

The continuous refill, short-burst, hand-powered water toy

by

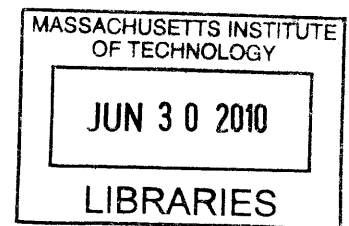
Long Lam

SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL
FULFILLMENT OF REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF SCIENCE
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MAY 2010
[June 2010]
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Submitted to the Department of Mechanical Engineering on May 10, 2010
in Partial Fulfillment of Requirements for the Degree of

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ABSTRACT

The water “blaster” has been one of the most popular toys because it is fun, safe, and easy to operate. The water guns have appeared in many design variations, ranging from the simple squirt gun to motorized water guns. This research proposes a new approach to water gun design. The design consists of a small single burst chamber, and an air bulb is used to pressurize the chamber between shots, creating the sense of multi-shot, large, pressurized tank. Similar to the currently popular Super Soaker, the water in this version is pressurized inside the water channel before each blast. This model also takes advantage of the pressure head between the channel and the reservoir, which is from a backpack, to have the water flow passively into the channel. The user then can pressurize the channel by hand with an air bulb and blast continuously. We implemented a prototype to demonstrate the concept

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Acknowledgement

I am indebted to Marlous Nacken and Professor David R. Wallace, who developed the original idea. This project would not be possible without their invaluable support and guidance. I am grateful to James Penn for his late-night assistance.

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1. INTRODUCTION

1.1 Objective

This research aimed to design a new model of the classic water gun. The prototype employs similar concept as the Super Soaker, where the channel is pressurized before each blast. Instead of drawing water into the chamber, this device takes advantage of the pressure head between the reservoir and the channel, allows the water to flow passively, and the user can pressurize and fire the gun continuously. This version serves as a friendlier alternative of the current water gun to small children without compromising its capabilities.

1.2 Background

Ever since its introduction, the water gun has been one of the most popular summer toys of all time. The water gun is a terrific toy that allows children and adults alike to cool off on a hot afternoon by waging an epic water battle against one another with little to clean up after. Unlike paint ball or Nerf gun darts, water is a relatively cheap and readily available supply, and it breaks upon impact, causing little damage. Due to the competitive nature of the toy industry, the water gun has evolved tremendously; water guns found on the shelves nowadays come from different shapes and sizes, ranging from machine guns, water bazookas and even grenade launchers.

The classic squirt gun, as seen in [Figure 1](#), consists a trigger lever that mechanically activated by pumping action. As the user pulls the trigger back, the

piston is pushed into the cylinder, forcing the water in the small channel and through a small nozzle. When this pumping action stops, the piston, which is connected to a small spring, draws water from the bottom of the water reservoir. The water reservoir is usually located inside the gun. The water does not travel back inside the reservoir thanks to a check valve. A check valve is a mechanical device that allows fluid flow through it only in one direction. Check valves have and forces the drawn water down a narrow channel and out through a small nozzle. There are two check valves in a classic water gun. When the user fires the gun by pulling the trigger, water is forced through check valve between the nozzle and the pump. As the piston is pushed out by the spring, the cylinder volume expands, drawing water or air from the reservoir to the pump through the second check valve.



Figure 1: The classic squirt gun¹

While this type of water gun has a simple design and is easy to operate, there are a few limitations. Since the amount of water in each blast depends on the pump cylinder's size, the user needs a larger size in order to increase the amount of compressed or expanded water. Furthermore, the range of the trigger mechanism

also needs to increase. The distance that the water travels is limited since it depends on the force exerted on the trigger. The duration of the blast is also limited; in order to continuously squirting, one must keep squeezing and releasing the trigger. Finally, the user has to run to a spigot more frequently for refill.

