2021 Stage Machine Design Competition Design Proposal

Purdue University
Issy Block
Kelsie Chisholm
Shep Dick
Tabi Wimsett

Table of Contents

The Process

Vertical movement with variable speed, lateral movement prevention, a firing mechanism, safety interlocks, a trigger mechanism, and a method of control are all integral components in the final design. The team started by creating a design specification to familiarize and expand their understanding of the challenge. From there, the concept design phase began with individual research of existing devices that were related to each axis of movement. The team formed sub-concepts for each axis that were then both designed and researched further. After discussing the pros and cons for each sub-concept, the team created a list of criteria that they deemed vital for a successful device. A decision matrix was then used to determine which mechanisms would best fit the criteria, which later informed the final design concept.

Design Specification

The team has been hired to develop some moving elements for an escape room with the theme of “Wisconsin Johnson and the Pop Up Dart Trap”. If Johnson makes a misstep, the statuary heads along the walls of the passage will rapidly rise off the floor, propel a poison dart from their mouths, and then slowly return to their position on the floor.

Physical Specifications

- The “Head” is a cylinder that is 18 inches tall and has a diameter of 18 inches
- The “Mouth” is 6 inches from bottom of head

Machine Sequence

- 1: Trigger is activated
- 2: Head rises 18 inches in less than 2 seconds
- 3: Dart shoots when head is at maximum height
- 4: Head lowers immediately and returns to its starting position in no less than 10 seconds after dart fires

Sequence Trigger

- Entire sequence must be initiated by one trigger
- Trigger type can be determined by the team

Successful Device Requirements

- The head must begin and end the sequence at its lowest (“zero”) position
- Sequence should run successfully 10 times in a row, with reloading periods in between

- Reloading should be as quick as possible
- Darts should land on the ground between 5 and 10 feet and should hit the same spot consistently
- Special consideration will be given to machines that use primarily mechanical means
- Aesthetic flairs beyond elegance of the implementation of the design are not being judged - culturally insensitive aesthetic choices are not allowed

Safety

- Mechanisms must be included to ensure that the dart will not launch during reload time.
- No explosives or pyrotechnics can be used
- No humans will be targeted in the testing of the device

Provided Resources at Competition

- Identical darts will be provided during design phase and competition day
- 10 darts will be provided at the start of our demonstration
- 15A 110-120VAC power will be supplied
- 100 psi air pressure through ¼" tube or quick-connect available (must request by 5/1)
- Air hoses and extension cords will be provided
- Testing will likely be in the Mallet Theater (Air and power hookups are located in the NW corner of the theater)
- Screwing and/or bolting into the deck should be avoided, if possible

Competition and Testing Details

- Load-in and strike should be as fast as possible, and should not take more than 30 minutes
- Members of our team will trigger the sequence and operate the machine during the competition

Concept Designs

Research

Before starting the concept design phase, the team members performed individual research. Each team member began the concept design phase by researching existing devices for vertical movement and firing mechanisms. This research included a wide variety of devices such as linear actuators, scissor lifts, DIY desk lifts, Nerf guns, catapults, tennis ball launchers, and blow guns. The team reconvened to discuss different options based on their findings. For the vertical movement, *Mechanical Design for the Stage* (Hendrickson 394) proved to be a useful tool in expanding on the research for scissor lifts which later became part of the final design concept. The video “How does a nerf gun work?” and the web article *Nerf Mods: a Beginner’s Guide* became the base for our firing mechanism concept.

Sub Concepts

Vertical Movement

1. Timing Belt with Double Threaded Rods (DIY Perks 1:02-8:17)

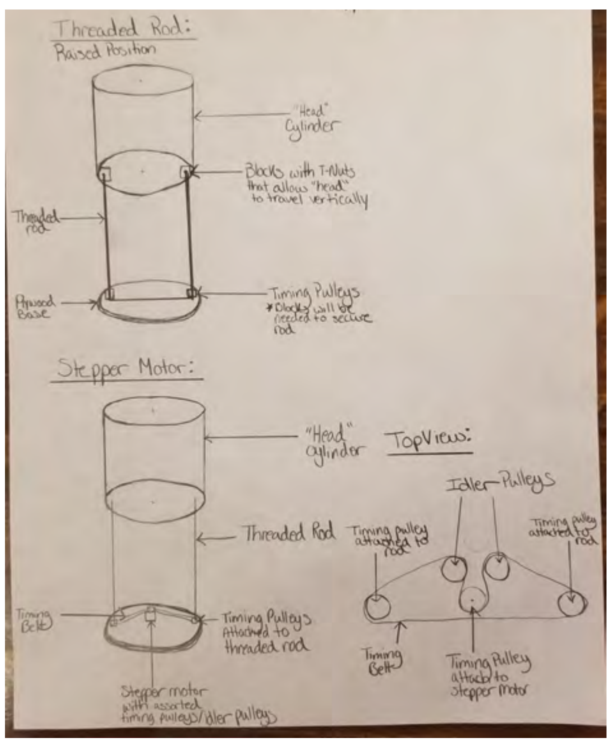

Figure 1.1 Timing Belt

How it Works:

