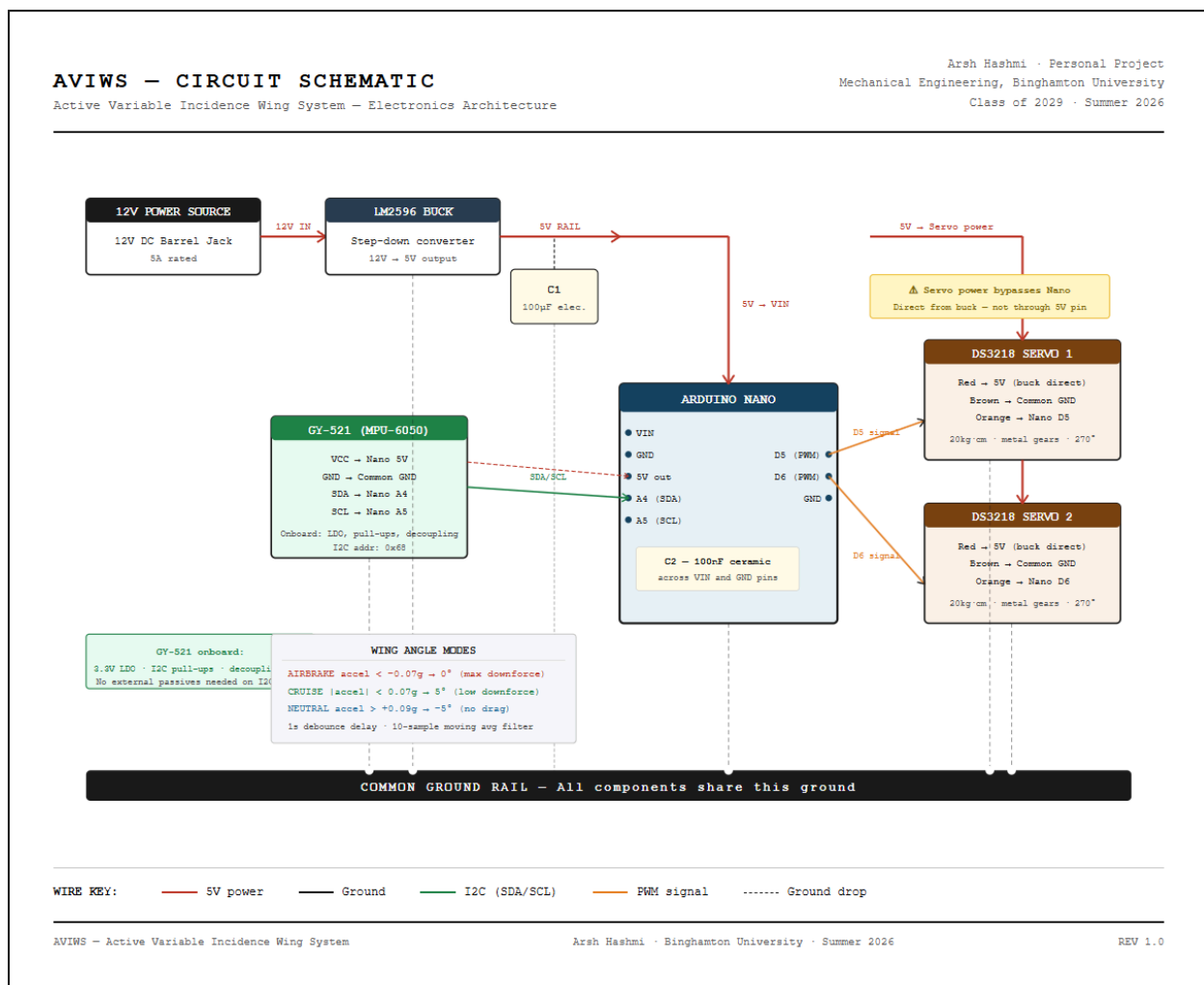


Figure 15. Full circuit schematic showing all connections between Nano, MPU-6050, servos, and buck converter.

