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Shooting Device for Free-Surface Impact Studies

by

Sarah L. Daigh

Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

BACHELOR OF SCIENCE

at the

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ABSTRACT

The hydrodynamics of free-surface impacts are of great interest to scientists across many disciplines including ocean engineering, fluids mechanics, and biology. This thesis focuses on designing a mechanism to shoot small projectiles downward. Two pneumatic shooting mechanisms were investigated: the potato gun and the paintball gun. Adaptations were made to the paintball gun, as a preliminary design; however, it was later concluded that pneumatics were not the best way to propel the projectile. The final design includes a pinball shooter to propel the ball and an electromagnet to suspend the ball before shooting. This shooting mechanism uses magnetic balls of diameter 1 inch and can achieve velocities of 278 m/s when located 1 m above the free surface. The adaptability of the mechanism to other downward shooting situations is discussed.

Thesis Supervisor: Alexandra H. Techet

Title: Doherty Assistant Professor of Ocean Utilization

Acknowledgments

As I look back on my progress on this project over the past nine months, I know that I could not have reached this point without the help and support of many wonderful people. First, I would like to thank my thesis advisor, Alex Techet, for her encouragement, help, and flexibility. I would also like to thank Tom Consi for his advice on electromagnets and for use of the Ocean Engineering Teaching Laboratory. Tadd Truscott and Steve Laverty's work on the weblab and baseball shooter adaptation took some pressure off me and also provided me with a mechanism against which to compare my own design. And, of course, I would like to thank my academic advisor, Wai Cheng, for always signing my add/drop forms.

On a more personal note, Anna Michel pestered me daily about my thesis progress to make sure I was on track. Anna also originally introduced me and Alex. Throughout the rough spots, I also found support from my sorority sisters, however cliché that may sound. Thank you, Sigmas! I would also like to thank my longtime friend Ryan Gajewski for letting my visit him in London over Spring Break. Returning from a wonderful week abroad, I realized that I didn't need to dabble in course 6 anymore; I needed to finish my thesis! Perhaps the largest thanks go to my parents, Gary and Rosemary Daigh, for their unending encouragement and for their emotional and financial support.

Contents

Chapter 1

Introduction

This thesis looks at the design of a mechanism that can be used to shoot projectiles downward into a tank of water. For example, Figure 1 shows a set of images comprising the free-surface impact of a pool ball. The ultimate goal of the project is to be able to study the hydrodynamics of the impact of a body with the free surface. In order to study this phenomenon a mechanism to shoot objects downward must be designed and constructed.

The physics of free-surface impact is of interest to a wide variety of communities from ocean engineering and naval architecture to biology. Seventy-five years ago, von Karman studied the maximum pressure acting on seaplane floats during landing in order to make a stress analysis of the floats [1]. This is an example of ship slamming, an area of interest to naval architects. When a bluff body, such as a ship hull, impacts the water surface, large loads often result, damaging the structure [2]. To avoid such damage, classification societies have compiled strength requirements and regulations for ship bow structures. Unfortunately, even the modern versions of these requirements vary from society

Figure 1. Impact of pool ball with water surface. Every fifth frame shown, 5/500 second between each frame (frame rate 500 fps). Courtesy of Alex Techet.

to society [3]. Such uncertainty demands further investigation into the hydrodynamic forces resulting during an impact event. Slamming-induced forces can damage other structures including rubble mound breakwaters, buoys, oil rigs, pipelines, floating bridges, and dams [4, 5]. Free-surface impacts also occur when objects such as life boats are lowered down onto or through the water surface. May's research in the 1950s was sponsored by the Office of Naval Research illustrating the interest and application of the free-surface impact problem to the military [6].

Free-surface impact theories also apply to situations outside of the engineering realm, such as in nature. For example, basilisk lizards use the hydrodynamic forces of low-speed water entry to run along the water surface as shown in Figure 2 [7]. Glasheen and McMahon conducted several free-surface impact experiments to study this behavior in order to develop a physical understanding of the lizard's propulsion mechanism. One experiment investigated an ecological theory that basilik lizards are able to reach high population densities because the juveniles and adults have differing water-running abilities [8]. After conducting experiments in which models of juvenile and adult feet were dropped through the water surface, Glasheen and McMahon concluded that there was a physical basis to the ecological theory.

There is little experimental data available on free-surface impacts. Non-classified works consist mostly of theoretical predictions and analytical solutions. These are available for many shapes including spheres, cylinders, and wedges and for oblique entry As Miloh

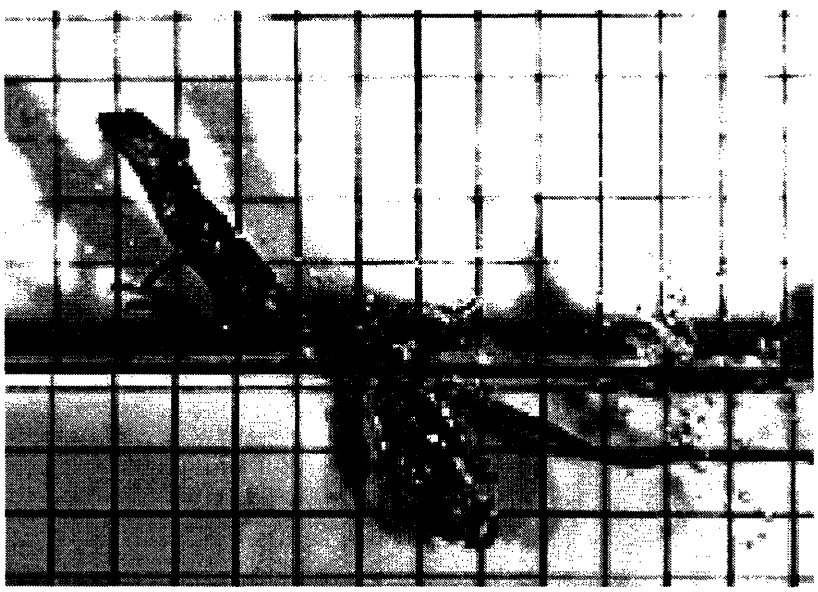

Figure 2. Basilisk lizard running on water. The rear foot has created an air pocket similar to one an object impacting the free surface would create [9].

notes, experimental measurements of early stage impact are very hard to perform; therefore, there are only a few experimental studies against which theoretical predictions on early stage impact can be compared [4].

Historically, different experimental apparatuses have been used to cause free-surface impact. Objects were often simply dropped because of the ease of this approach [7, 8, 10]. One of the drawbacks of this method is the limitations on impact velocities. To increase or decrease the impact velocity, the object had to be dropped from a higher or lower point, respectively. In a very recent study conducted by Shi, Itoh, and Takami, a German Anshultz rifle was used to fire projectiles downward [11]. Only one type of projectile could be used,: a small lead slug. Neither dropping nor shooting from a rifle give the flexibility that the many applications of free surface-impacts necessitate. An experimental apparatus for which many of the projectile parameters could be varied is ideal. Specifically, variation of shape, size, density, impact speed, and angle of entry are desired to model the applications previously described.

The Froude number, *Fr*, is a dimensionless parameter often used to characterize the impact of the ball on the free surface. The Froude number is defined as

$$Fr = \frac{U}{\sqrt{gL}}, \tag{1}$$

for velocity U and length scale L. In the case of free-surface impacts, the velocity is the impact velocity, and the length scale is the diameter of the projectile. Froude scaling produces a good first-order approximation of free-surface impact behavior [6]. In other words, impacts with similar Froude numbers should exhibit similar trends. Controlling the impact velocity and the size of the projectile will control the Froude number.

The purpose of this project was to design and build a shooting device to aid in the study of free-surface impacts. The shooting device would be able to shoot a variety of objects over a range of velocities. The use of this device in free surface-impact tests would allow a wider range of experimental data to be taken in this area than currently exists.

This paper will detail the problem and follow the design process of the shooting mechanism. In chapter 2, different mechanisms will be investigated and existing shooting mechanisms discussed and adapted. Included in this chapter will be pneumatic guns, baseball pitching machines, and electromagnetic guns. Chapter 3 will introduce and explain the final design and predict its performance. Chapter 4 will evaluate the final shooting mechanism and make recommendations for future designs.

Chapter 2

Concept and Design Process

The original scope of this thesis was to design and build a pneumatic shooting mechanism to be used as part of an experimental setup to study the impact of objects on the free surface of water. This mechanism was to be included in a series of web-based educational tools being designed to aid in the teaching of naval architecture and ocean engineering. The shooting device would shoot objects straight down using compressed air. The objects would be primarily two inch diameter balls, with future adaptability to other objects such as wedges. The desired muzzle velocity was 10 to 20 m/s. The functionality to shoot objects obliquely into the water was also desired. Students would then be able to input parameters such as muzzle velocity or air pressure and impact angle through a website controlling the operation of the shooting mechanism. Output would be provided to the website from webcams and high-speed cameras mounted strategically around the tank and shooting mechanism. The design and execution of the computer interface was not to be included in this part of the project.

Over the course of the design process, the scope and purpose of the project were altered. This chapter will discuss the evolution of the shooter and the pneumatic and non-pneumatic designs studied or adapted.

2.1 Pneumatic Designs

At first glance, pneumatics seemed to be the best way to solve this problem. Some of the experiments conducted by Gilbarg and Anderson in the 1940s used air guns to propel spheres downward into the water [12]. The air guns were not described in detail, but different size spheres were used and different impact velocities achieved. Air guns use pressurized air to propel an object. In the present day, two examples of air guns are commonly available: the potato gun and the paintball gun. Both of these examples need a source of pressurized air and a system for controlling and transmitting the air to the barrel of the gun.

