DEVCOM DAC-TR-2024-005
January 2024

Development of a Human Performance Baseline of Lay Error in Targeting

by Jennifer Forsythe, Parker Ensing, Nicholas Gans, Cody Lundberg, and Thirimachos Bourlai

DISCLAIMER

Research was sponsored by the DEVCOM Analysis Center and was accomplished under Cooperative Agreement Number W911NF-22-2-0001. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Army Research Office or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation herein.

WARNING

TRADE NAMES

DEVCOM DAC-TR-2024-005
January 2024

Development of a Human Performance Baseline of Lay Error in Targeting

by Jennifer Forsythe
DEVCOM Analysis Center

Parker Ensing and Thirimachos Bourlai
University of Georgia

Nicholas Gans and Cody Lundberg
University of Texas at Arlington

REPORT DOCUMENTATION PAGE

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED: START DATE	3. DATES COVERED: END DATE
January 2024	Technical Report	1 February 2022	15 August 2023

4. TITLE AND SUBTITLE
Development of a Human Performance Baseline of Lay Error in Targeting

5a. CONTRACT NUMBER	5b. GRANT NUMBER	5c. PROGRAM ELEMENT NUMBER
W911NF-22-2-0001		

5d. PROJECT NUMBER	5e. TASK NUMBER	5f. WORK UNIT NUMBER

6. AUTHOR(S)
Jennifer Forsythe, Parker Ensing, Nicholas Gans, Cody Lundberg, and Thirimachos Bourlai

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
Director DEVCOM Analysis Center 6503 Wayberry Road Aberdeen Proving Ground, MD 21005	DEVCOM DAC-TR-2024-005

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
In fire control, a primary source of error directly contributed by a gunner is called the lay error—the gunner's inability to lay the sight crosshairs exactly on the center of the target. As the U.S. Army considers the development of computer vision, artificial intelligence algorithms, and associated systems to assist direct-fire gunners' target performance, it is essential to establish a baseline of human performance against which to compare such new systems. In this work, we were motivated by two objectives: 1) Develop a model to represent a human's ability to lay the sight crosshairs on the center of the target. 2) Study the influence of engagement condition parameters (e.g., shape, size, range, motion) on the observed lay error and determine if single error measurement is sufficient to be extrapolated across any target. To address these objectives, a photorealistic simulation environment using the Unreal Engine was designed and developed, featuring a variety of targets and shooting conditions. The simulation environment (final prototype) includes four different targets, four motion configurations, five levels of zoom, and four ranges. Following a series of prototyping, testing, and evaluation, our simulation environment was used for collection of lay error, firing time, and human subjects' feedback (post-study analysis). Following an Institutional Review Board–approved protocol, 15 college-student subjects used our simulation environment and were instructed to align crosshairs on targets at multiple ranges under various motion conditions. Each participant aimed and fired 240 times for a total of 3600 shots over the course of the study. After data collection, we conducted various statistical analyses of lay error. We expect preliminary findings to be extended and conclusions reinforced by a more thorough study currently underway, in which an additional 100 subjects' data will be collected and analyzed under various conditions—including target occlusion scenarios in which fog and drone swarms will hinder the ability of the new subjects to align the reticle with the target.

15. SUBJECT TERMS
error budget, tank, probability of hit, aiming, lay error, quasi-combat, ground combat vehicle, human subject study, user interface, target size, target, reticle, zoom, unreal, direct fire, large caliber

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	C. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UU	27

19a. NAME OF RESPONSIBLE PERSON	19b. PHONE NUMBER *(Include area code)*
Jennifer Forsythe	(410) 278-6634

STANDARD FORM 298 (REV. 5/2020)
Prescribed by ANSI Std. Z39.18

(U) Table of Contents

List of Figures

List of Tables

Preface

Jennifer Forsythe is an Operations Research Master Analyst for the U.S. Army Combat Capabilities Development Command (DEVCOM) Analysis Center (known as DAC). She earned her bachelor's and master's degrees in biomedical engineering from Worcester Polytechnic Institute in 2001. She is a senior analyst on the Lethality Team for the Ground Effectiveness Branch.

Dr. Parker Ensing is a master's student in the School of Electrical and Computer Engineering at the University of Georgia (UGA). He previously attended UGA for his bachelor's degree in mechanical engineering. He has experience in quality engineering in the aerospace industry and was the chief engineer for the Small Satellite Research Laboratory at UGA where he oversaw technical development for two CubeSat missions.

Dr. Nicholas Gans is Division Head of Autonomy and Intelligent Systems at the University of Texas at Arlington Research Institute (UTARI) and an Associate Professor in the Department of Computer Science and Engineering and the University of Texas at Arlington. His research interests include robotics, nonlinear control, machine vision, and engineering education. Dr. Gans earned his Bachelor of Science in electrical engineering from Case Western Reserve University in 1999, Master of Science in electrical and computer engineering in 2002, and a doctorate in systems and entrepreneurial engineering from the University of Illinois at Urbana-Champaign in 2005.