The physical electronics assembly was integrated directly into the wing support bracket structure rather than housed in a separate enclosure, taking advantage of the open lattice geometry of the printed bracket to route and retain wiring within the assembly footprint. The Arduino Nano was mounted flat within a recessed pocket in the bracket, keeping its profile within the structural envelope of the support arm. The GY-521 IMU was first secured to the bracket surface using M3 fasteners through its mounting holes, then additionally retained with tape and zip ties to ensure it remained positionally stable under the vibration and aerodynamic loading conditions expected during on-car operation. The IMU was mounted as flat and level as possible relative to the vehicle's longitudinal axis so that the X axis of the accelerometer aligns with the direction of vehicle travel, ensuring clean longitudinal acceleration readings with minimal cross-axis gravity contamination (Madgwick, Harrison, & Vaidyanathan, 2011).

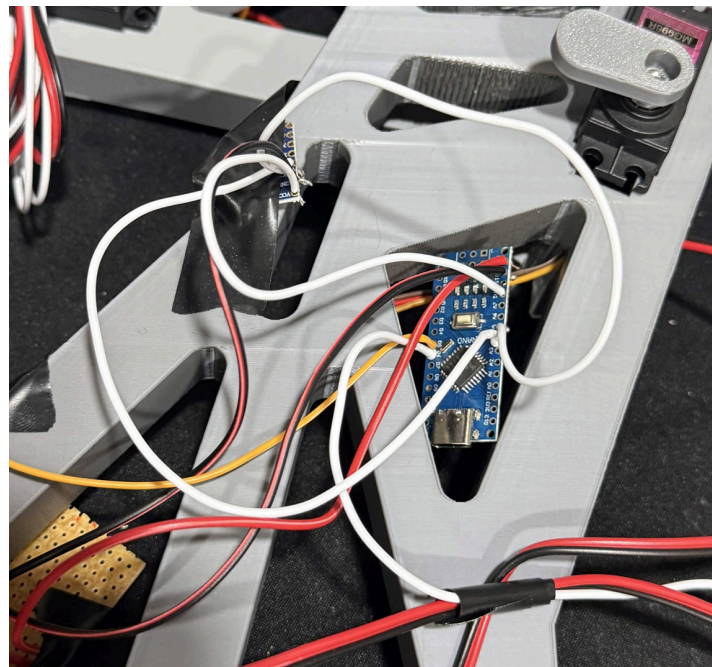


Figure 16. Assembled electronics mounted to the wing bracket showing Nano, IMU, and servo wiring.

Wiring was routed through the open lattice cutouts of the bracket structure and secured with zip ties at regular intervals to prevent movement under vibration. Red wires carry the 5V power supply, black and brown wires form the common ground rail, yellow and orange wires carry servo PWM signals, and the I2C lines run from the Nano to the IMU. The input power connection from the 12V source to the buck converter was made via a barrel jack connector, allowing the power source to be connected and disconnected without disturbing the rest of the wiring harness.

3.10 Mounting and Vehicle Integration

The AVIWS was mounted to the trunk lid of a 2011 BMW E93 for initial on-car testing and validation. The mounting method selected for this phase was a suction cup base system, chosen deliberately for its non-destructive nature, it allowed the wing assembly to be positioned, tested, and removed without modification to the vehicle's bodywork. This approach is consistent with the design goal of universal platform compatibility established in Section 2, as a suction-based mount imposes no vehicle-specific drilling or fastener requirements and can be repositioned across different trunk geometries without fabrication changes.

The two support brackets were mounted symmetrically on the trunk lid, centered spanwise relative to the vehicle's longitudinal axis to ensure balanced aerodynamic loading across both mounting points. The wing element was positioned at the rearmost practical point on the trunk lid to maximize the moment arm between the wing's center of pressure and the vehicle's rear

axle, consistent with standard rear wing placement practice for maximizing rear axle downforce contribution (Katz, 1995).



Figure 17. AVIWS mounted on BMW E33 trunk lid, rear view showing full wing assembly and bracket geometry.

Power was supplied via a wire routed from the 12V source through the trunk and into the passenger cabin, connecting to the LM2596 buck converter mounted within the wing assembly. A secondary monitoring wire was routed into the passenger seat area to allow real-time serial data from the Arduino Nano to be read on a laptop during initial calibration runs, enabling live observation of the IMU's acceleration readings and wing mode switching behavior without requiring the Nano to be disconnected from the assembly. This setup allowed the IMU offset calibration value of 0.07g to be identified and the acceleration thresholds to be tuned under actual driving conditions rather than on the bench.