2.1.1 Preliminary Theory and Calculations

The basics of a downward shooting system are shown in Figure 3. The pneumatic device is represented only as a gauge pressure P acting on the ball. From simple physics, the location y of the ball when the velocity is v is

$$y = \frac{v^2 - v_0{}^2}{2a} \qquad (2)$$

where v_0 is the initial velocity and a is the acceleration. Ignoring the pneumatic pressure and drag force, the ball would need to be dropped from a height h to reach a desired velocity v_b:

$$h = \frac{v_b{}^2}{2g}. \qquad (3)$$

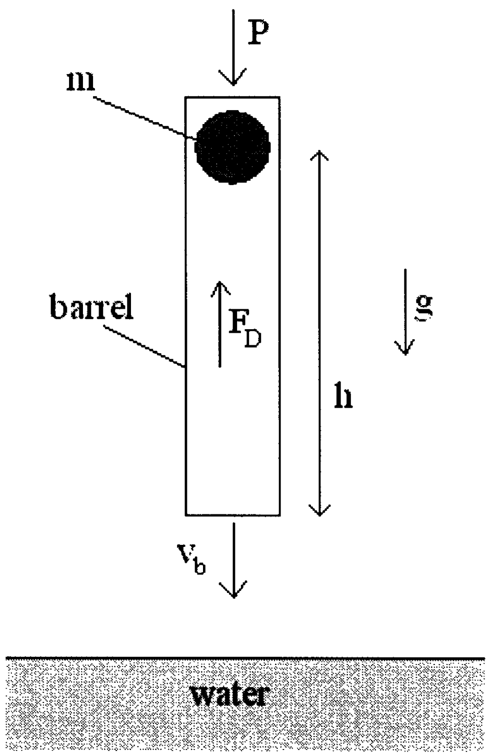

Figure 3. Basic shooting system. Barrel has cross-sectional area A and height h. Ball of mass m is acted on by pressure P, gravity g, and a drag force F_D. Ball exits barrel at velocity v_b.

As can be seen, the height h varies with the square of the desired velocity. For hypothetical parameters $m = 1$ kg and $v_b = 10$ m/s, it is found that $h = 5.10$ m. If the desired velocity was doubled to 20 m/s, then $h = 20.4$ m, one-fifth the length of a football field. Adding a pneumatic source allows the ball to reach higher velocities in a shorter distance. Assuming that the pressure P acts over the entire length of the barrel and that the diameter of the ball is equal to the diameter of the barrel, a force balance gives

$$\Sigma F = ma = PA + mg - F_D . \tag{4}$$

The drag force consists of the friction from the ball rubbing against the inside of the barrel and the air drag. Assuming the drag force can be ignored and combining (2) and (4), the velocity as the ball exits the barrel is

$$v_b = \sqrt{\frac{2h(PA + mg)}{m}}. \tag{5}$$

Solving for the gauge pressure P needed to reach a velocity v_b, it is found that

$$P = \frac{m}{A}\left(\frac{v_b^{\ 2}}{2h} - g\right). \tag{6}$$

For hypothetical parameters m = 1 kg, d = 0.1 m, h = 1 m, and v_b = 10 m/s, it is found that P = 5.1×10^3 Pa or 0.74 psi. Since P is the gauge pressure, the actual pressure acting on the ball would need to be (P + 1 atm). In the case of v_b = 10 m/s, the absolute pressure is 1.06×10^5 Pa or 15.4 psi. For v_b = 20 m/s, the absolute pressure increases to 1.25×10^5 Pa or 18 psi. Neglecting the influence of gravity, the absolute pressures necessary become 18.9 psi for 10 m/s and 31.8 psi for 20 m/s. As can be seen from (6), the gravitational force becomes less influential on the required pressure as the target velocity increases.

2.1.2 Components and Operation

Two sources of pressurized air were considered: an air compressor and pressure cartridges. Either source requires the pressure to be regulated to control the exit speed of the projectile as illustrated by (5). The pressurized air could be delivered to the shooter in two ways. The first would use a control system such as the one shown in Figure 4. Here, the electronic regulator controls the pressure of the gas which flows directly into the barrel when the solenoid valve is switched on. The second method involves a chamber that would be filled with air to a certain pressure. When the shooting mechanism is turned on, the chamber would open and air would flow into the barrel, decreasing the chamber pressure until it reached atmospheric pressure. A control system could still be used in this second method. In this case, a sensor would measure the current pressure chamber.

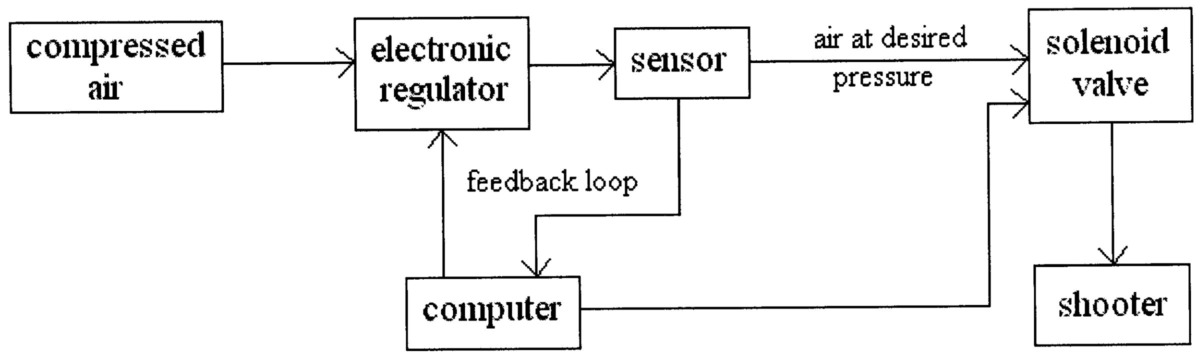

Figure 4. Sample control system. The electronic regulator transmits air from the compressed air source to the rest of the system at the desired pressures. The sensor adds a feedback control loop. The solenoid valve opens when signaled by the computer, transmitting the air to the shooter.

Using the chamber method described above, a set of operational tasks was considered when designing the pneumatic shooter: load projectile, pressurize chamber to correct pressure, locate barrel at correct angle to surface, activate warning light to signal operation of shooter, release trigger and open valve, trigger camera to record impact, projectile accelerates down barrel and impacts surface, return barrel to original location. Once the operational sequence was determined, various types of shooting mechanisms were considered.

2.1.3 The Potato Gun

A potato gun is a recreational apparatus that uses combustion or pneumatics to shoot a potato or other similar object such as a tennis ball. Most potato guns are made out of PVC pipe. PVC is not made to be used with pressurized air, and the material is not guaranteed under these conditions and can explode. When PVC is used, the gun is operated at air pressures much lower than the rated maximum pressure of the pipe. Potato guns can also be made of metal, though this is a less common and more expensive option.

Figure 5 shows a simple pneumatic PVC potato gun. Guns such as this one are shot horizontally or inclined upward at an angle. Operation is relatively easy. The air chamber is pressurized with a compressor of the operator's choosing. The target pressure depends on the size of the gun, the material out of which it was made, and the desired projectile distance. The projectile is slid down the barrel to load. Pushing the trigger opens the valve connecting the air chamber and the barrel. The air exits the chamber because of the pressure difference, and the projectile is propelled along the length of the barrel and out the end. The valve is usually

