Developing software to predict bullet impact angle and location using x-ray images

Jerry Zhang

Mentored by Dr. Richard Becker

Introduction

Army Research Laboratories (ARL) focuses on researching and producing cutting edge technology for the US Army. ARL has produced legacy software capable of analyzing bullets within x-ray images. ARL is looking to replace the software with a new version that is more maintainable and capable.

At the Armament Research Center in New Jersey, researchers designed a photography system which captured the motion of a bullet at two different times in flight to perform further analysis (Decker et al., 1993) using the ARL software. The bullets in the x-ray image were analyzed for their current angle and position in pixels. The difference in positions and angles between the two bullets in the image were projected to a target object, from which the angle and position of impact were calculated. The angle of impact is known as the angle of obliquity, the angular difference between the vector of the bullet and the vector normal to the object's surface. From a bird's eye view, the angle is known as the yaw angle. From a side view, the angle is known as the pitch angle.

This project involved creating a software to accurately predict bullet pitch and yaw angles, velocity, time to reach the target, and horizontal and vertical offset distances from the target. The final product was presented in the form of a graphical user interface (GUI) where users can input data and receive calculated outputs.

Methods and materials

This software was written in the Python language, chosen for its advanced computation libraries and image segmentation abilities. Python's Integrated Development and Learning Environment (IDLE) was selected as the programming environment.

To analyze the bullets, it was necessary to perform image segmentation on the x-ray image. Image segmentation involved classifying pixels in an image to detect objects. The Python OpenCV library contained functions which could convert colored images to binary and find boundaries around bullets.

The centroid of the bullet was calculated using moments. The back and tip were found by fitting a vector through the bullet and finding the minimum and maximum projection values, from which the endpoints of the bullet were calculated.

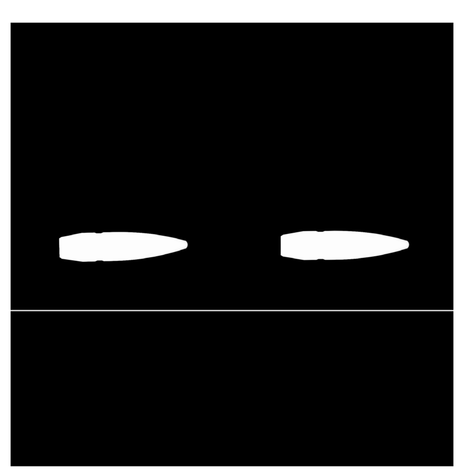

Figure 1 (left): X-ray image of a bullet at two different times which was analyzed by the software.

Methods and materials (continued)

Since the bullets were modeled by vectors, the tangent function was applied to calculate the angles. Constant angular and position change was assumed to project the bullet to the target.

The GUI was produced to allow users to input the x-ray images from top and side view, the date, scaling units for the image, times of the two bullets, and distance from the center of the image to the target. Based on the data input by user, the GUI was able to calculate the velocity of the bullet, time it would take for the bullet to reach the target, the vertical and horizontal offset from the desired target, and the pitch and yaw angles. The GUI was tested against user inputs that could cause errors and was aesthetically refined to improve the user experience. The GUI was also able to save the user data which could be exported to a text file.

```
xCenter = int(M['m10']/M['m00']) if M['m00'] != 0 else None
yCenter = int(M['m01']/M['m00']) if M['m00'] != 0 else None

# Fit bullet axis
vx, vy, x0, y0 = cv2.fitLine(points, cv2.DIST_L2, 0, 0.01, 0.01)
```

Figure 2 (left): Project code that utilized the OpenCV and NumPy libraries to calculate the centroid of each bullet and model the bullets using vectors.

