

Hovercraft

This is a hovercraft I built for a Science Olympiad engineering event, the second iteration of a device that won first place nationally.

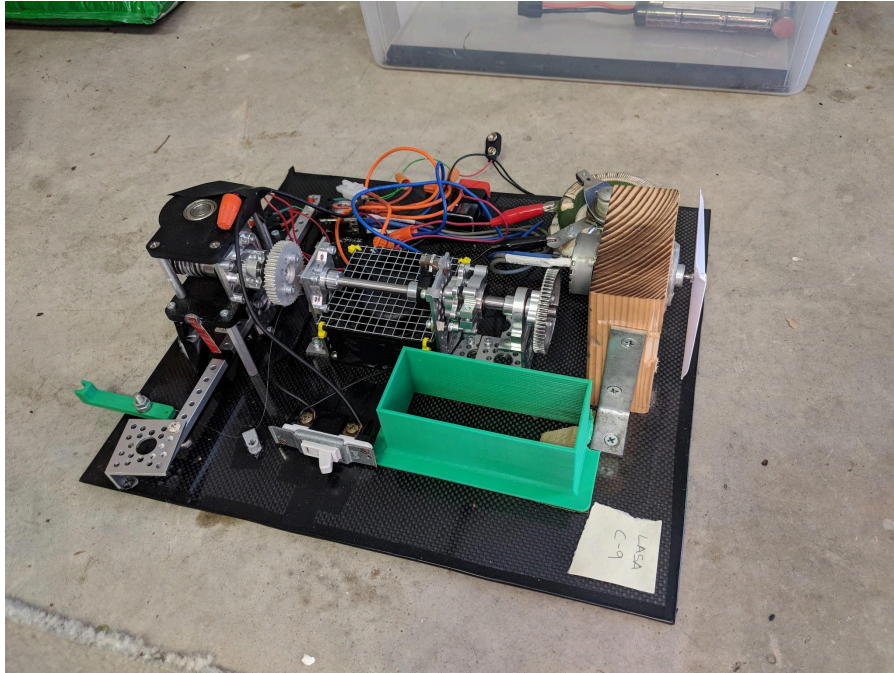
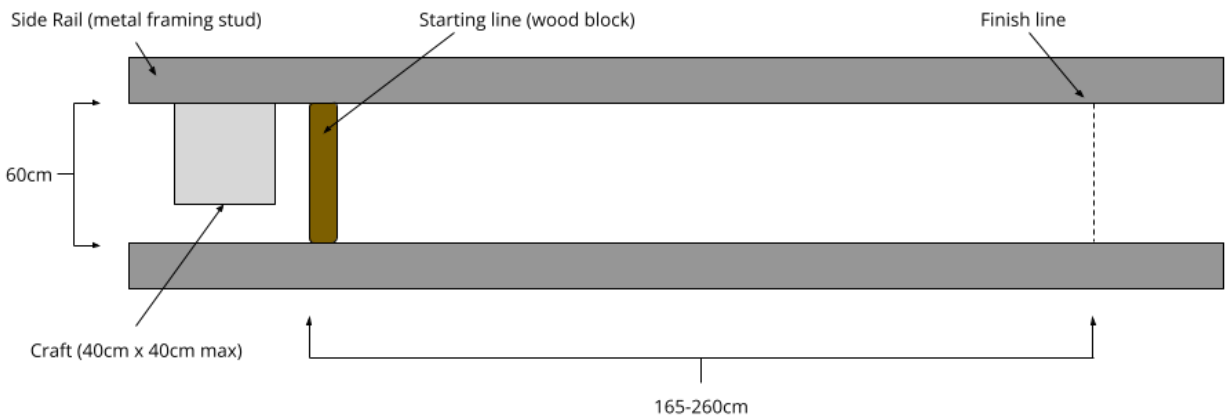


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The Challenge



A diagram of the track.

Construction Parameters:

- Build a device that levitates on a cushion of air and moves down a track using at most two brushed motors and two propellers/impellers.
- The device must fit in a 40cm x 40cm x 40cm cube at all times.
- The only electronic components permitted are batteries, wires, motors, switches, resistors, potentiometers, capacitors, and mechanical relays (no transistors, diodes, or integrated circuits).
- All of the energy used for the operation of the device must come from the batteries.
- The device must carry 16 rolls of 50 US pennies each (approximately 2kg).

The Track and Challenge:

- The track must consist of two side rails at least 3cm high (typically 2x4 metal framing studs) placed 60cm apart.
- At the start of a run, after the competitor is told the track length, the device must be configured, switched on, and press against the starting block on its own. The competitors must not touch or control the device in any way from this point forward.
- When the starting block is removed, the device must traverse the length of the track, which varies from 165-260cm, in **as close to 15 seconds as possible**.
- Time is measured by photogates placed right after the starting line and at the finish line. The device must include a ¼" dowel extending vertically upwards to activate the photogates.
- The device must not stop moving for more than 3 seconds at any time, or a run is declared over.
- The competitors get 2 successful runs, and the best time of the two is taken.

