A Modular, 3D-Printed Low-Speed Wind Tunnel as a Versatile Platform for STEM Education and Outreach

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A tabletop-scale low-speed wind tunnel is designed specifically for low-cost fabrication utilizing readily-available 3D-printing technology. The design optimizes for ease of use and exploratory inquiry by children across a broad range of age groups. The major interactive components of the design – test section access, test article mounts, lighting, and flow-visualization features – are all modularized for operation and reconfiguration without the use of tools. Even the basic building blocks of the tunnel flowpath itself can be rearranged with only a single hex wrench, permitting experimentation with the performance of the tunnel's flow-conditioning configuration. Originally conceived as a simpler hobby project and at-home STEM toy for the author's two daughters, the project has evolved to enable significant opportunities for broader aerospace education and outreach. In six months since the public availability of the project, many copies of the project have been built and employed in varied applications; this paper describes the project in detail and highlights some of these use cases.

I. Introduction

It has long been widely recognized that it is critical to the future of our national technical workforce that science, technology, engineering, and mathematics (STEM) be emphasized as important skill sets for children of all ages. Nearly any professional member of the aerospace community can point to a particular experience, project, or mentor in their youth that was formative in vectoring them toward a career in these areas.

The author, in his professional capacity, is a researcher in hypersonic aerodynamics and a high-speed wind tunnel engineer. His two young daughters, ages 4 and 8, have increasingly been curious about what Dad does at work, and so began a family project this past summer to address their curiosity in an engaging and collaborative way. The original intent was to design in CAD a shoebox-sized model of a wind tunnel and to together 3D-print and assemble it as a visual aid accompanying discussion of the parts of a wind tunnel and its applications. This modest exercise was completed quickly, followed by the inevitable reply by the eight-year-old, "so can we build one that works?"

The response to this challenge became a more-involved effort to design and build a working home wind tunnel principally for educational play and demonstration. This alone is certainly not novel; indeed, rare is the experimental aerodynamicist who has *not* built their own wind tunnel at home. However, such projects are commonly constructed from cardboard or plywood, and the resulting flow quality, performance, and utility can vary widely depending on the quality of the design, build, and components.

The scope and ambition of this project grew rapidly as it came together, but eventually the design became novel and worth sharing in that it:

- is easily and affordably reproducible on a wide variety of available hobby-grade 3D-printing machines,
- is modular in architecture, enabling piecewise production, flexible reconfiguration, and component upgrades,
- is optimized initially for flow-visualization,
- supports multiple types of experimental test articles, both educational and entertaining,
- is safe and easy to operate, even by small children.

Figure 1 shows a photograph of the "Modular STEM Wind Tunnel"[1] project in its baseline configuration, together with a set of available accessory modules for test articles and diagnostics. These are all discussed in further detail below, as are possible educational opportunities to be further explored as the project evolves.

This paper serves to document the project for the aerospace education community and aims to open a dialog regarding opportunities to collaboratively expand its reach, sparking interest in STEM fields – and aerospace in particular – among kids of all ages through educational play, experimentation, and exploration.

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Fig. 1 The table-top scale "Modular Wind Tunnel for STEM Education" and a collection of its compatible test articles, lighting modules, and other accessories. The tunnel is nearly fully fabricated on widely-available hobby-grade 3D printers and features excellent flow quality for smoke flow visualization.

II. Project Description

A. Basic Tunnel Configuration

In practice, there are many different wind tunnels architectures, each employed for different purposes or speed regimes. In pursuit of a low-cost, easy-to-operate simple design for educational flow visualization, this project uses a modular design implementing an "in-draft" (or open-return) architecture. In this concept, air from the room is drawn through a duct by a fan, accelerated over a test model, then decelerated and exhausted freely into the room. Figure 2 depicts the major components of the design, described further in the text that follows.

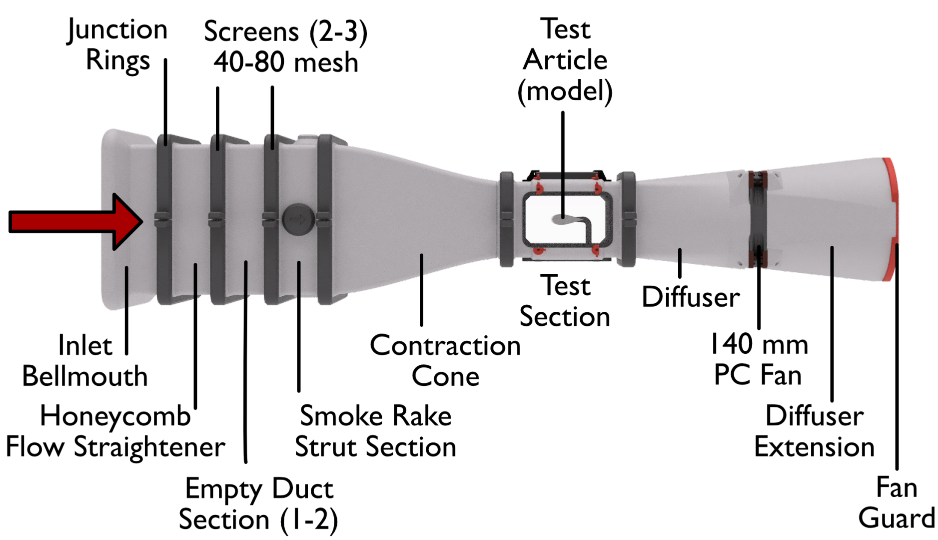


Fig. 2 Annotated side view highlighting major components of the Modular STEM Wind Tunnel.