The motorized water gun, as seen in [Figure 2](#), tries to overcome the aforementioned limitations of the classic water gun. This model works on the same principle as the basic squirt gun, but instead of employing the usual trigger, the pump is powered by a small motor. The switch now is a switch that completes an electrical circuit. One of the main advantages of this design is the user does not need to keep pumping the trigger to shoot continuously. This design also increases the blast range. However, this design depends on a motor and batteries, rendering itself bulky in size and somewhat difficult for the user to shoot.



Figure 2: The Tarantula, a motorized water gun²

The most popular version of water gun today, the Super Soaker, was invented by Lonnie Johnson and Bruce Andrade³. The water is pressurized before the blast by pumping air directly into one water reservoir. As more air is pumped inside the reservoir, the air inside the reservoir is more compressed, exerting

greater pressure to the water inside. When the user pulls the trigger, the ball valve, which stops the water from escaping, opens, forcing the water through a small nozzle.

2. DESIGN EXPLORATION

2.1 Spiral Impact

The original design consists of a water reservoir in the form of a backpack that connects to the water gun's channel through tubing. There is a one-way check valve between the reservoir and the channel, preventing water or air to travel back upstream when pressurized. Check valves are also located in the air bulb, which is used to pressurize the system (see [Figure 3](#)). The pressure head inside the tubing can be calculated by:

$$P = \rho gh \quad (1)$$

where P is the pressure head, ρ is the density of water, g is the gravitational acceleration and h is the height difference between the reservoir and the channel. Assuming that the height difference is 1 foot, the pressure head equals 0.87 psi.

In order to allow water flow down to the channel passively, the pressure exerted by the water in the tubing must be greater than the check valve's cracking pressure. To address this technical challenge, we can place the check valve as far down as possible and use tubing with spiral wall inside, guiding the water downward. When the water impacts the check valve, it provides a force that is large enough to open the check valve. The helical design also lets a free column in the

middle of the tubing that air can flow up to the reservoir as it is displaced by the water.

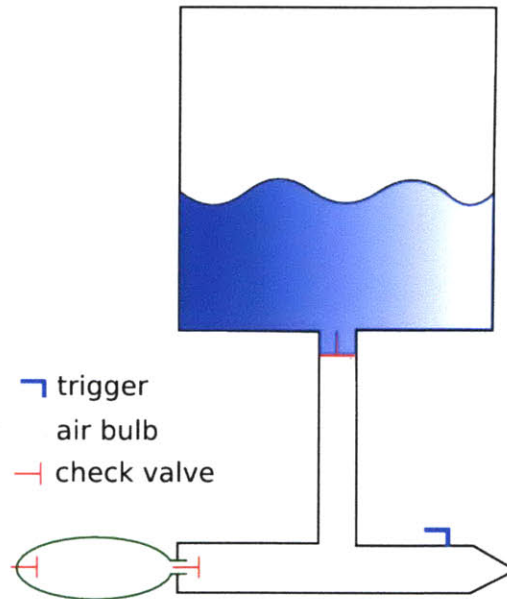


Figure 3: Schematic of basic design

While this is a novel approach, there are a few problems. Tubing with internal spiral wall is not readily available for purchase, so it must be customized. Similarly, it is difficult to find check valves with cracking pressure smaller than that from the water impact, and for the ones with small cracking pressure, their openings are too small to fit any reasonable tubing size. Furthermore, the water tends to stick to the wall of the tubing and is unlikely to provide any meaningful pressure. Lastly, there is no guarantee that the column of air is always available in the middle of the tubing for air displacement. The tubing may be bent or obstructed during active usage.

2.2 Active Pumping

In order to displace the air from the channel out with water from the reservoir, we can actively pump the air out using another air bulb. This secondary air bulb can be located under the case, in plane with the trigger. The user first pumps air into the channel using the first bulb. A check valve on the second bulb prevents the compressed air from escaping. After each blast, the user needs to pump air out of the channel using the second bulb. While this design works on principle, it is fairly crude and the configuration is not user-friendly. The user has to move his or her hand back and forth between the two bulbs and may drop the water gun during active uses.