Dr. Cody Lundberg is a Research Scientist II at UTARI. He focuses on assistive robotics, unmanned systems, system integration, autonomous software, computer vision, and remote infrastructure inspection.

Dr. Thirimachos Bourlai is an associate professor in the School of Electrical and Computer Engineering and has a Joint Appointment with Savannah River National Laboratory. He is the founder and director of the Multi-Spectral Imagery Lab, a member of the Board of Directors at the Document Security Alliance, and the former Vice President on Education of the IEEE Biometrics Council. He has published four books in the areas of biometrics and identity management and has written many conference papers, book chapters, and magazine articles.

1. INTRODUCTION

Warfighter performance can be improved by better understanding the sources of errors that cause weapons systems to be inaccurate and dispersed. The error-related factors contributing to dispersion include ammunition and gun dispersion, aerodynamics, and Soldier aiming or lay errors.[1,2] Among these factors, aiming or lay error, which is defined as the inability of the gunner to place the sight crosshairs precisely at the center of the target,[3] is considered significant. For the rest of this report, we only use the term “lay error.”

1.1 Motivation

There are seven motivational factors behind the decision to study the lay error:

1. Modern accuracy quantification: Such a study helps identify and understand the factors that contribute to aiming inaccuracy. The acquisition efforts for next generation technologies, such as AI, must quantify comparative improved accuracy of hitting the target.
2. Skill enhancement and performance optimization: By studying and analyzing these errors, gunners can improve their skills by identifying areas for improvement. They can work on specific techniques to enhance their ability to lay the sight crosshairs accurately on the target. They can also identify patterns or consistent mistakes that affect their performance, and thus, refine their techniques, leading to improved overall performance.
3. Professional development: The ability to accurately aim and hit targets is crucial for job performance and military safety. Lay error studies can improve a gunner’s professional skills; therefore, they can become more effective and proficient in their roles.
4. Operational advantage: In operational environments, gunners need to have a competitive advantage both for their own survival as well as for successfully completing their mission (high efficiency, no casualties). Lay error studies can gain a competitive edge by identifying and rectifying these errors, thereby increasing chances of operational success.
5. Psychological motivation: Overcoming challenges and improving a gunner’s abilities can be highly motivating. The study of such errors can help improve gunners’ abilities and achieve a greater level of mastery in aiming accuracy.
6. Team performance: The accuracy and effectiveness of each team member’s aiming can have a direct impact on the overall mission success. Studying lay errors can help identify team issues and, thus assist the leader implement strategies to improve accuracy and coordination of the team.

7. Safety considerations: By studying lay errors, gunners can identify potential safety risks associated with inaccurate aiming (e.g., accidents) and take appropriate measures to mitigate them.

Considering the aforementioned motivation factors, our proposed work is very important and has practical value for tank gunners. Our developed simulation environment, data collection, and analysis help quantify targeting skills. We do not discuss the reasons why simulation was used as the platform for testing, since it is a well-established method in the DOD Modeling and Simulation community.

1.2 Contributions

We focus on lay error and ground combat vehicles, particularly direct fire weapons systems, such as infantry fighting vehicles and main battle tanks. This study is a preliminary work of the lay error of human subjects under varying levels of task and visual complexity when using our newly designed and developed simulation environment (see Figure 1).

Figure 1. View of the Unreal Engine and simulation environment[4]

Specifically, we discuss the research and development of a realistic simulation environment in the Unreal gaming engine that features a variety of ground targets (see Figure 2). Then, following an Institutional Review Board (IRB)-approved data collection protocol, a cohort of 15 people that meet the criteria of military gunners is recruited. This group of participants is tasked to run our simulation environment and align crosshairs on targets at multiple ranges under different motion conditions. After the end of the simulation, and for each participant, our environment saves screen captures of each shot for offline processing. These shots are used to compute the lay error in the x and y directions (horizontal and vertical, respectively) in mils. Our study continues with data analysis toward the development of an accurate lay error statistical model.

This model will be used to assess the effect that varying conditions—namely, target parameters and levels of tasks and visual complexity—have on lay error.

Figure 2. The four targets in the simulated environment

The following are key takeaways:

- Experimental results answer our original question and show that the lay error changes with the shape and visual size of the target.
- The lay error is higher on closer targets because a subject can get a hit with the crosshair further from the center of the target.
- When using our simulation environment, the lay error for the majority of the human subjects tested is low. Less than 14% of the participants (i.e., two subjects) demonstrated a high error. This study is not focused on determining reasons for error (e.g., lack of focus and/or interest).

- In our study, we also determined that all subjects have some very large errors (outliers) that merit deeper consideration.
- Finally, the firing time for most of the shots is below 10 s for the majority of the subjects—independent of the test conditions, distance to target, or target type.

Our preliminary findings are expected to be extended and conclusions reinforced by a more thorough study currently underway, in which data from an additional 100 subjects will be collected and analyzed under various conditions, including new target occlusion scenarios in which fog and drone swarm will hinder the ability of the new subjects (simulation operators) to move the reticle to target.

