Design of an Air Track for Engineering and Physics Education

by

Jeremy Ernest deGuzman

Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of

Bachelor of Science in Mechanical Engineering at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

February 2014

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Abstract

An air track is a valuable tool for examining force and motion in the classroom, providing a low-friction environment to observe phenomena. Unfortunately, currently available models have limited functionality and are prohibitively expensive for many schools. To improve access to this helpful device, a number of smaller and less expensive variations on traditional air tracks are designed and tested. From an analysis of test results and theoretical performance calculations, the best design is identified. Further improvements to this design are also suggested.

Thesis Supervisor: Ian W. Hunter
Title: Hatsopoulos Professor of Mechanical Engineering
Acknowledgments

I would like to acknowledge the countless people that supported me and assisted me throughout this project. Firstly, I'd like to thank Professor Hunter, who gave me the opportunity to work in the wonderful BioInstrumentation Lab and helped direct the course of my work there, up to and including this project. I'd also like to thank Kate Melvin for her invaluable assistance with the details involved in the submission of a thesis. Furthermore, I have to thank Miri Skolnik, Franz Hover, and Brandy Baker for their support and assistance throughout my time at MIT. I have to thank Frederick Moore and Mike Nawrot for helping my proofread this work and Scott Curtis and Rachel Lewis for ensuring I maintained my sanity throughout the project. Most of all, I have to give thanks to my mother, who helped shape me into the person I am today and never ceased to push me to fulfill the potential she always knew I had.
Contents

List of Figures 9

List of Tables 11

1 Past and Current Air Tracks 13
   1.1 The MICA Project ........................................ 13
   1.2 History of the air track .................................. 14
   1.3 Modern air track benchmarking ............................ 15

2 Aerostatic Bearing Theory 17
   2.1 Concept overview ........................................... 17
   2.2 Symbol key .................................................. 19
   2.3 Theoretical bearing performance: Pasco track ............. 20

3 Air Track Design 23
   3.1 Acrylic proof of concept ................................... 23
   3.2 Version 1: aluminum track .................................. 24
   3.3 Version 2: aluminum-acrylic hybrid ........................ 28
   3.4 Version 3: acrylic V track .................................. 32
   3.5 Version 4: acrylic box track ................................ 35
   3.6 Other potential designs .................................... 38
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Design Evaluation</td>
<td>41</td>
</tr>
<tr>
<td>4.1 Version 2 track, profile B</td>
<td>41</td>
</tr>
<tr>
<td>4.1.1 Theory</td>
<td>41</td>
</tr>
<tr>
<td>4.1.2 Experimental performance</td>
<td>42</td>
</tr>
<tr>
<td>4.2 Version 4 track</td>
<td>42</td>
</tr>
<tr>
<td>4.2.1 Theory</td>
<td>42</td>
</tr>
<tr>
<td>5 Conclusion</td>
<td>45</td>
</tr>
<tr>
<td>Bibliography</td>
<td>47</td>
</tr>
</tbody>
</table>
List of Figures

2.1 Aerostatic bearing configuration .................................. 17

3.1 Acrylic aerostatic tube bearing ...................................... 24
3.2 Version 1 prototype ..................................................... 25
3.3 Full Version 1 track layout ............................................ 26
3.4 Tubing adapter detail .................................................. 27
3.5 Version 2 track detail .................................................. 29
3.6 Glider detail ............................................................. 30
3.7 Delta centrifugal blower ............................................... 31
3.8 Acrylic tube forming ................................................... 33
3.9 Version 3 track design ................................................. 34
3.10 Laser cutting plastics .................................................. 35
3.11 Version 4 track design ............................................... 37
3.12 A parallel tube air track .............................................. 39
List of Tables

1.1 Air supply specifications ........................................... 15
2.1 Symbol key .................................................................... 19
2.2 Pasco track specifications .............................................. 20
3.1 Version 2 air track performance .................................... 32
1 Past and Current Air Tracks

For the past fifty years, the air track has been used as an apparatus for enhancing physics education. The very low friction obtainable through the use of an air track allows for a very strong connection of collision theory and other physics principles to the real world. The ability to go back and forth between calculation and experimental result with high accuracy is one way to easily demonstrate to students the value that a knowledge of physics has even in everyday life. Although the value of the air track and other physics demonstrations is not disputed, many students still do not get a chance to interact with them due to their expense.