2.3 Air Bleeding

There is another way to allow the water from the reservoir to displace the air inside the channel after each blast. The pressure P exerting on the check valve is always greater than the atmospheric pressure. Therefore, if the pressure inside the channel is less than P , water will flow down passively from the reservoir.

Immediately after each blast, the channel is depressurized and becomes closer to the atmospheric pressure. However, because the ball valve within the nozzle opens and closes fairly quickly, the pressure in the channel does not have enough time to come to equilibrium with the atmosphere. In order to facilitate this “air bleeding” process, we can build a trigger that can open easily yet perfectly sealed when closed and. A spring is an ideal mechanism for this purpose since it can push against the lid, hermetically closing the valve. It takes little force to perturb this spring-loaded lid, and we only need a small crack to bleed the air out.

3. MOCKUP

In order to test our proof of concept, we built a mockup from PVC. As seen in [Figure 4](#), an air bulb is connected to a check valve, which is then connected to a T-connector. Another check valve is located between the T-connector and the tubing that goes to the water reservoir, permitting water flowing downward only. The second T-connector joins the air reservoir and the trigger. On top of the air reservoir is an air-bleeding ball valve identical to the one acting as a trigger.

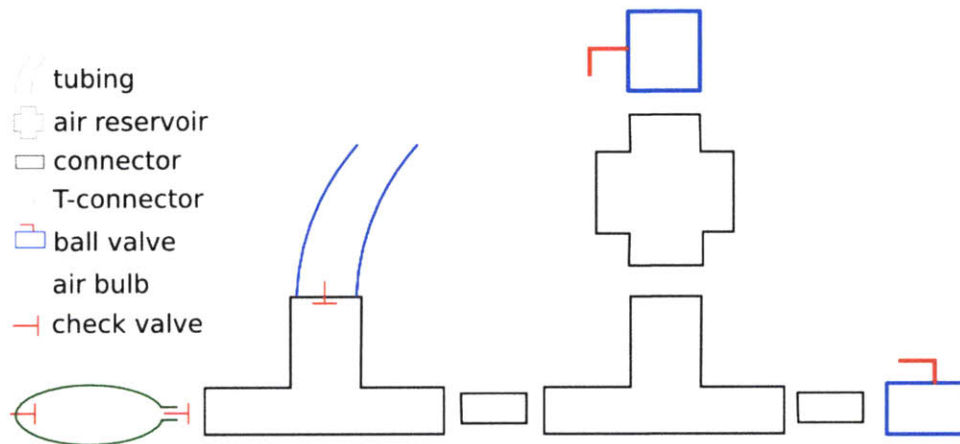


Figure 4: Schematic of mockup design

After the water fills up inside the channel, air is forced from outside through the bulb to the channel. As the system is sufficiently pressurized, we open the ball valve, which causes the air to escape. To refill the channel, we open the ball valve on top of the air reservoir. The water then flows through the check valve whose cracking pressure is approximate 0.5psi.

We built the mockup model with PVC as seen in [Figure 5](#). The purple paint is PVC cement, which acts as an an-tight adhesive. With the mockup model, we were able to shoot several feet with a few pumps. However, the mockup model is fairly large and heavy, and it does not have a cover on the outside. Besides miniaturizing the model, we also need to make the triggers semi-automatic so the user does not have to reach for them every blast.