Results

Image	Type	Predicted bullet 1 angle (degrees)	Actual bullet 1 angle (degrees)	Predicted bullet 2 angle (degrees)	Actual bullet 2 angle (degrees)	Bullet 1 absolute error (degrees)	Bullet 2 absolute error (degrees)
1	Side	1.54	1.5	−1.03	−1	0.04	0.03
1	Top	3.07	3	−2.38	−2	0.07	0.38
2	Side	1.53	1.5	−1.03	−1	0.03	0.03
2	Top	0	0	2.04	2	0	0.04
3	Side	−0.53	−0.5	1.5	1.5	0.03	0
3	Top	−1.5	−1.5	0.53	0.5	0	0.03
4	Side	1.52	1.5	0.52	0.5	0.02	0.02
4	Top	−1.02	−1	0	0	0.02	0
5	Side	0	0	2.54	2.5	0	0.04
5	Top	−1.49	−1.5	1.53	1.5	0.01	0.03

Table 1 (above): The absolute error of the angles between the predicted values from the software and actual values for five x-ray images was calculated.

The software was tested on five pairs of x-ray images, each consisting of side and top views of the bullet. Outputs were compared with real data to verify the accuracy of the GUI.

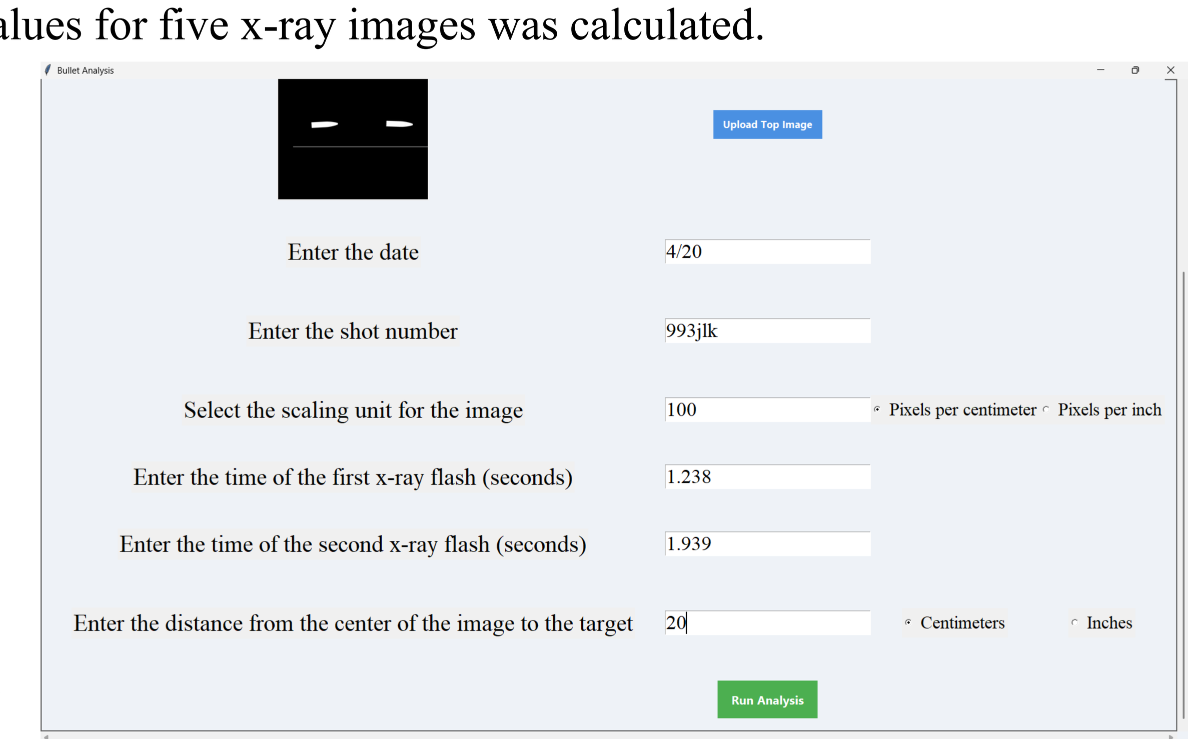

Figure 3 (above): The user input x-ray images, date, shot number, scaling units, two times, and distance to the GUI.