This work is based on a previous National Defense Industrial Association (NDIA) paper.[5] This work includes more results and a more detailed discussion on the experiments performed, including target size comparison to lay error.

1.3 Related Work

While lay error is one of the sources affecting the accuracy of direct-fire small-caliber weapons systems, it is not the primary subject of this study. Factors affecting aiming error (e.g., combat stress, training, position, and time to aim), have been identified by Weaver.[6] Notable research has been conducted to quantify aiming error and other errors contributing to dispersion in order to improve Soldier performance. Glumm et al.[7] compared the lay error that resulted when gunners used two distinctive styles of control Yoke. Corriveau et al.[8] evaluated the lay error between various firing positions (e.g., prone, kneeling, standing, and trenched) and ranges (between 100 and 500 m [about 328.08 ft]). Using Monte-Carlo simulations, the probability of a hit was determined for each firing position and for three different ranges.[8] Both the experimental and simulation results are presented to demonstrate the lay error's impact on Soldier performance.

James et al.[9] evaluated Soldier performance under the stress of competition. One of the major conclusions of the study is that the aiming error is greater in burst mode than in semi-automatic mode. Strohm studied the primary sources of delivery error for direct-fire ballistic projectiles.[10] The vibration of both the vehicle body and the weapon affects the hit-probability of gunshots fired from moving ground combat vehicles. Song et al. presented a relationship between road roughness and vehicle speed when a predefined hit probability is needed.[11]

1.4 Study Highlights

Highlights of this work are summarized as follows:

- We present a realistic tank gunning simulation to analyze lay error under a variety of targets and conditions that mimic training such as requiring the participant to zoom-in on targets when needed. We include discussion of the design of the simulation as well as the testing scenarios.
- We discuss the original and the advanced simulation environment built to support the data collection process. The IRB process is also discussed.
- We present results of lay error for 15 subjects (Data Collection Session 1) taking 3600 shots at 4 targets, 4 distances, and under 4 moving conditions.
- We present initial key findings/deductions of our study and lay out plans for future analysis.

To our knowledge, this is the first time a dataset of this type has been collected, processed, and analyzed focusing on various targets.

1.5 Study Impact and Benefits

This study is a science and technology study focused on quantifying human hand-eye coordination for a task, which can be extended to Warfighters as well as specific weapons system–human interfaces. Quantifying human ability with modern techniques is key to assessing the potential advantages of AI and deciding when it is advantageous to use AI and when to rely on the human to find the center of the target. This research may be of interest to the broader scientific community for applications such surgical robotics or piloting a drone through environments with obstacles.

The report is organized as follows: Section 2 discusses the simulation environment. Section 3 provides a brief discussion on the data collection process. Section 4 contains data analysis, and conclusions are in Section 5.

2. ADVANCED SIMULATION ENVIRONMENT

The simulation environment was built using Unreal Engine.[4] Figure 1 shows an image from the simulation environment, in which a reticle is near a tank target that is 2000 m away. A red bar at the top shows the time left to fire. Our simulation features four ground targets, four moving conditions, and four target distances. The four targets were based on those used in the Army Training Ranges Circular[12]: 2.3- × 2.3-m square, 2- × 2-m trapezoid, 7.0- × 3.6-m trapezoid, and detailed 3D tank sized approximately 5.7- × 4.0-m. Targets were at distances of 500 m, and 1, 2, and 5 km from the shooter. The movement conditions were static shooter/static target, moving shooter/static target, static shooter/moving target, and moving shooter/moving target.

A timer was presented for 30 s to fire at four targets to compel speed in addition to accuracy. Only a single shot on each target was allowed, for which the shooting and environment data were saved. An Xbox controller was used for controlling the simulation.

Figure 3 shows an image of an Xbox controller from the top and front, with the controls highlighted. An Xbox controller is a universal human–computer interface that requires very little, if any, training for the human subjects. The Xbox controller is cost-efficient and suitable for the population; it was not possible to use government-furnished equipment of a true vehicle controller because it is controlled unclassified information.

Figure 3. A front and top view of the Xbox controller with the previously described controls highlighted in red

Because turret aiming makes use of an analog input device (left joystick), the inputs must be mapped to digital values to control the direction of the reticle. The Unreal Engine modifies axis values with four parameters: sensitivity, dead zone, exponent, and invert. Sensitivity affects the slope of the input curve such that a higher sensitivity value results in a greater amount of camera motion for the given input. Dead zone can be used to mitigate drift by clamping the axis input to zero near the idle position of the joystick. As dead zone increases, the subject must rotate the joystick to greater angles to see motion on the screen. The exponent parameter can modify the input curve from a linear relationship to a nonlinear one.

Finally, checking the Invert box in the editor will swap the output direction for a given input such that a positive input results in a negative output. Throughout development and data collection, our simulation used the following values to affect input: Sensitivity: 0.95; Dead zone: 0.04; Exponent: 1.85; Invert: False.