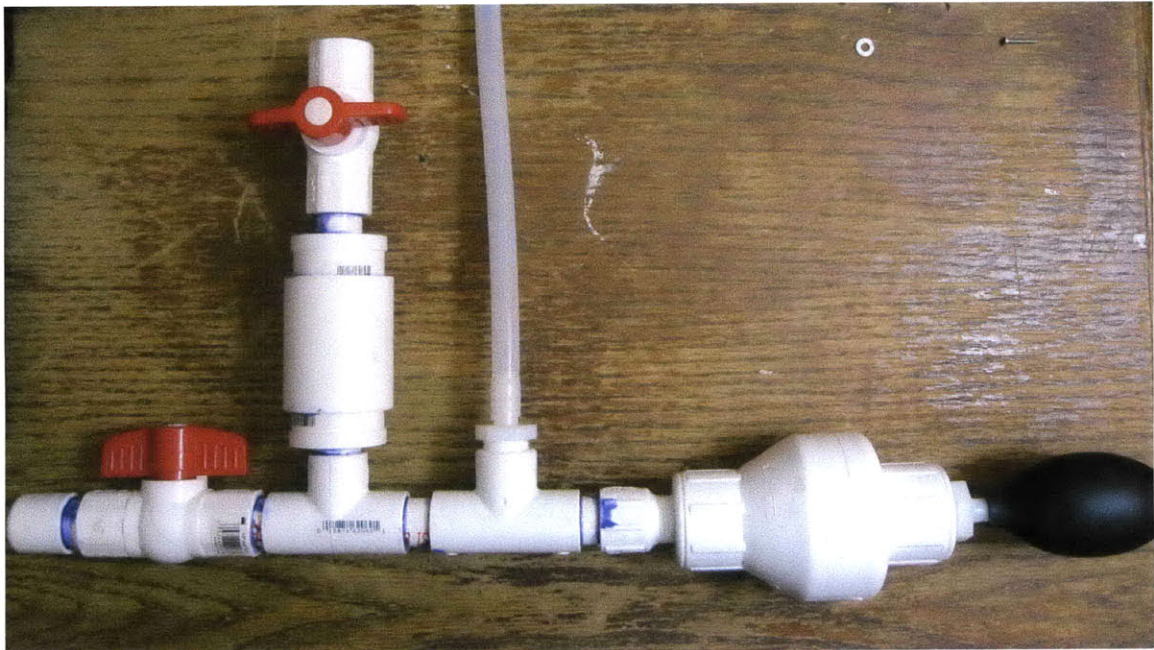


Figure 5: Mockup Model

4. ALPHA PROTOTYPE

4.1 Design Description

The prototype drew inspiration from the mockup model. We needed to miniaturize the mockup model since we planned to rapid-prototype via 3D printing. However, the 3D printer has a relatively small tray (12 inches) so we had to take

that into consideration. Due to this limitation, the prototype was designed outside-in. We wanted the body to have a bullet shape since it will complement the shape of the air bulb. See [Figure 6](#).