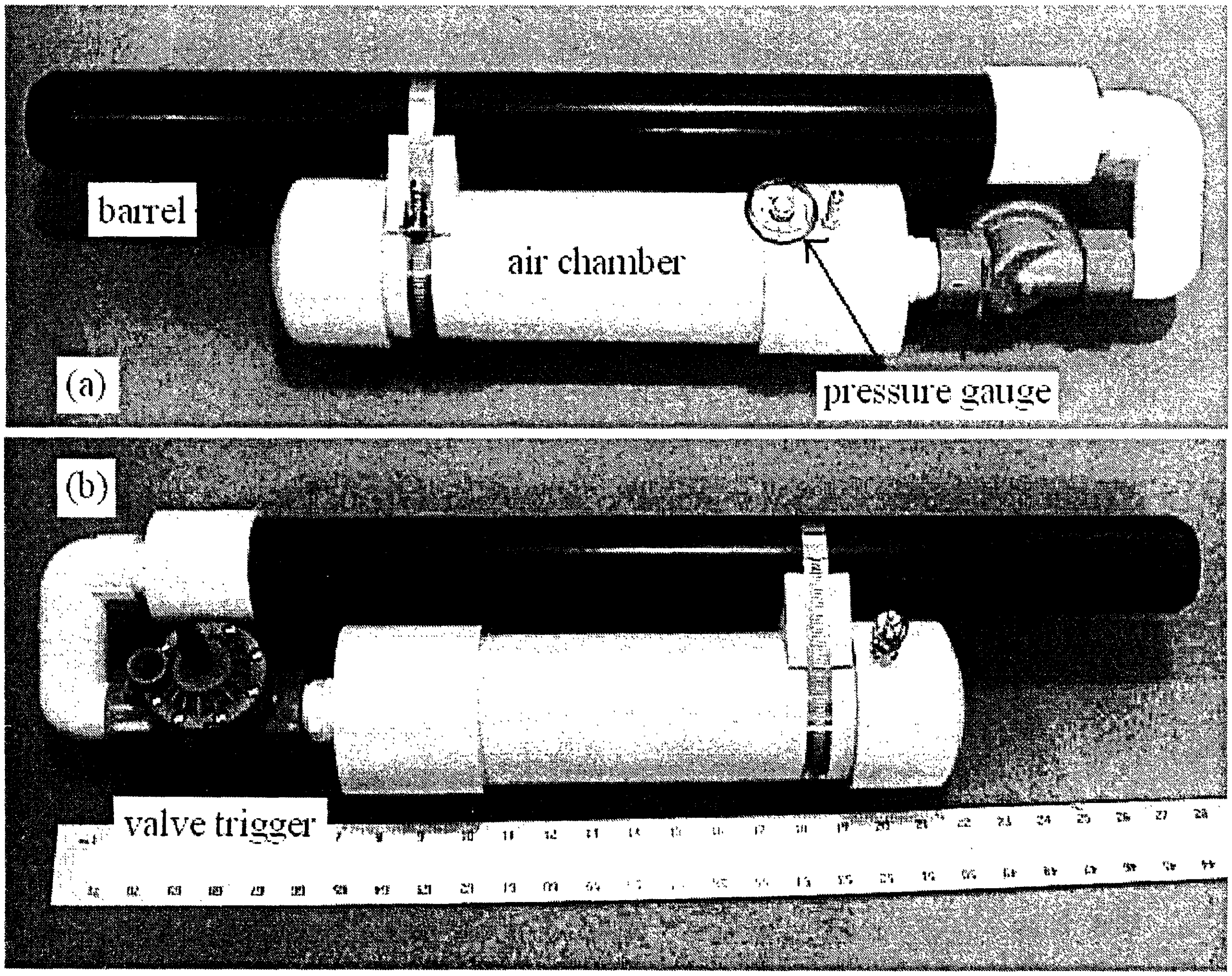

Figure 5. Two views of simple potato shooter. (a) Pressure gauge monitors pressure in air chamber. (b) Valve trigger allows air to flow from chamber to barrel to shoot potato [13].

either a ball valve or a solenoid valve. A ball valve must be turned manually, and it opens more slowly than a solenoid valve. On the other hand, a solenoid valve needs a source of power such as a battery.

In a simple pneumatic potato gun, the main design parameter is the ratio of the chamber volume to the barrel volume. The projectile size fixes the barrel diameter. For the air to efficiently propel the projectile, it should be in contact with the inner surface of the barrel. Any gaps between the projectile and the barrel surface will allow the high pressure air to escape without transferring its momentum to the projectile. For a pneumatic launcher, there is no ideal chamber to barrel ratio. Joel Surprise, the owner of the Spudtech Technology Center, recommends a ratio of between 2:1 and 4:1 [13]. Once the ratio exceeds 4:1, the increase in power is not noticeable. One of the pneumatic launchers available for purchase from the Spudtech Technology Center has a 0.75:1 ratio and can achieve muzzle velocities of 300 feet per second (90 m/s) with a tennis ball.

The Spudtech Technology Center website includes a spreadsheet which predicts the muzzle velocity of a potato launcher from seven input parameters: barrel diameter, barrel length, chamber volume, projectile mass, friction, start pressure, and dead volume (the volume between the valve and the projectile). Figure 6 shows how the predicted muzzle velocities vary with pressure and volume ratio. As the chamber to barrel ratio increases, the velocity increases but by a lesser amount. As the pressure increases, the velocity also increases. This data shows that using a chamber pressure of only 5 psi can lead to velocities of 10 to 20 m/s, depending on the chamber to barrel ratio. Figure 7 compares the potato gun predicted velocities for a 1:1 ratio and the velocities calculated from (5).

Neither model takes into account friction. As can be seen, the preliminary calculations predict higher velocities. This can be attributed to the gravitational force.

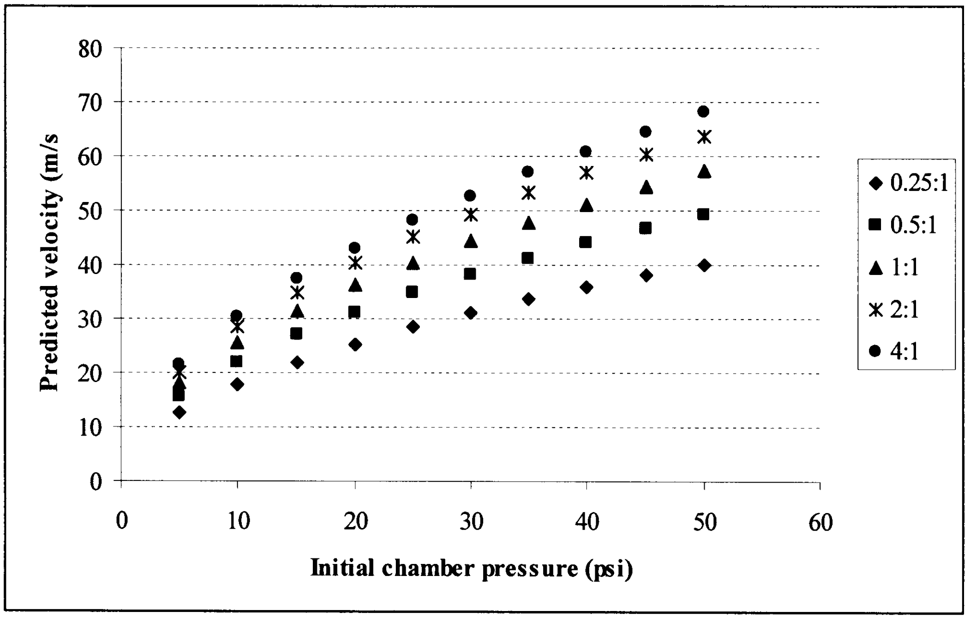

Figure 6. Predicted potato launcher muzzle velocities as a function of initial chamber pressure for barrel diameter = 0.1 m, barrel length = 1 m, projectile mass = 1 kg, no friction, and no dead volume. Volume ratios are ratios of chamber volume to barrel volume. Pressure is absolute pressure.

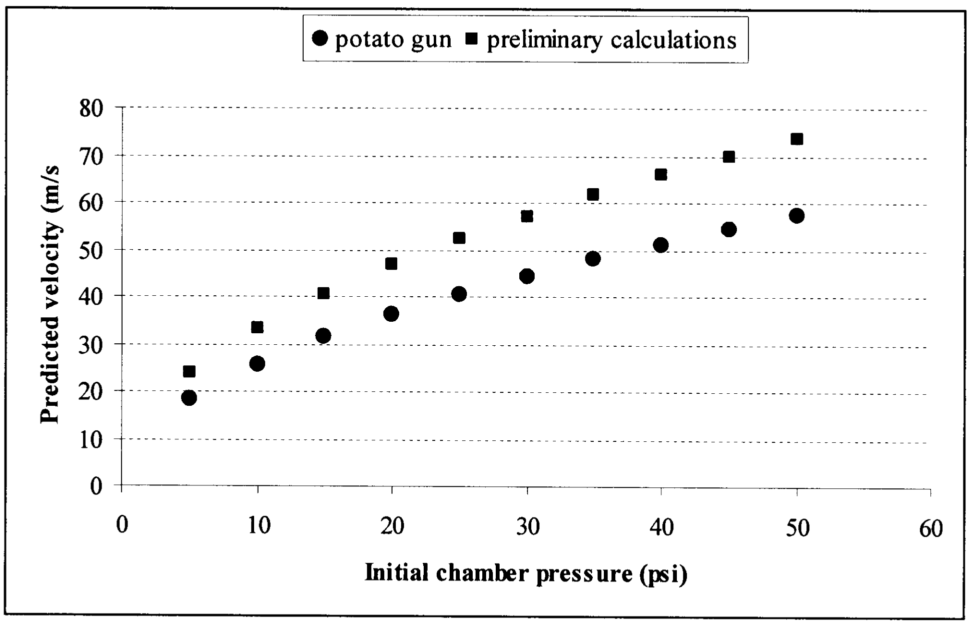

Figure 7. Predicted potato launcher and preliminary calculations muzzle velocities as a function of pressure for barrel diameter = 0.1 m, barrel length = 1 m, projectile mass = 1 kg, no friction, and no dead volume. Volume ratio for potato launcher is 1:1. Pressure is absolute pressure.

The potato gun was not adapted for this project because the valve does not release the air quickly enough for the desired application.

2.1.4 The Paintball Gun

The paintball gun is used in the recreational game of paintball. The paintball gun employs compressed gas – commonly carbon dioxide, nitrogen gas, or air – to shoot small balls of paint horizontally. Small cartridges or larger tanks are attached to the gun and supply the compressed gas. The balls of paint weigh a few grams and are 1.7 cm in diameter [14]. Since the game of paintball requires players to shoot paintballs at each other, regulations keep the top speed of the guns around 300 feet per second (90 m/s).