We mimicked the button requirements of the Abrams gunner yoke by the following configuration: 1) Aiming with the right joystick; 2) The left lower trigger is a dead man switch that must be pressed for any control to be accepted; 3) The left upper shoulder button and the left directional pad button turns on laser ranging and shot calibration; 4) The right lower trigger fires; 5) Up and down directional buttons optically zoom in and out the gunner’s view; 6) The X button is used to move to the next target.

3. DATA COLLECTION

Trials were conducted on 15 human subjects at the University of Georgia. The participants were each introduced to the project via a review of the consent forms, the study procedures, and the simulation workstation. After signing the consent forms, the subjects were asked basic demographic questions. Each subject first participated in an interactive tutorial to learn the task, user interface, and controls in a step-by-step manner.

Performance was monitored during the practice target segment, and undesirable behaviors (e.g., not aiming for the center of the presented area, inaccurate range finding, prioritizing speed over accuracy) were addressed. Once the participant demonstrated sufficient familiarity with the system, the tutorial ended, and the data collection segment began. Additionally, subjects were free to practice on as many tutorial targets as they wanted.

Subjects targeted and fired at all four targets, distances, and moving conditions, with 80% of cases being the static–static condition and the remaining 20% of cases evenly divided between the three other motion scenarios. The simulation then saved screen captures of each shot for offline processing to compute the lay error. Each subject fired at 240 targets, resulting in 3600 shots fired. See the breakdown of shots per condition in Table 1.

Once the data collection was completed, the subjects filled out a brief exit survey about their experience with the simulation and the control scheme. Subjects were compensated with a gift card.

Table 1. Total number of shots fired by subjects and by each specific firing condition

Range (m)	Target types	Motion condition	Shots per motion condition	Shots per conditions	Shots per subject per range	Shots per range for all subjects
500	4	SS	12	48	60	900
		SM	1	4		
		MS	1	4		
		MM	1	4		
1000	4	SS	12	48	60	900
		SM	1	4		
		MS	1	4		
		MM	1	4		
2000	4	SS	12	48	60	900
		SM	1	4		
		MS	1	4		
		MM	1	4		
5000	4	SS	12	48	60	900
		SM	1	4		
		MS	1	4		
		MM	1	4		
Totals					**240**	**3600**

Notes:

- Zoom level was user selectable (×1, ×2, ×10, ×25)
- SS = Static shooter, static target; SM = Static shooter, moving target
- MS = Moving shooter, static target; MM = Moving shooter, moving target

4. DATA ANALYSIS

The first step in analyzing the collected data is to calculate the lay errors in the x (horizontal) and y (vertical) directions in mils. To this end, the horizontal and vertical distances between the aim point and center point of the target are calculated in terms of the number of pixels, then converted to NATO mils as

$$e_{xm} = 17.\overline{7} \cdot e_{xp} \cdot \left(\frac{F_x}{W}\right), \tag{1}$$

where e_{xm} is error along the x-axis in mils, e_{xp} is error along the x-axis in pixels, F_x is the field of view in degrees along the x-axis, and W is the image width in pixels. A comparable calculation is made for y-axis error. If the reticle was over any part of the target, the shot was recorded as a "hit"; otherwise, it was recorded as a "miss." As this study focuses on lay error, no ballistics model was used in the determination of a hit, only if the reticle was on the target.

Scatter plots of error in meters for shots fired from all distances at each target type are shown in Figure 4. *Note that the term "hit" is used in several of our graphics, and it should be interpreted as reticle on target.* This was calculated by estimating where the shot would have crossed a plane through the center of the target and normal to the camera view. This conversion to error in meters is calculated as

$$e_{xc} = D \cdot Sin(e_{xr}), \tag{2}$$

where e_{xc} is the error in meters along the x-axis, D is the distance to the target, and e_{xr} is the error in radian along the x-axis. The color of each circle is green if the reticle was on target and red if it was off target. In each figure, a black bounding box is seen showing the outline of the target size. Note that as this study focuses on lay error, no ballistics model was used in the determination of a hit, only if the reticle was on the target.