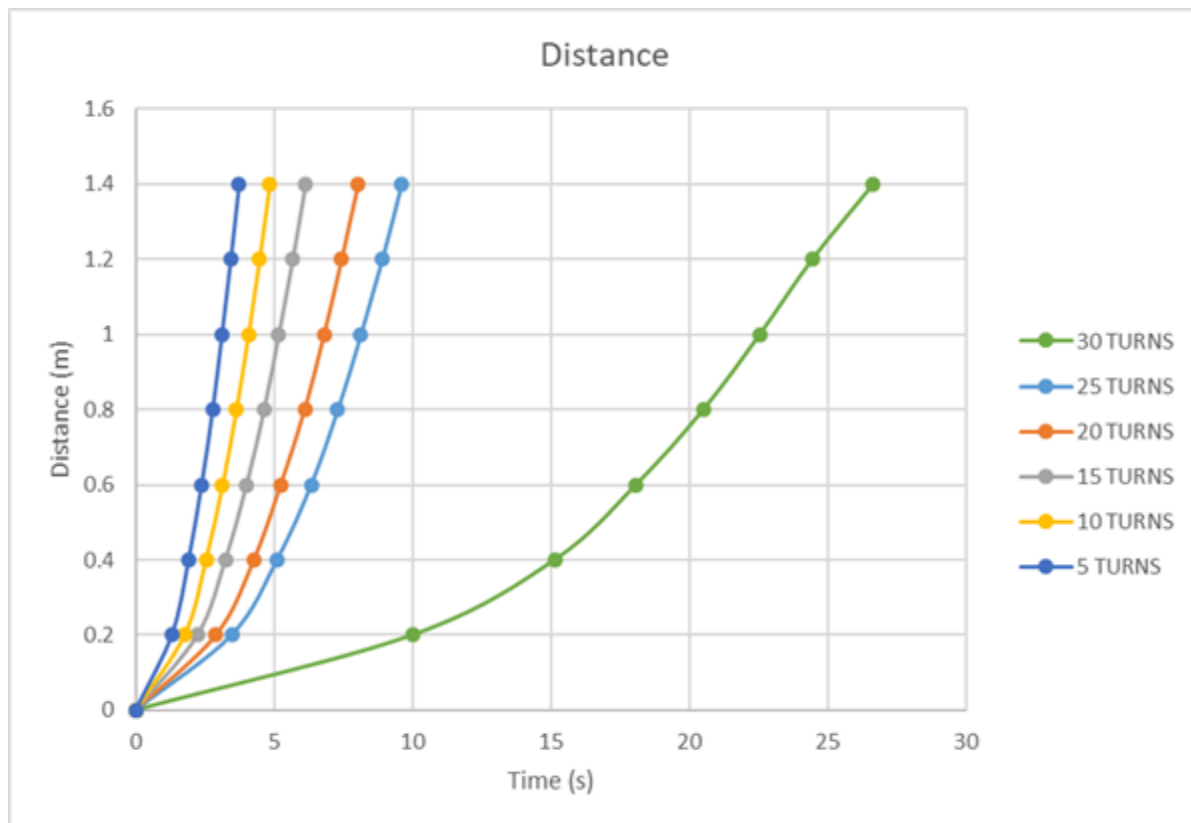
Levitation & Basics



The bottom of the device, with the skirt and fan visible.

- The final device turned out to be **over 4kg** with the pennies. Luckily, the problem of levitating that much weight was largely solved during last year's challenge, and proved not to be a huge difficulty.
- The lift fan was a very powerful Orion computer cooling fan powered by an 8.4V NiMH battery. The datasheet listed 971.5 Pa as the static pressure, which over a 40cm x 40cm area could lift **15.9kg as a theoretical maximum**.
- The skirt was made out of a 2-gallon ziploc bag, with a circle cut out of the middle where the fan was mounted.
- The electrical tape holding down the edges of the circle allowed air to escape out from under the skirt, greatly reducing friction.
- The asymmetrical pattern of tape caused more air to escape from one side than the other, holding the craft against one of the side rails and preventing it from drifting side-to-side or rotating when traveling forward.
- Most working aspects of this skirt design were found empirically, through much trial-and-error.
- The base plate was made out of **1.5mm-thick bidirectional carbon fiber weave**, in order to provide maximum tensile strength with minimum weight.
- The thrust fan (not pictured, on top of device) was a 2-blade quadcopter propeller mounted to a simple 12V brushed DC motor powered by the same battery.