A diagram of a simple paintball gun is shown in Figure 8. The How-Stuff-Works website describes the operation of such a gun [14]. The bolt slides back, compressing the main spring, to allow the paintball to drop into the barrel. As the bolt slides back, the sear

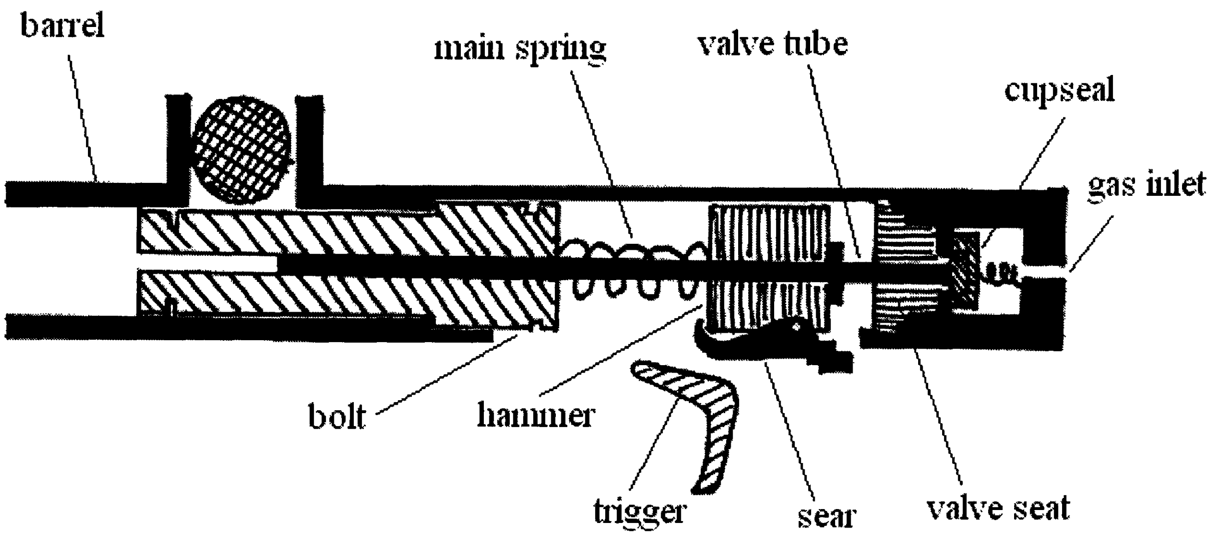

Figure 8. Cross-sectional diagram of simple paintball gun before shooting. Not to scale. Pin attaches sear to hammer. Cupseal is fixed. Valve tube can move freely through bolt, hammer, and valve seat.

hooks into the notch on the bolt. This binds the bolt to the hammer so that both parts will move as one unit. The paintball gun is now ready to shoot. When the trigger is pulled, it pushes against the sear, causing the sear to pivot about its connection to the hammer. Momentum pushes the hammer to the right. When the hammer moves to the right, the valve tube also moves to the right. The valve tube slides through the fixed valve seat and pushes the cupseal to the right. This action exposes small slits in the valve tube through which the pressurized air from the gas inlet travels. The air travels through the valve tube and propels the paintball down the barrel. The small spring attached to the cupseal forces the valve tube back to the left, into its resting position with the slits covered.

The paintball gun design was adapted to shoot downward. First, the original design was simplified. Only the essential parts were kept: the valve tube, to transport the air; the bolt, to hold the valve tube; and the cupseal, to seal the valve tube from the gas inlet. The adapted design is shown in Figure 9. The mechanism is made of two main parts – the air chamber and the barrel. Each one would be made separately and joined by the threaded interface shown. In this specific design, the chamber would be filled with the compressed air and possibly resupplied via the gas inlet. Optimization of this aspect of the design was not completed. The seal and valve tube were not changed in the adapted design. The valve tube still contains small slits which are exposed during shooting as described previously. The bolt is now fixed to the barrel because the triggering mechanism was discarded. An o-ring was added to seal the barrel. The details of the retractable nub and loading mechanism are not included in the design in Figure 9. These mechanisms represent two of the complex problems in designing an automated, downward-shooting mechanism and will now be discussed.

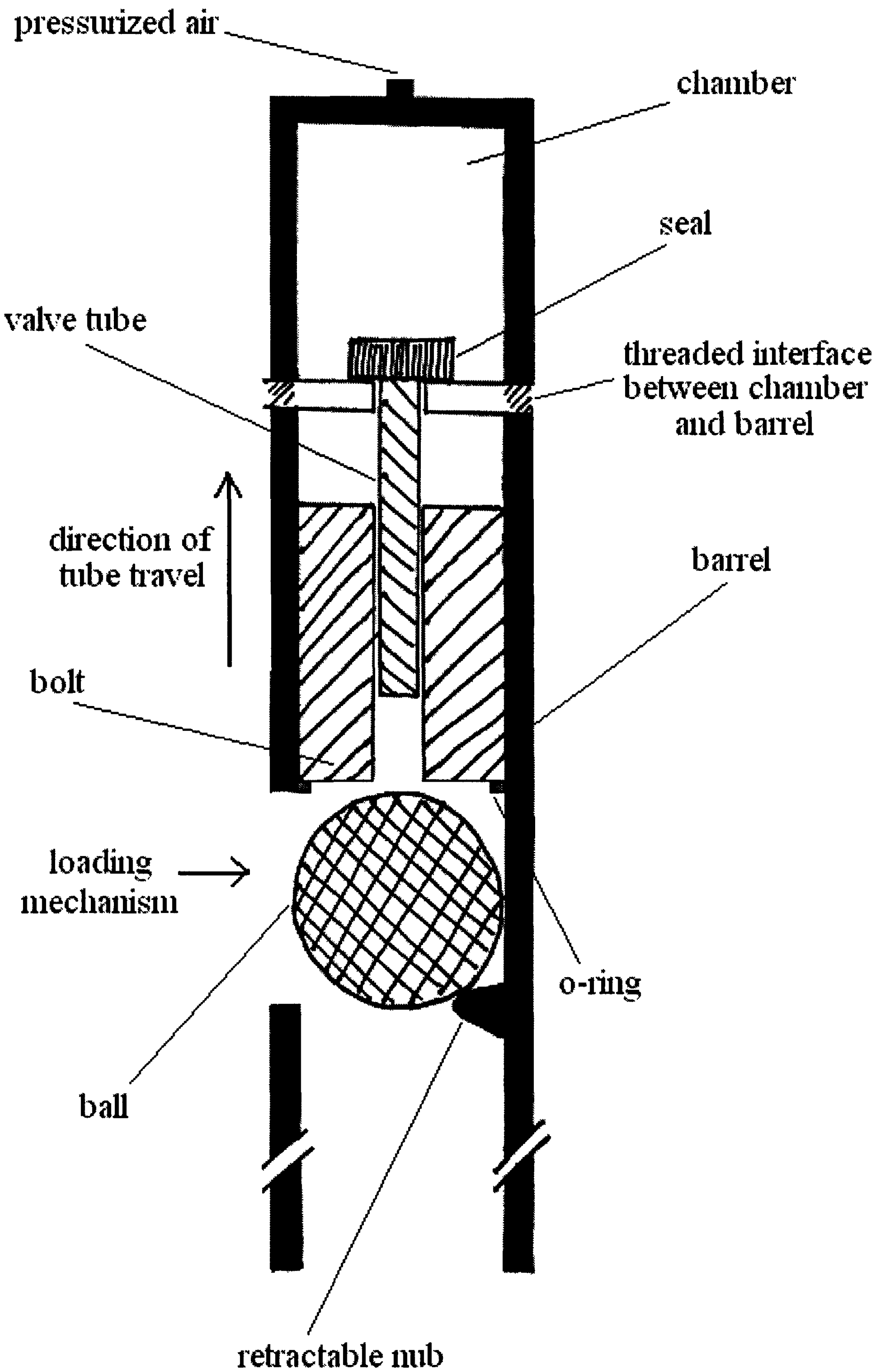

Figure 9. Cross-sectional diagram of paintball gun adaptation. Not to scale. Bolt is fixed in barrel. Loading mechanism and retractable nub discussed later.

Methods for holding the ball in place before shooting were investigated. Four possible solutions are shown in Figure 10. In each of these solutions, the ball is supported at the end of the barrel. In Figure 10a, the ball rests on the flap. The flap is hinged on one side and falls away upon the release of the other side, letting the ball fall. This method might cause the ball to spin as it exits the barrel because the flap is fixed only on one side of the barrel. To avoid this, the idea illustrated in Figure 10b was suggested. It uses two half-circle flaps to release the ball more evenly and avoid spin. This method would not work well in automation because of the complications in resetting the hinged pieces. A better solution is shown in Figure 10c. Two sliding plates retract to release the ball. To reset the system, the plates slide back in the same manner that they slid out. In Figure 10d, a thin rubber annulus with an inner diameter slightly smaller than the ball diameter is used. The rubber annulus can support the weight of the ball. When the pressurized air impacts the ball, extra force is added to the annulus which it cannot support. Thus, the ball pops through the inner diameter of the annulus. The main drawback with these holding mechanisms is that they are located at the end of the barrel. The pneumatic system needs a certain length of the barrel in which to

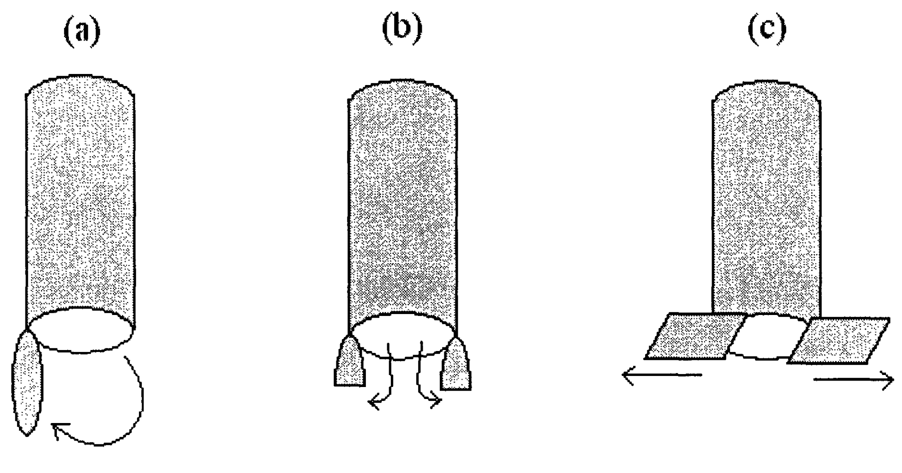

Figure 10. Ideas to hold ball at end of barrel: (a) one hinged flap, (b) two hinged flaps, (c) two sliding plates, and (d) rubber annulus.

accelerate the ball before it exits the barrel. It would be very difficult to construct a system in which these holding mechanisms were located in the middle of the barrel length; therefore, the use of pressurized air eliminates the holding mechanisms illustrated in Figure 10.