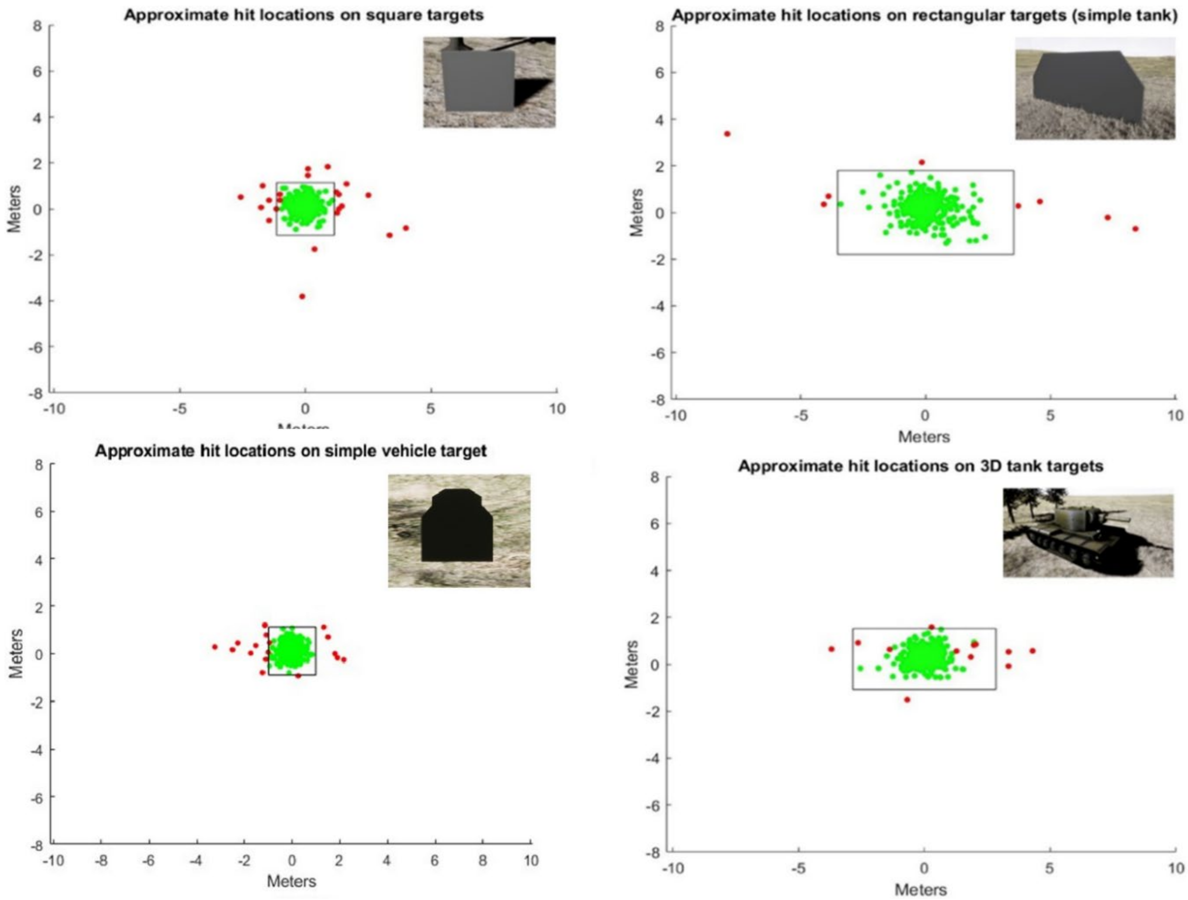

Figure 4. Scatter plots of lay error in meters with respect to four target types

Figure 5 presents box plots for the lay error in the x and y direction for the four target types. The bottom and top of each box are the 25th and 75th percentiles of the sample, respectively.[13]

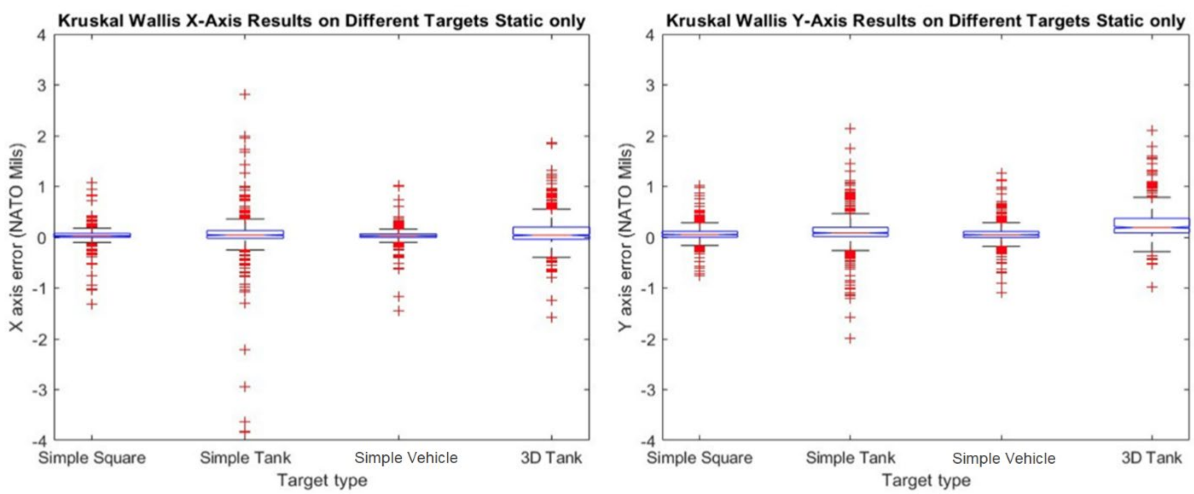

Figure 5. The error in mils box plot for the four targets at the stationary firer stationary target scenario

