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AN UNDERGRADUATE SYSTEMS ENGINEERING DESIGN PROJECT FOR USING CONSTRUCTIVE AND VIRTUAL SIMULATION FOR AN ARMED UAV DESIGN

Suzanne Oldenburg DeLong
Paul West

Department of Systems Engineering
United States Military Academy
Mahan Hall
West Point, NY 10996, U.S.A.

ABSTRACT

This paper presents a design project for undergraduate systems engineering students in which Armed Unmanned Aerial Vehicles (AUAV's) are designed, using the systems engineering design process taught at the United States Military Academy, and tested using constructive and virtual simulation. These results are compared to theoretical results obtained through applying Lanchester analysis. Students first analyze the stakeholders' needs and develop alternatives. The students research commercial off the shelf (COTS) UAV airframes, sensors and weapon systems that meet the stakeholders' needs. Using design of experiments and response surface optimization, laboratory experimentation is conducted using Janus simulation and Janus Evaluator Tool Set (JETS) software to test the feasible alternatives under varying weather conditions and altitudes to examine performance against a predetermined threat. The students evaluate the alternatives using multi-attribute utility theory and encompassing all the objectives defined in the stakeholder analysis. Sensitivity analysis is applied and a recommendation is made to the decision maker.

1 INTRODUCTION

Undergraduate combat modeling courses serve an important role in teaching young engineers the engineering science needed to model combat systems. Simulation is a great tool to evaluate theoretical combat systems. Simulations such as Janus allow the users to alter existing combat system characteristics to test theoretical ideas. A basic appreciation for the principles of modeling combat and combat systems should be of interest to many engineers who are interested in predicting combat systems performance, especially those involved in the design of the actual combat system.

2 THEORY: LANCHESTER ANALYSIS

Frederick Lanchester was an English engineer with a wide range of interests. His interests in military strategy led him to develop mathematical models for land combat. He developed a model for one-on-one duels (1st Linear Law) and refined it to consider a concentration of forces. These equations come with many assumptions that may have been sufficient for Napoleonic combat, but fall short in modeling modern warfare in the 21st century. By convention, friendly forces are referred to as the blue side and the enemy forces are known as the red side. Equations 1 – 4 below were adapted from *DARCOM Pamphlet 706-101 (Grubbs, 1977)* and *DARCOM Pamphlet 706-102 (Grubbs, 1979).* The variables are defined in all equations as follows:

B_o = Blue initial strength
R_o = Red initial strength
B_t = Blue strength at time t
R_t = Red strength at time t
β_B = Constant rate at which Blue attrits Red using aimed fire
β_R = Constant rate at which Red attrits Blue using aimed fire
α_B = Constant rate at which Blue attrits Red using unaimed fire
α_R = Constant rate at which Red attrits Blue using unaimed fire

Equation 1, Lanchester's Square Law, looks at a concentration of forces with both sides using aimed fire.

$$\beta_B\left(B_0^2 - B_t^2\right) = \beta_R\left(R_0^2 - R_t^2\right) \quad \textbf{or} \quad \frac{\beta_R}{\beta_B} = \frac{B_0^2 - B_t^2}{R_0^2 - R_t^2} \qquad (1)$$

Parity between red and blue forces is achieved when $\left(\frac{B_0^2}{R_0^2} = \frac{\beta_R}{\beta_B}\right)$, blue forces win when $\left(\frac{B_0^2}{R_0^2} > \frac{\beta_R}{\beta_B}\right)$, and blue forces lose to red when $\left(\frac{B_0^2}{R_0^2} < \frac{\beta_R}{\beta_B}\right)$.

Many combat modelers have since refined Lanchester's equations to more accurately portray modern combat. The 2nd Linear Law, equation 2, takes into consideration un-aimed fire concentrated on an enemy location. This effect is accounted for in the attrition coefficients.

$$\alpha_B(B_0 - B_t) = \alpha_R(R_0 - R_t) \text{ or } \frac{\alpha_R}{\alpha_B} = \frac{B_0 - B_t}{R_0 - R_t} \qquad (2)$$

Parity between red and blue forces is achieved when $\left(\frac{B_0}{R_0} = \frac{\alpha_R}{\alpha_B}\right)$, blue forces win when $\left(\frac{B_0}{R_0} > \frac{\alpha_R}{\alpha_B}\right)$, and blue forces lose to red when $\left(\frac{B_0}{R_0} < \frac{\alpha_R}{\alpha_B}\right)$.

