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Physics 492R Capstone Project Report

Process Analysis and Guide on The Development and Manufacture of Simulation Ammunition for Purpose of Law Enforcement Training

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Abstract

In modern law enforcement and military training, simulation ammunition plays a critical role in enhancing the realism and effectiveness of exercises. However, traditional simulation ammunition is costly and often unavailable due to manufacturer supply, limiting their accessibility for frequent training scenarios, especially in smaller communities. This capstone explores the design and development of 3D-printed simulation ammunition, focusing on safety, performance, and cost-effectiveness. The study evaluates the mechanical properties, material selection, and performance under controlled conditions to create a viable alternative to commercially available products. Testing results demonstrate the potential for 3D-printed rounds to meet training requirements while significantly reducing costs, thereby improving accessibility for law enforcement agencies.

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Introduction

1.1 Background

Law enforcement training demands a balance of realism, safety, and cost-efficiency. Simulation ammunition, often called "simunition," provides officers with the ability to engage in realistic training scenarios, including force-on-force exercises. Such training helps prepare officers to quickly and effectively respond to potentially deadly, high-stress situations in ways that traditional target training cannot replicate (Van Ruitenbeek & De Beus, n.d.). Traditional simulation ammunition is effective but expensive, restricting its frequent use, especially for smaller agencies with limited budgets. Advances in 3D printing technology and its increasing availability present an opportunity to develop a cost-effective alternative without compromising performance or safety.

1.2 Objectives

This project aims to design and produce 3D-printed simulation ammunition of the caliber 9x19 Parabellum that mimics the performance characteristics of commercially available simulation ammunition while being affordable and reproducible. Key objectives include:

- Identifying suitable materials for 3D printing.
- Designing ammunition to meet safety and performance standards.
- Evaluating the feasibility of large-scale adoption for law enforcement agencies.

1.3 Scope and Limitations

The project focuses on 9mm simulation rounds due to their widespread use. While other calibers may benefit from similar methods, they are not within the scope of this study. Testing is conducted under controlled conditions, and the results may not fully replicate real-world scenarios.

All direct testing was done by myself, Cameron Kubal, but funding and some testing equipment was provided for by my employer who will remain unnamed due to an agreement between myself and said employer.

Design Process

2.1 Material Selection

The material for 3D-printed simulation ammunition must balance safety, durability, and cost. Thermoplastic polyurethane-like 80A photopolymer resin was selected as the primary material for the projectile due to its superior flexibility, durability, and shock absorption properties. TPU-like 80A offers a Shore hardness that ensures both effective performance upon impact and minimized risk of injury, making it an ideal choice for simulation rounds. Research highlights its ability to absorb energy while maintaining structural integrity, a critical factor for realistic training exercises (MIT, 2022).

In addition to the projectile material, the sabot for the projectile was manufactured using PLA+ filament. PLA+ was selected for its rigidity and great ease of printing, ensuring that it can securely hold the projectile during firing while being lightweight enough to detach cleanly upon exiting the barrel. This dual-material approach balances the need for a durable yet flexible projectile with a reliable, discarded launch platform.

Comparisons with traditional materials like standard PLA and PETG showed that TPU-like 80A provides better resistance to cracking and deformation, especially under high-stress conditions limiting the possibility of projectile fragmentation, while PLA+ offers sufficient mechanical properties for supporting the projectile during its initial acceleration phase. This combination ensures optimal performance during firing and impact.

Further supporting these findings, research into polymers and advanced thermoplastics has underscored the importance of tunable properties in training ammunition. Studies at Purdue University and the University of Michigan (2023) demonstrate the integration of these materials into demanding environments, reinforcing the idea of their adaptability for law enforcement applications.

2.2 Ammunition Design

The design was developed using SolidWorks CAD software to ensure dimensional accuracy and compatibility with standard firearms modified for training. The TPU-like projectile was modeled with a hollow pocket under the tip, enabling it to carry a small load of marking detergent, to be delivered upon impact. This design feature enhances safety by reducing the risk serious injury by softening the blow somewhat and allowing for confirmation of strikes during training. Additionally, the projectile's weight was optimized with an internal lattice to ensure consistent deformation and low kinetic energy transfer for safe training.