As air enters the *bellmouth inlet* and proceeds into the tunnel, it is first processed by a set of "flow conditioning" components: a *honeycomb flow straightener* serves to align the flow and break up large-scale turbulence, and a set of *mesh screens* breaks up progressively smaller scales of turbulence. Empty duct sections then further allow the remaining smallest scales of turbulence to relax – or decay – due to viscosity.

Next, the flow is then drawn through a *contraction cone*, which accelerates the flow and reduces the static pressure as the cross-sectional area is reduced (here by a 4:1 ratio).

At the end of the contraction, the airstream has accelerated to the test (or "freestream") velocity of ≈ 4.0 m/s for the baseline configuration or ≈ 15 m/s with an upgraded fan and diffuser. Here we locate the *test section*, where various test articles (or "models") may be placed for flow visualization or, with future upgrades, the measurement of data such as aerodynamic forces and moments or surface pressures. The test section features removable modules in the walls, floor, and ceiling, permitting compatibility with optical access, lighting accessories, and a wide variety of mechanical supports for various test articles.

As a primary optical diagnostic for this project, linear arrays of smoke or fog lines can be introduced via hollow struts, or *smoke rakes*, placed upstream of the contraction cone, producing streaklines over the test articles. Visualization may be aided by introducing a laser sheet from above, illuminating only a thin sheet of the smoke flow to isolate certain flow features.

Downstream of the test section, a diffuser slowly expands the flow out to a larger area, exchanging flow velocity for recovered static pressure as it approaches the fan and exhausts back to the room.

One benefit of the highly-modular design of this 3D-printed wind tunnel design is that the configuration of the wind tunnel itself can be a source of rich experimentation. Starting with just the core components (contraction, test section, diffuser, and fan), one can make an engaging project of simply observing how the flow quality improves as additional upstream flow-conditioning components (bell-mouth inlet, honeycomb, screens, empty duct sections) are added.

- How does the honeycomb section contribute to flow uniformity?
- How do various screen configurations affect flow steadiness?
- What effect does the extended diffuser section have?
- How does the performance of the provided diffuser and 140 mm PC fan differ from the upgrade options?

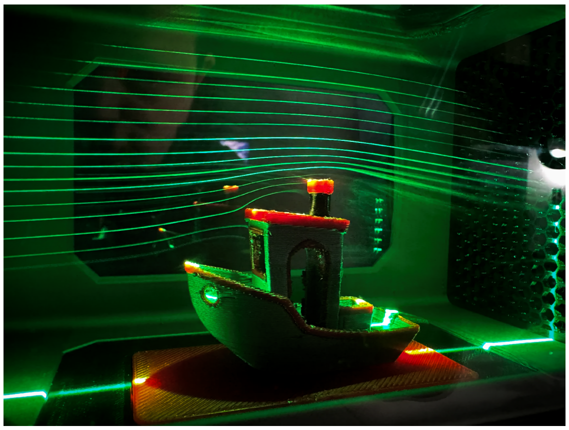
B. Test Articles and Diagnostics

To maximize the appeal of the project across a diverse set of age groups and interests, the tunnel's initial release in May 2024 included support for a wide variety of test articles, each easily and securely installed in the test section via self-locating magnetic baseplates based on a popular design standard for 3D-printed organizational desk accessories called Gridfinity[2]. The initial set of test articles and mounting adapters includes:

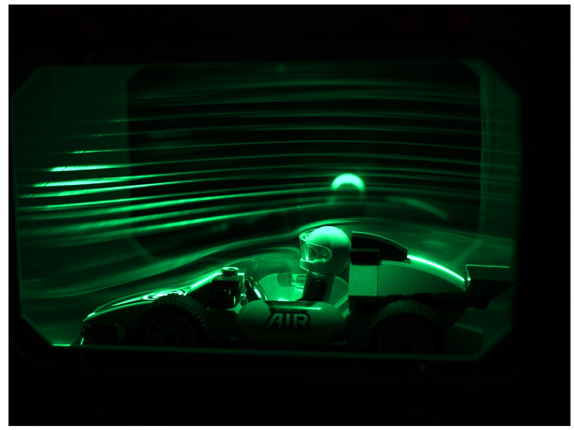
- Traditional aero models on a strut/sting base
  - Configurable angles of attack, sideslip, and roll
  - Large flat plate with side fences (notice the boundary layer)
  - Example aircraft and spacecraft shapes (AGARD-B, SpaceX Starship)
  - Mounting interace model provided for adaptation to any STL model
- Bases for for interactive exploration:
  - LEGO
  - LEGO Technic (plus compatible smooth and dimpled spheres)
  - LEGO DUPLO
- Strut for miniature paper airplanes (from card stock or playing/index cards)
- Automotive models:
  - 1:43 and 1:64 die-cast cars (e.g. Matchbox)
  - an F1-style rear wing assembly with and without DRS (drag reduction system) enabled
- Sidewall-mounted test article support
  - Magnetic hot-swap mounting and print-in-place AoA adjustment for "half-span" aircraft models - F-22 included.