- Two threaded rods would need to be mounted on a base that sits on the ground
- Threaded rods would run the full height of the "head" (18")
- To attach the head to the threaded rods you would use blocks with T-nuts secured in them
- Timing Pulleys would need to be attached to the two rods and to the stepper motor located at center (number of pulleys not yet calculated)
- Timing belt would be wrapped around all pulleys to spin the rods (both rods run on one motor)
- The head would then be secured to both rods preventing the head from spinning
- Some kind of switch would be needed for end of travel in both directions

Pros:

- Variable speed
- Compact
- Mechanically simple- Calculations still needed for speed and torque
- Double rod would allow for more space for the firing mechanism

Cons:

- More points of failure involved.
- Additional support needed to stabilize side to side movement

2. Stepper Motor with a Single Threaded Rod

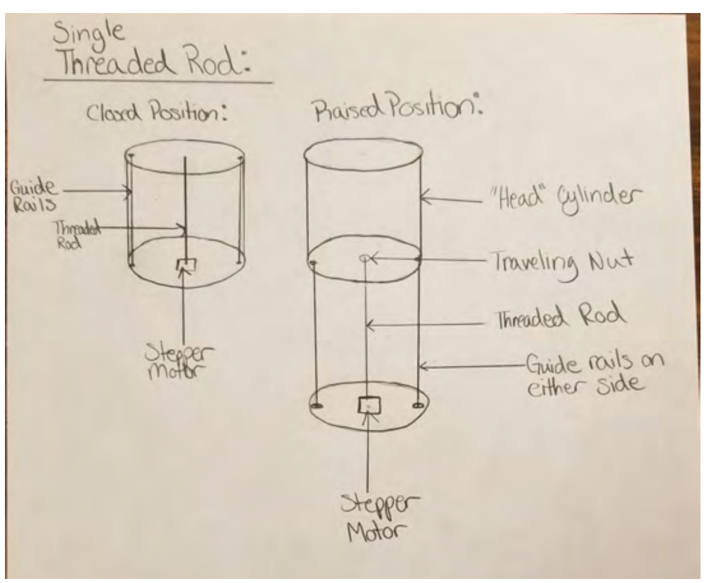

Figure 1.2 Stepper Motor

How it Works:

- Single threaded rod on a stepper motor (Pololu - Stepper Motor) will be attached to a base
- Guide rails on either side of the cylinder would prevent unwanted movement
- Threaded rod and guide rails would run the full height of the “head” (18”)
- Head would attach to the threaded rod with hardware
- Some kind of switch would be needed for end of travel in both directions

Pros:

- Variable speed
- Compact
- Mechanically simple

Cons:

- Speed and torque would depend solely on the motor -- no pulleys/gears to adjust speed/torque
- Center rod might interfere with firing mechanism
- Additional support needed to stabilize side to side movement

3. Pneumatic Actuator Concept 1

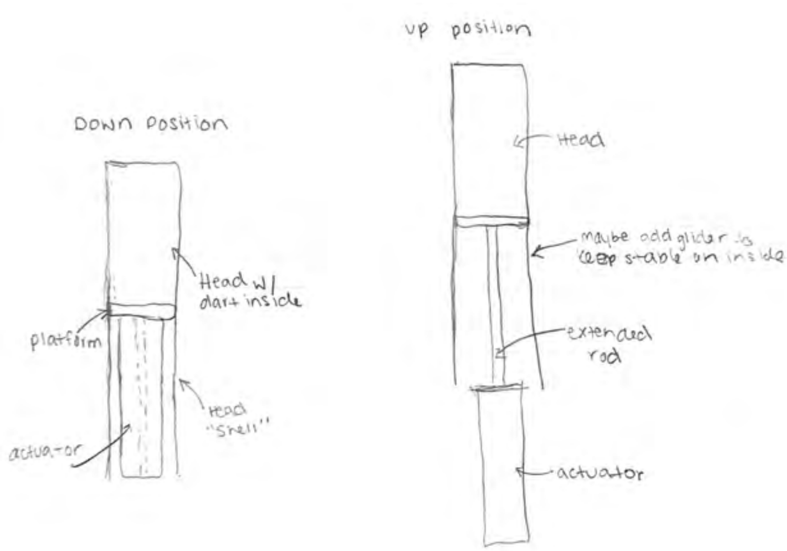

Figure 1.3 Pneumatic Actuator 1

How it Works:

- Pneumatic actuator hooked up to a solenoid (Heney)
- Solenoid air valves would be tightened differently to control extension and compression speed (Crazy Russian Haunter 2:09-5:02)

- Head would be attached to the rod by a platform to allow the dart mechanism to live inside
- An outside shell could be used to hide the actuator in down position and the rod in up position
- Gliders on the inside may be useful to keep it sturdy