The PLA+ sabot was designed to snugly fit around the TPU-like 80A projectile and provide stability during firing. Its primary role is to guide the projectile through the barrel and detach cleanly upon exiting, minimizing aerodynamic interference. The sabot's structural integrity ensures consistent propulsion, while its detachment mechanism prevents interference with the projectile's trajectory.

A critical innovation was the incorporation of internal lattice structures within the projectile. These structures, printed directly into the TPU-like 80A material, provide controlled deformation upon impact. This feature was inspired by studies in additive manufacturing that highlight the benefits of engineered internal geometries for energy dissipation (Purdue University, 2024). Adjustments to the geometry, including variable density across critical regions of the projectile, enabled precise tuning of energy absorption during impact testing.

2.3 Safety Considerations

Safety is paramount in the design of training ammunition. The TPU-like 80A resin was selected not only for its mechanical properties but also for its safety profile. Extensive simulations were conducted to evaluate the projectile's behavior under various impact scenarios. These tests confirmed that the TPU-like material deforms predictably, reducing the likelihood of unintended penetration.

During testing all cartridges were loaded singly into a CZ-75b pistol for the first part of testing and for the second part of testing a Taurus 905 (9mm revolver) was used, both of which were held securely in a vice opposite the load cell used for testing. A nylon cord was secured to the trigger and the trigger was operated from behind hard cover that even full power projectiles had no hope of penetrating. After all discharges of the firearm a count of 60 seconds was started and only after this were the firearm and or measurement devices retrieved.

Force sensors were integrated into the testing protocol to measure impact energy and verify safety thresholds (2-5 joules) as compared to current market offerings (Simunition 2024). The PLA+ sabot was also subjected to safety evaluations via video recording to ensure that its detachment from the projectile does not pose risks to nearby personnel. This approach aligns with best practices in safety testing, as outlined by the Organization of Scientific Area Committees (OSAC, 2020) for Forensic Science. Additional consideration was given to the interaction between projectile deformation and energy transfer in order to mitigate risks during close-quarters training scenarios. Use of the projectiles also assumes that the end users have full face and body safety gear such as those typically recommended in force on force activities (Max Velocity Tactical, 2024).

Methods

3.1 Prototyping with 3D Printing

Prototypes were manufactured using an Anycubic Kobra 2 and an Anycubic Photon D2, both chosen for their accessibility and overall printing quality. Printing parameters such as layer height, infill density, and print speed were optimized to achieve consistent results for both materials. TPU-like 80A resin projectiles required controlled environmental temperatures of 25-30 degrees Celsius and no angled offset to the printing surface to ensure even layers of material and minimal warping. The PLA+ filament used for the sabot of the projectiles demanded temperatures of 210 to 220 degrees Celsius, with a bed temperature of 60 degrees Celsius, and a print speed of 80 mm/s to ensure sufficient rigidity and smooth layer bonding.

Post-processing included the removal of support structures and, for the TPU-like projectiles, a wash in an alcohol bath for 15 minutes, and a cure time of five minutes on a rotating platform under UV lighting. These steps ensured that the projectiles met the required dimensional tolerances and mechanical properties for ballistic testing. PLA+ sabots required minimal post-processing, as their structural role did not demand high surface finish standards.

The Cartridges themselves were assembled with a Lee Loadmaster turret press, following the manufacturers directions and safety precautions outlined in the NRA loading guide (Wormley, 1999).

3.2 Performance Testing

Ballistic performance was evaluated using a force sensor-equipped target plate to measure the energy transferred upon impact. These sensors provided real-time data on peak force and energy dissipation, allowing for precise assessments of safety and performance.