The distance between the bottom and top of each box is the interquartile range (i.e., the middle 50% of data is withing the range of the blue box). The red line in each box is the median of the data set. The black “whiskers” extend 1.5 times the distance from the median to the corresponding quartile. Any data point outside this range is considered an outlier and is marked by a red cross. There is a very large number of outliers for each data set, which indicates that a notable number of shots have large lay error. We have observed this in all data sets to date and the source of this error is an area of future research. Furthermore, the simple square and the simple vehicle have a similar box size, and the simple tank and 3D tank boxes have a similar size. The two tank models have larger boxes than the square and simple vehicle, indicating a wider spread of lay error. This indicates that the shape of the target does affect the lay error. Figure 6 illustrates the preponderance of the human subjects to actuate the trigger using the highest zoom level of 25 times—in both close- and long-range conditions. Of the 3600 shots, only 1 shot was taken at 01-times zoom and 6 shots at 02-times zoom; while 388 shots were taken at 10-times zoom and 3205 shots at 25-times zoom. Figure 7 uses color to indicate range to the target and filled or empty circles to denote when the reticle was on or off the target. Figure 7 also shows the counterintuitive yet clear concept that humans are more accurate when aiming at smaller presenting targets such as those at 5000 m (~3.11 mi).

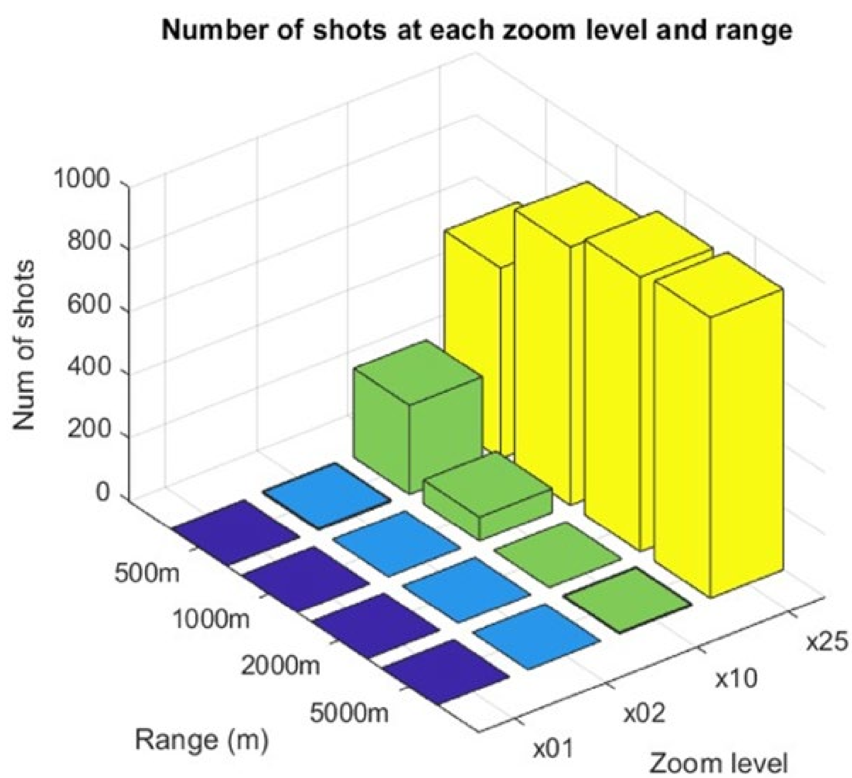

Figure 6. Number of shots by zoom level

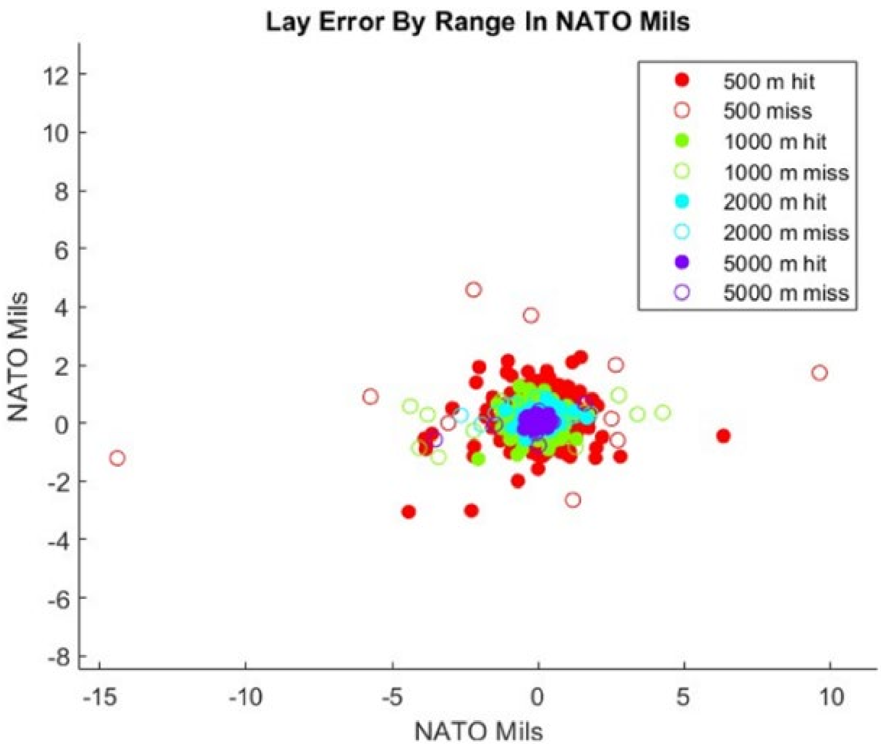

Figure 7. **Lay error by range (in NATO mils)**

Figure 8 shows the Euclidian error in meters as it related to the total visible target pixels (i.e., the apparent target size) for each shot. The number of visible target pixels is a function of target shape, range, and user zoom level. Overlaid on top of this plot is a linear regression of the visible pixel-to-error relationship, which shows that the error in meters reduces as the number of visible target pixels increases. This relationship is given by

$$e_m = -7.523 * 10^{-7} * T_p + .3987, \quad (3)$$