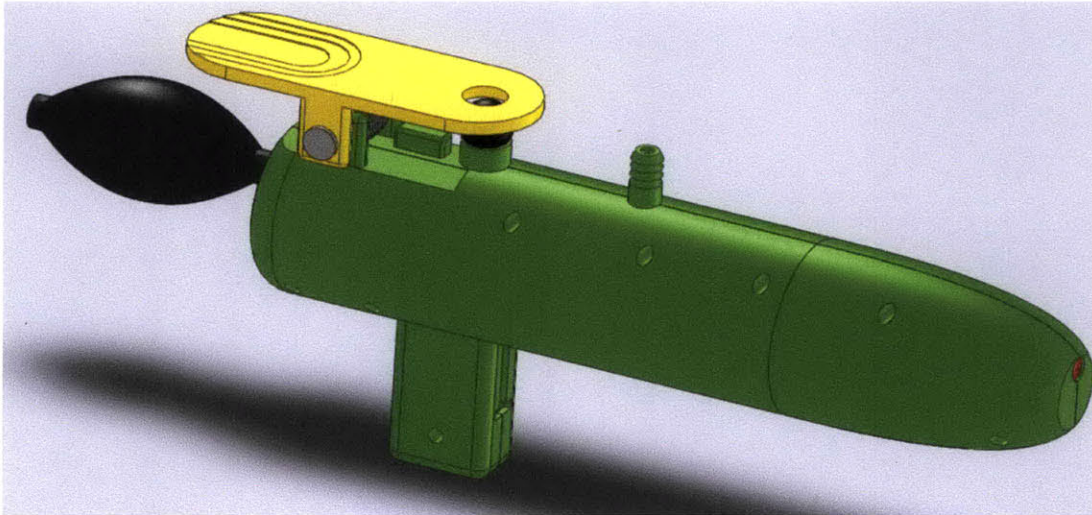


Figure 6: Solid model of the final product

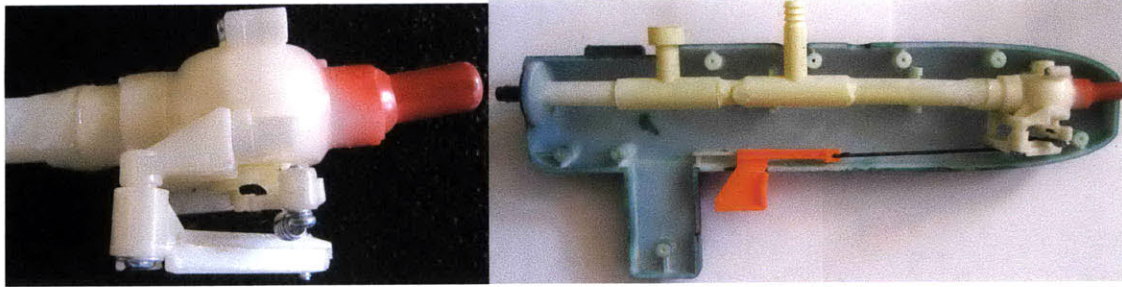
A backpack with a plastic bag serves as the water reservoir. With this large, easy-to-fill water reservoir the user can take less trips to the spigot since the water supply lasts longer. At the bottom of the plastic bag is a valve, which is connected to a one-way check valve, whose cracking pressure was approximately 0.5 psi.

Originally the air-bleeding orifice was located in front of the barbed fitting. The lever was connected to another trigger right in front of the main trigger, pivoting around its midpoint of gun's case. A series of extension springs connected the lever to the body, holding the rubber ball in place against the air-bleeding orifice. As the user pulls the trigger back, the lever would rotate around its midpoint, cracking the ball-orifice interface and thus allowing inside air to escape. However, we found this design to be cumbersome for the user. Particularly, it was

more awkward for the user to hold and fire the gun when there were two triggers right next to each other. Furthermore, the center of gravity was too forward, causing the gun to accidentally tip over.

The air-bleeding orifice is now located in the back of the water gun. The lever is on top of and parallel to the air bulb. This configuration takes away some burden from the user. Instead of switching hand after each blast, the user can permanently place one hand on the trigger and the other one on the back, pumping and bleeding air alternatively.

In order to make the triggers semi-automatic, we used two types of spring. As seen in [Figure 7a](#), we use an extension spring for the nozzle. This way, the trigger will always return to its initial position after each blast. The nozzle is connected to two T-connectors via a series of pipes (see [Figure 7b](#)). The first T-connector goes to the water reservoir and the second T-connector is the air-bleeding orifice. Finally, the second T-connector is connected a diaphragm check valve which allows air to flow on in one direction. We used a diaphragm check valve because it has low cracking pressure as well as it is small enough that can fit into the air bulb. We used the air bulb from a sphygmomanometer system. The bulb is made of rubber with a one-way check valve on one end.



(a)

(b)

Figure 7: nozzle (a) and the internal structure with the water-storing channel (b)

The air-bleeding orifice is covered by a rubber ball, which is glued to the lever. The lever is free to rotate around the shaft, though its resting position will always be at an angle with the horizontal plane. The torsion spring underneath the lever ensures that the ball tightly shuts the orifice until the user pushes on the lever.