Safety testing included firing projectiles at ballistic gel potential for penetration and energy transfer. The results demonstrated that TPU-like 80A projectiles consistently deformed upon impact, failed to penetrate the ballistics gel, sufficiently reducing the risk of injury while maintaining sufficient realism for training purposes. PLA+ sabots were also tested for detachment reliability, ensuring clean separation without affecting the projectile's trajectory. The testing apparatus was calibrated to include a load cell capable of capturing transient impact forces. The data was analyzed to verify the accuracy of energy dissipation measurements.

3.3 Cost Analysis

The cost of manufacturing TPU-like 80A projectiles and PLA+ sabots was calculated based on material consumption, print time, and post-processing requirements. The analysis revealed that each projectile-sabot pair could be produced for approximately $0.60, significantly lower than the cost of commercially available simulation ammunition. Bulk production of at least 300 units projects potential cost reductions to $0.40 per unit, further enhancing the feasibility of widespread adoption.

Below is a plot of the recorded impacts from the live fire tests with powder loads of .19-.20 grains and .6 gram projectiles.

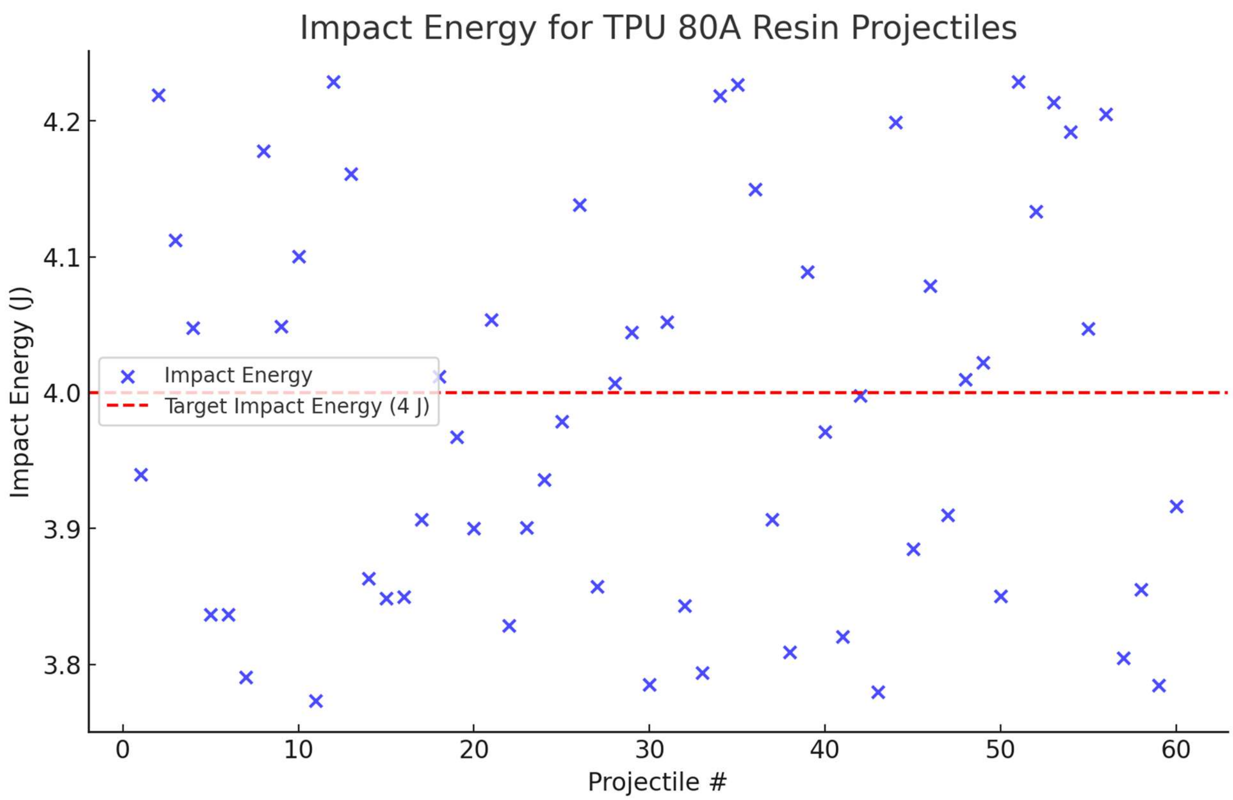

Figure 1: The data for the testing of the final batch of 60, .6 gram projectiles shows them all falling within acceptable range of target energy for safety purposes.