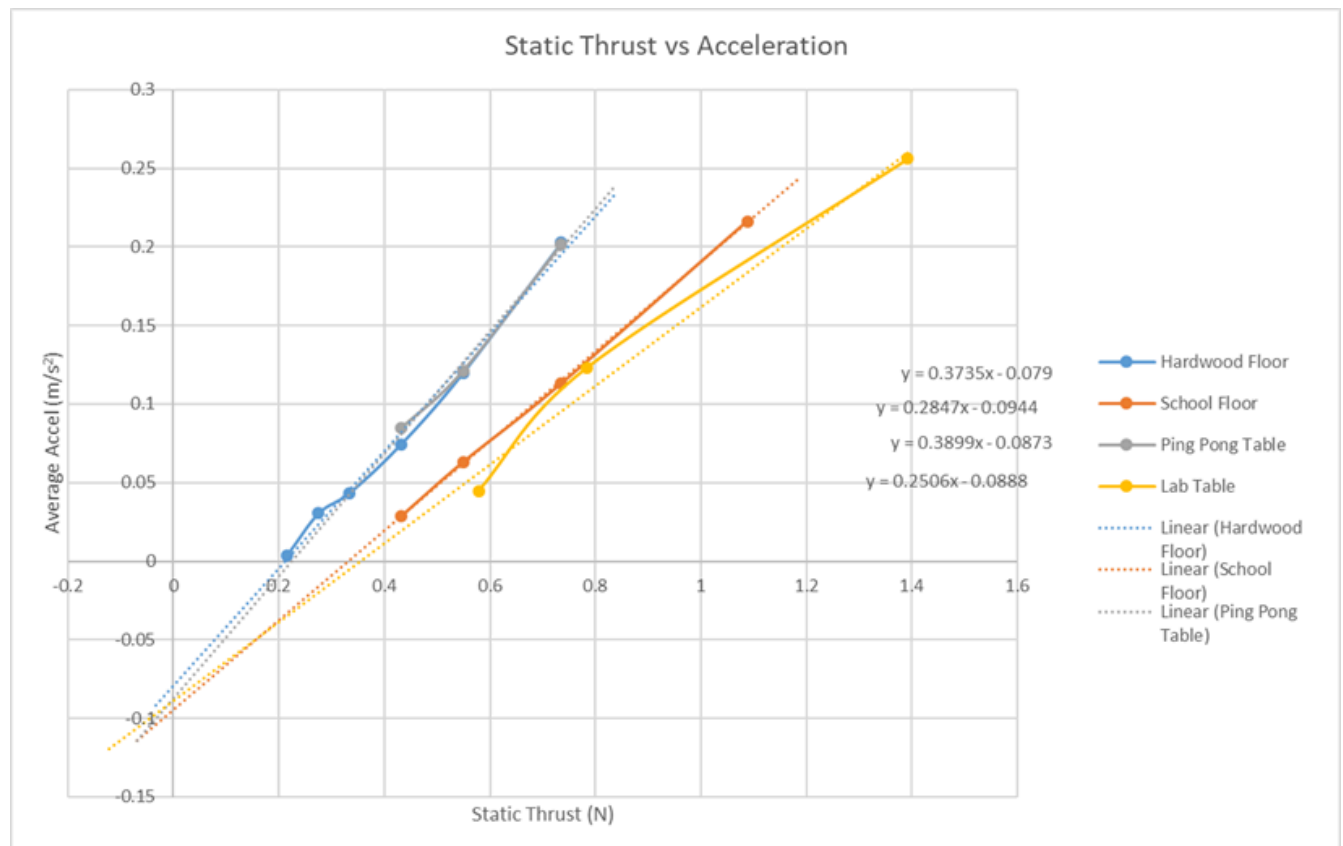
Design Rationale: Previous Strategy (Adjustable Thrust)



Time vs. distance curves for different potentiometer settings for only one surface tested with last year's device.

- **The primary challenge was to build a device with a precisely configurable speed**, in order to always traverse the variable-length track in exactly 15 seconds.
- An easy solution, which I employed in last year's challenge, was to regulate the voltage on the thrust motor using a potentiometer, and thus the speed of the craft. It then became a matter of testing the device and analyzing data at different settings (see above figure) on different surfaces in order to improve accuracy.
- However, the input value I was varying (resistance) goes through many complicated transformations that depend on many factors before it affects the target value (time taken to traverse the track). Converting a track distance back to a resistance setting was therefore a difficult regression problem on a complex function with a lot of parameters. Ultimately, as with any real system, my model had to have a lot of simplifications and assumptions that didn't hold up perfectly in practice.

Design Rationale: Previous Strategy (Adjustable Thrust)

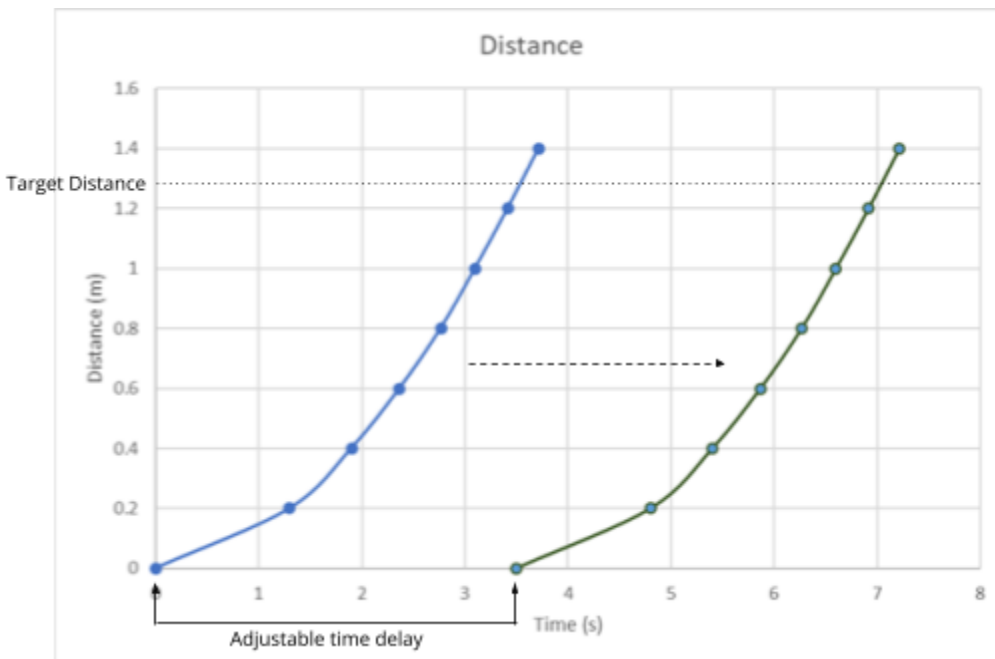


Static thrust (controlled through potentiometer resistance setting) vs. average acceleration (still an approximation, since acceleration was not constant) on slightly different surfaces tested with last year's device.

- In addition, there remained a huge amount of variance caused by the difference in track surfaces that was impossible to eliminate (see above figure).
- Even on well-made, level, smooth surfaces, achieving consistent accuracy within 1 second was essentially impossible.¹

¹ Almost every other team employed the same potentiometer solution, so using a combination of extensive data-taking (including thrust readings), data analysis, and more than a little bit of good fortune, last year's device still managed to win first place nationally. However, as I knew everyone else would refine that solution and improve their own data-taking and data analysis, I realized I had to come up with something better if I wanted to ensure I could do the same again.