1.1 The MICA Project

The MICA (Measurement, Instrumentation, Control, and Analysis) Project is a system under development at the BioInstrumentation Lab at MIT to create a unified framework for lab-based education. Both sensors and data generators, such as the air track, are being created and integrated into the system. At the heart of the project is the MICA sensor hardware, a 25 mm sided cube packed with an assortment of sensors, and capable of real-time wireless data transmission to a laptop computer. The use of MICA sensor hardware greatly simplifies the collection of data from air track experiments, as the cubes themselves could be affixed to the colliding objects on the air track. The air track designs below were made specifically with the MICA Project in mind.
1.2 History of the air track

The air track used in force and motion experiments is a special type of aerostatic bearing. A similar type of bearing using liquid instead of air, the hydrostatic bearing, has been experimented with since the middle of the 19th century, but it was another century before the air track configuration most commonly used today was invented by Professor John L. Stull of Alfred University in 1964 [1]. Stull’s patent depicted a track formed from a hollow, triangular profile aluminum extrusion with orifices on two surfaces. The collision gliders, as he called them, took the form of inverted Y-shaped extrusions that straddled the two bearing surfaces of the track. Fifty years later, the three commercially available units evaluated below still use this basic track layout with minimal modifications. The biggest changes have been not in the mechanics of the air tracks, but in the way position data is recorded. The original track used a marker strip that could be colored by electrical pulses derived from a 60 Hz AC household power source [2]. This created distinct tick marks corresponding to the position of each glider over set intervals of time. The modern tracks use photogates or ultrasonic rangefinders in conjunction with a microprocessor to get velocity or position data [3]. The MICA system’s sensors could be used in addition to or in lieu of these sensors to collect motion data, further advancing the air track capabilities and making the air track package cheaper to produce and distribute by eliminating the need for standalone, single-purpose sensors.
1.3 Modern air track benchmarking

To better formulate the desired specification for the MICA air track and to guide the design of its aerostatic bearing, three commercial air tracks intended for educational use were examined. Models from Pasco, United Scientific, and Sargent Welch were evaluated for price, track dimensions, glider dimensions, and the specification of the air supplies used for each. The results are shown in Table 1.1.

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pasco</td>
<td>SF-9216</td>
<td>0.0170</td>
<td>870</td>
<td>$529.00</td>
<td>242</td>
</tr>
<tr>
<td>United Scientific</td>
<td>QAS001</td>
<td>0.0097</td>
<td>700</td>
<td>$256.24</td>
<td>N/A</td>
</tr>
<tr>
<td>Sargent Welch</td>
<td>CP33875-00</td>
<td>0.0097</td>
<td>600</td>
<td>$327.25</td>
<td>N/A</td>
</tr>
<tr>
<td>Sparkfun</td>
<td>COM-11270</td>
<td>0.0076</td>
<td>0</td>
<td>$4.95</td>
<td>10</td>
</tr>
<tr>
<td>Delta</td>
<td>BFB1212EH-A</td>
<td>0.0033</td>
<td>790</td>
<td>$28.27</td>
<td>34</td>
</tr>
<tr>
<td>Rigid</td>
<td>WD1851</td>
<td>0.0708</td>
<td>790</td>
<td>$219.99</td>
<td>4850</td>
</tr>
</tbody>
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Table 1.1: Compilation of air supply specifications. The first three entries are commercial units, and the last three are air sources used with prototypes [4, 5, 6, 7, 8, 9].

The full systems (including air track, gliders, and air supply) ranged in price from about $750 to $1250, making them prohibitively expensive for many school districts, particularly considering the limited, focused nature of applicable experiments that may be performed with the systems. The air supply specifications were fairly similar. The most powerful and expensive unit (the Pasco SF-9216) claimed sufficient capability to power two tracks simultaneously, appropriate considering it costs twice as much as the other two units. Another observation worth noting is that all three tracks are quite large, ranging from 1.5 to 2 m in length. The maximum estimated load the tracks could support based on the weights provided is between 5 and 10 times more than the minimum capacity necessary to support a MICA cube and a small amount of additional ballast weight if desired for experiments, implying that the MICA air track could be significantly smaller than the current models and still provide usable data. While basic information was available for all three units, more detailed data was
provided by Pasco about their products. This included the diameter of the orifices
used on their track and their spacing as well as detailed dimensions of the glider. In
fact, there is enough data to model the track according to aerostatic bearing theory,
providing a solid, well-tested reference to guide the design of the MICA air track.
2 Aerostatic Bearing Theory

2.1 Concept overview

In its most basic form, an aerostatic bearing consists of two surfaces separated by a film of pressurized gas, usually air. By eliminating contact between the two surfaces, they are allowed to move relative to each other with an extremely low amount of friction. The force exerted by the pressurized gas on the two surfaces supports them in a self-regulating manner, because as the gap between them increases, pressure and force drop, and inversely, if the gap is decreased, the gas pressure and force exerted increase. Because there is no seal along the periphery of the bearing, the pressurized gas is free to escape outward and the bearing pressure must be maintained by flow from a pressure source [10, p. 25].

![Diagram of an aerostatic bearing](image-url)

**Figure 2.1:** A section drawing of an aerostatic bearing in the configuration used for air tracks. The unpowered glider floats above the pressurized air track.