A GoPro action camera was mounted to the vehicle's roof using a suction cup mount, positioned to capture the wing element in frame during driving. This provided a continuous video record of

the wing's actuation behavior, confirming that mode transitions between neutral, cruise, and airbrake positions were occurring at the correct points in the vehicle's acceleration profile and that the 1-second debounce delay was preventing spurious switching on minor road surface inputs.



Figure 18. GoPro live feed, this what was visible from the driver view.

The on-car installation confirmed that the suction mount provided sufficient retention at the speeds tested, with no observed movement or vibration of the bracket assembly relative to the trunk lid surface during normal driving maneuvers. Future iterations of the mounting system will incorporate a more permanent bracket solution with direct fastening to the trunk lid or trunk lip, improving structural rigidity at higher speeds and allowing the wing to be mounted at a more aerodynamically optimal height above the trunk surface.



Figure 19. Live g-force MPU calibration, live from driver view.

4. Firmware

The AVIWS firmware was developed in the Arduino IDE using C++ and deployed to the Arduino Nano microcontroller. The control logic is intentionally simple, a three-state controller that maps filtered longitudinal acceleration data from the MPU-6050 to one of three discrete servo positions. This architecture was selected over a proportional control approach on the basis that the AVIWS operates between three well-defined aerodynamic configurations rather than

along a continuous angle spectrum, making bang-bang control both sufficient and more robust against sensor noise than a proportional implementation would be (Barr & Massa, 2006).

4.1 IMU Data Acquisition and Filtering

On each control loop iteration, the firmware reads the raw 16-bit accelerometer output from the MPU-6050 over I2C and converts it to gravitational units by dividing by 16,384, the sensitivity scale factor corresponding to the sensor's default $\pm 2g$ full-scale range (InvenSense, 2013). A static calibration offset of 0.07g is subtracted from every reading to account for the gravitational component bleeding into the longitudinal axis due to minor IMU mounting imperfection. This offset was determined empirically by observing the serial output of the raw accelerometer axis while the vehicle was stationary on a level surface.

The offset-corrected reading is then passed through a ten-sample moving average filter implemented as a circular buffer. Each new sample replaces the oldest value in the buffer, and the filter output is the arithmetic mean of all ten stored samples. This approach attenuates high-frequency vibration noise from the engine, road surface, and aerodynamic buffeting of the wing structure, which would otherwise cause spurious threshold crossings and erratic wing behavior (Madgwick, Harrison, & Vaidyanathan, 2011). The filter introduces a lag of approximately 500ms at the 50ms loop rate, which was considered acceptable given that the 1-second debounce delay described in Section 4.2 is the dominant timing constraint on mode switching response.

4.2 Mode Switching Logic and Debounce

The filtered acceleration value is compared against two thresholds on each loop iteration. If the filtered acceleration exceeds $+0.09g$ the system enters neutral mode, commanding the wing to -5° angle of incidence to minimize drag during acceleration. If the filtered acceleration falls below $-0.07g$ the system enters airbrake mode, commanding the wing to 40° angle of incidence to maximize drag and downforce during deceleration. If the filtered acceleration falls between these two thresholds the system remains in or transitions to cruise mode, commanding the wing to 5° angle of incidence for baseline downforce at constant speed.

A one-second debounce timer governs all mode transitions. When the target mode differs from the current mode, a timer begins. The transition is only executed if the new target mode is consistently maintained for the full one-second duration, any reversion to the current mode resets the timer. This prevents the wing from responding to brief acceleration transients such as road surface undulations, gear changes, or minor throttle inputs that would otherwise cause rapid oscillatory switching between positions. The debounce implementation uses Arduino's `millis()` function for non-blocking timing, ensuring the sensor polling loop continues to run at full rate during the debounce window (Barr & Massa, 2006).