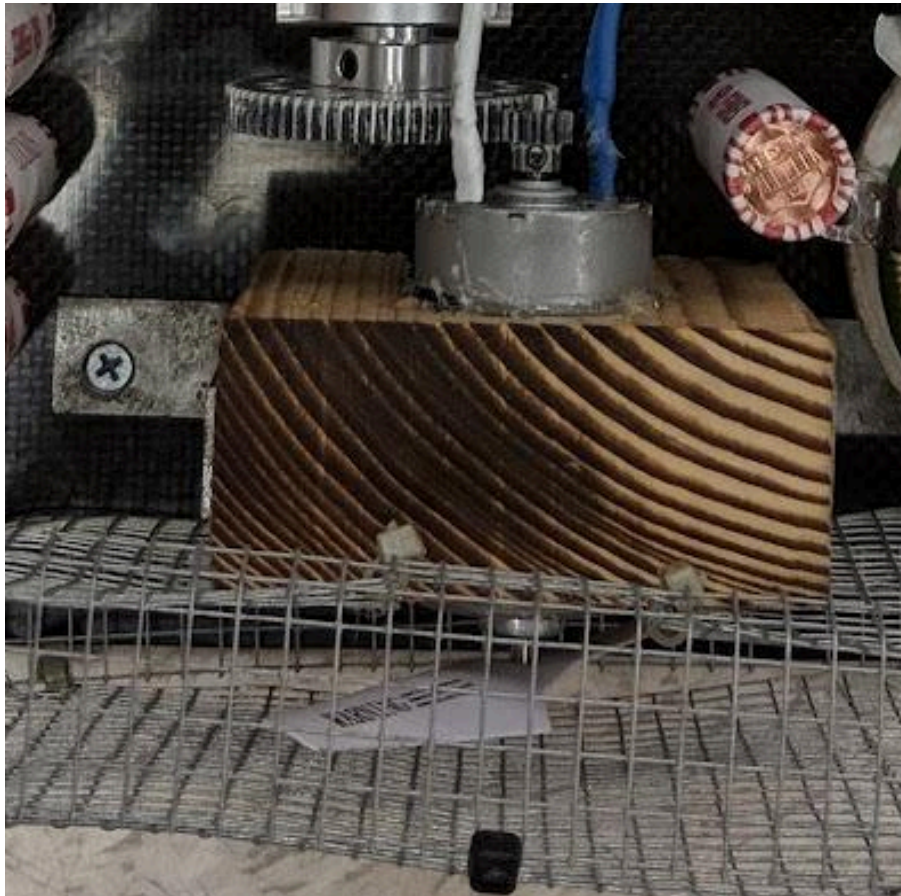
Design Rationale: New Strategy (Adjustable Delay)



The theoretical working principle of the new device.

- For the next year, I realized that most of the challenge came from trying to control the target value (time) using an input value (resistance) hidden behind complex physics that was affected by many unpredictable factors (like track surface).
- I realized that the way to eliminate the most variance would be to **control the target value (time) more directly**.
- A device could achieve this if, instead of having a variable thrust/acceleration/speed, it had a **variable "delay" at the beginning of the run**, simply shifting the entire time/distance curve to the right (see above figure).
- If I only had one attempt, I would still have to figure out where the distance curve intersected the target distance ahead of time, which would make the strategy pointless.
- However, the competitor gets two attempts, and the time from the first attempt is given to the competitor. Therefore, I can **"correct" any error from the first run by adjusting the time delay**. For the most part, as long as the thrust and the surface is consistent, the distance curve will remain the same. That means I can use any thrust value and not worry about the actual time/distance curve—instead, based on the intersection point from the first run, I can simply shift the whole curve to the left or right in order to make it intersect the target distance at exactly 15 seconds.
- Giving the device an adjustable delay at the beginning of the run while staying within construction parameters turned out to be a significant engineering challenge.