where e_m is the error in Euclidean meters and T_p is the number of target pixels visible.

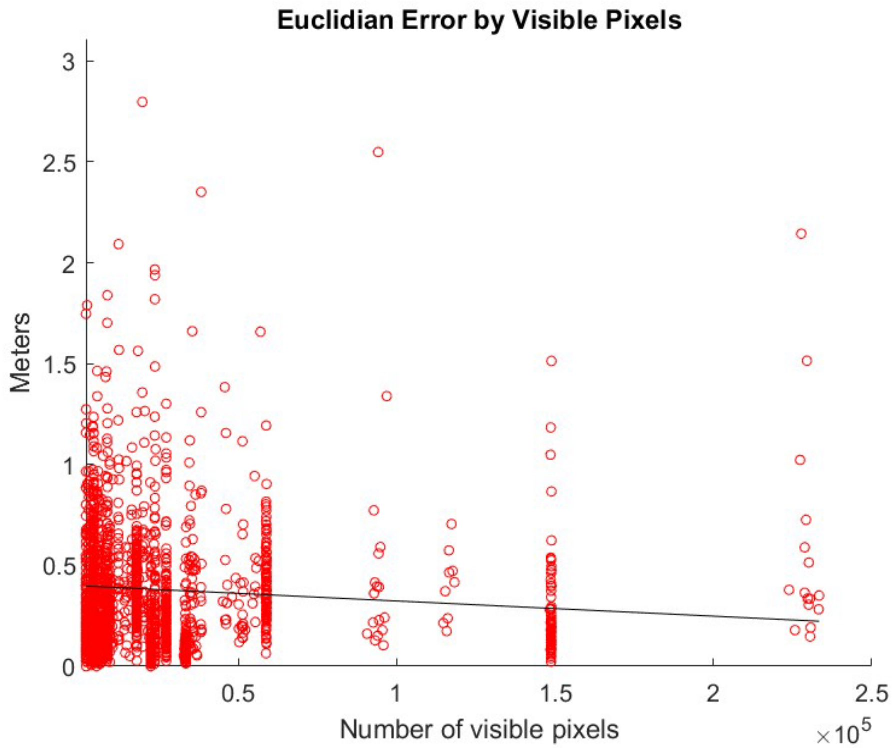

Figure 8. The results of a linear regression to fit Euclidian error as a function of the targets presented area in pixels

5. CONCLUSIONS

Currently, tank crews use a manual process to detect, identify, and engage targets. As the U.S. Army considers the development of computer vision, AI algorithms, and associated systems to assist direct-fire gunners' target performance, it is essential to establish a baseline of human performance against which to compare such new systems. Thus, establishing a baseline for lay error is critical when evaluating the performance of AI algorithms to determine the statistical difference[14–16] between manual and AI-assisted aiming.

In this report, we presented the first design of our study, test, and analysis of human-subject trials for modeling and predicting the lay error of a tank gunner. We focused on quantifying the ability of several operators to move a reticle to a target under variable simulation conditions. One goal was to determine whether the lay error changes with the target. Unreal Engine was used to develop a photorealistic simulation environment featuring a range of targets at different distances and moving conditions.

Fifteen people were asked to align crosshairs on targets at multiple ranges and under various motion conditions using the simulation environment. Analysis of the lay error was conducted using the collected data. We observe that the lay error did change with the target; specifically, the results of lay error are different for differently sized targets. This is an interesting finding, as most current work and testing is predicated on defining the inputs to the probability of hit based on the weapon and munition, not based on the target. The lay error is higher on closer targets and low for approximately 86% of the subjects. The firing time for most shots was below 10 s for the majority of the subjects, independent of the test conditions, distance to target, or target type. Finally, in our study, we also determined that all subjects have some very large errors (outliers) that merit deeper consideration.