Pros:
- Simple
- Can control speed
- Reliable

Cons:
- Boring
- Might not be sturdy
- Shell might be more of an obstacle

4. Pneumatic Actuator Concept 2

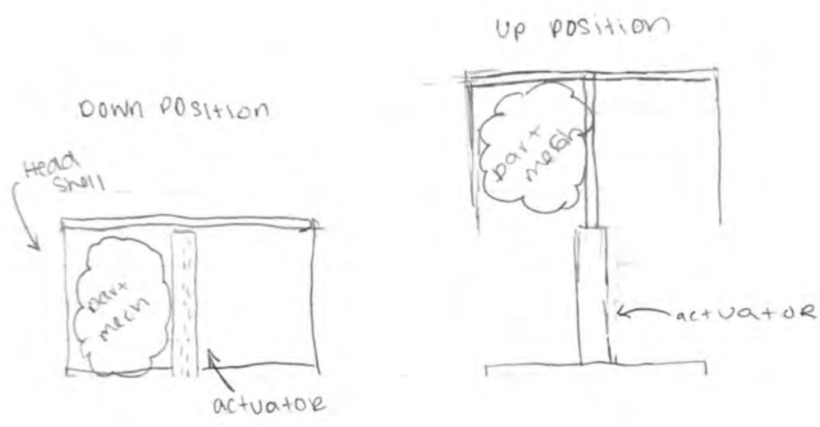

Figure 1.4 Pneumatic Actuator 2

How it Works:
- Similar concept to the one above except allows the head to fully sit on the ground

Pros:
- Simple
- Can control speed
- Reliable
- Nicer appearance

Cons:

- Boring
- Might not be sturdy
- Shell might be more of an obstacle
- Less room for the dart mechanism

5. Rack & Pinion Concept 1 (moving rack, fixed pinion)

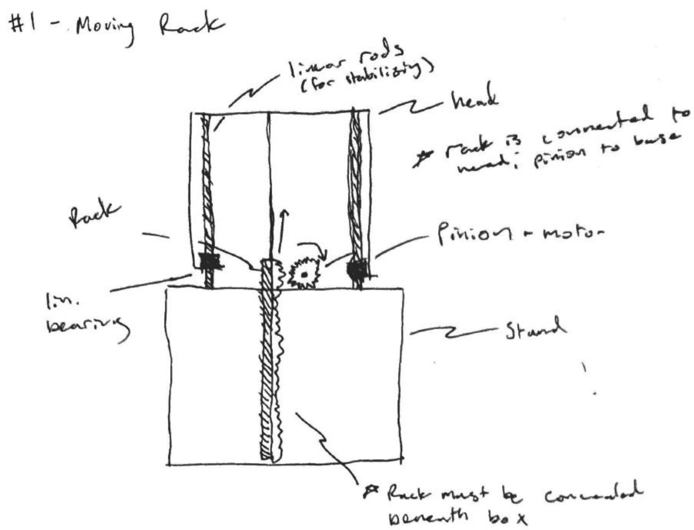

Figure 1.5 Rack & Pinion 1

How it Works:

- At rest, the head sits atop an ~18” tall box, which hides an 18” toothed rack that’s connected to the base of the head. The pinion is attached to the box, and two linear guide rods ensure that the head will travel straight.
- When the effect is triggered, the pinion will spin clockwise, interfacing with the rack to raise the head 18”. After the dart is fired, the pinion will spin counterclockwise, lowering the head.

Pros:

- Adjustable speed
- Original & interesting

Cons:

- Large box is necessary to provide clearance for rack
- Complex control - need to know when to stop movement
- Mechanically complex, lots of failure points

6. Rack & Pinion Concept 2 (moving pinion, fixed rack)

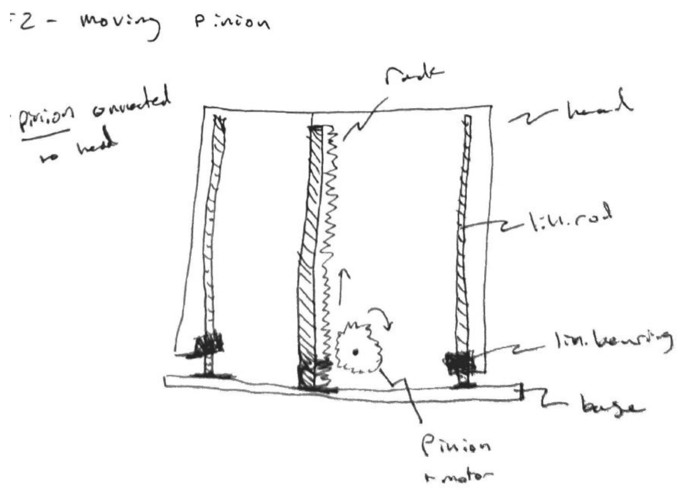

Figure 1.6 Rack & Pinion 2

How it Works:

- Similar to the previous design, but the pinion is fixed to the head and the rack is fixed to a flat base. As the pinion rotates, it will climb up the fixed rack and drive the head upwards

Pros:

- Eliminates the need for a box beneath the head

Cons:

- With the pinion attached to the head it'll be much less stable than with the rack