Results (continued)

For all tested x-ray images, the scaling unit and distance inputs were fixed at 100 px/cm and 20 cm, respectively. The time inputs were determined by the user. Velocity calculations were within the significant error threshold of 3 m/s. Horizontal and vertical offsets were within the significant error threshold of 1 mm. Pitch and yaw angle calculations were within the significant error threshold of 0.2 degrees.

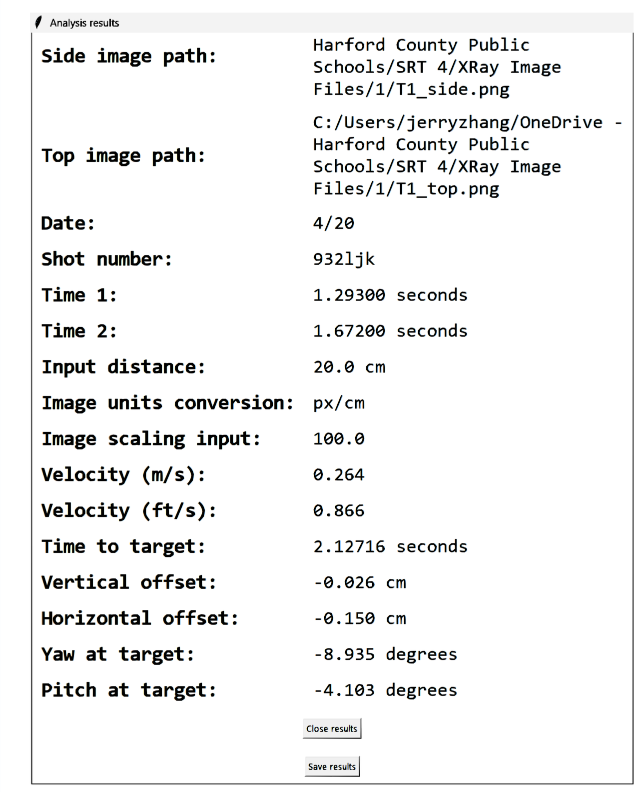

Figure 4 (left): Based on the data input, the GUI calculated velocity, time to target, offsets, and pitch and yaw angle.

Figure 5 (right): The user clicked the "save results" button. The data was exported to a text file which would be added to ARL data archives.

```
Bullet analysis results

Side Image: T3_side.png
Top Image: T3_top.png
Date: 4/24/26
Shot number: 943jslj
Time 1 (s): 3.29238
Time 2 (s): 5.92938
Distance: 50.0 cm
Image units: px/cm
Image scaling: 30.0
Velocity (m/s): 0.126
Velocity (ft/s): 0.415
Time to target (s): 3.95579
Vertical offset (cm): -1.55
Horizontal offset (cm): 0.55
Yaw (degrees): -4.947
Pitch (degrees): 6.16
```

Conclusion

A software program capable of analyzing x-ray images of a bullet at two different times to predict its velocity, time to target, angle, and location of impact was successfully developed and presented through a GUI. The GUI was tested multiple times using sample inputs, and the accuracy of the outputs was validated against real data within acceptable error thresholds.

In its current state, the project is useful for the U.S. Army when conducting bullet simulations, as they often need to test firearms, bulletproof gear, and helmets to make improvements. In the future, features such as calculating the bullet's spiral motion using physics concepts and differential equations could be incorporated. An even more beneficial addition would be mapping the bullet's trajectory in flight using three-dimensional visualization.

References

Decker, R., Duca, M., & Spickert-Fulton, S. (2017). Measurement of bullet impact conditions using automated in-fight photography system. *Defense Technology, 13*(4), 288–294. https://doi.org/10.1016/j.dt.2017.04.004