In its present state, the principal flow diagnostic for the Modular STEM Wind Tunnel is smoke flow visualization. A Vosentech "Microfogger 5 Pro" handheld, battery-powered fog generator with an integral fan is connected via an interlocking modular acetal coolant hose (Loc-Line) to any of a number of 3D-printed struts installed into one of several mounting locations upstream or downstream of the contraction cone. Small brass tube stubs are pressed into the rake exit ports to provide a clean exit, maximizing the extent of laminar smoke traces for sharp flow visualization in the test section; when the rakes are mounted upstream of the contraction, the contracting streamtube of the accelerating flow helps with definition of the smoke lines as they are elongated along with the freestream.

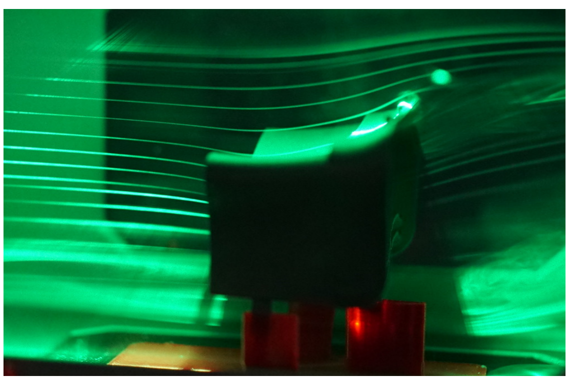
Figure 3 shows several examples of smoke flow visualization over some of the initial set of provided test articles. The “3D Benchy” boat model, shown in Figure 3a, is one of several designs ubiquitous in the 3D-printing community as a printer benchmark model. It is included in the project and pictured on the download webpage in an effort to attract interest from 3D-printing hobbyists – the same is true of support for other “silly” test articles like a silly-haired Troll doll or a bobble-head featuring a 3D-printed likeness of Dwayne “The Rock” Johnson. As the author is a professional wind tunnel researcher in his day job, it has been liberating to keep in mind that, for this project, generating excitement and engagement is a principal goal of this project, and silliness is therefore to be permitted if not encouraged. Science is fun!



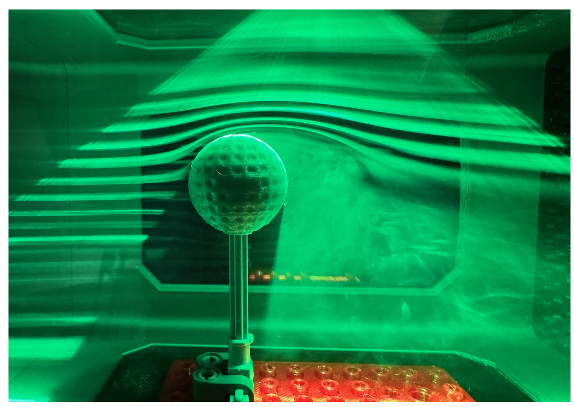
(a) “3D Benchy”, a print-quality benchmarking test print popular in the 3D printing community,



(b) A LEGO race car, mounted to a 3D-printed LEGO stud plate.



(c) A rear wing from a generic Formula One car, showing significant downforce-generating upwash. The wing and support are 3D printed and secure to the floor with magnets.



(d) A 3D-printed dimpled sphere, supported by a LEGO TECHNIC strut and compatible printed magnetic base-plate.

Fig. 3 Example smoke flow visualization over several test articles in the Modular STEM Wind Tunnel. Sheet illumination is provided by an inexpensive construction-grade continuous-wave laser-line generator.

C. Optional Upgrades

A number of optional upgrades and accessories are available alongside the designs for the main tunnel configuration. Most notably, one upgrade includes printable designs for a longer, larger-area two-piece diffuser section and internal hub nacelle and flow straightener that together enable the use of a 720 CFM 8-inch duct fan in place of the comparatively low-performance 160 CFM, 140 mm computer fan recommended for the baseline design. This upgraded fan and diffuser produce a test section freestream velocity of approximately 15 m/s versus 4.0 m/s for the baseline design.

Figure 4 shows the large-fan configuration of the tunnel supported by an optional desktop stand with cradles built

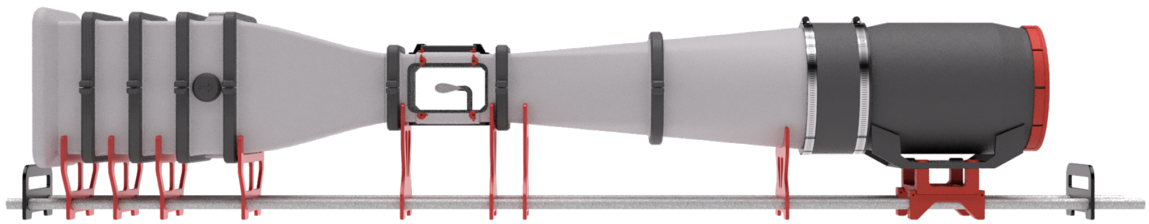


Fig. 4 Side view render of upgrade configuration of the Modular STEM Wind Tunnel, included extended diffuser section, 8-inch high-CFM duct fan, and conduit-based rail stand.

onto a pair of EMT conduit sections as structural rail.