4.3 Servo Output

Wing position commands are issued to both DS3218 servos simultaneously through a single `setWingPosition()` function. Because the two servos are mechanically mirrored on opposite sides of the wing hinge axis, they are commanded to supplementary angles, servo 1 receives the direct position value and servo 2 receives 180° minus that value, ensuring both servos rotate the wing in the same physical direction. The three commanded positions in firmware units are 65 for

neutral, 110 for cruise, and 0 for airbrake, determined empirically during bench calibration by sweeping the servos via serial input and observing the physical wing angle at each firmware position value.

The firmware operates on a 50ms polling loop, giving a control update rate of 20Hz. This is sufficient for the time constants involved, aerodynamic forces on a street vehicle change over hundreds of milliseconds during normal driving maneuvers, and the 1-second debounce delay is the binding constraint on system response time rather than the polling rate.

Wing positions (empirically calibrated)

```
#define POS_NEUTRAL 65 // -5° angle of incidence
```

```
#define POS_CRUISE 110 // 5° angle of incidence
```

```
#define POS_AIRBRAKE 0 // 40° angle of incidence
```

Thresholds (offset-corrected)

```
#define ACCEL_THRESHOLD 0.09 // +0.09g → neutral
```

```
#define BRAKE_THRESHOLD -0.07 // -0.07g → airbrake
```

```
#define OFFSET 0.07 // empirical gravity offset
```

```
#define CHANGE_DELAY 1000 // 1s debounce (ms)
```

```
#define FILTER_SIZE 10 // moving average window
```

5. Testing and Results

System validation was conducted in two phases: an initial bench test to verify electrical and firmware functionality prior to vehicle installation, and an on-car test to validate real-world actuation behavior under actual driving conditions on the development vehicle, a 2011 BMW E93.

5.1 Bench Testing

Bench testing was performed with the fully assembled electronics circuit powered by the 12V DC source through the LM2596 buck converter, with the Arduino Nano simultaneously connected to a laptop via USB for serial monitoring. The I2C connection between the Nano and the GY-521 was verified first by running an I2C bus scan, which confirmed the MPU-6050 was communicating correctly at address 0x68. Both DS3218 servos were then tested individually and in unison using a manual angle input sketch, confirming correct signal routing on pins D5 and D6 and verifying that the mirrored position logic produced symmetric physical rotation on both sides of the wing hinge axis.

IMU axis orientation was confirmed by manually tilting the sensor along each axis while observing the serial output, identifying the longitudinal accelerometer axis and establishing the 0.07g resting offset from stationary readings. The moving average filter was verified to be smoothing the signal correctly by observing the serial output during rapid hand-tapping of the sensor, confirming that brief impulses did not trigger threshold crossings in the filtered value.

The complete firmware was then uploaded and the three wing modes verified on the bench by hand-tilting the IMU to simulate acceleration and deceleration inputs. All three positions,

airbrake at 0, cruise at 110, and neutral at 65 in firmware units, were confirmed to actuate correctly and hold position under manual load applied to the wing element.

5.2 On-Car Testing and Calibration

Following successful bench validation the system was installed on the vehicle as described in Section 3.10. A laptop was connected to the Nano via USB through a wire routed into the passenger cabin, allowing real-time serial monitoring of the acceleration readings and mode switching behavior during driving. A GoPro camera was mounted to the roof to provide a continuous visual record of the wing's physical actuation during the test run.

On-car testing confirmed that the system operated correctly under real driving conditions. The wing transitioned between all three modes at the expected points in the vehicle's acceleration profile, flattening to the neutral position under throttle application, returning to the low-angle cruise position at steady speed, and deploying to the full airbrake position under braking. The 1-second debounce delay proved effective at preventing spurious switching on minor road surface inputs and gear change transients, which had been observed to cause erratic behavior in earlier firmware iterations without the delay.

The acceleration threshold values of $+0.09g$ for neutral and $-0.07g$ for airbrake, established during bench calibration, were found to be appropriately sensitive for street driving conditions. The wing responded to moderate throttle and braking inputs without requiring aggressive driver inputs to trigger mode changes, while remaining stable during normal cruise without hunting between modes.