Figure 8 shows the final product.



Figure 8: The final product

4.2 Calculations

To calculate the pressure inside the channel, we use the ideal gas law

$$PV = mRT \quad (2)$$

where P is the absolute pressure of the gas; V is the volume; n is the amount of substance; R is the gas constant; and T is the absolute temperature. Since air is the only fluid being compressed, we can use m (mass) in place of n . Assuming the change in temperature is negligible and the volume is constant we have

$$\frac{P_1}{m_1} = \frac{P_2}{m_2} \quad (3)$$

where state 1 is before air being forced inside the channel and state 2 is after.

The bulb has a volume of 4in^3 . If each pump pushes 75% of the air from the bulb to the channel, the change in mass is approximate $5.9 \times 10^{-5}\text{kg}$. If initially there is 1in^3 in the channel in the beginning, the change in pressure is 0.44 psi. That means the pressure inside the channel after the first pump is 15.14 psi. Using

$$P = \frac{F}{A} \quad (4)$$

we calculate the force exerting on the rubber ball is 0.81 pound.

In order to calculate the distance that the water travels, we use the first law of thermodynamics⁴. Take the control volume to be the area right behind (1) and right in front of (2) the nozzle. The first law states that the rate of change of energy in a control volume is

$$\frac{dE_{CV}}{dt} = \dot{Q} - \dot{W}_s + \sum_{in} \dot{m}_{in} \left(h + \frac{\vartheta^2}{2} + gz \right) - \sum_{out} \dot{m}_{out} \left(h + \frac{\vartheta^2}{2} + gz \right) \quad (5)$$

Because water is an incompressible fluid, enthalpy h can be substituted by $u + Pv$, where u is the internal energy, P is the pressure and v is the specific volume. Since there is no heat and work transfer, and since mass flow rate in is the same as the mass flow rate out, Equation 5 becomes

$$(u + Pv + \frac{\vartheta^2}{2} + gz)_1 = (u + Pv + \frac{\vartheta^2}{2} + gz)_2 \quad (6)$$

$$(cT + Pv + \frac{\vartheta^2}{2} + gz)_1 = (cT + Pv + \frac{\vartheta^2}{2} + gz)_2 \quad (7)$$

Because the temperature does not change from area 1 to area 2, Equation 7 is now

$$(Pv + \frac{\vartheta^2}{2} + gz)_1 = (Pv + \frac{\vartheta^2}{2} + gz)_2 \quad (8)$$

Since there is no flow in the area 1, the first velocity term goes to zero.

Assuming the distance between the gun and the ground is 1m, we can calculate the exiting horizontal velocity to be 5.1m/s. Using Equation 8 again after the water exits the nozzle, we have find the vertical velocity to be

$$\vartheta_z = \sqrt{2gz} \quad (9)$$

and for constant acceleration, the velocity is given by

$$\vartheta_z = gt \quad (10)$$

Combining the two equations, we find that the time it takes for the water to hit the ground is

$$t = \sqrt{\frac{2h}{g}} \quad (11)$$

It takes .45 seconds for the water to hit the ground from 1 meter. This translates to a total travel distance of 2.3 m, or approximately 7.5 feet for the first pump of air.

4.3 Results

While we expected each pump to move the water as far as 7.5 feet, we measured the distance to be consistently close to 10 feet. [Figure 9](#) shows the water toy in action. We tried to pump the bulb more than once, but we found that it was very difficult to do so since the channel was displaced mostly by incompressible water. After each blast, the water refilled as soon as the level was open, and it took about two second for the water level to fill up to its previous level. This was dependent on the height different between the water reservoir and the bottom of the tubing. The greater the distance was, the faster the water filled up.