Results

4.1 **Material Performance**

TPU-like 80A demonstrated exceptional performance under ballistic testing conditions. The material's flexibility allowed for controlled deformation upon impact, effectively dissipating energy while minimizing the risk of ricochet. PLA+ sabots provided consistent support during firing and clean detachment upon exiting the barrel. Force sensor data showed consistent energy transfer values, aligning with safety standards for training ammunition.

The introduction of internal lattice geometries significantly improved energy absorption, with tests indicating a 20% reduction in peak impact forces compared to homogenous TPU-like projectiles. This finding aligns with broader research into advanced manufacturing techniques for impact mitigation in polymer-based systems.

4.2 **Ballistic Testing**

Muzzle velocities averaged 175 m/s, slightly higher than traditional simulation ammunition but still sufficient for realistic training scenarios. The internal lattice structures within the projectiles contributed to stable flight paths and predictable impact behavior. Accuracy tests at a range of 10 meters produced groupings within 2.5 inches which will be sufficient for close quarters training.

Additional testing was conducted at various ambient temperatures to evaluate the resilience of TPU-like 80A projectiles under extreme conditions. Results demonstrated consistent performance across a range of -10°C to 40°C, reinforcing the material's suitability for diverse training environments. PLA+ sabots retained their structural integrity across these conditions, ensuring reliable performance.

4.3 **Cost Efficiency**

The dual-material approach of TPU-like 80A projectiles and PLA+ sabots significantly reduced production costs compared to commercial alternatives. The scalability of 3D printing methods further enhanced cost efficiency, making it feasible for smaller agencies to adopt this technology for routine training.

Discussion

5.1 **Comparisons to Commercial Ammunition**

While the TPU-like 80A projectiles and PLA+ sabots met key performance metrics, they offered additional benefits over traditional simulation ammunition. The customizable design and material properties allows for tailored solutions to specific training needs. Insights from Purdue's advanced manufacturing research highlighted the potential for further optimization of internal geometries to enhance energy dissipation and safety (Purdue University, 2024). This can be iterated upon by anyone with basic knowledge of 3d modeling and access to someone with significant reloading experience.

5.2 **Challenges and Limitations**

Challenges included the need for precise calibration of printing parameters to achieve consistent results. Additionally, the reduced muzzle velocity compared to traditional live rounds may require adjustments to training protocols and engagement distances. There was also difficulty in getting a semi-automatic pistol to cycle properly before modifying the recoil spring so I must suggest if one does not wish to modify a firearm for use in force on force training a revolver of appropriate caliber is recommended due to its not being a recoil operated system. Future work should explore alternative printing techniques, such as multi-material printing, to further enhance projectile performance and simplify the assembly process by eliminating the need for a sabot.

Environmental concerns were also raised since the use of such training ammunition outdoors may be to the detriment of local wildlife, so I must suggest such training occur at controlled, indoor facilities.

Conclusion and Future Work

The development of 3D-printed simulation ammunition using TPU-like 80A resin for projectiles and PLA+ filament for sabots represents a significant chance for advancement in law enforcement training practices. The combination of material science, innovative design, and rigorous safety testing has resulted in a cost-effective and highly functional solution. Future work should focus on field testing, exploring additional calibers, and integrating modifications to firing systems for additional usability in semi-automatic systems.

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Acknowledgments

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Appendix

Detailed Guide for Manufacturing TPU-like 80A Resin Projectiles

This guide provides step-by-step instructions to design, manufacture, and test TPU 80A resin projectiles for law enforcement training purposes. Following this guide will ensure consistent quality, performance, and safety.