7. Scissor Lift

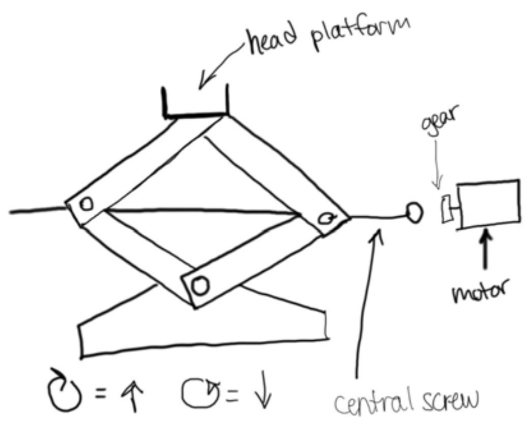

Figure 1.7 Scissor Lift

How it Works:

- There is a long screw that goes through the jack horizontally
- Rotating this screw clockwise will thread the screw further into the jack, causing the far leg of the jack to move closer, and therefore lifting the jack
- Rotating the screw counterclockwise will have the opposite effect
- The central screw is usually self locking

Pros:

- Compact at rest

Cons:

- Mechanically complex
- Motor will have to move up and down

8. Motorized Lift (Genie Lift)

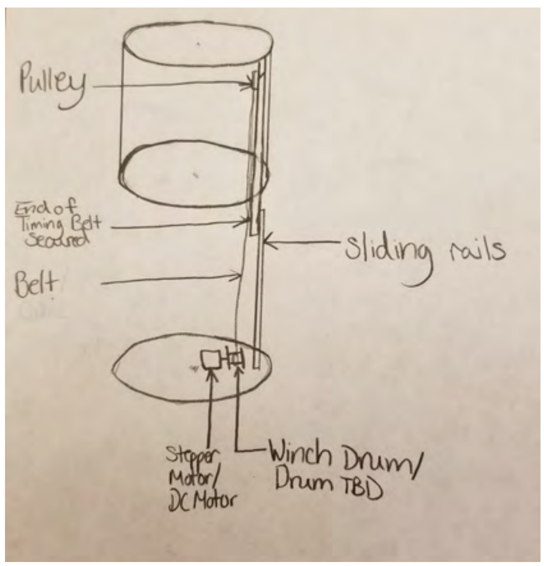

Figure 1.8 Motorized Lift (Genie Lift)

How it Works:

- Drum and motor would be mounted to a base
- Inside sliding rail would be attached to the “head” cylinder
- One end of the timing belt would be secured at the bottom of the inside slide
- Belt path: Termination point -> up to a mounted pulley on inside slide-> down to the drum (Gunter)
- Additional pulleys and slides may be needed
- Some kind of switch would be needed for end of travel in both directions

Pros:

- Original and inventive

Cons:
- Height of slides might allow for side to side movement
- Calculations needed for correct speed, torque
- Calculations for pulleys could be quite extensive
- More points of failure involved

Firing Mechanism

1. Rack & Pinion with a Spring

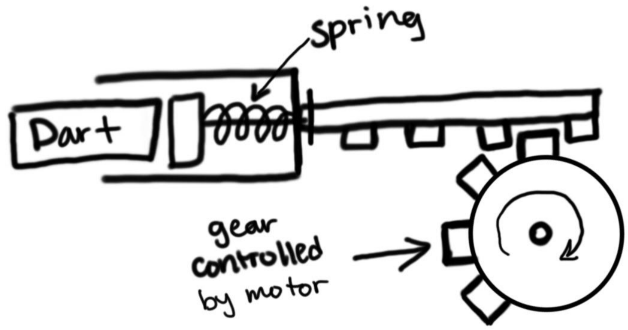

Figure 2.1   Rack & Pinion with Motor

How it Works:
- There would be a housing tube with a spring loaded catch inside
- The catch part would continue out the back of the tube with multiple teeth
- The teeth would catch on a special gear that we can 3D print that only has three or four teeth that would be able to pull the spring back all the way by rotating the gear clockwise with a motor
- When the gear runs out of teeth, the catch and spring will be released, firing the dart
- There will be a stopper of the outside of the tube that makes sure the spring will not fly away and that the gear will be able to connect with the catch as it rotates back around

Pros:
- Ability to control distance with spring lengths

Cons:
- Multiple areas for failure
- Not compact

2. Spiral Motor

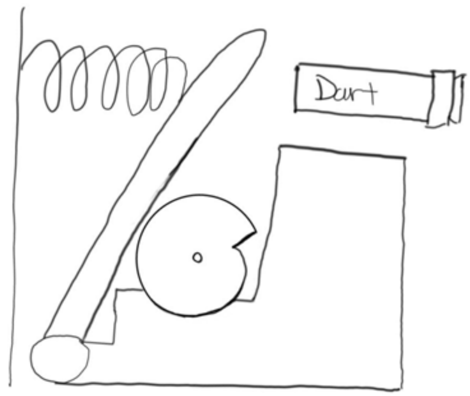

Figure 2.2 Spiral Motor

How it Works:

- A cam, powered by a motor, pushes back a bar as it's radius increases (Mechanisms X)
- The bar pushes back a spring, increasing pressure
- When the cam reaches the notch, the bar is released
- The bar propels the dart out of the head due to the force from the spring