5.3 Issues and Observations

One mechanical failure was observed during testing. The connecting arm linking the servo horn to the wing element sustained a fracture on one of its thinner structural sections under the combined aerodynamic and actuation loads experienced during driving. The failure was localized to a geometry in the arm where wall thickness was insufficient to resist the bending moment induced by the servo horn's force applied at the connection point, compounded by aerodynamic hinge moment acting on the wing simultaneously. The system continued to function partially following the fracture but with reduced positional accuracy on the affected side.

This failure is identified as the primary mechanical design deficiency of the current iteration and directly informs the next design revision. The connecting arm geometry requires redesign with increased wall thickness at the fracture location, a larger fillet radius at the stress concentration point, and potentially a switch to a higher-stiffness material such as CF-PLA for that specific component to improve the strength-to-weight ratio at the critical cross section (Shigley, Mischke, & Budynas, 2004).

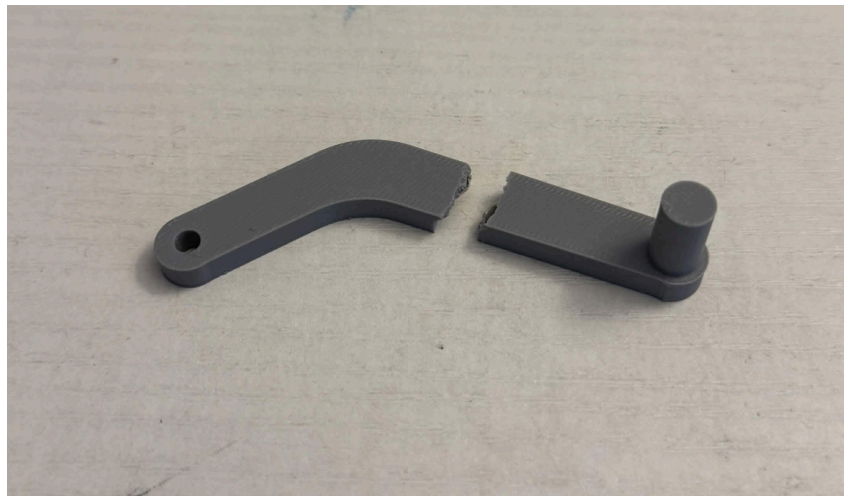


Figure 20. Fractured connecting arm showing failure location on thin structural section.

6. Conclusion

The Active Variable Incidence Wing System demonstrates that a functional, IMU-driven active aerodynamic system can be designed, fabricated, and validated within the constraints of a solo build using accessible tools: FDM 3D printing, off-the-shelf embedded electronics, and standard hardware. The system successfully achieves its core design objective: autonomous, real-time adjustment of wing angle of incidence across three discrete aerodynamic modes driven entirely by onboard acceleration data, with no external vehicle integration or driver input required.

The project validated several key engineering decisions made during the design phase. The selection of the DS3218 servo over lower-torque alternatives proved correct, the metal gear construction resisted back-driving under aerodynamic hinge moment throughout testing, and the torque margin at 5V was sufficient for reliable actuation across the full 45° range of motion. The MPU-6050 moving average filter effectively attenuated road noise and vibration from the acceleration signal, and the 1-second debounce delay eliminated the mode hunting that characterized earlier firmware iterations. The modular wing element design, joined by dowel pins and plastic welded at the seams, maintained structural integrity and spanwise alignment throughout the test campaign, confirming that FDM-fabricated aerodynamic surfaces can be sufficiently precise and rigid for this application.

The primary failure observed: fracture of the connecting arm at a thin cross section under combined aerodynamic and actuation loading, is a straightforward mechanical design deficiency rather than a fundamental system limitation. It provides clear direction for the next design iteration: increased wall thickness at the failure location, improved fillet geometry to reduce

stress concentration, and potential material substitution to CF-PLA for the connecting arm specifically. Addressing this failure is the first priority for the next build cycle.