Our preliminary findings will be extended by a more thorough study currently underway, where an additional 100 subjects' data will be collected and analyzed under various conditions, including target occlusion scenarios in which fog and drone swarm will be hindering the ability of the new subjects to move the reticle to target. Another point is that in the absence or delay of regular live fire training sessions a gunner's accuracy can be negatively impacted, because without such sessions, gunners may experience a decline in proficiency due to lack of practice and reinforcement of these skills.[17] The presented work's simplified simulation mimics robust simulation environment trainers at a fraction of the cost and a focus on lay error analysis. Other future work could include the expansion of data collection to include lay error data collection to corroborate study findings with actual military testing. Finally, it is expected to be valuable to see an expansion of error budget to include an adjustment based on target type and size.

6. REFERENCES

1. Norman, R. M., & Geddie, J. C. (1981). *The increasing influence of gunner lay error on first-round hit probability for tanks* (TN 2-81). Human Engineering Research Laboratories.

2. Chaikin, G., Chipser, J., & Rich, N. (1972). *Field investigation of gunner aiming error as a function of launcher weight* (RL-72-10). U. S. Army Missile Command.

3. Bunn, F. L. (1993). *The tank accuracy model* (ARL-MR-48). Army Research Laboratory.

4. Sanders, A. (2016). *An introduction to Unreal Engine 4*. AK Peters/CRC Press.

5. Gans, N. R., Lundberg, C. L., Forsythe, J., Ensing, P., & Bourlai, T. (2023). *Targeting simulation for assessment of lay error under varying conditions*. In 2023 NDIA Michigan, Chapter Ground Vehicle Systems Engineering and Technology Symposium, Technical Session, August 15–17, 2023 - NOVI, Michigan, USA.

6. Weaver Jr., J. M. (1990). *System error budgets, target distributions and hitting performance estimates for general-purpose rifles and sniper rifles of 7.62 x 51 mm and larger calibers* (ARL-TR-461). Army Research Laboratory.

7. Glumm, M. M., Grynovicki, J. O., & Waugh, J. D. (1997). *Gunner performance in a motion environment: a comparison of controls*. In Proceedings of the Human Factors and Ergonomics Society Annual Meeting, Vol. 41, No. 2, pp. 1056–1060. SAGE Publications Sage CA, Los Angeles, CA.

8. Corriveau, D., Rabbath, C., & Goudreau, A. (2019). Effect of the firing position on aiming error and probability of hit. *Defense Technology*, *15(5)*, 713–720.

9. James, P., Wansack, S., Hudgens, G. A., King, J. M., & Fatkin, L. T. (1991). *Effects of competition and mode of fire on physiological responses, psychological stress reactions, and shooting performance* (TM 11-91). U. S. Army Human Engineering Laboratory.

10. Strohm, L. S. (2013). *An introduction to the sources of delivery error for direct-fire ballistic projectiles* (ARL-TR-6494). Army Research Laboratory.

11. Song, J.-B., Choi, S.-Y., & Park, K. (2015). Aiming error analysis of guns in ground combat vehicles operating on bumpy roads. *Journal of Mechanical Science and Technology*, *29*, 5145–5150.

12. [DA] Department of the Army (2004). Training Circular Training Ranges (TC 25-8).

13. MathWorks. (2020). *Support documentation*. https://www.mathworks.com/help/matlab/ref/boxchart.html

14. Stephens, M. A. (1974). ED statistics for goodness of fit and some comparisons. *Journal of the American Statistical Association*, *69(347)*, 730–737.

15. Kruskal, W. H., & Wallis, W. A. (1952). Use of ranks in one-criterion variance analysis. *Journal of the American Statistical Association*, *47(260)*, 583–621.

16. Karson, M. (1968). *Handbook of methods of applied statistics*. Taylor & Francis.

17. Mroszczak, M. C. (2009, February 20). *Efficient training for crew served weapons Marines* [EWS contemporary issue paper]. Marine Corps Combat Development Command, Quantico, CA.

LIST OF ACRONYMS

3D	three-dimensional
AI	artificial intelligence
DAC	DEVCOM Analysis Center
DEVCOM	U.S. Army Combat Capabilities Development Command
DOD	Department of Defense
IRB	Institutional Review Board
MM	moving shooter, moving target
MS	moving shooter, static target
NATO	North Atlantic Treaty Organization
NDIA	National Defense Industrial Association
SM	static shooter, moving target
SS	static shooter, static target
UGA	University of Georgia
UTARI	University of Texas at Arlington Research Institute

DISTRIBUTION LIST

DEVCOM Analysis Center
FCDD-DAG-G/J. Forsythe
6503 Wayberry Rd.
Aberdeen Proving Ground, MD 21005-5071

University of Georgia
T. Bourlai
P. Ensing
Athens, GA

University of Texas at Arlington
N. Gans
C. Lundberg
Arlington, TX

DEVCOM Analysis Center
FCDD-DAD-TP/E. Chatterton
Redstone Arsenal
Huntsville, AL 35898

DEVCOM Army Research Laboratory
FCDD-RLB-CI/Tech Library
2800 Powder Mill Rd.
Adelphi, MD 20783

Defense Technical Information Center
ATTN: DTIC-O
8725 John J. Kingman Rd.
Fort Belvoir, VA 22060-6218