Another adaptation takes into consideration the ambush scenario, where one side is employing aimed fire and the other side un-aimed or area fire. Equation 3, known as the Guerrilla Warfare Model, is shown in two cases. Case 1, equation 3.1: red ambushes blue and case 2, equation 3.2: blue ambushes red. Note that this equation is a combination of the square law and the 2nd linear law.

$$\textbf{Red Ambush} \quad \alpha_B\left(B_O^2 - B_t^2\right) = 2\beta_R(R_o - R_t) \qquad (3.1)$$

Parity between red and blue forces is achieved when $\left(\frac{R_0}{B_0^2} = \frac{\alpha_B}{2\beta_R}\right)$, red forces win when $\left(\frac{R_0}{B_0^2} > \frac{\alpha_B}{2\beta_R}\right)$, and red forces lose to blue when $\left(\frac{R_0}{B_0^2} < \frac{\alpha_B}{2\beta_R}\right)$.

$$\textbf{Blue Ambush} \quad \alpha_R\left(R_O^2 - R_t^2\right) = 2\beta_B(B_o - B_t) \qquad (3.2)$$

Parity between red and blue forces is achieved when $\left(\frac{B_0}{R_o^2} = \frac{\alpha_R}{2\beta_B}\right)$, blue forces win when $\left(\frac{B_0}{R_o^2} > \frac{\alpha_R}{2\beta_B}\right)$, and blue forces lose to red when $\left(\frac{B_0}{R_o^2} < \frac{\alpha_R}{2\beta_B}\right)$.

The next refinement is the Logarithmic Law, equation 4, where the element of surprise causes a greater attrition rate earlier on in the battle rather than the constant attrition rate which is assumed in the previous 3 equations.

$$(1/\beta_R)(\ln B_0 - \ln B_t) = (1/\beta_B)(\ln R_0 - \ln R_t), \text{ or}$$

$$\left(\frac{B_t}{B_0}\right)^{\frac{1}{\beta_R}} = \left(\frac{R_t}{R_0}\right)^{\frac{1}{\beta_B}} \qquad (4)$$

Hartley III (2001) concludes that combat attrition for every historical battle can best be modeled using an equation that is between the 2nd linear law and the logarithmic law. While Lanchester's original equations may be outdated, the research in applying these equations to modern warfare continues.

Students in a senior-level combat modeling course at West Point are given this background as a baseline for developing an analytical solution to a real-world problem facing the military today. The students are given a scenario and fit Lanchester models to the situation. Janus databases are used to calculate the attrition coefficients for the enemy and friendly weapon systems employed in the scenario. Students then test their combat systems in simulation and further analyze the results – keeping in mind the assumptions used to develop the Lanchester equations and the assumptions used in creating the scenario. Students can validate their simulation by comparing the results to their analytical solutions and determine which model more accurately fits the simulation results.

3 EXPERIMENTAL PROCEDURES

Undergraduate students apply the principles described above to predict the performance of friendly and enemy forces in a given scenario. After predicting the outcome of the scenario, students test these principles by conducting experiments using two alternatives developed by the student. The students also test their alternatives by building virtual prototypes and testing them in a virtual terrain model while running the scenario in Janus.

The following sequence of events lays out the experimental procedure:

1. Complete an in-depth analysis of your alternatives to include a comparison using the analytical tools of Lanchester's models of warfare. Update the Janus database to reflect your alternatives. Select your measures of effectiveness for your two alternatives. Initiate your simulations by first conducting pilot runs to determine the number of replications required to capture the desired precision of your experiment. Conduct confidence interval testing on your alternatives to verify that each alternative is statistically significantly different. Verify and validate your simulation results by discussing some of the techniques to verify and validate and

how you can use these techniques to check that your simulation is performing correctly.

a. Set up and execute pilot runs (iterations) for each alternative until you've approximately captured the true variance. Use the *First Shot* tutorials and Janus Users Manual as a guide.
b. Assuming that you've captured the true variance, determine the number of replications required to be 95% confident that you've captured the true capabilities of the armed UAV within x% of the true mean (desired relative precision, DRP) or within +/- x (desired absolute precision, DAP) for your MOE. The following method of computing sample size comes from *Combat Modeling Notes (*Benson et al. 2002).
    i. Perform m replications
    ii. Compute $\bar{x}_m$ and s_x
    iii. Compute t $_{m-1,\ 1-a/2}$