The standard configuration of the tunnel is well-suited for smoke flow visualization for home or occasional school use – the more-conservative flow speeds are actually ideal for this application in preserving the sharpness and steadiness of the streaklines. The main motivations for the higher speeds of the optionally-upgraded fan and diffuser are:

The default configuration is well-suited for basic smoke flow visualization and produces very sharp and steady streaklines; the higher velocities of the upgraded configuration may be most useful for:

- a future force-balance upgrade enabling measurement of forces and moments acting on test articles. More velocity = more-significant aerodynamic forces to measure.
- improved robustness and flexibility for permanent installations that may wish to connect an optional silencer, filter, and/or flexible exhaust ducting for management of high-duty-cycle smoke usage, such as in an indoor classroom or science museum setting.

Two possible concepts for the force balance system are shown in Figure 5, each replacing the test section's rigidly-mounted magnetic baseplate floor with one that is floating. The first concept (Fig. 5a-5b) uses two inexpensive (i.e., kitchen-scale) load cells, a parallelogram linkage, and basic ball bearings to provide direct measurements of lift and drag forces with minimal crosstalk and relatively straight-forward calibration. The second concept (Fig. 5c-5d), using eight of the same inexpensive load cells, should be able to resolve as many as 3 components of force (normal, axial, side) and 3 moments (pitch, roll, yaw), but properly separating these sensitivities will require a much more-complicated calibration and data-reduction approach yet to be developed.

D. "LabPacks"

In addition to the included test articles and diagnostics described above – some of them outright silly – the author has also created two initial "LabPacks" containing sets of test articles and accompanying documentation to focus on illustrating specific aerodynamic concepts. The first two examples include:

- **Lab Pack: Aerodynamic Drag Basics** - Compare wake flows behind airfoil, flat plate, bullet, cylinder, and prism shapes. All have equal frontal area but very different drag coefficients. Learn concepts core to "streamlining" for drag reduction. Supported by documentation in NASA Glenn's Beginner's Guide to Aeronautics[3].
- **Lab Pack: Vortex Generators** - Visualize the wall flows around 4 basic "vortex generator" shapes. Learn how creating momentum exchange in the boundary layer can delay stall, preserve control surface effectiveness, and more.

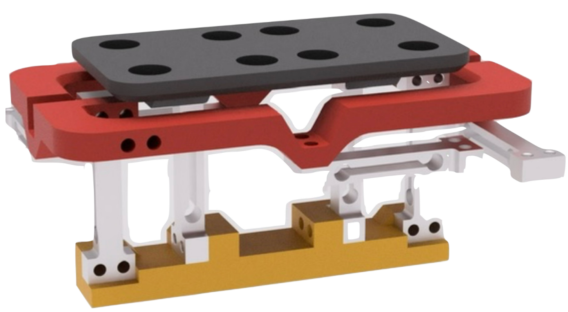
Figure 6 shows several of the components of the Aerodynamic Drag Basics LabPack.

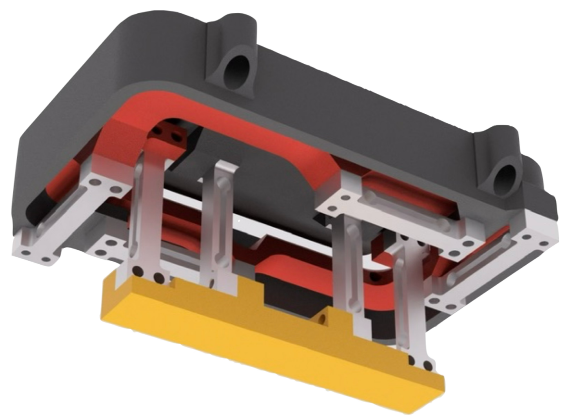
E. Fabrication Requirements and Cost Estimate

In its standard configuration, the wind tunnel's largest project components were designed for compatibility with printers that have a 256 × 256 × 256 mm print volume (e.g., Bambu A1, X1C, X1E, P1P, P1S, Creality K1 Max, Anycubic Kobra Plus/Max, Prusa XL, etc.). Smaller components downstream of the contraction cone can all be printed on smaller, lower-cost models in-class with a Bambu A1 Mini or Prusa Mini+ (min. 180 × 180 × 180 mm print volume). Additionally, a update to the design files provides an alternate design (Fig. 7) for the inlet, honeycomb, settling chamber, and contraction cone pieces that can *all* be printed on these smaller-size printers. With this update, nearly any home 3D

(a) 2 degree-of-freedom (2-DOF) balance prototype, enclosure.

(b) 2-DOF balance prototype, internals.





(c) 6-DOF balance prototype, view 1.

(d) 6-DOF balance prototype, view 2.

Fig. 5 Two prototype concepts for inexpensive force and moment measurement devices for the Modular Wind Tunnel for STEM Education.

printer can print the entire project.

An example build sequence is shown in Figure 8, with all of the essential 3D-printed components of the baseline tunnel configuration laid out across 22 build plates. The major components of the wind tunnel project are completed in the first 10; the remainder are accessory hardware (junction rings, stands, braces, plugs), smoke struts, and test section modules for test-article support and lighting features.