Pros:

- Mechanically Simple
- Ability to control distance with spring lengths

Cons:

- Multiple areas for failure
- May not be able to achieve necessary distance

3. Nerf Gun Spring

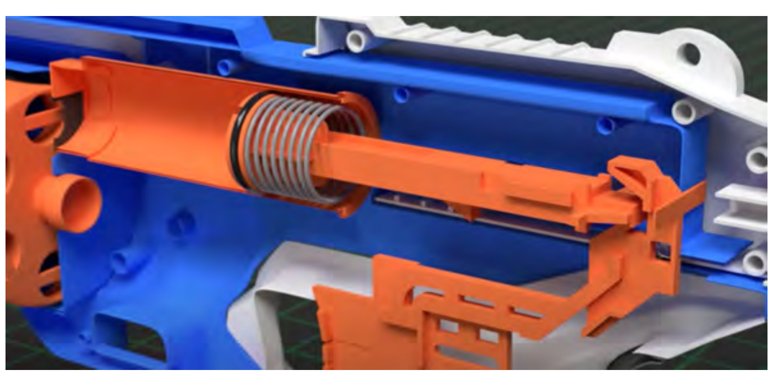

Figure 2.3 Nerf Gun Spring

How it Works:

- The dart launcher would be very similar to a Nerf gun firing mechanism (Owen 1:19-4:42). We'd need to build a housing around a catch that would release the spring-loaded piston arm when the head reaches the correct height (Villaluz)
- The catch would be pulled or pushed down, releasing the piston & spring, and would vary based on the vertical movement method, but could include an <18" string that pulls the catch down when taut or a protrusion that pushes the catch down when the head reaches a certain height
- Additionally, we'd have to include a way to pull back the spring from the outside of the head, and a physical safety interlock to ensure that the catch isn't tripped during reload

Pros:

- Purely mechanical; interesting design
- No separate control system, cuts down on complexity
- Compact & lightweight

Cons:

- Because it's a physical catch, there's a lot of room for error or inconsistency if the machine's geometry isn't perfect

4. Blow Gun CopyCat

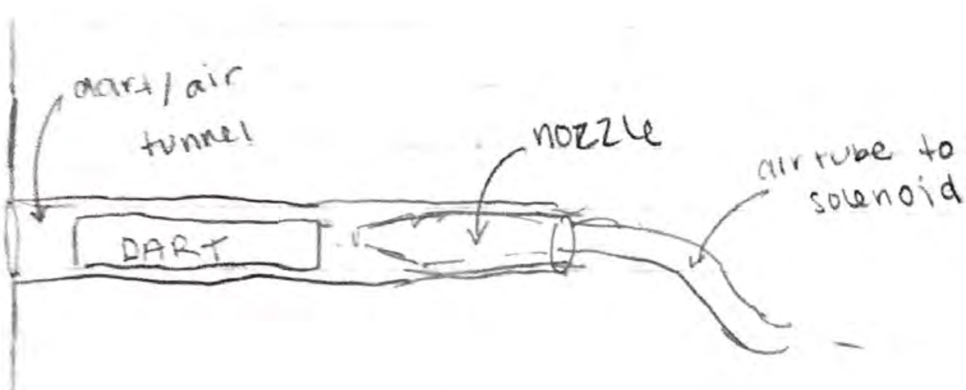

Figure 2.4 Blow Gun CopyCat

How it works:

- Nozzle attached to a solenoid sits behind the dart in a straight tunnel
- When solenoid is activated, air will be allowed through
- The force will propel the dart similar to a blow gun

Pros:
- Easy implementation
- Simple
- Control distance with pressure

Cons:
- Boring
- Might not always be consistent

5. Pneumatic Cylinder

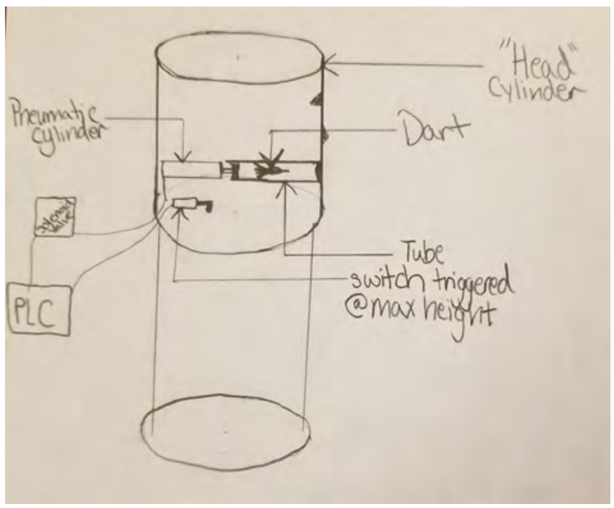

Figure 2.5 Pneumatic Cylinder

How it works:
- Pneumatic will need to be connected to a solenoid valve to control air pressure
- PLC will be used to control the trigger and cylinder
- A switch will be triggered at max height
- Trigger will cause the pneumatic cylinder to extend and propel the dart through a tube (PVC?)
- Pneumatic cylinder will retract -- might need another switch or a sensor to make sure pneumatic retracts before head drops (offroadenthu)