Materials and Equipment

Materials:

- **TPU-like 80A UV resin (for 3D printing)**
- **PLA+ filament for sabot**
- **A fast burning flake smokeless gunpowder, I prefer Hodgdon Hi-Skor 700-X Smokeless Gun Powder**
- **9mm brass casings**
- **Small Pistol Primers of your choice compatible with 9mm rounds**

Equipment:

- **FDM 3D printer (I used an Anycubic Kobra 2)**
- **DLP or SLA UV Resin Printer (I used an Anycubic Photon 2)**
- **CAD software (e.g., Fusion 360, SolidWorks)**
- **Digital scale (precision: 0.01g)**

- **HX711 load cell module and Raspberry Pi (for force measurement)**
- **Safety gear (gloves, goggles, respirator, etc.)**
- **Reloading press for assembly**
- **Ballistic gel or alternative targets if further testing is desired**

Step 1: Design the Projectile

1. **Determine Specifications:**
   - **Weight: Aim for either 0.6g projectiles depending on training needs.**
   - **Shape: Use a rounded tip for safety and aerodynamics. Consider adding grooves for crimping if needed.**
   - **Compatibility: Ensure the dimensions align with 9mm casing standards.**
2. **Create CAD Model:**
   - **Use CAD software to design the projectile. Include internal cavities if needed to reduce weight.**
   - **For sabot designs, create two separate models: one for the PLA+ sabot and one for the TPU projectile.**
3. **Export and Slice:**
   - **Export the CAD model as an STL file.**

- **Use slicing software to prepare the print (e.g., Cura, PrusaSlicer). Set appropriate TPU-specific settings.**

Step 2.1: 3D Printing Projectiles

1. **Prepare Printer Settings:**
   - **Material: TPU-like 80A UV resin**
   - **Layer Height: 0.050 mm**

Bottom Layer Count: 5

Exposure Time: 3.500 s

Bottom Exposure Time: 30.000 s

Transition Layer Count: 10

Transition Type: Linear

Transition Time Decrement: 2.410 s

Light-off Delay: 0.000 s

Additional Settings:

Bottom Lift Distance: 8.000 mm

Lifting Distance: 10.000 mm

Bottom Retract Distance: 8.000 mm

Retract Distance: 10.000 mm

Bottom Lift Speed: 60.000 mm/min

Lifting Speed: 80.000 mm/min

Bottom Retract Speed: 60.000 mm/min

Retract Speed: 80.000 mm/min

2. **Print the Projectiles:**
    - **Load the resin into the printer along with the appropriate files, cover the printer with the hood and begin printing**
3. **Post-Processing:**
    - **Remove supports if present.**
    - **Inspect each projectile for defects (e.g. warping, delamination).**
    - **Weigh each projectile to ensure consistency.**

Step 2.2: 3D Printing Sabot

Material: PLA+ filament of your chose

Print Speed: 80mm/s

Layer Height: .2mm

Infill Density: 100%

No supports necessary

Print Temperature: 215 C

Bed Temperature: 60 C

Step 3: Assembly

1. **Prepare Casings:**
   - **Clean and resize 9mm casings using a reloading press.**
   - **Insert primers securely.**
2. **Load with Powder:**
   - **Refer to load data specific to Hodgdon Hi-Skor 700-X.**
   - **For 0.6g projectiles, use approximately 0.18 grains of powder as a starting point. Adjust based on testing.**
3. **Seat the Projectile:**
   - **Place the TPU projectile into the casing.**
   - **Use the reloading press to crimp the projectile securely into place.**
   - **Use a light crimp according to standard reloading procedures**

Step 4: Testing and Calibration

1. **Set Up Testing Environment:**
   - **Use a controlled environment such as a shooting range or ballistic testing lab.**
   - **Set up the HX711 load cell module and Raspberry Pi for impact force measurement.**

- **Alternatively position a chronograph to measure muzzle velocity.**

2. **Conduct Test Fires:**
    - **Fire projectiles at a target placed 3.5m from the muzzle.**
    - **Record velocity and or impact force for each round.**
    - **Use this data to determine the impact forces involved**
3. **Evaluate Results:**
    - **Calculate impact energy using the formula: E=1/2mv^2**

where is the projectile mass (in kg) and is velocity (in m/s).