In total, these 22 build plates shown require approximately 5 to 6 kg of filament (at nominally \$20-25 per kg). The 140 mm PC fan, speed controller, and miscellaneous hardware such as bolts, heat-set threaded inserts, magnets, and screen material add perhaps another \$100 total. Assuming the hobbyist or institution seeking to build the tunnel project

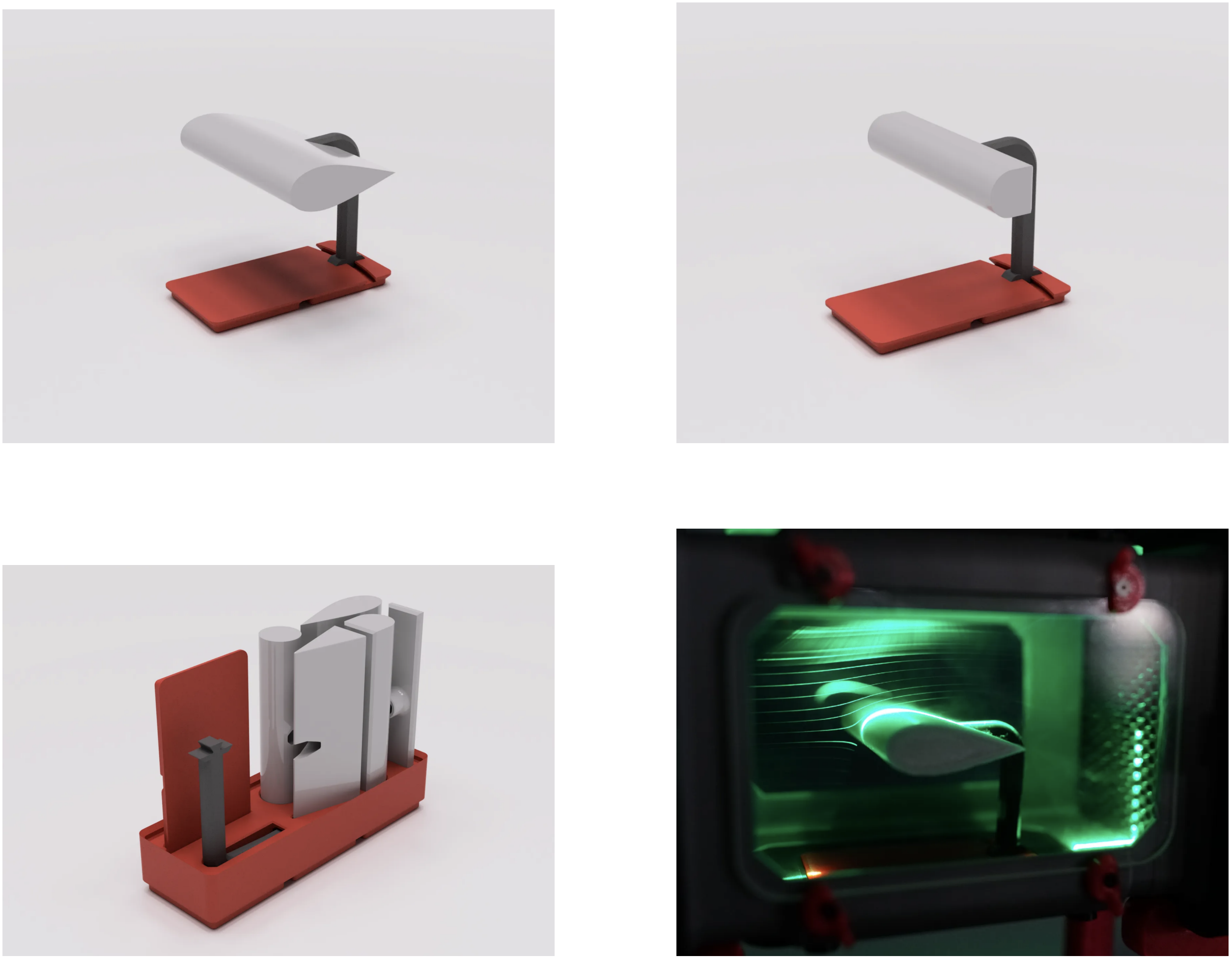


Fig. 6 An example "LabPack" featuring test articles and documentation. This LabPack highlights Aerodynamic Drag Basics, focusing on comparing the wake flows behind five objects with identical projected frontal area.

already has a suitable printer, fog machine, and light source, a functional configuration of the wind tunnel that produces good-quality airflow *can be produced for under $250 in total material costs*. If the handheld fog generator and LED or laser light sources also need to be purchased, the total "green-field" project cost may approximately double to $500 – still a good value for a student project, science exhibit, or multi-purpose classroom apparatus.

F. Distribution and Licensing

At time of this writing, the Modular STEM Wind Tunnel is made available for download from `printables.com`*, a community-driven 3D-printable design repository backed by Prusa Research.

The project, its several upgrades and accessories, and an initial slate of "LabPacks" are currently downloadable for a nominal fee under a license permitting their personal, non-commercial use. Institutional use by non-profits for educational purposes is also highly encouraged and the author is excited to actively collaborate on these applications – interested parties are encouraged to reach out. A commercial-use license can be made available by request, permitting third parties to, for example, sell entire pre-built wind tunnels, hardware bundles, or "build kits", or to use the design in for-profit applications.