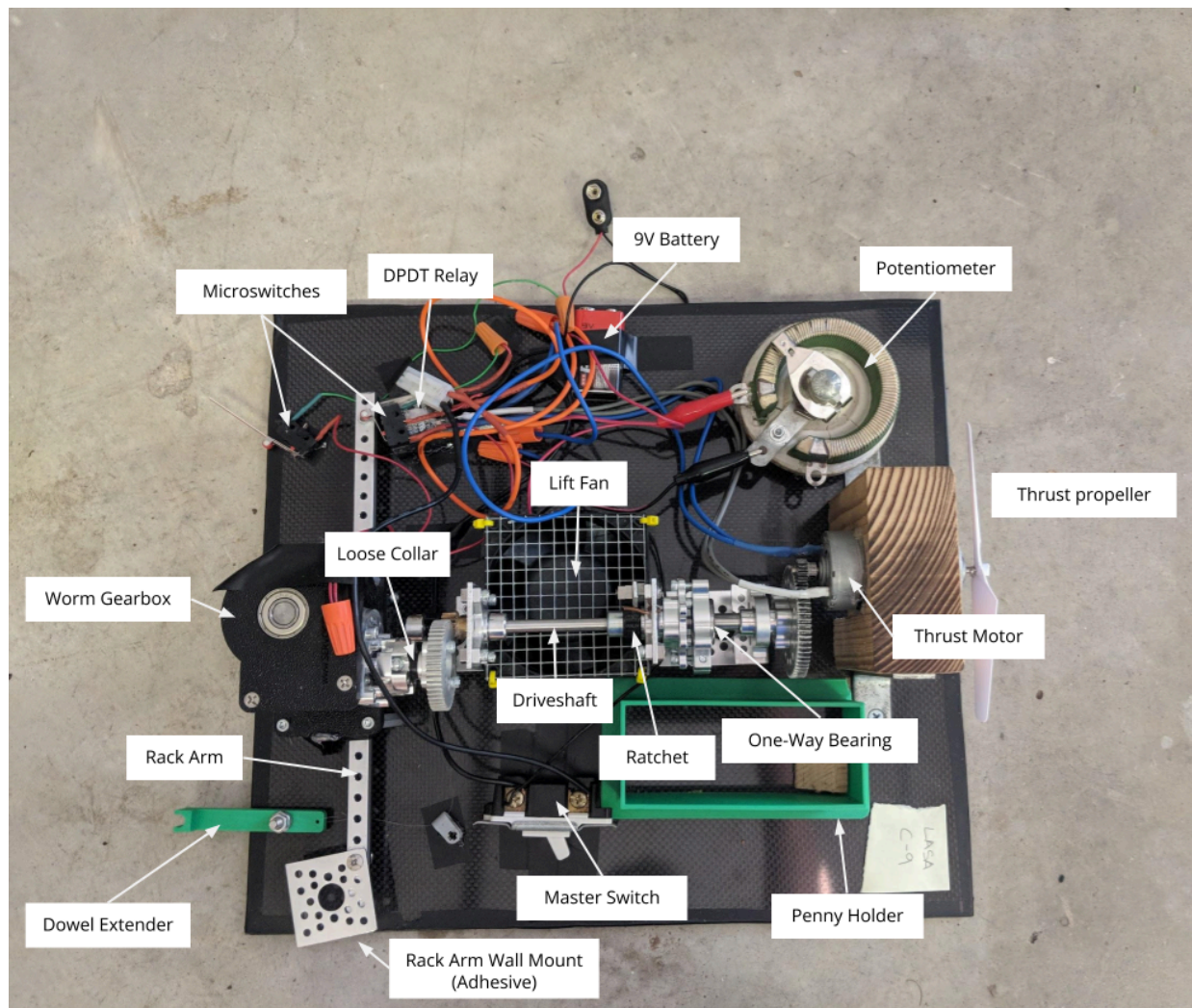
Design Rationale: Implementing Adjustable Delay



Thrust motor from above. The propeller (surrounded by wire shielding) is visible at the bottom; the small 9-tooth gear that serves as the first step of the drivetrain is visible at the top.

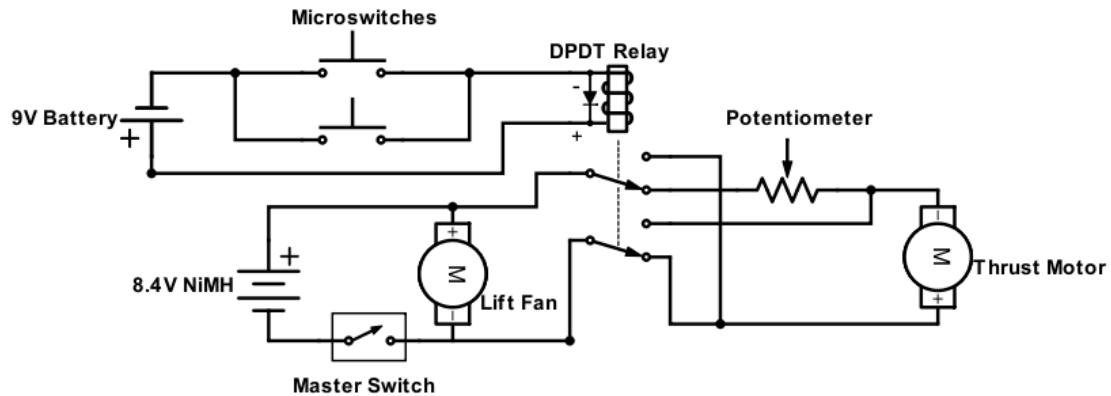
- The rule prohibiting integrated circuits or transistors eliminated the possibility of any electricity-based timers.
- The rule prohibiting energy sources besides batteries eliminated the possibility of any spring-driven mechanical timers.
- The rule prohibiting more than two motors eliminated the possibility of any separate electromechanical timers.
- The only remaining possibility was an **electromechanical timer driven by one of my existing motors**. The obvious choice was the thrust motor, since the lift motor was buried within a fan chassis and would be impossible to extract energy from.
- As such, I replaced my thrust motor with an identical dual-shaft one, so that I could keep the propeller on the main shaft and put a gear on the backshaft to drive the rest of the timing mechanism (see image).
- The rule preventing the device from stopping for more than 3 seconds during a run meant that the timing mechanism **would also have to ensure that the device moved at least every 3 seconds** throughout the delay period.

Device Diagram



- The drivetrain consists of:
- **Thrust motor** → 1st gear reduction → **one-way bearing** → **driveshaft** → 2nd gear reduction → **worm gearbox** (3rd gear reduction) → **rack arm**.
- The total gear reduction of the drivetrain up to the pinion that drives the rack arm is **630:1**. The necessary gear reduction was estimated before designing the drive train by measuring the thrust motor's speed with a photogate.
- The 8.4V NiMH main battery is not pictured, but it is attached by velcro to the front of the device (left side of diagram) in front of the worm gearbox.

Wiring Diagram



- The lift fan is always on as long as the master switch is on.
- When neither of the microswitches are pressed, the thrust motor runs **backwards (reverse polarity)** with the potentiometer reducing the voltage.
- When either of the microswitches are pressed (inclusive OR), the relay is powered, the relay switches throw, and the thrust motor runs **forwards (normal polarity)** at full power without any current running through the potentiometer.