Looking beyond the immediate mechanical revision, the AVIWS architecture was designed from the outset with future capability expansion in mind. The MPU-6050's full 6-DOF dataset, only one axis of which is currently used, provides the lateral acceleration data necessary to implement cornering-responsive aero adjustment in a future iteration, analogous to the lateral wing actuation of the Zenvo TSR-1 that served as one of the original inspirations for this project. A second servo axis added to the hinge mechanism would enable the wing to generate yaw-stabilizing aerodynamic moments under cornering loads, representing a meaningful performance upgrade over the current single-axis system. Migration to an ESP32 microcontroller would additionally enable real-time wireless telemetry logging of wing angle, acceleration, and mode state to a mobile device, facilitating more rigorous data-driven tuning of threshold values under track conditions.

The AVIWS represents a functional first iteration of a multi-axis active aero platform. The core system works, the failure mode is understood, and the path to the next iteration is clearly defined. As a solo engineering project completed within a single week using consumer-grade fabrication tools, it demonstrates that the engineering principles underlying some of the most sophisticated aerodynamic systems in motorsport and aviation are accessible, buildable, and testable at a personal scale.

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Appendix A: AVIWS Arduino Firmware

The following code was developed and deployed to the Arduino Nano microcontroller for the Active Variable Incidence Wing System. The firmware was written in C++ using the Arduino IDE and relies on the following libraries:

- Servo.h — included in the Arduino standard library, no installation required
- Wire.h — included in the Arduino standard library, no installation required
- MPU6050.h — Electronic Cats MPU6050 library, installed via Arduino Library Manager

```
#include <Servo.h>

#include <Wire.h>

#include <MPU6050.h>

Servo servo1;

Servo servo2;

MPU6050 mpu;

// Wing positions

#define POS_NEUTRAL    110 // acceleration

#define POS_CRUISE     65  // constant speed

#define POS_AIRBRAKE   0   // braking

// Acceleration thresholds

#define ACCEL_THRESHOLD 0.09

#define BRAKE_THRESHOLD -0.07

// Moving average filter
```

```
#define FILTER_SIZE 10

float readings[FILTER_SIZE];

int filterIndex = 0;

float filterSum = 0;

// Calibration offset

#define OFFSET 0.07

// Delay before changing position

#define CHANGE_DELAY 1000

unsigned long lastChangeTime = 0;

int currentPosition = POS_CRUISE;

int targetPosition = POS_CRUISE;

void setup() {

    servo1.attach(5);

    servo2.attach(6);

    Serial.begin(9600);

    Wire.begin();

    mpu.initialize();

    if (mpu.testConnection()) {

        Serial.println("MPU6050 connected");

    } else {

        Serial.println("MPU6050 connection failed");

    }

    for (int i = 0; i < FILTER_SIZE; i++) {
```



```

        readings[i] = 0;

    }

    setWingPosition(POS_CRUISE);

    Serial.println("Wing starting at cruise position");
}

void setWingPosition(int pos) {

    servo1.write(pos);

    servo2.write(180 - pos);

    currentPosition = pos;
}

float getFilteredAccel() {

    int16_t ax, ay, az, gx, gy, gz;

    mpu.getMotion6(&ax, &ay, &az, &gx, &gy, &gz);

    float accelG = (ax / 16384.0) - OFFSET;

    filterSum -= readings[filterIndex];

    readings[filterIndex] = accelG;

    filterSum += readings[filterIndex];

    filterIndex = (filterIndex + 1) % FILTER_SIZE;

    return filterSum / FILTER_SIZE;
}

void loop() {

```

```
float accel = getFilteredAccel();

Serial.print("Accel: ");

Serial.print(accel);

Serial.print("g → ");

if (accel > ACCEL_THRESHOLD) {

    Serial.println("NEUTRAL (accelerating)");

    targetPosition = POS_NEUTRAL;

}

else if (accel < BRAKE_THRESHOLD) {

    Serial.println("AIRBRAKE (braking)");

    targetPosition = POS_AIRBRAKE;

}

else {

    Serial.println("CRUISE");

    targetPosition = POS_CRUISE;

}

if (targetPosition != currentPosition) {

    if (millis() - lastChangeTime >= CHANGE_DELAY) {

        setWingPosition(targetPosition);

        lastChangeTime = millis();

    }

} else {

    lastChangeTime = millis();

}
```

```
delay(50);  
}
```

All threshold values, servo position constants, and calibration offset were determined empirically during bench and on-car testing as documented in Section 5. Firmware version: Rev 1.0, Summer 2026.