Figures 11 and 12 illustrate four solutions that hold the ball above the barrel end. In Figure 11a, a pressure difference is created such that $P_{vac} < P_{atm}$, resulting in a net upward

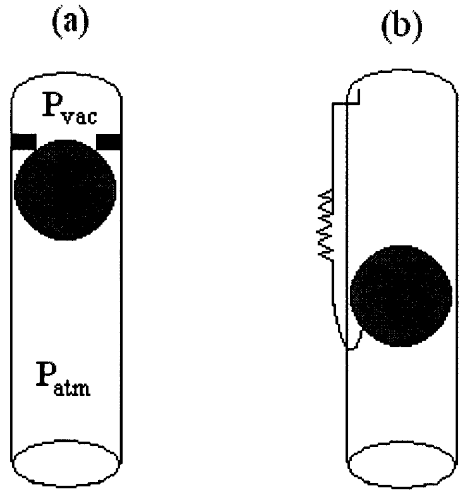

Figure 11. Ideas to hold ball in barrel: (a) suction and (b) spring and hook.

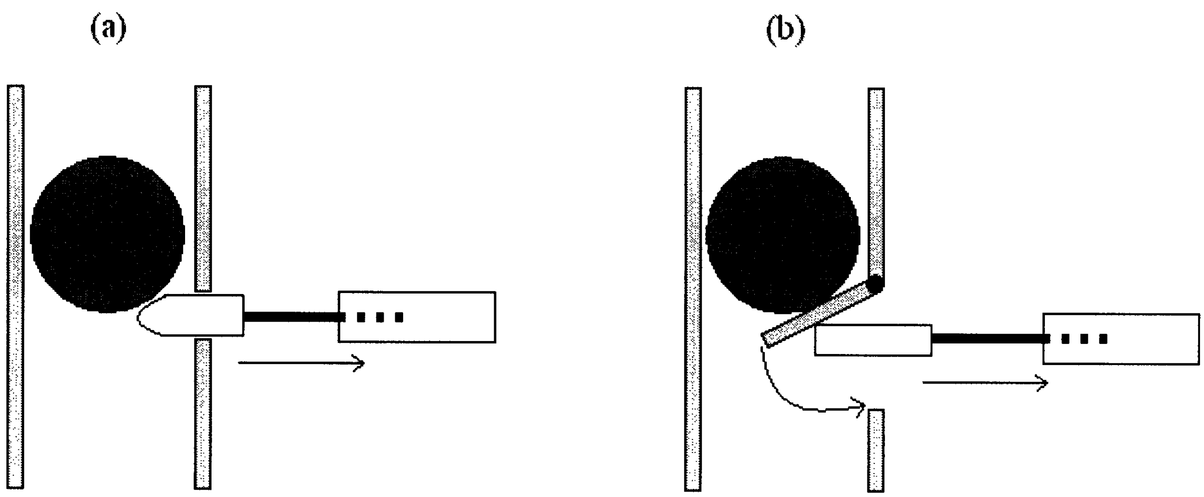

Figure 12. Ideas to hold ball in barrel involving a retractable piston: (a) linear nub and (b) hinged flap.

force. The ball remains in place, held by the stoppers, until the high pressure air is released. The pressure would need to change from P_{vac} to the high pressure P in a short time period. It is not clear how this could be implemented. Two pressure chambers may need to be used. A spring and hook holding mechanism is shown in Figure 11b. The spring is under compression when loaded, so when it is released, it will expand and the ball will begin to fall. In the determination of the exact configuration, it would be necessary to ensure that the hook did not interfere with the downward path of the ball. The two ideas illustrated in Figure 12 involve retractable pistons. The retractable nub in Figure 9 represents one of these two options. In Figure 12a, a rubber tip is attached to the piston end on which the ball would rest. A hinged flap supports the ball in Figure 12b. The piston would be triggered to retract just before the ball was shot. One concern with the piston is the torque the ball would put on the piston. This depends on where the piston is fixed, how far the piston extends into the barrel, and the size of the ball relative to the barrel. If excessive torque is applied, the piston will deform over time and eventually not slide smoothly back and forth. A variation on these two ideas could be implemented with two or three pistons located around the barrel circumference. The ball would be supported in multiple points, and no torque would act on any of the pistons.

Loading the ball was another difficult problem. To achieve the functionality necessary for the weblab, a loading mechanism was needed that stored multiple balls and could be successfully automated. Figure 13 illustrates four possible loading mechanisms which use gravity. Each solution has a part blocking the ball from falling into the barrel. To load, the part is actuated, and the ball falls into the barrel. The actuating part in Figure 13a is similar to the moving bolt in the simple paintball gun shown in Figure 8. A variation on this is a sliding sleeve, shown in Figure 13b. Depending on the fit of the bolt in the barrel and the sleeve around the barrel, either of these methods, in its resting position, could effectively seal the barrel. The mechanisms shown in Figure 13c and 13d, apply methods previously suggested for holding the ball in the barrel before shooting. The retracting plates in Figure 13c correspond to Figure 10c, and the retractable nub in Figure 13d corresponds to Figure 12a. Each of the solutions in Figure 14 includes a spring-loaded piston. Pushing on the piston overcomes the holding mechanism in each situation and deposits the ball into the barrel. A rubber annulus such as that in Figure 10d is shown in Figure 14a. In Figure 14b, a spring-loaded plate keeps the balls out of the barrel. The spring is strong enough to support the balls but compresses under the piston's pushing force. The idea illustrated in Figure 14c

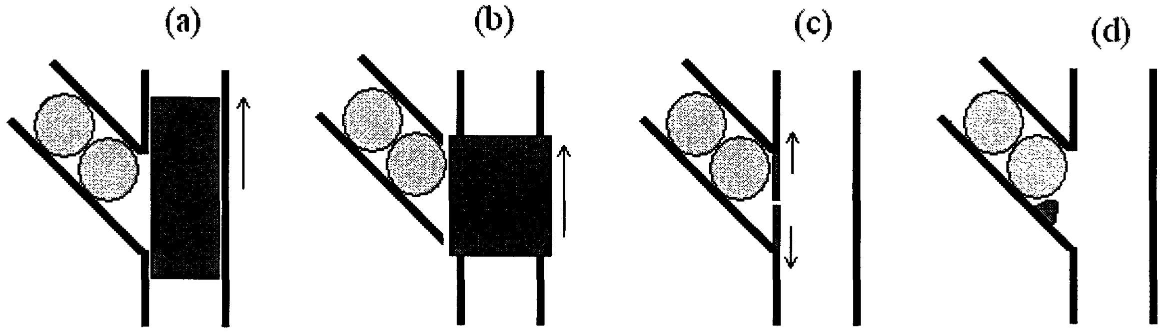

Figure 13. Possible gravitational loading mechanisms: (a) sliding bolt, (b) sliding sleeve, (c) sliding plates, and (d) retractable nub,.

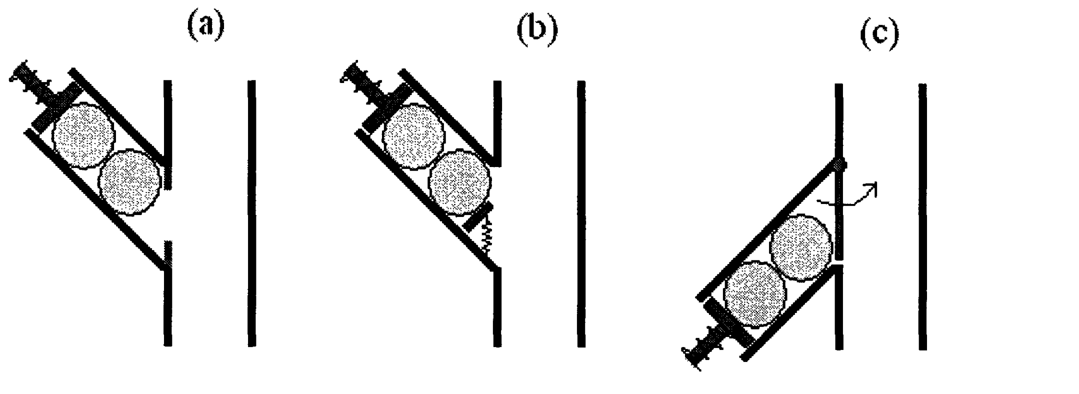

Figure 14. Possible spring-loaded piston loading mechanisms: (a) rubber annulus, (b) spring-loaded plate, and (c) hinged flap.

consists of a hinged flap which simply separates the barrel and loading mechanism. The spring-loaded piston is used to overcome the force of gravity and push the first ball just over the cusp between the ball and the barrel.