    If using DAP (+/- mean)

    iv. $$N = \frac{s \bullet t_{n-1,1-\alpha/2}}{DAP}$$
    v. $$N = \left(\frac{s \bullet t_{m-1,1-\alpha/2}}{DAP} \right)^2$$

    or, if using DRP (% mean)

    iv. $$N = \left(\frac{s \bullet t_{m-1,1-\alpha/2}(1+DRP)}{(DRP)\bar{x}} \right)^2$$
    v. $$N = \left(\frac{s \bullet t_{n-1,1-\alpha/2}(1+DRP)}{(DRP)\bar{x}} \right)^2$$
    vi. Iterate until N repeats.
c. Report the number of required replications to your instructor before proceeding. Your instructor will give you your "budget" which will determine the number of replications to be performed. (This will preclude a design team from spending an inordinate amount of time running replications.) Post-process this number of replications from each alternative and evaluate the simulation output using JETS. At a minimum consider two measures of effectiveness (MOE) for your alternatives.
d. Select two appropriate MOE's and determine if there is a significant difference in the results of your two alternatives at the 90% confidence level. In comparing two different simulation situations, the following methodology was used from *Combat Modeling Notes (Benson et al. 2002)*:
    i. Collect data on your MOE for both alternatives and conduct a paired t-test where you follow the convention of subtracting system 1 - system 2.
    ii. Compute $\bar{x}_n$, $s_x{}^2$ and the resulting CI_n
    iii. If the confidence interval, CI_n, contains zero, then (at the 100(1-α) percent confidence level) we cannot distinguish between the means of the two output distributions. The two systems have equal effectiveness.

        Otherwise,

        $CI_n > 0$ implies system 1 is better, and
        $CI_n < 0$ implies system 2 is better.

    In looking at the armed UAV, the student may wish to consider measures of effectiveness such as the number of kills, number of detections, or the number of UAV's not returning.

2. Use experimental design methods to determine the optimal weather conditions and altitude for each of your alternatives. We are interested in examining the weather factors of temperature and wind speed and altitude. Your task is to find which factors have a significant effect on each of your alternatives ability to detect and kill the enemy and to find the optimum combination of weather conditions and altitude in which your alternatives detects and kills the most enemy targets while minimizing your losses. Set up a full factorial design, using the factor settings shown in Table 1:

Table 1: DOE Factor Settings

	Temperature	Wind speed	Altitude
Low	35° F	0 kmph	100 m
High	100° F	50 kmph	1000 m

This procedure (Law and Kelton, 2000) allows the student to examine the environment that the UAV's will be operating in and be able to refine the alternative's sensors or weapons systems based on the results.

3. Virtual and Distributed Simulation. Create a virtual prototype of your best alternative using 3D modeling tools (MultiGen-Paradigm Creator Software) and distributed interactive simulation (DIS) compliant software (Janus and Stealth software). This prototype will be evaluated in the 3D environment and will allow students to see how sensors and weapons will be incorporated into the COTS

airframe. Additionally, the value of virtual prototyping allows the student to gain an appreciation for the terrain, terrain representation and the line of sight algorithm, one step in the determination of a system being able to detect a target.

4. Decision Making. Interpret your alternatives using the objectives you developed in your stakeholder analysis. Conduct multi-attribute utility analysis that combines your simulation results with your other objectives. Conclude with final recommendations and an action plan.

4 RESULTS AND DISCUSSION

The purpose of this design project is to demonstrate the systems design process in the development of combat systems through the use of constructive and virtual simulation. The student takes the stakeholders needs and formulates, analyzes and interprets their alternatives. One design team's results are as follows:

1. Looking at the enemy weapon systems, SA7, RPG7, AT7, and an SA14, averaging the rates of fires yields an attrition coefficient of, $\beta_R = 0.206$. Using the predator airframe and a 7.62 coax machine gun, $\beta_B = 18.97$.

   Given 90 enemy forces and applying the square law it was determined that the enemy has the advantage. In order to reach parity, the blue force needs approximately 10 UAV's.

$$\frac{\beta_R}{\beta_B} = \frac{B_0^2 - B_t^2}{R_0^2 - R_t^2} = \frac{0.206}{18.97} = \frac{B_0^2 - 0}{8100 - 0} \qquad B_0 = 9.38$$

   A. Using the number of detections as the measure of effectiveness, the standard deviation was found to be 7.48 with a mean of 48.

   B. Using a desired relative precision of 10%, the following number of replications are needed:

$$N = \left(\frac{7.48 \bullet 3.182(1+0.1)}{(0.1)48} \right)^2 = 29.8 \cong 30$$

$$N = \left(\frac{7.48 \bullet 2.042(1+0.1)}{(0.1)48} \right)^2 = 12.25 \cong 13$$

$$N = \left(\frac{7.48 \bullet 2.160(1+0.1)}{(0.1)48} \right)^2 = 13.7 \cong 14$$

$$N = \left(\frac{7.48 \bullet 2.145(1+0.1)}{(0.1)48} \right)^2 = 13.5 \cong 14$$

   C. 14 replications were accomplished on each alternative and the design team analyzed the number of detections.

   D. Using the number of detections resulted in the following confidence interval: (-5.78, 4.92). This confidence interval indicates that there is no statistical difference between the two alternatives when evaluating the number of detections.