Having successfully recovered the cost of a new 3D-printer and the material used in the development of this project, the author is strongly considering a switch to an open-source, community-driven model in the near term in an effort to maximize the project's reach and accelerate its future development. Prospective collaborators are invited to reach out.

*Full Link: https://www.printables.com/@JerrodH

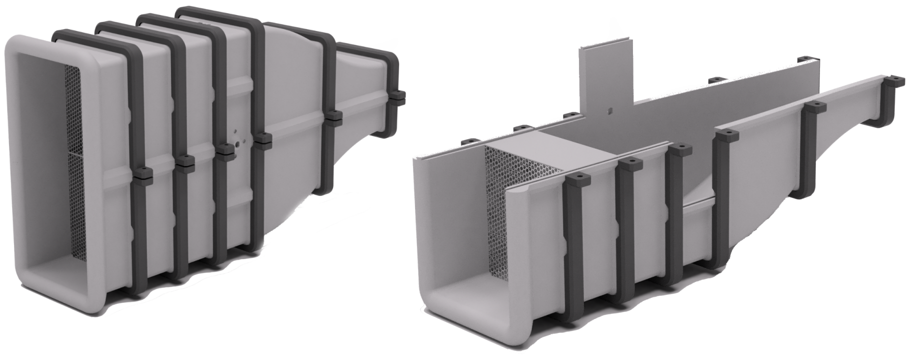


Fig. 7 An alternate, split tall-aspect design for the upstream components of the tunnel, enabling its construction on even the smallest of typical home 3D printers.

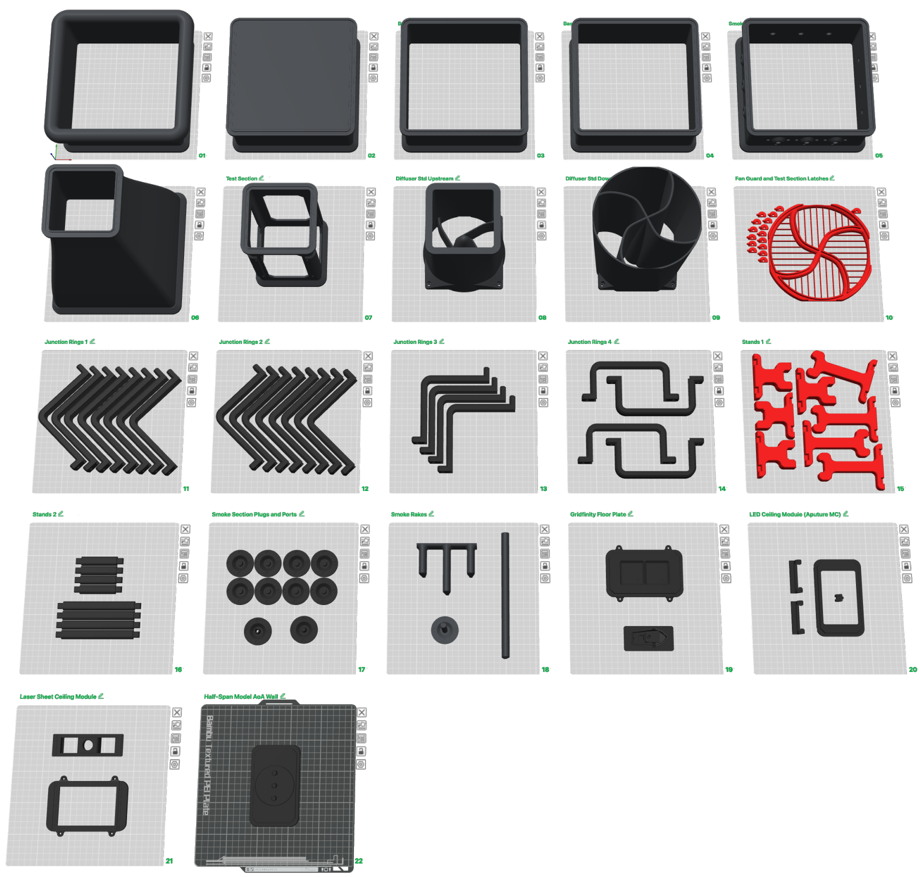


Fig. 8 Components of the Modular STEM Wind Tunnel arranged for printing onto 22 build plates for the Bambu X1 Carbon. Included is the baseline configuration of the major tunnel components, plus two smoke rakes, an LED lighting module, laser sheet module, and model support plates for floor- and wall-mounted test articles. Total filament usage is approximately 5 to 6 kg and print time is approximately 6 to 7 days.

Fig. 9 Modular STEM Wind Tunnel Booth at TN Maker Fest 2024

III. Applications

In the first six months of its availability, the project has seen varied types of application examples and opportunities across a broad set of educational and outreach activities. Those highlighted here are examples only – additional input from the aerospace education community is strongly desired, and again – interested parties are invited to reach out to the author.

A. As a system for free-form STEM play and exploration at home

As described above, the project unexpectedly grew into existence from considerably more modest ambitions – the author simply set out to build a "toy wind tunnel" for his young daughters (ages 3 and 7) in order to interactively share what he does at his day job (though in the supersonic and hypersonic regime).