The seven loading mechanisms proposed in Figures 13 and 14 all are attached to one side of the barrel, shifting the center of the mass of the shooting system. Assuming the shooter would be mounted by the barrel, this unbalance would cause a moment about the mounting point. It is not clear what impact this will have on the shooter's ability to consistently shoot straight down. A final loading mechanism proposed is shown in Figure 15. The weight of the loading mechanism is distributed evenly around the barrel to avoid an unbalanced shooting mechanism. Each time a ball is to be loaded, the case is rotated one section, and the ball in that section drops into the barrel.

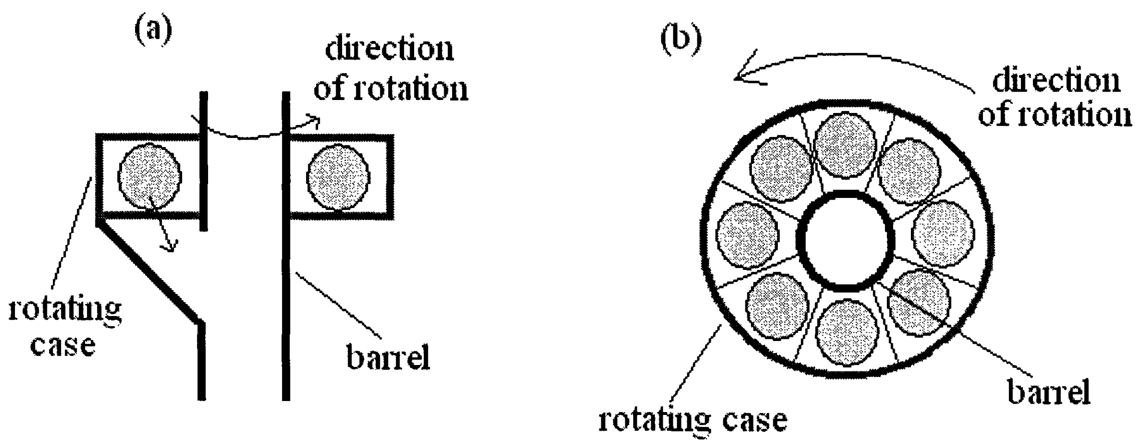

Figure 15. Rotating loading mechanism. (a) Side cross-sectional view. (b) Top view of rotating case.

2.2 Non Pneumatic Designs

Two non-pneumatic designs were also investigated – the baseball pitching machine and the railgun – leading to the decision to use electromagnets in the final design.

2.2.1 The Baseball Pitching Machine

The baseball pitching machine uses two rotating wheels to pitch a baseball to a batter. The wheels rotate in opposite directions, and the friction between the wheels and the ball pushes the ball out with a high speed. Zooka Sports, Inc. designed a portable pitching machine that throws baseballs or machine-pitch dimple balls at speeds of 10 to 65 mph (4.4 to 29 m/s) [15]. Since this design shoots balls horizontally, it does not solve the problem of shooting downwards.

In the Marine Hydrodynamics Laboratory at MIT, a downward shooting mechanism is being developed using an adapted baseball pitching machine [16]. The current working mechanism is shown in Figure 16. It can shoot pool-ball-size objects downward at speeds up to 65 mph (29 m/s). The mechanism can be translated in the x-direction and rotated in the θ-

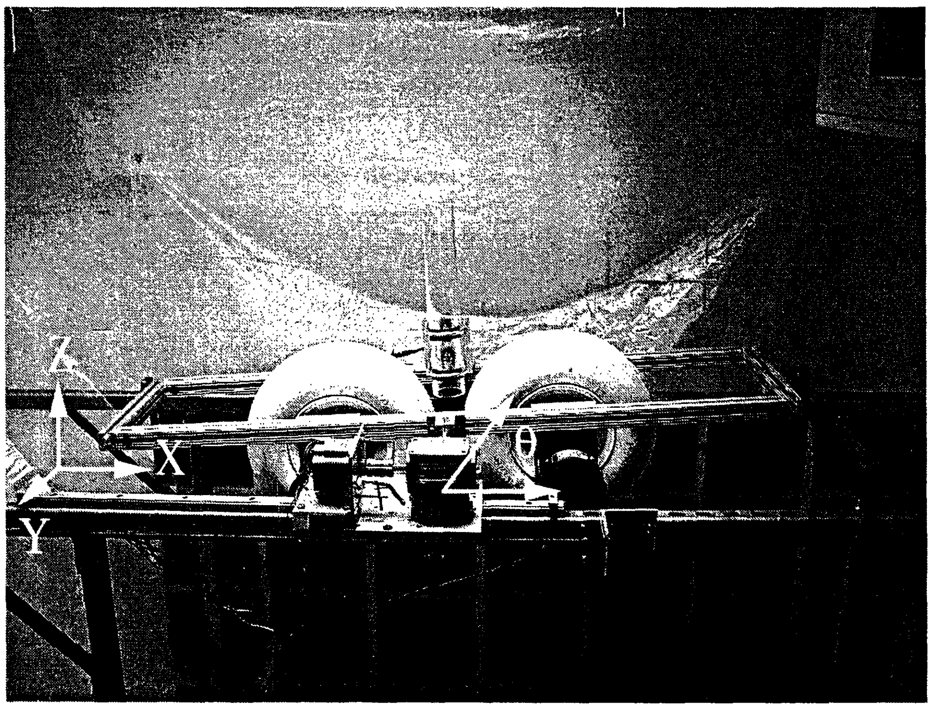

Figure 16. Baseball pitching machine adapted to downward shooting of pool balls. Mechanism is mounted over large tank of water with x, y, z, θ coordinate system shown. Courtesy of Tadd Truscott.

direction to create oblique impact experiments. The basic baseball pitching machine design was used because it could shoot downwards without much adaptation. The pneumatic solution was deemed impractical because of the short duration of the necessary air pulse needed to accelerate a projectile sufficiently for the desired velocities.

The adapted baseball pitching machine has a few main drawbacks. Since the two rubber wheels each spin around a fixed point, the shooting mechanism can only shoot projectiles the size of a pool ball (or baseball). The speed of the wheel spin is not computer-controllable in the current configuration. An interesting phenomenon is the stretching of the rubber wheels at different speeds. The wheels deform enough that a pool ball does not fit between the two wheels at all speeds. Thus, the range of output speeds is limited with this mechanism.

2.2.2 Electromagnetic Design

A rail gun uses electromagnetism to propel an object. The gun employs two rails which conduct a current. The projectile (or armature) electrically connects the rails, and the electromagnetic forces propel the projectile forward. The muzzle velocity of a projectile shot with a rail gun is

$$v_{muzzle} = I\sqrt{\frac{2DL\mu}{m}}, \tag{7}$$

for the current I, the distance between the rails D, length of the rails L, the mass of the projectile m, and the magnetic permeability of free space $\mu = 1.26\times10^{-6}$ H/m [17]. For the hypothetical parameters used in 2.1.1 (m = 1 kg, D = 0.1 m, L = 1 m) and v_{muzzle} = 10 m/s, the required current is 19.9 kA. To achieve a muzzle velocity of 20 m/s, the required current is 39.8 kA. High currents such as these are dangerous. Because of the high currents, a large amount of heat is generated. The system must be designed to withstand the generated heat. A typical problem is that the heat causes the switch to weld closed [17].

Despite the complications of railguns, an electromagnetic solution was not abandoned. A simple electromagnet seemed to be a straightforward way to suspend the projectile before shooting. The electromagnet could be turned off just before the actual shooting mechanism was triggered, or if the force delivered to the ball was strong enough, the electromagnet would not need to be turned off.

Two possible locations of the electromagnet are shown in Figure 17. In the first orientation, the electromagnet is integrated into the piston which transfers momentum to the ball to accelerate it to the desired velocity. Two metal connectors are embedded in the pipe walls. Before the ball is shot, the electromagnetic piston is in contact with the metal connectors, and the magnetic force suspends the ball. When the piston is moved down the barrel to impact the ball, the electrical connection is broken, and the piston is no longer magnetic. Thus, the ball begins to fall just as the piston impacts it. In the second orientation, the electromagnet is attached to the outside of the barrel. Here, the opening and closing of

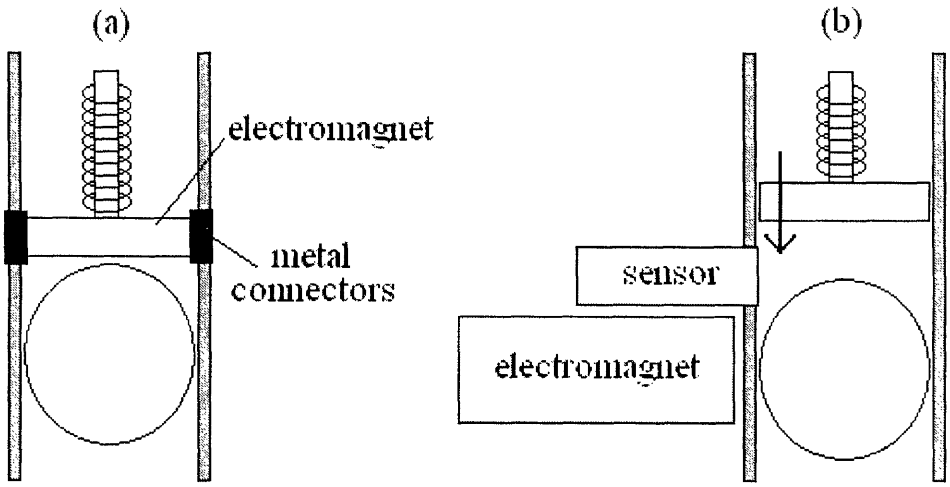

Figure 17. Possible electromagnet locations: (a) integrated in the piston and (b) outside barrel.

the electrical loop necessary to power the electromagnet is not directly connected to the piston's movement. The electromagnet needs to be turned off just as the shooting mechanism triggers. One possible solution is the inclusion of a sensor on the inside wall of the barrel. As the piston passes the sensor, the electromagnet is switched off. The use of a piston in these two examples does not preclude the use of other shooting mechanisms; a method for switching the electromagnet on and off would need to be devised if other mechanisms such as direct pneumatics were employed.