2. In analyzing the design of experiments it was found that the altitude setting, using alpha = .1, is the only significant factor. In examining the number of kills, the temperature factor was significant. In maximizing detections and kills and minimizing losses, the following factor settings were found to be optimal: temperature = 67 degrees and altitude = 740 m. The wind speed setting is not significant.

3. The virtual prototype of one alternative incorporated the predator airframe and hell fire missiles. The results are shown in figure 1 in computer aided design (CAD) view.

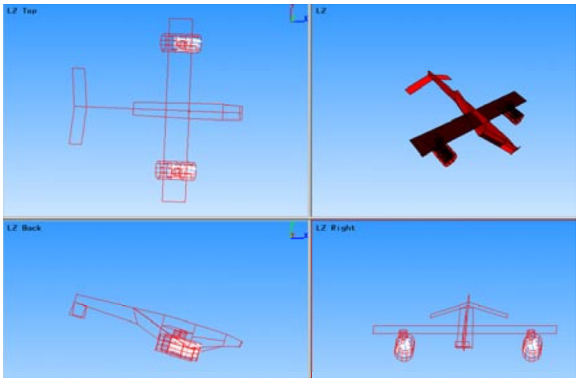

Figure 1: Virtual Prototype in CAD View

4. Using multi-attribute utility the two alternatives were examined using all the objectives identified as a result of conducting the stakeholder analysis. Incorporating all the objectives resulted in alternative 1 having a higher utility score as shown in Table 2.

Table 2: Multi-Attribute Utility Scores for each Alternative

Measure of Effectiveness	Global Weight	Alternative 1	Alternative 2
Probability of Hit	0.0870	100.0000	94.3700
Total Kills	0.2100	100.0000	60.0000
Weapon Range (m)	0.0525	100.0000	75.5600
Fuel Capacity (Gal)	0.1000	100.0000	64.0600
Max Speed (knots)	0.0750	63.6300	100.0000
Payload Weight (lbs)	0.0750	47.3300	78.6700
# of UAVs Returning	0.0600	100.0000	66.6700
# of Times Detected	0.0900	100.0000	98.1200
Sensor FOV	0.0880	100.0000	32.7900
# of Enemy Detections	0.0750	100.0000	94.1300
Intel Processing Time	0.0625	85.7000	76.1900
Flight Range (m)	0.0250	100.0000	86.6700
	Total Utility =	92.4283	74.2882

5 CONCLUSIONS

The intent of this paper is to show that the basic principles of combat modeling – from needs analysis to experimentation – are not beyond the capabilities of the undergraduate level. There exists an excellent opportunity to demonstrate the process of developing combat systems and testing them in constructive and virtual simulations.

The decision of which topics to include in an undergraduate course in combat modeling continues to be a challenge to any course instructor. How much time to dedicate to the underlying software algorithms, learning the basic techniques of combat modeling, and the amount of time to invest in creating the virtual prototype and learning the 3D software are all questions that should be answered.

A lesson is defined as a 55-minute block of instruction. Two lessons are sufficient for a basic introduction to the subject matter of simulation and combat modeling. The study of Lanchester's equations requires a minimum of three lessons. Five lessons should be spent on learning simulation basics and output analysis. Four lessons are required to teach design of experiments and response surface methods so the students can apply multiple response optimization. Eight lessons should be dedicated to covering the computer algorithms used to calculate line of sight, detection, damage and kill assessment algorithms as well as terrain representation. Five lessons are needed to learn the 3D modeling software and one lesson to then create the virtual prototype. One lesson at the end of the course brings together the virtual prototype and the simulation through the use of advanced distributed simulation.

Exploring the fundamentals of combat modeling in a real-world project context provides valuable insight into the interrelationships of large-scale military systems. This deeper understanding of the role of modeling and simulation promises to better prepare undergraduate students as analysts and leaders.

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AUTHOR BIOGRAPHIES

MAJ SUZANNE OLDENBURG DELONG is an Assistant Professor in the Department of Systems Engineering at the United States Military Academy, West Point. She received a B.S. degree in Mechanical Engineering (Aerospace) from USMA in 1990, a M.S. in Systems Engineering at the University of Virginia, May 2000 and has also completed her PhD course work. Her e-mail address is <fs3213@exmail.usma.army.mil>.

PAUL WEST is an Instructor in the Department of Systems Engineering at the United States Military Academy, West Point. He received a B.S. degree from University of the State of New York in 1983, an MBA from Long Island University in 1993, an MTM from Stevens Institute of Technology in 2000 and is currently a PhD candidate in Systems Engineering and Technology Management, Stevens Institute of Technology. His e-mail address is <fp8049@exmail.usma.army.mil>.