As the project evolved from its modest beginnings into a functional platform, the girls have since enjoyed exploring flows over 1:64- and 1:43-scale toy cars, Troll dolls, bobble-heads, Fischer-Price Little People, LEGO mini-figures and custom vehicles, various nondescript shapes crafted from Play-Doh and modeling clay, and small paper airplanes made from index cards. The 3D-printed, magnetic base-plate fixtures and LEGO compatibility that themselves enable several of these "everyday test articles" were actually the result of their suggestions.

If all that ever came of this project was the fun we had in putting it together, iterating on it, and talking about neat flow patterns over quirky objects, it would have been worth it. The author hopes that many of those who have built the project have similarly had this much fun enjoying it and creating memories with their kids.

B. As an engaging platform for small-group demonstrations

Recently, the author took both of his wind tunnel assemblies to a local "Maker Fest" and found it to be a wonderful opportunity for outreach, talking about wind tunnels and basic aerodynamic concepts to hundreds of kids of all ages.

The author is scheduled to deliver a compact lesson and interactive demonstration in a small-group setting to his daughter's troop of "Brownie" Girl Scouts. This activity is currently in development and will occur in the spring as part of a meeting where the scouts in attendance will earn their STEM Career Exploration and/or "Think Like an Engineer" badges[4]. The author plans to deliver a brief overview of aerodynamics with a demonstration of the wind tunnel, and will bring the CAD project and a 3D printer to discuss the project's development and construction, showing additive manufacturing in action. The girls will finally be able to build their own test articles as LEGO vehicles or paper airplanes and test them in the wind tunnel, operating it on their own.

C. As an interactive exhibit for science centers

The author has demonstrated the project to the director of a major science museum local to his area, where there was considerable interest in employing it as an interactive element in their "maker space" as-is, or in working together to further develop the concept into a larger, more robust permanent exhibit.

D. As a group project for science fairs or summer interns

One university this summer utilized the Modular STEM Wind Tunnel as a project for a team of high school students to complete in their brief summer internship at their aerospace laboratories. The team began with the provided designs for the wind tunnel components, fabricated and assembled them in the recommended configuration, and used several of the many available laboratory diagnostics to characterize its performance. Along the way, the students were asked to engineer and test various modifications, improvements, and additional features to be considered for inclusion as revisions to the publicly-available designs. Feedback from the students and faculty was positive.

E. As a platform for outreach and recruitment

Two other universities have expressed their interest in using the tunnel project for other outreach opportunities:

A professor in one university's mechanical engineering department has planned to fabricate and integrate several complete sets of the project hardware for donation to high school science labs in their area. The donations were to be accompanied by student-developed experimental curriculum and companion computational fluid dynamics (CFD) simulations of the scale wind tunnel and the test articles provided.

A professor and aerospace laboratory director at another university is fabricating a system to be used as a portable demonstration platform to use at outreach events to that may include career/major fairs, recruitment events, hosted "STEM Day/Night" events for local schools, STEM summer camps, teacher professional developments, and more.

F. As a platform for product demonstrations

One company in the test and measurement field has purchased a commercial-use license and is using a full assembly of the upgraded configuration of the Modular Wind Tunnel to interactively demonstrate their data acquisition, control, and instrumentation products at trade shows. The entire setup fits on a standard booth table, and integrates velocity measurement, unsteady pressure measurements, force measurements, smoke visualization, digital video, and fan control using the vendor systems.

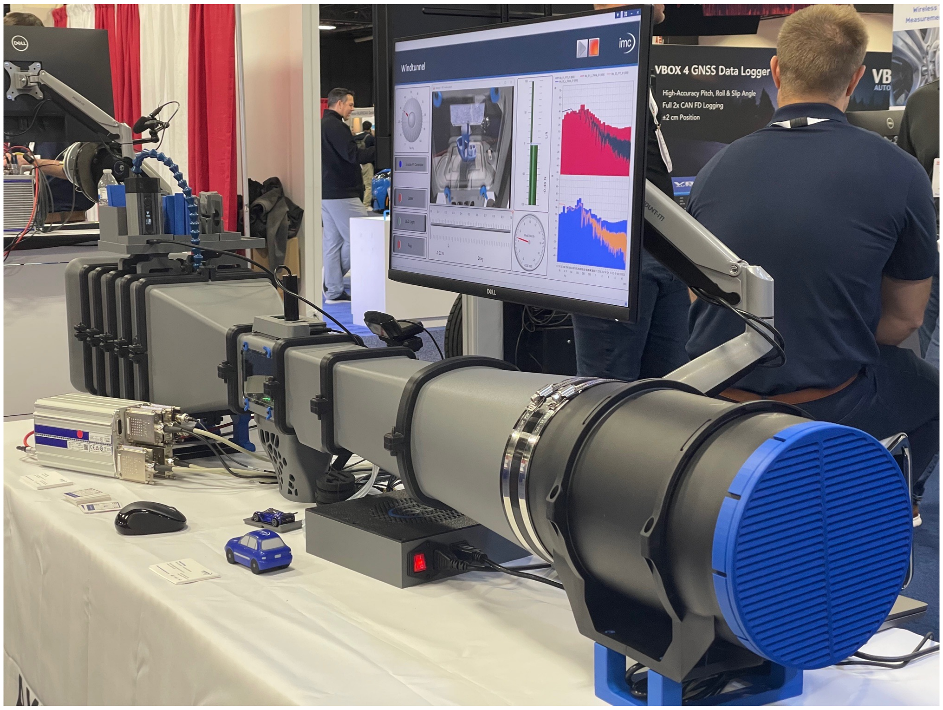


Fig. 10 Trade show demonstration of instrumentation and data systems

IV. Future Direction

The following sections detail possible future evolution of and additions to the Modular STEM Wind Tunnel project. This "fuzzy roadmap" detail is provided simply to illustrate the spectrum of possibilities that may exist to enable opportunities for new collaborative educational and outreach activities. It is the author's hope that this paper can serve as a vector to spark conversations with those who may have an interest in investing time and effort in using the project as a platform toward their own goals.