In the following chapter, the specifics of the final design will be presented and explained in depth.

Chapter 3

Final Design

The final design of the shooting system is shown in Figure 18. The major components of the design are the pinball shooting mechanism and the electromagnet. First, the actual method for propelling the ball was chosen. As previously mentioned, for a pneumatic system to work effectively, the high pressure must be applied during a time on the order of microseconds [16]. Conversely, the pinball shooting mechanism was a straightforward way to apply a force to the ball to accelerate it downward. It was also readily available. With a pneumatic shooter, a more complicated system would need to be constructed. Determining a mechanism to hold the ball up was also challenging. Of the many ideas presented in chapter 2, the electromagnetic solution seemed the most straightforward. It lacked the moving parts that the other solutions required which simplified its integration into the design.

The selection of the other parts and materials was based on the ease of construction and the availability of materials. The nested PVC pipe, while perhaps not the most elegant solution, is the most convenient. The base of the pinball shooting mechanism already has three mounting holes at a location just inside the inner radius of the 1-3/4 inch PVC pipe. The nested PVC pipe acts as an adapter from the 1-3/4 inch to the 1-1/4 inch PVC pipe. The welded aluminum circular flange fits snugly around the 1-3/4 inch PVC pipe and is easily bolted to the mounting plate on which the pinball shooting mechanism is mounted. The details of the electromagnet's mounting were not determined besides its location on the side of the barrel.

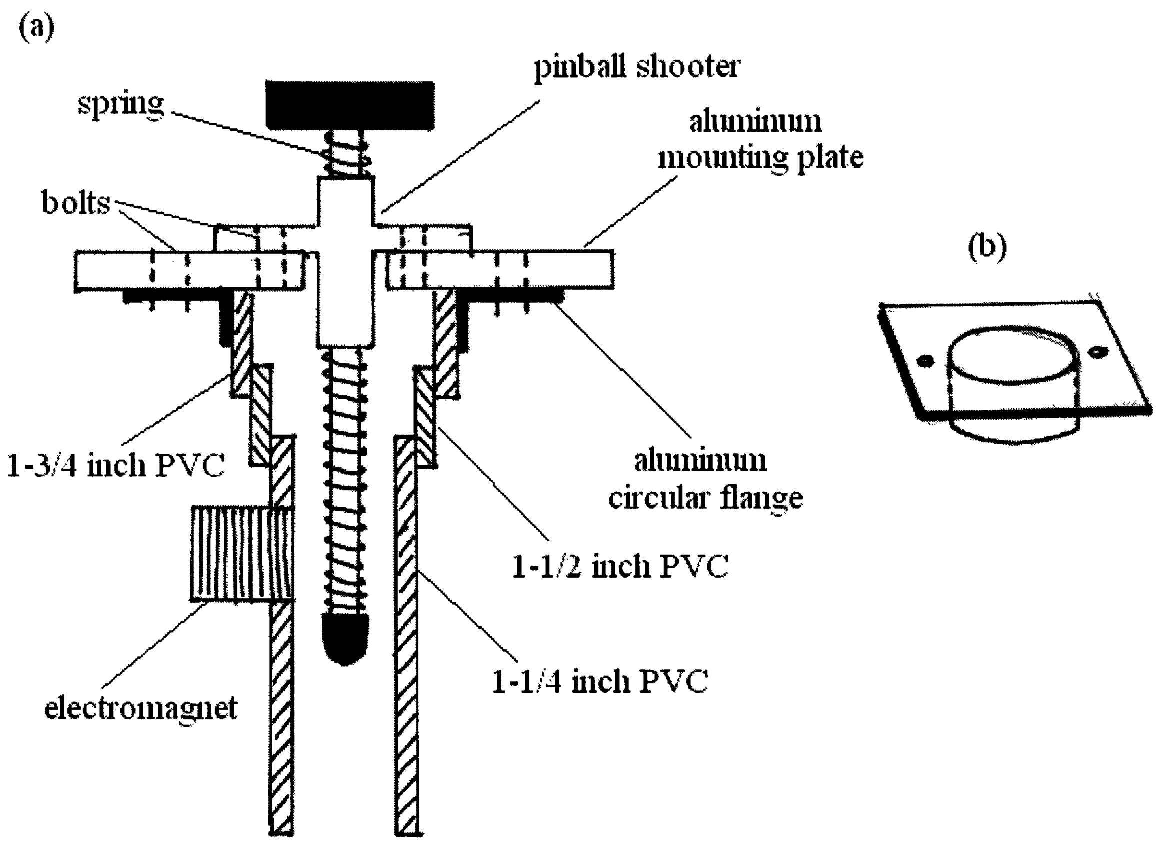

Figure 18. Diagram of final design. Not to scale. (a) Cross-sectional view of entire design. (b) Welded aluminum circular flange.

3.1 Pinball Shooting Mechanism

The chosen pinball shooting mechanism is shown in Figure 19. Tests were conducted to determine the spring constant *k* of the shooter. The force-displacement data are presented in Figure 20. Following Hooke's Law, the relation between force F and displacement x in a linear spring is

$$F = kx\,; \tag{8}$$

therefore, the slope of the graph in Figure 20 is the spring constant. It is found to be 3.025 N/cm or approximately 300 N/m. Knowing this, the velocity of the ball can be predicted.

The balls used are 1 inch diameter carbon steel (1010/1020) which have an approximate density of 0.284 lb/in^3 or 7880 kg/m^3 [18]. Thus, the mass of each ball is 0.15 lb or 0.067 kg. As in (4), summing the forces acting on the ball gives

$$\sum F = ma = mg + F_{pinball} = mg + kx\,. \tag{9}$$

The acceleration of the ball has increased from g to

$$a = g + \frac{F_{pinball}}{m} = g + \frac{kx}{m}\,. \tag{10}$$

If the pinball shooter spring is compressed all the way (x = 6 cm), the acceleration of the ball has increases to 278 m/s^2, almost 30 times larger than the acceleration from gravity alone (9.8 m/s^2). This extremely large increase in acceleration can be seen in Figure 21.If it is assumed that the spring can be compressed accurately to differences of 0.5 cm, accelerations from 9.8 m/s^2 to 278 m/s^2 in increments of about 22 m/s^2 can be achieved.

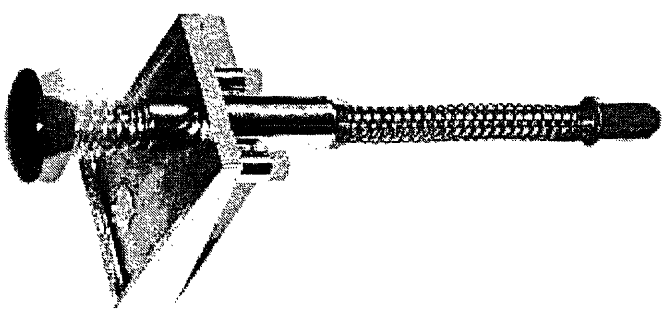

Figure 19. Pinball shooting mechanism used in final design [19].

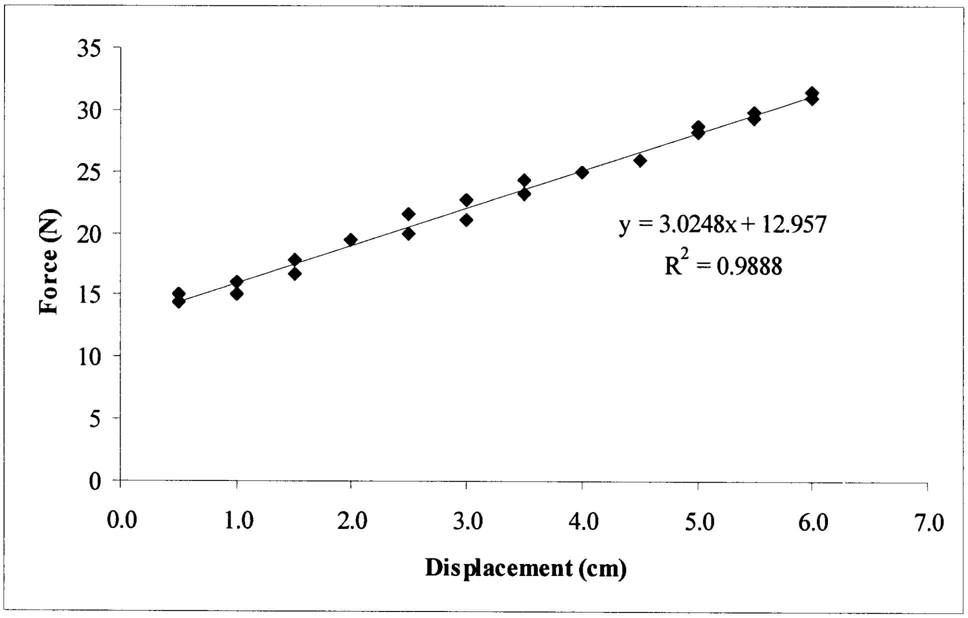

Figure 20. Force as a function of displacement for pinball shooter spring. Spring constant k is the slope.