Pros:
- Control distance with pressure
- Simple setup

Cons:
- Requires a more involved control system
- Size of pneumatic cylinder might interfere with vertical mechanism

6. Horizontal Wheel Shooter

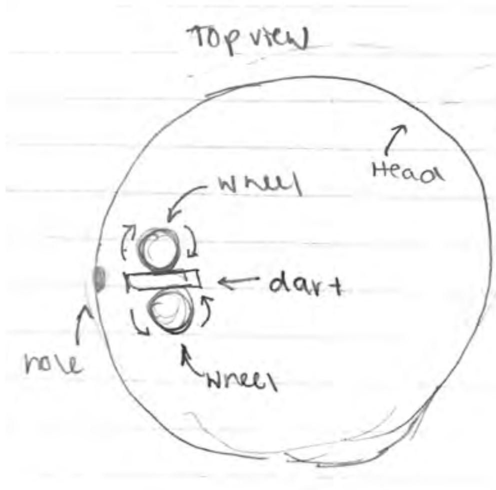

Figure 2.6 Horizontal Wheel Shooter

How it works:

- Dart is preset in between two wheels that are hooked up to a motor
- Once power is on, the wheels will push the dart out (Davis)

Pros:

- Control distance with wheel speed

Cons:

- Very complex
- Space consideration
- A lot of room for error

7. Vertical Wheel Shooter

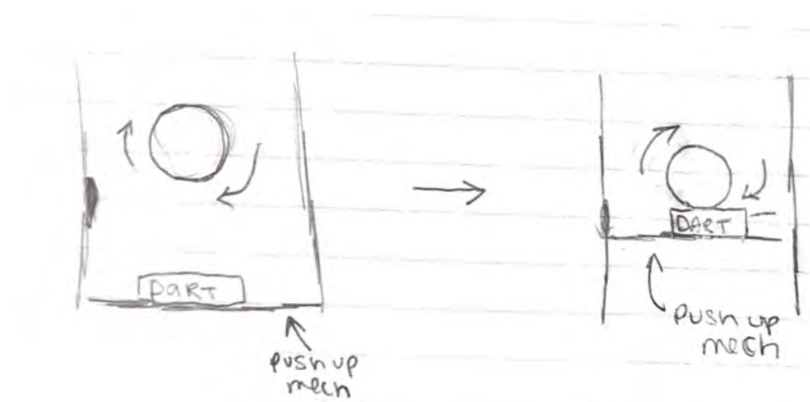

Figure 2.7 Vertical Wheel Shooter

How it works:

- Wheel sits right where the dart needs to shoot out of
- Wheel can be continuously spinning
- As the head moves up, it will push the dart to the wheel
- Once the wheel and the dart touch, the dart will be shot out

Pros:

- Control Distance with wheel speed
- Built in safety (dart won't move unless it touches the wheel0

Cons:

- Very complex
- Space consideration
- A lot of room for error
- Push Up mechanism is another thing to have to design

Trigger Mechanism and Control

From the beginning of the concept design phase, the team understood that the device would need a trigger and a control system of some kind. The team spent time researching and discussing different options for triggers and methods of control. For the trigger, the team considered options including, but not limited to:

- Pressure Plates
- Tripwires
- Buttons
- Through-beam Sensors

After weighing the pros and cons for each trigger, the team unanimously decided that a pressure plate or button would be the most reliable choice and that a decision matrix would be unnecessary at this point in the design process. For the control system, the team considered options including, but not limited to:

- Programmable Logic Controllers
- Arduino microcontrollers
- Physical, mechanical triggers

Upon further discussion, the team decided that the best control system for the device would be entirely dependent on what design concept the team constructed. It became clear that the team's resources at this time were better spent exploring the mechanisms for the device. After a design is fully resolved, the team will implement a control system based on the needs of the other components.

Evaluation

After analyzing the various concept designs, the team created a decision matrix. To create the matrix, the team started by developing a list of criteria for each sub-concept design: the firing mechanism (*fig. 3.1*) and the vertical movement (*fig. 3.2*). Using what was learned from the design specification, the team brainstormed criteria such as the ability to complete the goals of the effect, the overall safety of the machines, the safety of the firing mechanism, and the originality of the design. After finalizing the criteria, each team member assigned a weight of importance and priority and ranked how well each concept design met the criteria.