Beyond the exploration of specific use-case applications, the author is also interested in discussing possible partnerships or alternate models under which this system can proliferate into the hands of more kids and students. As a "side-gig" project of a single private individual, it is recognized that bandwidth limitations will preclude rapid expansion and limit the speed of ongoing development. As discussed earlier, a partnership and/or a full community-driven open-source approach may be possible if there appears to be sufficient interest.

A. Near-Term Design Revisions

- Revise the smoke-rake support section to allow the rake(s) to be translated across the test section to highlight off-center flow features without disassembly. Add new rake designs for unique configurations.

B. Additional "LabPacks" and Guided Curriculum Kits

Perhaps the most valuable expansion of the project offerings from a STEM perspective is the creation of additional "LabPack" kits with designs for test articles and supporting hardware illustrating specific interesting aero principles. These should each include guidance for facilitating group demonstration sequences and/or laboratory curriculum to guide engaging, age-appropriate, inquiry-focused individual or team experimentation.

The list of candidate "LabPack" ideas below is by no means exhaustive; the possibilities are endless, and suggestions or community contributions are encouraged.

- **Velocity measurement** - Build an incline manometer using a 3D-printed housing for inexpensive flexible tubing. Fabricate a functioning Pitot-static probe and airfoil with integral ports at the leading edge, trailing edge, and suction peak. Apply Bernoulli's equation and basic hydrostatics to calculate the wind tunnel's freestream velocity at various fan settings and plot the effect of angle-of-attack on the airfoil pressures.
- **Principles of lift** - Compare flow over a stationary and motorized rotating cylinder to visualize circulation and how it relates to lift. Compare symmetric and cambered airfoils at various angles of attack. Visualize the peak suction generated on an airfoil section using a simple fluid manometer.
- **Parts of the wing** - Visualize the flow over an airliner-class wing and its various distinctive features: winglets, ailerons, flaps, slats, and spoilers
- **Spacecraft aerodynamics** - Visualize flow over NASA's SLS on ascent, SpaceX's Starship during its "belly flop" maneuver, and the Space Shuttle Orbiter during a high-alpha flare.
- **Automotive aero** - Explore various features of everyday automotive aerodynamics. See the benefits (or not) of spoilers and aero kits, and learn about various drag-reducing aerodynamic features prevalent on semi trucks.
- **Formula One aerodynamics** – Test several designs for front and rear wings (with and without "DRS" enabled) and measure the resulting downforces generated using a kitchen scale or Lift/Drag balance kit. Understand the value of the closely-guarded flow features of the underbody floor in generating crucial downforce.

C. Additional Capability Upgrade Kits

As mentioned early in this paper, the process of building, characterizing, and iteratively improving the Modular STEM Wind Tunnel is itself seen to hold tremendously educational valuable for students. From this perspective, and in order to support an ever broader suite of experimental capabilities, several capability upgrades are planned. The following project ideas expand the scope of the tunnel project from additive manufacturing and aerodynamics to include an even broader set of STEM disciplines: electronics, basic instrumentation, control and data acquisition, "mechatronics", and microcontroller programming:

- **Modular control console kit** - Create a simple control console that can modularly incorporate fan speed control, LED/laser operation, smoke triggering, and – optionally – interfaces to the additional kits below.
- **Instrumentation and velocity control kit** - Build and program an Arduino or similar microcontroller system that reads from low-cost instrumentation for measurement of pressure and test-section flow velocity and display it on a small display. Optionally, incorporate PWM fan control for closed-loop control of velocity.

- **Lift-drag balance kit** - Build and calibrate a force balance for measuring lift and drag on any of the project's Gridfinity-mounted test articles. Incorporate 500g and 100g load cells into a floating 3D-printed frame as an test-section floor module, and acquire and process calibrated force data using an Arduino Uno and I2C load-cell amplifier modules.
- **Model attitude control kit** - Add a capability for motorized pitch and roll of the test article, either via LEGO Technic or RC servos and a microcontroller.
- **Closed-loop circuit conversion kit** - Convert the standard in-draft tunnel design into a full closed-loop / closed-return circuit. Learn about the advantages of this approach for flow quality, noise, and efficiency. This will not be ideal for smoke visualization due to smoke build-up in the circuit.

Acknowledgments

This work was performed entirely in the author's personal capacity. His two young daughters, Eleanor and Evelyn, were invaluable members of the team, providing "user feedback" and creative ideas (like adding LEGO plates!) throughout the development process. The author also gratefully appreciates his wife's support during a runaway project that "just started" randomly one day and then subsequently fully consumed several weeks' worth of precious evening and weekend time.

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