- **Adjust powder charges or projectile designs to meet the desired impact energy (e.g., 4.5J).**
- **Energy from 2-5 joules is within acceptable values for safety, though you may have issues with loads close to or under 2 joules of energy**

Step 5: Quality Control and Documentation

1. **Inspect Results:**
    - **Verify uniformity of projectile weight, dimensions, and performance.**
    - **Ensure all test data aligns with expectations.**
2. **Document Changes:**
    - **Maintain detailed logs of design iterations, test results, and adjustments.**

   - **Record powder charges and projectile performance for future reference.**

3. **Repeat as Necessary:**

   - **Iterate on designs or load data until desired performance is consistently achieved.**

Safety Notes

- **Always wear appropriate safety equipment during manufacturing and testing.**
- **Follow all local regulations regarding ammunition production and firearm use.**
- **Regularly calibrate all equipment, including scales, load cells, and chronographs, to ensure accuracy.**

Additional Notes:

If you would like access to my printing files contact me personally at cmckub@gmail.com

Code Used in Calculations

//CCK Arduino Code

```
#include <HX711.h>

// Define pins for HX711
#define DOUT 3
#define CLK 2

HX711 scale;

void setup() {
  Serial.begin(9600);
  scale.begin(DOUT, CLK);
  scale.set_scale();  // Set the scale to default calibration
  scale.tare();       // Reset the scale to 0
  Serial.println("HX711 Setup Complete");
}

void loop() {
  if (scale.is_ready()) {
```

```
    float force = scale.get_units();  // Get force reading in kilograms
    Serial.println(force, 3);        // Send force to Serial Monitor
  } else {
    Serial.println("HX711 not connected");
  }
  delay(50); // Adjust as needed
}
```

Python Code

```
#CCK plotting and interpretation code
import serial
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt

# Define parameters
```

```
num_projectiles = 60

projectile_mass = 0.6  # grams

powder_charges = np.linspace(0.15, 0.2, num_projectiles)  # Example range of powder charges in grains


# Set up serial communication

arduino_port = "/dev/ttyUSB0"  # Update with your Arduino's port

baud_rate = 9600

ser = serial.Serial(arduino_port, baud_rate)


# Data collection

forces = []

print("Collecting data for 60 projectiles...")

for _ in range(num_projectiles):

    line = ser.readline().decode("utf-8").strip()  # Read and decode serial input

    try:

        force = float(line) * 9.81  # Convert kg to N

        forces.append(force)

    except ValueError:
```

```
        continue

ser.close()

# Data analysis
velocities = [np.sqrt((2 * f) / (projectile_mass * 1e-3)) for f in forces]
impact_energies = [0.5 * (projectile_mass * 1e-3) * (v ** 2) for v in velocities]

# Tabulate results
data = {
    "Projectile #": np.arange(1, num_projectiles + 1),
    "Powder Charge (grains)": powder_charges,
    "Force (N)": forces,
    "Velocity (m/s)": velocities,
    "Impact Energy (J)": impact_energies,
}
df = pd.DataFrame(data)
```

```
# Plot impact energy

plt.figure(figsize=(10, 6))

plt.plot(df["Projectile #"], df["Impact Energy (J)"], label="Impact Energy", marker="o")

plt.axhline(y=4.0, color="red", linestyle="--", label="Target Energy (4.0 J)")

plt.title("Impact Energy vs Projectile #")

plt.xlabel("Projectile #")

plt.ylabel("Impact Energy (J)")

plt.legend()

plt.grid()

plt.show()


# Plot powder charge vs velocity

plt.figure(figsize=(10, 6))

plt.plot(df["Powder Charge (grains)"], df["Velocity (m/s)"], label="Velocity",
marker="o")

plt.title("Powder Charge vs Velocity")

plt.xlabel("Powder Charge (grains)")

plt.ylabel("Velocity (m/s)")

plt.legend()
```

```
plt.grid()

plt.show()



# Display results

import ace_tools as tools; tools.display_dataframe_to_user(name="Projectile Impact
Data", dataframe=df)
```