While most aerostatic plane bearings in industrial use take the form of a pres-
surized pad or glider moving along a solid, flat surface, the air track concept uses a solid glider on a pressurized track instead. This configuration is demonstrated in Figure 2.1. Since the pressurized portion of the bearing is stationary, complexity is reduced at the expense of efficiency. Instead of only feeding air into orifices in the active bearing surface of the pad or glider, all orifices along the track are pressurized at all times, even though only a fraction are actually supporting the glider as it moves along the track. For the purposes of creating a low friction environment for studying force and motion, efficiency is not as important as it would be in an industrial setting, so this is an acceptable trade-off.
2.2 Symbol key

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
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<tbody>
<tr>
<td>(a)</td>
<td>land width</td>
</tr>
<tr>
<td>(B)</td>
<td>bearing width</td>
</tr>
<tr>
<td>(L)</td>
<td>bearing length</td>
</tr>
<tr>
<td>(\tilde{A})</td>
<td>area shape factor</td>
</tr>
<tr>
<td>(\tilde{B})</td>
<td>flow shape factor</td>
</tr>
<tr>
<td>(W)</td>
<td>atatic bearing film force (load)</td>
</tr>
<tr>
<td>(p_a)</td>
<td>absolute atmospheric pressure</td>
</tr>
<tr>
<td>(p_r)</td>
<td>absolute recess pressure</td>
</tr>
<tr>
<td>(p_s)</td>
<td>absolute supply pressure</td>
</tr>
<tr>
<td>(p_r)</td>
<td>gauge recess pressure</td>
</tr>
<tr>
<td>(P_s)</td>
<td>gauge supply pressure</td>
</tr>
<tr>
<td>(q)</td>
<td>volume flow</td>
</tr>
<tr>
<td>(h)</td>
<td>bearing film thickness (gap size)</td>
</tr>
<tr>
<td>(\eta)</td>
<td>fluid viscosity</td>
</tr>
<tr>
<td>(\rho_a)</td>
<td>fluid density of air</td>
</tr>
<tr>
<td>(k_o)</td>
<td>choked flow constant for air</td>
</tr>
<tr>
<td>(C_d)</td>
<td>orifice discharge coefficient</td>
</tr>
<tr>
<td>(n)</td>
<td>number of orifices in bearing</td>
</tr>
<tr>
<td>(K_p)</td>
<td>absolute pressure ratio</td>
</tr>
<tr>
<td>(C_{kp})</td>
<td>orifice flow factor</td>
</tr>
<tr>
<td>(A_o)</td>
<td>orifice area</td>
</tr>
<tr>
<td>(d_o)</td>
<td>orifice diameter</td>
</tr>
</tbody>
</table>

*Table 2.1:* The meanings of the symbols used when discussing aerostatic bearing theory.
2.3 Theoretical bearing performance: Pasco track

Performance of an aerostatic bearing is based on two primary groups of parameters: those based on the geometry of the bearing surface \((a, B, L)\), and those based on the pressurized air supply \((P_s, P_r, q, h)\) [10, p. 69]. For the Pasco track, all of the aforementioned parameters are available. These can be used to see how well the track's specifications match design guidelines, figure out how close to the limits of the air supply the track is operating at, and calculate the optimal orifice diameter for the gas pressure and volume flow at maximum rated load.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>(a)</td>
<td>10 mm</td>
</tr>
<tr>
<td>(B)</td>
<td>129 mm</td>
</tr>
<tr>
<td>(L)</td>
<td>50 mm</td>
</tr>
<tr>
<td>(W)</td>
<td>3.92 N (max)</td>
</tr>
</tbody>
</table>

**Table 2.2:** The specifications of the Pasco air track [3].

From these we can calculate the land/width ratio to be

\[
\frac{a}{L} = \frac{10 \text{ mm}}{50 \text{ mm}} = 0.2,
\]

very close to the middle of the recommended range \(0.05 < \frac{a}{L} < 0.3\). The length/width ratio is

\[
\frac{B}{L} = \frac{129 \text{ mm}}{50 \text{ mm}} = 2.58,
\]

also safely within the normal range \(1 < \frac{B}{L} < 5\). These ratios were used with charts from the text to obtain an area shape factor \(\bar{A} = 0.72\) and a flow shape factor \(\bar{B} = 2.8\).
Consider that

\[ \tilde{A} = \frac{W}{P_r \times B \times L'} \quad (2.1) \]
\[ \tilde{B} = \frac{q \times \eta}{P_r \times h^3} \quad (2.2) \]

Using equation 2.1, the recess pressure can be found for any load. For the maximum recommended load, the track’s recess pressure would be

\[ P_r = \frac{\tilde{A} \times B \times L}{W} = 686.4 \text{ Pa.} \]

Using a typical 2:1 \( P_s : P_r \) ratio, \( P_s = 1373 \text{ Pa} \), significantly above the only given specification for the Pasco blower (no P-Q curve was made available). Using the flow shape factor in equation 2.2, the flow rate can be calculated for that recess pressure as follows:

\[ q = \frac{(p_r^2 - p_a^2) \times h^3}{2 \times \eta \times p_a} = 0.0033 \text{ m}^3/\text{s}, \]

well within the Pasco supply’s specification of 0.0170 m\(^3\)/min at 867 Pa, even considering the higher supply pressure.