FIRING MECHANISM CONCEPT DESIGNS WEIGHTED MATRIX								
Criteria	Weight	Rack & Pinion	Spiral Motor	Nerf Gun Spring	Blow Gun	Pneum. Cylinder	Wheels Hor.	Wheels Vert.
Safety	10	7	8	8	8	8	7	7
Size	7	7	6	8	8	6	6	6
Consistency	9	6	8	6	8	8	6	6
Achieve Required Distance	9	8	7	8	9	9	7	7
Weight	5	7	7	9	9	7	5	5
Reloading Capability	6	6	9	6	8	7	5	6
Safety Interlock	9	6	7	8	7	7	7	8
Amount of Moving Parts	6	4	6	7	9	8	4	6
Amount of Failure Points	8	4	6	6	7	7	5	5
Originality	5	9	9	7	7	7	9	9
Cost	6	7	7	7	8	7	5	5
Time to Build	6	6	6	7	8	8	5	5
Time to Set Up	7	8	8	8	8	8	7	7
Complexity of Control	8	6	6	8	6	6	4	4
Design Complexity	7	5	6	6	9	7	4	4
TOTAL (Score x Weight)		**688**	**762**	**786**	**853**	**797**	**625**	**652**

Figure 3.1 Firing Mechanism Concept Designs Weighted Matrix

The team decided on a weight scale of 1-10 to allow for an accurate score. Once everyone finished their individual design matrices, the team compiled them and took the averages to account for differences in team members' opinions. With the top 3 scoring concepts highlighted for each axis of the effect, the team began discussing which designs would fit best together.

VERTICAL MOVEMENT CONCEPT DESIGNS WEIGHTED MATRIX									
Criteria	Weight	Timing Belt	Stepper Motor	Pneum. Acutator 1	Pneum. Acutator 2	Rack & Pinion 1	Rack & Pinion 2	Scissor Lift	Motorized Lift
Safety	9	8	8	8	8	7	7	7	6
Achieve Required Speed	9	6	5	9	8	6	7	8	6
Room for Dart Mech.	7	9	8	8	5	6	4	9	7
Stability	8	7	6	8	9	7	6	9	4
Amount of Moving Parts	5	5	7	8	8	5	5	7	4
Amount of Failure Points	9	5	7	8	8	5	5	6	4
Originality	5	8	8	4	4	8	8	8	9
Cost	6	6	7	6	6	6	5	5	5
Time to Build	5	6	6	7	7	6	6	6	4
Time to Set Up	7	7	8	8	8	7	7	8	6
Resting Size	4	9	8	7	8	5	6	7	6
Complexity of Control	8	6	7	7	7	5	5	7	4
Design Complexity	6	5	7	6	8	6	5	4	3
TOTAL (Score x Weight)		**584**	**617**	**652**	**646**	**536**	**515**	**623**	**456**

Figure 3.2 Vertical Movement Concept Designs Weighted Matrix

In the end, the team decided upon a pneumatic powered scissor lift for the vertical movement and a mechanical nerf gun firing mechanism. These concepts were ranked second and third, respectively, in the two decision matrices. The concept designs with higher scores are all variations of relatively simple designs involving pneumatic cylinders. The team believes that the pneumatics scored higher because this concept is the most familiar to them, so their scores were naturally biased. The simplicity of the pneumatic cylinder ensures a good back up, but not a good challenge. The purpose of this competition is to learn and grow -- without a challenge, neither is possible. Unlike the pneumatics, the scissor lift and mechanical firing mechanism will allow the team to push themselves and broaden their horizons, which the team, after deliberation, realized holds more value than simplicity.