Principle of Operation

[Here is a video of the entire mechanism working.](#)

[Here is a close-up of the rack arm moving at constant speed, then stopping when it triggers the second microswitch.](#)

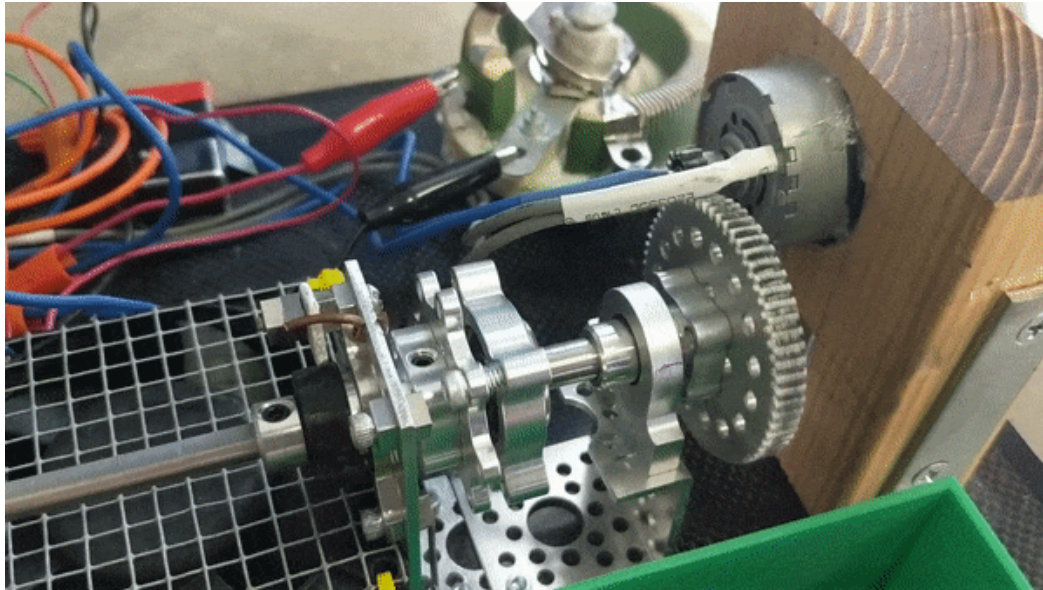
- At the beginning of the run, the device is levitating and pressed against the starting block, parallel to the track, with the rack arm extended and **attached to the side wall** using adhesive (double-sided tape).
- The presence of the wooden starting block activates one microswitch on the front of the device, so the **thrust fan is spinning forward at full power (normal polarity)**. This keeps the device pressed against the starting block. The driveshaft, and thus the rack arm, do not move due to the ratchet mechanism.
- **When the block is removed**, the microswitch is deactivated and the thrust fan immediately switches directions to **spin backwards at reduced power (reverse polarity)**.
- Due to the backwards thrust from the fan, the device pivots such that a bearing mounted at the back left corner also touches the side wall. However, the front left corner stays at the start line, since the rack arm is stuck to the wall.
- **The ratchet mechanism allows the driveshaft to turn**, causing:
 - **The dowel at the front left corner to swing outward**, activating the starting photogate just in front of the start line (and starting the time).
 - **The rack arm to slowly move inwards**. This pulls the entire device towards the side wall such that it continuously moves.
- Once the front left corner of the device reaches the side wall, a bearing mounted there contacts the wall instead of the rack arm. The rack arm **pulls itself off of the wall**, de-attaching the adhesive.
- Immediately afterwards, the other (right) side of the rack arm activates another microswitch. This immediately switches the direction of the motor to again **spin forwards at full power (normal polarity)**. The ratchet mechanism again prevents the driveshaft from turning, and the rack arm stops moving.
- The device traverses the length of the track at its maximum speed, riding along the two bearings on its left side and crossing the finish line some amount of time later.
- For the second run, **the starting delay time is adjusted by adjusting the starting position of the rack arm**.

Remarks:

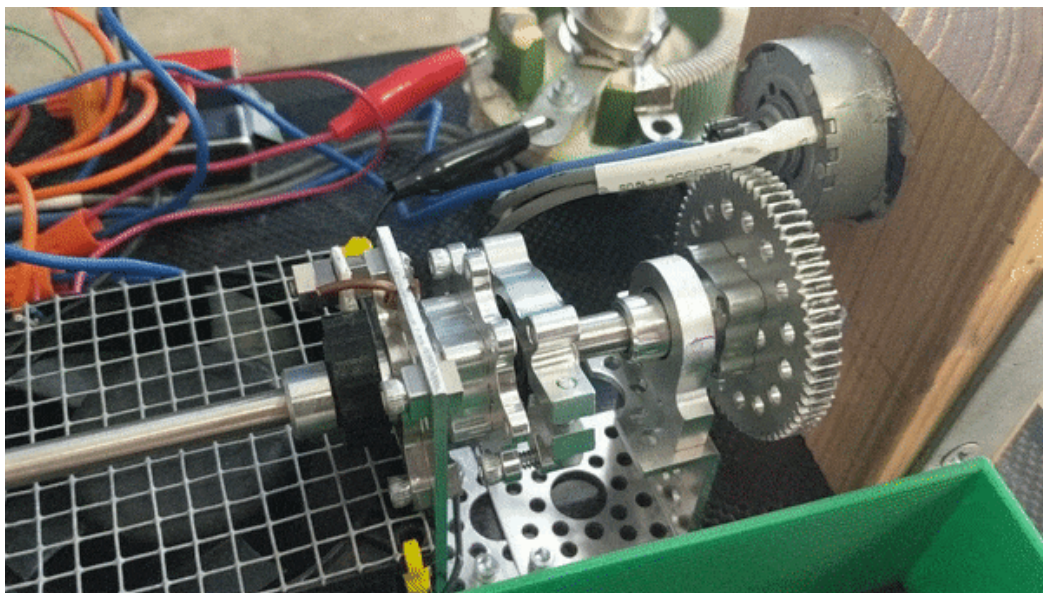
- The rack arm moves at a fairly constant speed, so no matter the track length or material, the rack's starting position can be offset corresponding to the error from the first run in order to achieve exactly 15 seconds on the second run.
- The speed of the rack is adjustable using the potentiometer. However, this was not meant to be adjusted during the competition, and instead was set to a permanent value that could provide the necessary delay while maximizing precision.