Going further, optimal orifice diameter can be calculated, given a few constants for considering the orifice flow \( (k = 1.41, C_d = 0.96, n = 12) \), which are plugged into the following equations:
\[ K_p = \frac{p_r}{p_s} = 0.993, \quad (2.3) \]
\[ C_{kp} = \sqrt{\frac{k}{k-1}} \times [K_p^{\frac{\gamma}{k-1}} - K_p^{1+\frac{1}{k}}] = 0.0815, \quad (2.4) \]
\[ A_o = \frac{q}{n \times C_d \times C_{kp}} \times \frac{p_a}{p_s} \times \sqrt{\frac{\rho_a}{2 \times \rho_a}} = 0.270 \text{ (mm)}^2, \quad (2.5) \]
\[ D = \frac{A_o}{\pi \times h} = 0.858 \text{ mm}. \quad (2.6) \]

This orifice diameter calculation is very close to the actual diameter of 1 mm, supporting the idea that this track is well-designed and a good basis for future designs.
3 Air Track Design

3.1 Acrylic proof of concept

Proof that acrylic could be a suitable material for an air track comes in a basic form from the existence of a functioning aerostatic bearing demonstration made from two sizes of acrylic tubing. This bearing is shown in Figure 3.1. The main component of the demonstration is a long acrylic tube with four rows of small holes spaced evenly every 90 degrees along the circumference of the tube. The holes were quickly and precisely formed by a laser cutter. Over this tube a short section of a slightly larger tube is slid, with inner and outer diameters matched to leave a sufficient gap to allow air to pass between the two tube segments. One end of the long tube is capped and the other one is fed by the blower output of a Rigid 4850 W [6.5 HP] shop vacuum, supplying air through the central tubes holes to form a circular air bearing between the two pieces of tubes. While this simple demo is not constrained well enough to allow for the accurate examination of collisions, the basic concept of an air bearing surface formed from holes laser cut in acrylic is an appealing one. The use of acrylic over the conventional aluminum for the air track should lower material costs and the price of manufacturing by eliminating the machining step required for a metal-based air track.
3.2 Version 1: aluminum track

Version 1 of the air track was fairly simple and meant to be a testbed for experimentation with various air sources and loads. To allow for rapid construction and modification, the majority of the track was created from MK aluminum extrusion. In particular, the bearing surfaces were made up by two pieces of 45-degree profile extrusions arranged with the bearing surfaces facing each other in a V. This layout is depicted in Figure 3.2.

This was a deviation from the track designs examined, but the track still works in fundamentally the same way, with the two angled bearing surfaces each providing some vertical load support and some horizontal stabilization in opposition to each other. The V-shaped design was chosen because it better lends itself to cradling a MICA cube than the inverted Y-shaped gliders of the other tracks. It also proved to be slightly easier to construct out of the MK extrusion available. Another immediately noticeable difference was that the Version 1 track was much shorter and significantly smaller in bearing area than the benchmarked tracks. This choice was made for numerous reasons: the limited sizes of 45-degree aluminum extrusion offered by MK, to aid ease of construction of the prototype, and the fact that from calculation, the reduced bearing surface was still deemed sufficient to carry a MICA cube, the
primary load requirement. In addition to a reduced bearing surface, the Version 1 bearing orifice configuration was a very simple design. Instead of the two staggered rows of orifices used on the Pasco track, only a single row of vertically-centered orifices was used. This design simplified initial calculations for the bearing and construction of the track, but led to some weaknesses in the air track performance that will be discussed below.

The other vital component of an air track system is its air source. As discussed earlier in the theory section, one of the most significant differences between an air track and a conventional air bearing is in the air source requirements. This is because the entire track is lined with static orifices that need airflow, as opposed to a conventional blown pad with moving orifices, where only the pad needs airflow. This leads to difficulty in selecting an air source. It should be noted that it is not clear what mechanism is used in the air sources of the traditional air tracks, but all have similar specifications and a roughly cylindrical shape. The pressures desired for good load capacity are normally supplied by a pump, a miniature diaphragm pump
in the case of the MICA system. Unfortunately, no reasonably sized diaphragm pump could be found that could meet the high flow rate requirements of the many orifices of the air track. Conversely, most fans have sufficient flow rate but cannot begin to approach the necessary pressure. As a compromise, a centrifugal blower was selected to test with the air track, specifically a 10\( \text{W} \) model from Sparkfun. No P-Q graph was supplied with the chosen blower, so exact performance at high pressures was unknown, but the air source previously proven to work with the acrylic tube bearing, a 4850 W [6.5 HP] Rigid shop vacuum, was also available for testing. Details on these air sources can be found in Table 1.1.