Final Design

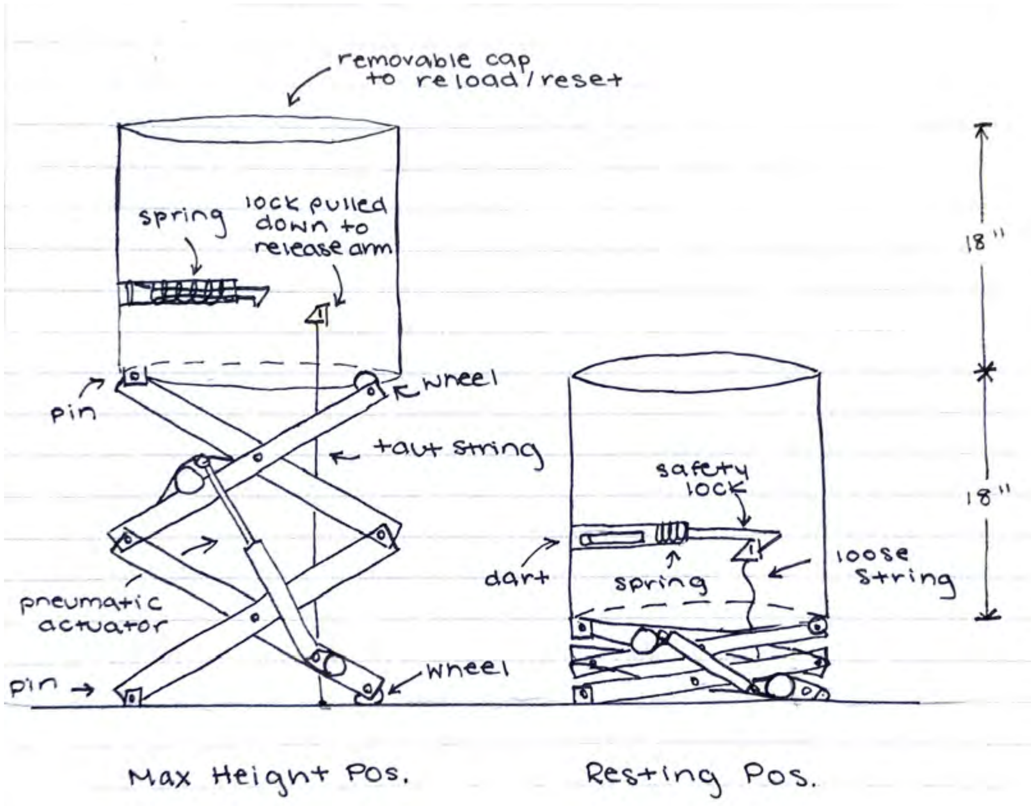

Figure 4.1 Final Design

How it Works

- The machine consists of a pneumatic cylinder-driven scissor lift (DRHydraulics), a mechanically triggered spring-loaded firing mechanism, and an electronic control system
- The machine is loaded by inserting a dart in the front of the mouth
  - To prime the firing mechanism, the top of the head is removed and the piston arm is pulled back until it engages with a physical catch, which holds it in place
- When the effect's trigger switch -- a pressure plate or button -- is closed, the pneumatic arm will quickly extend, expanding the scissor lift and raising the head
- When the head reaches its maximum height, a string -- connected to the catch -- becomes taut and the catch is pulled down, releasing the piston arm and firing the dart
- When the dart has been fired, the pneumatic arm begins to retract, slowly lowering the head

- The system will be controlled with a PLC, which will interface with a directional control valve to control speed and direction of the actuator
- Limit switches will be included as safety interlocks to ensure safety conditions are met before effect sequence proceeds

Moving Forward

While the concept design outlines the high-level functionality of the machine, the team will perform the structural and mechanical analysis to make design decisions on material, construction, and geometry. Some items that are targeted for further exploration include:

- Safety interlocks and positioning of limit switches
- Finalizing a specific design for the dimensions of the scissor lift
- Housing for the dart firing mechanism, and specifics of the catch
- The initial sequence trigger
- Pneumatic cylinder selection and control

Over the next three months, the team will work to create a detailed design, source or fabricate necessary parts and components, and assemble and test the realized prototype.

Works Cited

"Ball throwing mechanism" *YouTube,* uploaded by offroadenthu, 7 Aug. 2016, https://www.youtube.com/watch?v=mnuEiVvtbk8.

"Build a MOTORIZED monitor lift (on a budget!)" *YouTube,* uploaded by DIY Perks, 7 Apr. 2017, https://www.youtube.com/watch?v=kaJVWoKj2a4.

Gunter, David. "DIY Electric Standing Desk." Everyday Knosticism, 23 July 2020, www.davidgunter.com/2020/07/23/diy-electric-standing-desk/?fbclid=IwAR3zZiCKSCGRw7vgJ9V985mgYDfqsZjyrJ6X6t4L0uMU0FuwGENlNYfK3Wk.

Davis, Jay. "HomeMade Baseball Pitching Machine ." Google Sites, sites.google.com/site/jaywdavis/Home/baseball-pitching-machine.

Heney, Paul. "What Are Pneumatic Cylinders?" Pneumatic Tips, 26 Sept. 2012, www.pneumatictips.com/what-are-pneumatic-cylinders/#:~:text=Pneumatic%20actuators%20are%20mechanical%20devices,load%20along%20a%20linear%20path.&text=Double%2Dacting%20cylinders%20have%20an,receives%20the%20high%20pressure%20air.

"How does a Nerf Gun work?" *YouTube,* uploaded by Jared Owen, 28 Sep. 2018, https://www.youtube.com/watch?v=N8JpePwvuHw&t=86s.

"How to use a pneumatic cylinder | Arduino tutorial" *YouTube,* uploaded by Crazy Russian Haunter, 26 Feb. 2017, https://www.youtube.com/watch?v=Vb0yov7UFy8.

"Linear Actuators: 4 Types." Del-Tron Precision, Inc. Linear Motion Engineering, Deltron Precision, Inc., 27 July 2018, www.deltron.com/Linear-Actuators.html.

"Pololu - Stepper Motor with 18cm Lead Screw: Bipolar, 200 Steps/Rev, 42×38mm, 2.8V, 1.7 A/Phase." Pololu Robotics and Electronics, www.pololu.com/product-info-merged/2689.

"Small Hydraulic Scissor Lift Animation (solidworks)" *YouTube,* uploaded by DRHydraulics, 21 Dec. 2010, https://www.youtube.com/watch?v=6g60eUcbGZA.

"Thomson Linear Motion Optimized." Motorized Lead Screw - Stepper Motor Linear Actuator, www.thomsonlinear.com/en/products/motorized-lead-screws.

"Three-Link Impacting Oscillating-Follower Cam Mechanism" *YouTube,* uploaded by Mechanisms X, 24 Dec. 2016, https://www.youtube.com/watch?v=-19IotQKqhI.

Villaluz, Kathleen. "Check out the Cool Engineering Design Behind This Simple Nerf Gun." Interesting Engineering, Interesting Engineering, 12 Mar. 2018, https://www.interestingengineering.com/check-cool-engineering-design-behind-simple-nerf-gun.