Ratchet Mechanism

The ratchet mechanism is what allows the driveshaft (and thus the rack arm) to move while the fan is spinning backwards but not forwards. It was made using a **3D-printed single-tooth ratchet**, an **aluminum gravity-powered pawl**, and a **one-way bearing**.



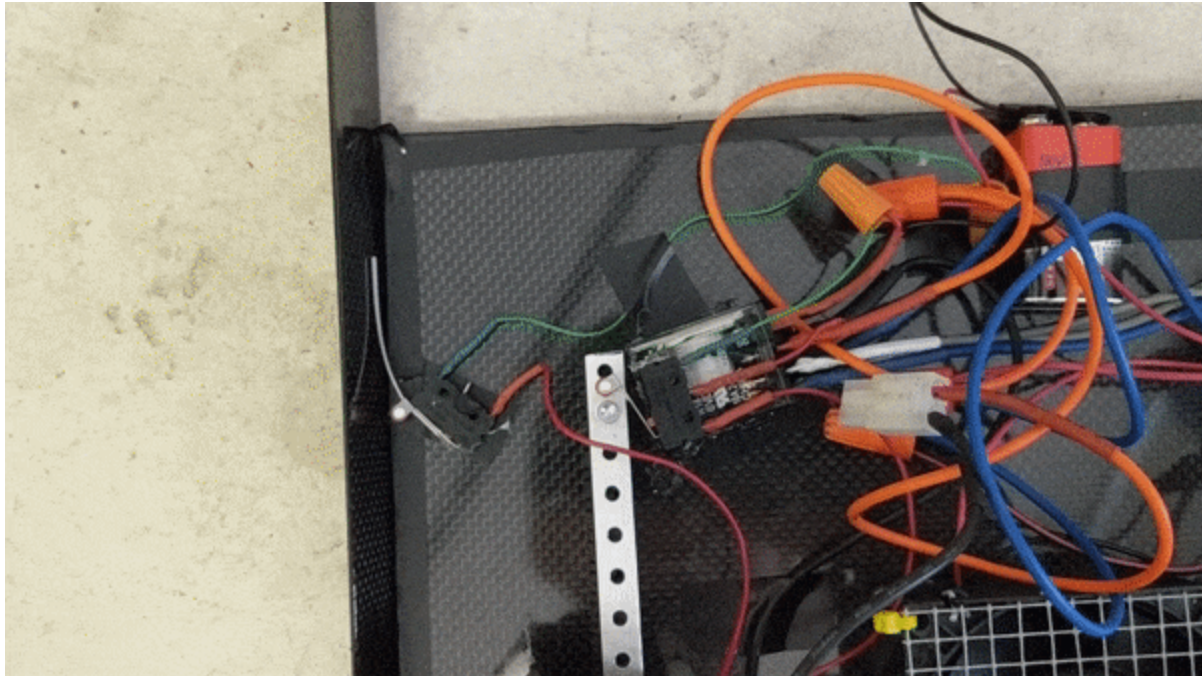
When the fan is spinning forwards, some torque is still transferred through the one-way bearing (though it is designed to spin freely that way, it is not frictionless). However, the ratchet and pawl prevent the driveshaft (left) from spinning more than one rotation in that direction. Once the ratchet is engaged, the driveshaft stops spinning and the fan (right) can still spin freely thanks to the one-way bearing.



When the fan is spinning backwards, all of the torque is transferred through the one-way bearing (the inner race locks in that direction). The ratchet allows the driveshaft to spin freely, moving the rest of the drivetrain and the rack arm.

Motor Direction Switching Mechanism

The motor direction switching is done using a **double-pole double-throw mechanical relay powered by a 9V battery in a separate circuit**. The two microswitches are wired in parallel such that **when either one is activated, the relay becomes powered, causing the motor to spin forwards**. When neither is activated, the relay is unpowered, and the motor spins backwards. (See wiring diagram for more detail.)