The assembly of Version 1 of the air track was mostly straightforward due to the majority of the structure being made from aluminum extrusion. The orifices for the track were drilled manually on a mill with the smallest drill bit that the mill’s chuck could accommodate, 1.25 mm in diameter. This is slightly larger than the specification used on the Pasco air track, but the use of only one row of orifices on the Version 1 air track helped to compensate for the larger diameter. The rest of the track assembly was simple, using aluminum extrusion and the associated hardware.

![Figure 3.3: The full air track showing tube routing. It is pictured here with the Delta blower. The original circular adapter used with the Sparkfun blower is below in yellow.](image)

The biggest challenge in the construction of the Version 1 system was the connection between the air source and the track itself. The two lengths of chamfered...
extrusion already had a central circular hole, 10 mm in diameter, running the length of the track and connecting all of the holes drilled into the face of the extrusion. The Sparkfun blower had a 33 mm circular outlet. To connect to two, Tygon tubing was used in conjunction with a series of tube fittings as seen in Figure 3.3. Two types of tube fittings were non-standard and had to be designed and 3D printed on a Makerbot Replicator 2X: a neck down fitting reducing the 33 mm outlet to 9.5 mm to interface with the tubing, and two couplers with male M10×1.5 threads on one side and barbs for the tubing on the other, as can be seen in Figure 3.4.

![Figure 3.4: The adapters used to supply air to the Version 1 air track. They are 3D printed from ABS.](image)

Initial testing of Version 1 of the air track proved to be disappointing. Three different objects were used as gliders: a bare MICA cube, a 50 mm length of aluminum cut from 25 mm×25 mm square stock, and a 125 mm length of aluminum cut from the same stock. None of the three gliders showed any signs of reduced friction upon initial testing with the Sparkfun blower. The experiment was repeated with the Rigid shop vacuum, and even though airflow was markedly stronger at the surface of the track when blown with the overpowered air source, the track still failed to function.
Three possible sources of problems were identified. Firstly, the air source, particularly the Sparkfun blower, may have been underpowered, a problem exacerbated by the significant flow restriction created by the narrow tubing connecting the blower to the air track and the narrow diameter of the air track’s center channel, an inherent limitation. Since the extremely powerful Rigid also failed to work, this could not be the only issue, but it could be a contributing factor. Next, the glider selection may have been inappropriate, especially considering that the flow restriction encountered would decrease the actual load capability compared to the assumptions made for the bearing calculations. The MICA cube likely presented insufficient surface area to the V-track to support its mass, and the aluminum gliders could have been too heavy for an air track system with such heavy flow restriction. Finally, the change in bearing orifice layout eliminated the virtual recess formed between the two rows of orifices on the Pasco track. This theoretically would increase the load capacity of the bearing, but the lack of a real recess in the bearing or glider resulted in uneven pressure distribution and poor load capacity.

To test the source of the problem, a physical recess was milled into two faces of the 50 mm length aluminum prism. With this modification, the track still didn’t work when powered with the Sparkfun blower, but it did when powered from the Rigid shop vacuum. The recess enhanced the pressure distribution along the glider-track interface enough to support the aluminum mass. The experiment also served to confirm that the Sparkfun blower was not powerful enough to drive the track, at least not with the amount of flow restriction present in the Version 1 track.

3.3 Version 2: aluminum-acrylic hybrid

With the basic concept for the V-configuration air track proven to work, Version 2 was intended to allow for rapid testing of different orifice layouts without having to machine a new length of aluminum for each test. To accomplish this, the original
Version 1 aluminum track was turned into a hybrid aluminum-acrylic track. A close-up of the Version 2 track can be seen in Figure 3.5.

![Figure 3.5: A close-up of one of the sets of acrylic tracks used for the Version 2 prototype air track.](image)

The original air tubing setup remained unchanged, but a Trotec laser cutter was used to cut thin sheets of acrylic to the shape of the bearing surface of the chamfered extrusion [11]. These sheets were affixed to the extrusion over the top of the machined holes with double-sided tape. Each pair of acrylic sheets had a different orifice layout cut into it for experimentation. The underside of the sheets had a shallow pocket cut into them and the original orifices in the chamfered extrusion were also bored out to attempt to mitigate flow restriction. This setup successfully allowed for the testing of different bearing configurations and the suitability of acrylic as the bearing surface in general.

In addition to interchangeable acrylic sheets, the Version 2 track was tested with various new gliders and a new air source. In addition to the pocketed aluminum glider that worked in the previous test, three V-shape gliders were 3D printed to provide some lighter gliders for testing: one made of sanded ABS with a physical recess, and
two more made of PLA with no recess. One of the PLA gliders was also sanded to remove surface imperfections from the printing process. All three plastic gliders were V-shaped with a length of 50 mm along the axis of motion of the glider and leg lengths of 25 mm each. These are shown in Figure 3.6.