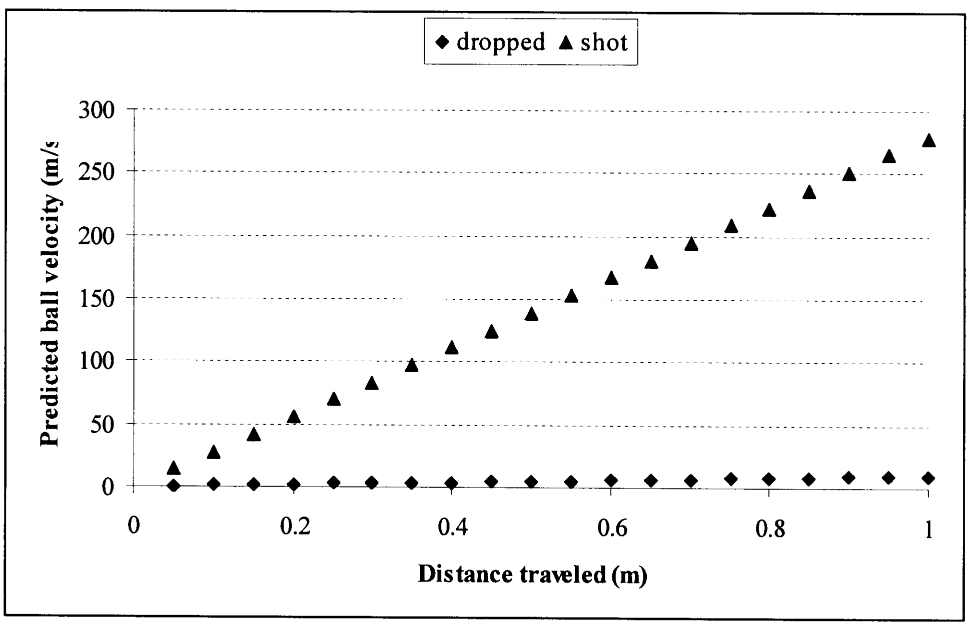

Figure 21.Predicted ball velocity from dropping ball and shooting it with fully-compressed pinball shooter. Drag is neglected. Slope of each data set is the acceleration.

3.2 Electromagnet

When the electromagnet was turned on and the ball suspended as shown in Figure 17b, the ball was held. Unfortunately, with very little direct force or wiggling of the electromagnet, the ball fell off. According to the electromagnet retailer, the magnet could hold up to 12 lbs when powered with a 12 V DC battery. Derating the electromagnet by 50% (as recommended by the retailer for holding applications), it should still be able to hold 6 lbs and derating it by 75 % (as recommended for lifting applications) gives a holding force of 3 lbs. As calculated in 3.1, the mass of each steel ball is only 0.15 lb. Two possible situations can explain this unsatisfactory behavior. First, the electromagnet sent may not have been the correct one. More likely, the electromagnet's holding behavior differs when it is suspending something that is next to it as the ball is. The behavior of one electromagnet does not provide sufficient data from which to draw conclusions on the strength needed for this application.

3.3 Considerations for Implementation

If this system were to be built, some adaptations should be considered. First, the force needed to cock the shooter (compress the spring) must not pull the system apart. The connection between the aluminum flange and the 1-3/4 inch pipe may need to be fixed, so the shooter, mounting plate, and flange do not come off during the cocking process. In the design presented here, the pinball shooting mechanism must be manually pulled back and released, and there is no way to cock the shooter and lock it in that position. Ideally, the shooter would be cocked automatically. Since the electromagnet used here did not satisfactorily suspend the ball, modifications are necessary before the system is implemented.

A stronger electromagnet could be used in conjunction with a thinner tube, and hollow balls could be used as long as they have some magnetic properties and are negatively buoyant. Even using a stronger electromagnet, the force from the pinball shooter will be large enough to detach the ball from the magnet; thus, the electromagnet may remain on during shooting.

Chapter 4

Conclusions

Throughout the course of the project, several challenges were faced and conclusions reached. Three major design challenges were confronted. First and foremost was the conclusion that shooting downwards is difficult because of the need for a mechanism that can hold the projectile up and release it at the desired time. Second, in choosing an appropriate loading mechanism, it was determined that there are many viable options. Finally, the automation design parameter required an involved design and strict timing constraints and was not included in the scope of this project.

It was determined that a pneumatic shooting system is not advantageous because of the precision needed in the air release mechanism. The pinball shooter was the more practical solution. It is easily-operable and can deliver a wide range of forces. Automating the pinball mechanism, however, creates difficulties. Also, the adaptability of the pinball shooter to other projectiles is unclear because of the single point at which the rubber tip impacts a surface.In addition to the shooting mechanism, holding systems were considered to allow the ball to be shot downward. The electromagnet suspension system is a simple way to solve this problem, provided the electromagnet was strong enough. The availability of an appropriately-sized electromagnet is not a limit on this design as electromagnets come in a large range of strengths. The final design presented in chapter 3 will be able to create free-surface impacts over a large range of velocities. If the shooter is located 1 m or less above the free surface, the velocities can reach 280 m/s.

The applicability of this design to future downward shooting endeavors depends on the desired experimental parameters. The pinball-electromagnetic shooting mechanism can not provide incremental changes in velocity accurately, and it will only work with magnetic, spherical projectiles of about 1 inch in diameter. To study the free-surface impact of other objects, a different mechanism is needed. However, this particular shooter is useful because it can shoot smaller projectiles, compared with the baseball shooter being developed in the MIT Marine Hydrodynamics Laboratory; therefore, a lower range of Froude numbers can be achieved, and a wider range of physics can be investigated.

References

[1] T. von Karman, "The impact on seaplane floats during landing," *National Advisory Committee for Aeronautics Technical Note,* no. 321, 1929.

[2] X. Mei, Y. Liu, and D. K. P. Yue, "On the water impact of general two-dimensional sections," *Applied Ocean Research*, vol. 21, no. 1, pp. 1-15, February 1999.

[3] G. V. Boitsov and M. A. Koudrin, "Slamming strength requirements for ship bow structures," *Marine Technology*, vol. 38, no. 2, pp. 102-105, April 2001.

[4] T. Miloh, "On the initial-stage slamming of a rigid sphere in a vertical water entry," *Applied Ocean Research*, vol. 13, no. 1, pp. 43-48, 1991.

[5] M. Greenshow and S. Moyo, "Water entry and exit of horizontal circular cylinders," *Philosophical Transactions of the Royal Society London, Series A (Mathematical, Physical and Engineering Sciences)*, vol. 355, no. 1724, pp.551-563, March 1997.

[6] A. May, "Vertical entry of missiles into water," *Journal of Applied Physics*, vol. 23, no. 12, pp. 1362-1372, December 1952.

[7] J. W. Glasheen and T. A. McMahon, "Vertical water entry of disks at low Froude numbers," *Physical Fluids*, 8 (8), pp. 2078-2083, August 1996.

[8] J. W. Glasheen and T. A. McMahon, "Size-dependence of water-running ability in basilik lizards (*Basiliscus Basiliscus*)," *Journal of Experimental Biology*, 199, pp.2611-2618, 1 1996.

[9] S. T. Hsieh, graduate student in Department of Organismic and Evolutionary Biology at Harvard University, "Research interests," 2004, http://www.people.fas.harvard.edu/~sthsieh/tonia_resint.htm.

[10] A.W. Troesch and C.-G. Kang, "Hydrodynamic impact loads on three-dimensional bodies," in *Proceedings of the 16th Symposium on Naval Hydrodynamics*, 1987, pp.537-556.

[11] H.-H. Shi, M. Itoh, and T. Takami, "Optical observation of the supercavitation induced by high-speed water entry," *Transactions of the ASME*, vol. 122, no. 4, pp. 806-810, December 2000.

[12] D. Gilbarg and R. Anderson, "Influence of atmospheric pressure on the phenomena accompanying the entry of spheres into water," *Journal of Applied Physics*, vol. 19, no.2, pp. 127-139, February 1948.

[13] The Spudgun Technology Center, 2004, http://www.spudtech.com.

[14] How Stuff Works, "How Paintball Works," 2004, http://entertainment.howstuffworks.com/paintball.htm.

[15] S. Kirby, "State-of-the-art pitching machine wows baseball fans of all ages," Kirby Communications, Seattle, Washington, November 2000.

[16] T. T. Truscott (private communication), 2004.

[17] Jengel and Fatro's Rail Gun Page, 2002, http://home.insightbb.com/~jmengel4/rail/rail-intro.html.

[18] National Precision Ball Group of Mechatronics, Inc., 2002, http://www.nationalball.com/7_1010-1020.htm.

[19] K&K Amusement, 2001, http://www.pinballdirect.com/.