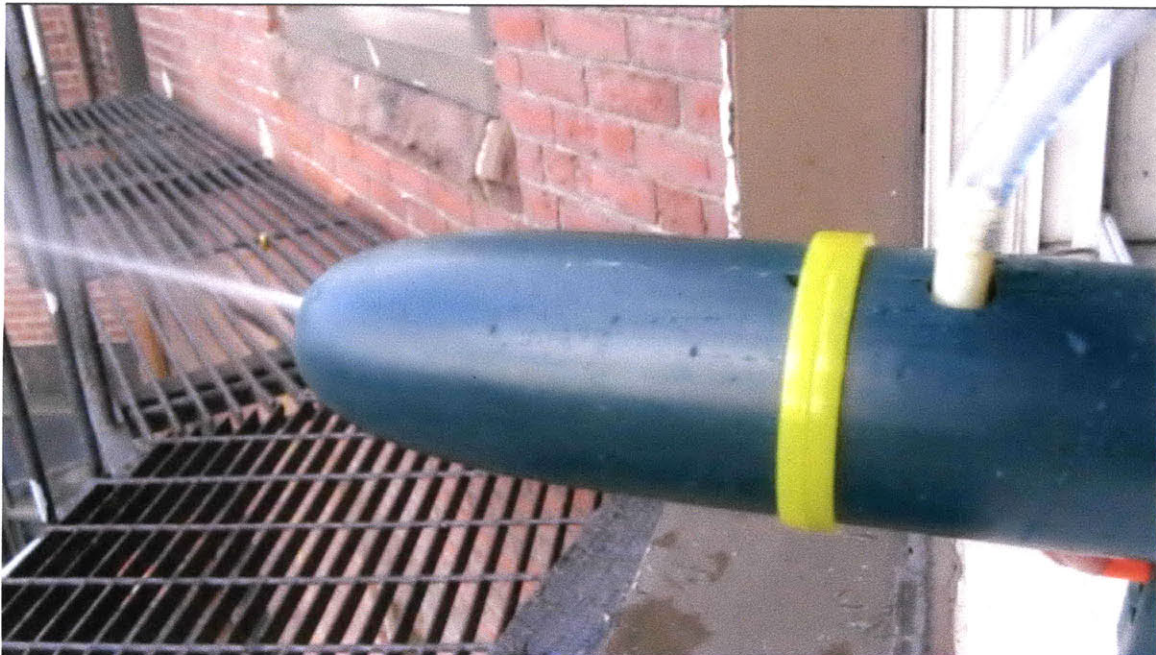


Figure 9: The water toy in action

5. DISCUSSIONS AND FUTURE WORK

As mentioned in the previous section, there is a discrepancy between expected travelled distance and measured travelled distance. This discrepancy may stem from our initial assumption that only three quarters of air inside the bulb is forced inside the channels. In fact we noticed that almost all the air inside the bulb travels across the check valve after each pump.

The limiting factor of this design is the air-bleeding orifice-ball interface. The torsion spring can no longer keep the ball in place after a few pumps since the pressure inside the channel is too high. We can address this problem by either using a stiffer torsion spring, modifying the different interface, or adding an air reservoir. Using a stiffer torsion spring may be problematic, since most stiff torsion springs are fairly large and they may not fit with the current model. While the second option is likely to take more work, it may be the better approach. Currently the rubber ball does not sit entirely inside the orifice. We can change this by using a cylindrical stopper instead. We can also use a sliding interface, where the user can slide the spring-loaded stopper away from the orifice. Adding an air reservoir seems to be the most ideal approach since it builds on the current design rather than altering all together. We can add air reservoir to the top of the body, well above the channel to ensure that water does not flood it. The air inside the channel can then be more pressurized, helping to water to travel further.

To make the product more marketable, we need to alter the design so it appeals to a specific range of audience. For example, to attract young adults, the product needs to have larger size and high capabilities. A larger case allows larger

channels, more water pressurized at a higher pressure and ultimately higher mass flow rate and duration. If the product is geared toward young children, the air bulb can be customized so it requires less force to pump.

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