![Figure 3.6: Four of the gliders used when testing the Version 2 air track. Note the difference in surface finish between the two PLA gliders on the right.](image)

After the Sparkfun blower was destroyed in a maximum airflow test, a larger centrifugal blower was needed. The unit purchased was a Delta BFB1212EH-A, a larger unit with a 30 W rating, three times greater than the Sparkfun blower. The new blower had a 32 mm × 64 mm rectangular outlet instead of the smaller circular outlet found on the Sparkfun blower. An adapter plate was 3D printed that screwed onto the bottom of the blower and reduced the outlet size to fit the tubing carried over from Version 1 of the air track, as seen in Figure 3.7b.

The four gliders were then tested with six different bearing configurations with various hole spacing and diameters. All but one of the configurations used two rows of orifices to create a virtual recess; one used three rows in an attempt to create...
a more even pressure distribution along the underside of the gliders. The use of acrylic allowed for the holes as small as 0.8 mm in diameter. The most notable initial observation was that the aluminum glider with the large pockets milled in it no longer worked on any of the new tracks. The combination of a physical recess and virtual recess seemed to increase the apparent recess volume to a level that couldn't support the mass of the aluminum glider. The ABS glider with a shallow pocket was light enough that it was supported by the more successful track profiles, but the combination of large apparent recess volume and low mass of the ABS glider resulted in a phenomenon known as pneumatic hammer, where the recess volume is too large for the amount of orifice flow through the bearing and the bearing gap size fluctuates rapidly, making the glider appear to vibrate unsteadily [10, p. 6]. The unsanded PLA proved to be unsuitable because the surface roughness of the plastic was too high to maintain a consistent gap size, but the sanded PLA glider with no pocket performed very well. Three of the six bearing configurations didn't work at all, including the three-row variation, and the other three (B, E, and F) were compared back to back with the sanded PLA glider to see how much mass they could support. The results are contained in Table 3.1.

It was clear that even the new blower was struggling to power any configuration of Version 2 of the air track; the extra layer of acrylic only made the flow restriction worse, despite the aforementioned attempts made to mitigate it. Useful information
had been obtained about the efficacy of various track layouts, but to achieve better results, a new design was needed. The 10 mm inner diameter of the chamfered aluminum extrusion was simply too small to supply sufficient airflow to the track. For comparison, all three of the commercial units had 30 mm diameter hoses connected directly to a large central cavity that fed both bearing surfaces, one advantage a triangular (inverted V) track has over the extrusion-based upright V shape used in the first two versions of the homebuilt air track. Furthermore, to make the track as affordable as possible, it was highly desirable to avoid the use of any aluminum and construct the entire track from acrylic.

### 3.4 Version 3: acrylic V track

The design of Version 3 of the air track was an initial attempt to preserve the V-track design with a fully acrylic construction. A primary concern was the flexibility of the acrylic bearing surface without aluminum supporting it and the difficulty of getting a precise right angle formed from acrylic. Further complicating the construction of a full acrylic track is the limited range of profile shapes available for acrylic stock. One idea that was considered early on in the design process was that of heat forming a V-shaped indentation into a large acrylic tube. This was appealing because the main body of the air track would be all one piece instead of various sheets adhered to each other, as demonstrated by Figure 3.8.
This method of forming the track proved to be unfeasible with the equipment available. While an initial test with a very short length of tube was fairly successful, longer lengths couldn’t be uniformly heated quickly enough to become easily formable. Unlike ABS and polyethylene, common plastics used in thermoforming, acrylic sheets of the desired thickness could not be heated sufficiently for good forming with a heat gun. Specialized equipment such as an infrared heater or forced-air oven would be required to form acrylic, and even then the recommended minimum radius of curvature of any bend is 200 times the thickness of the sheet, too large to make a good V-track bearing [12]. Instead, a design was created that consisted of a piece of V-track adhered to a series of flat pieces of acrylic to form a large box profile with a V notch in one side, depicted in Figure 3.9.
The size of the box section of the track was designed to fully encompass the outlet of the Delta blower for unimpeded airflow. The initial Version 3 design required pre-formed V profile acrylic, which was not available from the normal materials suppliers used. Instead, an order for acrylic V-track was placed with a company specializing in display products. After all the flat pieces of the Version 3 track were cut, the bearing profile was ready to be laser cut into the V-track. The profile was modified slightly from the one used in the Version 2 experiments to reflect the discoveries made upon detailed analysis of the Pasco air track; these changes are detailed in a later section. Upon attempting to laser cut the V-track, the material was discovered to be not acrylic, but rather polycarbonate. As demonstrated in Figure 3.10, polycarbonate does not cut well and tends to melt instead of vaporize, leaving a poor surface finish and inconsistent hole size when cutting small diameter holes.
Figure 3.10: Macro photographs of two polycarbonate holes followed by two acrylic holes. The holes were laser cut to a diameter of 1 mm. Note the melted material around the polycarbonate holes, particularly the partial blockage of the second hole.