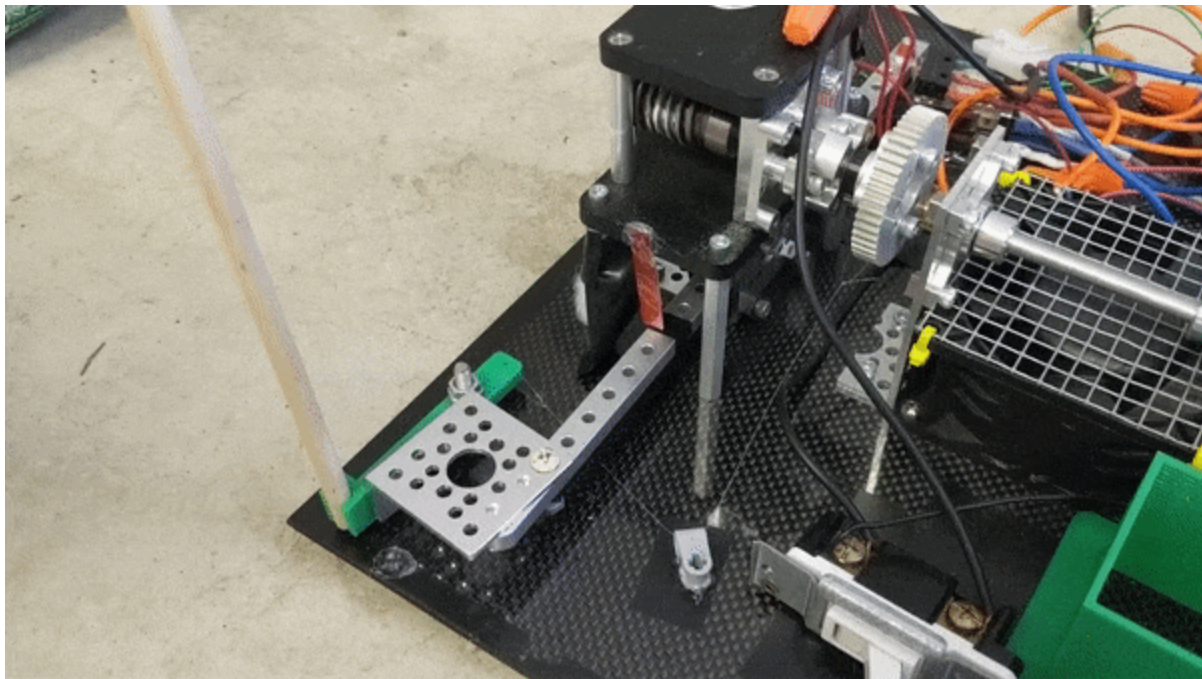
First, the front microswitch (left) is pressed. This is the one that causes the motor to spin forward when pressed against the wooden block at the beginning. The bendy piece of material is to make sure the craft has some room to vibrate without the switch getting deactivated immediately.

Second, the other microswitch, which is mounted on top of the relay itself, is pressed by the rack just as it would be at the end of the delay period. This causes the fan to spin forward again at the end of the delay period, stopping the rack arm from moving any further and propelling the craft down the track.

If you look closely, you can see the relay contacts move when either switch is pressed. The battery powering the relay can be seen in the top right.

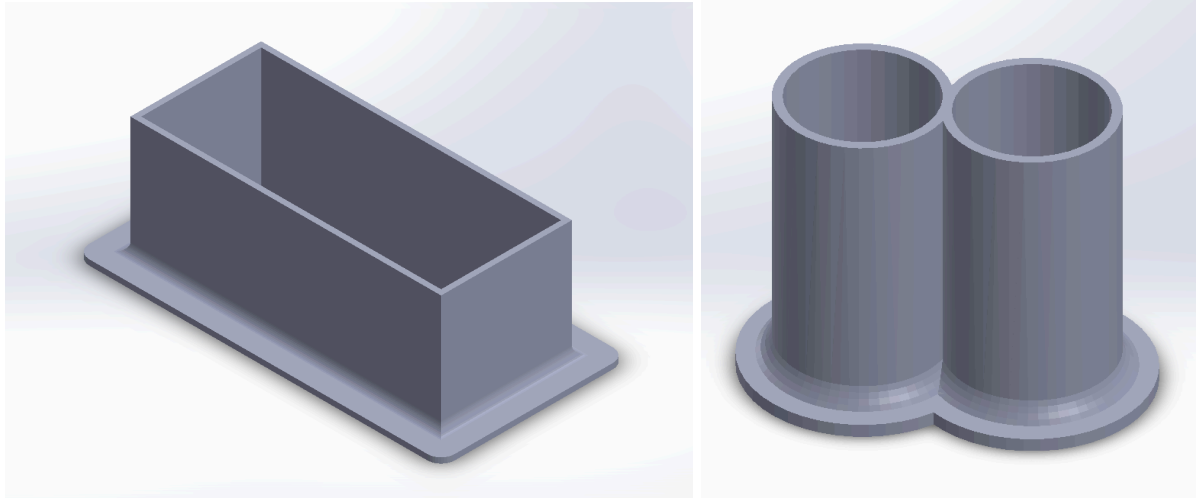
Dowel Extender Mechanism

In order to start timing, the dowel has to **cross the photogate** at the start line. The photogate can't be right on the start line, or it would be activated early, so it has to be placed several centimeters in front of the start line. Most devices move forward right away, so it makes no difference. However, since my device waits at the start line, it needs a way to trip the photogate when the block is removed. It achieves this by attaching the dowel to a 3D-printed lever that is pulled by a piece of fishing line as soon as the driveshaft starts turning. The driveshaft end of the fishing line is attached to a 3D-printed loose collar, so it has enough torque to pull the lever but won't lock up the driveshaft once the line is taught.



As the driveshaft spins (which first happens when the starting block is removed), the 3D-printed collar (small black thing to the left of the large spur gear) pulls on the fishing line, which passes through a right-angle joint and pulls on the lever to extend the dowel. Once the dowel is at full extension, the line goes taught, and the loose collar slides around the driveshaft, allowing it to keep spinning.

Holding Pennies



Left: box used to hold 10 penny rolls. Right: double tubes, 3 of which held the remaining 6 penny rolls.

Once the rest of the device was complete, pennies were placed upright wherever there was room in order to balance out the craft. 10 penny rolls were held in a green 3D-printed box shape on the left side of the device. The rest were held in 3D-printed double tubes. All were affixed to the base using double-sided mounting tape.

Competition Day

[Here is a video of the device's second run at state.](#)

On the first run, the device was configured based on an educated guess, and it crossed the finish line after 13.9 seconds. Before the second run, the rack arm was adjusted the equivalent of 1 second backward, and it crossed the finish line after exactly 14.9 seconds.