Despite various attempts, no combination of settings could be found that worked well enough to use the polycarbonate V-track. Further searches completely failed to find a suitable supplier of acrylic V-track, making it extremely difficult to construct a working model of the Version 3 air track.

3.5 Version 4: acrylic box track

Although the V-track concept initially seemed like a convenient way to cradle the MICA cube securely for use in force and motion experiments, two main factors make it unfeasible for application to a purely acrylic air track. The first and more obvious of the two is the lack of availability of preformed acrylic in the shapes required to
simplify the construction of the air track. Without a ready source of accurately formed acrylic angle stock, forming a V-track from acrylic would require the manual alignment and fixture of many flat sheets, making it harder to offer the product at an affordable price. Furthermore, the concave profile of the V-track makes it challenging to create a track where both bearing surfaces share a single air cavity. Flow restriction is one of the major problems encountered when making a scaled-down air track, and using a convex triangular or square profile would also greatly simplify the design and manufacturing of the track. Furthermore, besides a slight decrease in the size of the glider required, there are few obvious benefits of the V-track design over the traditional styles. Considering these factors, a fourth design was created with a more traditional profile, visible in Figure 3.11. This design was built around the acrylic square stock available from McMaster-Carr [13].

The largest acrylic square profile tubing available measured 50.8 mm [2"] to a side with a wall thickness of 3.175 mm [1/8"], large enough to accommodate 90% of the Delta blower outlet with only minimal restrictions along the corners of the outlet. The Version 4 design combines the large central air channel of the Version 3 concept with simple construction using off-the-shelf components wherever possible. Even custom parts such as the acrylic legs and the adapter plate between blower and track are designed to be quickly laser cut out of acrylic stock, minimizing the amount of manual machining and assembly required.

Unfortunately, the Version 4 air track's performance was crippled by the acrylic stock available. The tube ordered had an outside and inside tolerance of 0.381 mm [0.015"] and it appeared to be close to this tolerance limit at the midpoint of each side, where the sides all bowed inwards considerably. A variation of less than half a millimeter may seem inconsequential at first, but since the volume flow rate of an aerostatic bearing is proportional to the cube of the bearing gap, even minute changes in the air gap can affect the stability and performance of the bearing. The 2 m Pasco track claims to be straight to within 0.04 mm along its length, a number which is
crucially less than half of the track's specified bearing gap of 0.1 mm [3].

In spite of the dimensional variance, it was decided to attempt to create a prototype track anyway. Laser cutting the acrylic was fairly straightforward except for the fact that that laser would cut through the top layer of the square profile and then start to melt the lower acrylic layer with its unfocused beam. Putting some kind of protective sheet in the center of the acrylic tube while cutting could prevent this from happening, although the damage was purely cosmetic and would not have affected the performance of the air track. After cutting the track, a quick test with the shop vacuum demonstrated extremely good airflow through the unobstructed center section of the track. However, when gliders were tested on the track's surface the gap was clearly too large for the track to function properly.
One idea was to cut a separate length of the square tubing in half diagonally to obtain a glider with a matching variance in shape, but the act of cutting the tubing in half appeared to relieve enough stress in the acrylic that the cut pieces were a significantly different shape than they were before being separated, rendering them unusable for the Version 4 air track and preventing the completion of the prototype. In lieu of experimental data, theoretical calculations were made to estimate the load capacity of the track at different pressures. This determined the maximum load and pressure the Delta blower would be able to support while still maintaining sufficient air flow to fully supply the track.

3.6 Other potential designs

The lack of acrylic stock available in the appropriate sizes and tolerances necessary to create a high-quality air track is the largest unresolved issue remaining for acrylic air track designs. In addition to the Version 4 air track design, two other designs were considered to try to mitigate this problem. While neither was developed enough to attempt the construction of a prototype, their inclusion may be useful for those considering future work.

The first of these is a design that would be very similar to the Version 3 air track, but of a simpler profile. Instead of a V track, the bearing surfaces would be oriented with the Version 4 track and commercial tracks. This would allow the track to have a triangular profile, greatly reducing the number separate acrylic pieces that would have to be joined. Such a design could also easily be made large enough to accommodate the large rectangular outlet of the Delta blower.

38
The second design is based on the tubular aerostatic bearing examined earlier. The acrylic tubes available have tighter tolerances than any other acrylic stock except for flat sheets and the rotational symmetry of a circular cross section further helps mitigate the problems exhibited by the square cross section used in the Version 4 design. However, a tubular glider has no constraint on its rotation. One solution could be to use two tubular bearings in parallel, a concept demonstrated in Figure 3.12. This could reduce the difficulty of construction by allowing for the use of preformed acrylic tube in the same way the Version 4 design could.
4 Design Evaluation

Two of the many configurations designs were evaluated: the one with the best experimental load capacity, and the one designed to have the highest theoretical load capacity. The same equations used earlier when working with the Pasco track can be used to predict performance for comparison with actual results after real world testing.

4.1 Version 2 track, profile B

4.1.1 Theory

The parameters of the bearing and air supply are found to be as follows:

Bearing geometry: $a = 8 \text{ mm}, \ L = 20 \text{ mm}, \ B = 50 \text{ mm},$

Air supply: $P_s = 785 \text{ Pa}, \ q_{\text{max}} = 0.0033 \frac{\text{m}^3}{\text{s}}$ at 785 Pa.

With these dimensions, $\frac{a}{L} = 0.4,$ which is very large and may induce uneven pressure distribution, but $\frac{B}{L} = 2.5,$ which is average for this type of bearing. From this we can get an area shape factor $\bar{A} = 0.5$ and a flow shape factor $\bar{B} = 0.9.$ From there, we can use Equations 2.1 and 2.2 to find the performance of the bearing:
\[ W = A \times P_r \times B \times L = 0.241 \text{ N}, \]
\[ m = 0.0246 \text{ kg} = 24.6 \text{ g (insufficient)}, \]
\[ q = 2.0 \times 10^{-5} \frac{\text{m}^3}{\text{s}} \text{ for bearing surface}, \]
\[ q = 15 \times 10^{-5} \frac{\text{m}^3}{\text{s}} \text{ for whole track}. \]

This flow rate requirement is only 5% of the maximum flow rate at this pressure.

4.1.2 Experimental performance

In reality, the maximum load supported by the track was only 15 g, barely half of the theoretical prediction. Since the track was known to suffer from flow constriction, the effective source pressure for that load can be calculated using Equation 2.1:

\[ P_r = \frac{W}{A \times B \times L} = 239 \text{ Pa}, \]
\[ P_s = 479 \text{ Pa}. \]

This indicates that flow restriction was so bad with the convoluted tubing and adapter setup that there was a pressure drop of over 45% compared to the theoretical performance of the Delta blower with that bearing configuration.

4.2 Version 4 track

Only theoretical performance is calculated for this track because it was not constructed.

4.2.1 Theory

Bearing geometry: \( a = 10.4 \text{ mm}, L = 50.8 \text{ mm}, B = 75 \text{ mm}, \)
Air supply: \( P_s = 785 \text{ Pa}, \ q_{max} = 0.0033 \frac{\text{m}^3}{\text{s}} \) at 785 Pa, \( 0.0010 \frac{\text{m}^3}{\text{s}} \) at 588 Pa.

These numbers yield \( \frac{q}{B} = 0.205 \), which is average, and \( \frac{B}{L} = 1.48 \), a slightly low value that may have a negative impact on volume flow efficiency. These values result in an area shape factor \( \bar{A} = 0.68 \) and a flow shape factor \( \bar{B} = 1.5 \). We again use Equations 2.1 and 2.2 to evaluate the bearing:

At 785 Pa:

\[
W = \bar{A} \times P \times B \times L = 1.25 \text{ N},
\]

\[
m = 0.1276 \text{ kg} = 128 \text{ g},
\]

\[
q = 3.2 \times 10^{-5} \frac{\text{m}^3}{\text{s}} \text{ for bearing surface,}
\]

\[
q = 23 \times 10^{-5} \frac{\text{m}^3}{\text{s}} \text{ for whole track.}
\]

At 588 Pa:

\[
W = \bar{A} \times P \times B \times L = 0.94 \text{ N},
\]

\[
m = 0.096 \text{ kg} = 96 \text{ g},
\]

\[
q = 2.3 \times 10^{-5} \frac{\text{m}^3}{\text{s}} \text{ for bearing surface,}
\]

\[
q = 18 \times 10^{-5} \frac{\text{m}^3}{\text{s}} \text{ for whole track.}
\]

These results show that the Version 4 air track using the Delta blower can support a load that is more than sufficient to carry a MICA cube and extra ballast weight for experimentation.
5 Conclusion

While the acrylic air track concept still requires development, it is still very promising. Throughout iteration of the design, many problems were identified and solved to varying degrees. These include determining the optimal profile, selecting an appropriate air source, dealing with flow restriction issues, and working with imperfect acrylic stock. Even the problems that were not completely solved were by no means insurmountable, and much progress was made toward a methodology for designing and evaluating future designs. The development of the design led toward the creation of a fully acrylic track with a convex cross section and optimized bearing profile, driven by a relatively small and cheap centrifugal blower, and easily capable of supporting the mass of MICA sensor hardware. The feasibility of the concept is clear and has potential to help improve lab-based education for students everywhere.
Bibliography


