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Application of a Deliberate System Design Framework to Develop Effective Marksmanship Feedback

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Abstract: This research demonstrates a deliberate systems engineering approach towards the development and selection of an effective feedback system to be used in virtual marksmanship scenarios. It focuses heavily on modeling stakeholder value to estimate total value provided. Three candidate solutions are proposed, all of which meet the client's basic functional requirements. When measured and scored, the candidate designs are differentiated in the value vs. cost trade space to assist the stakeholders with the final design decision. This research is a novel application of a systems engineering framework towards an eminent problem that spans multiple topics. Though the implementation initially seems specific to the client's technology, there is evidence that this methodology is widely applicable in the field of systems engineering and will be of interest to the design community.

Keywords: Systems Engineering, Simulation, Marksmanship, Sensors Integration, Modeling, Decision-making

1. Introduction

1.1 Problem Statement

As a subordinate unit of the U.S. Army Combat Capabilities Development Command (DEVCOM), the Soldier Center's Applied Ergonomics research team is pursuing enhanced soldier lethality through simulated marksmanship training focused on human performance. To address this, the Soldier Center developed the Team Shooting Scenario (TSS) (S. Brown et al., 2022; S. Brown & Mitchell, 2017). Their simulator apparatus was developed to train and experiment with individual and team-based marksmanship drills. For this system to be effective and enable widespread use throughout the Army, it must ease the burden of live-fire training while maintaining realism and meeting design criteria. The current configuration consists of commercially available subsystems in addition to custom components built at the Soldier Center. While the current system has its merits, it lacks an instantaneous feedback system for Soldiers completing the test. There is no indication of whether a shot was a hit or miss immediately after a Soldier pulls the trigger. This project team set forth to address the problem: *How can a deliberate systems-oriented design approach improve the existing TSS to provide an accurate hit-or-miss feedback solution?*

1.2 Simulated Marksmanship Background

The Army must maintain high-quality training amidst budget constraints. To address the challenge, Soldier Center invested in marksmanship simulation training to provide Soldiers the advantages of live-fire training at a lower cost (Banks et al., 2010). Simulated marksmanship offers additional benefits; literature shows that simulated marksmanship significantly improves marksmanship through training visual-motor coordination paired with shot feedback (Liu et al., 2021). Although Soldier complaints suggest simulations feel unrealistic, technological advancements during the last 30 years have transformed combat simulations into realistic emulators providing significant training value (Schloo & Mittal, 2020). Recent research suggests that skill training for motor learning tasks can now transfer into real-world scenarios while simulating realistic stress (Liu et al., 2021). Simulated marksmanship is still a developing field, but significant process in recent years has made it increasingly relevant to the Army, driving projects such as the Team Shooting Scenario.

1.3 Team Shooting Scenario (TSS)

The TSS requires a three-person fire team to detect, identify, and potentially engage targets over approximately six minutes (S. Brown et al., 2022; S. A. T. Brown & Mitchell, 2017). Soldiers are equipped with a simulation M4 rifle which functions. Attached is an FN Expert™ optical unit, a marksmanship training device that utilizes an IR beam to simulate and provide shot accuracy feedback. In addition, an Inertial Measurement Unit (IMU) is attached to the other side of the rifle.

Twenty-eight light node targets are set up in a circular shape, with a radius of 7.5 meters from a 2.5-meter inner circle.

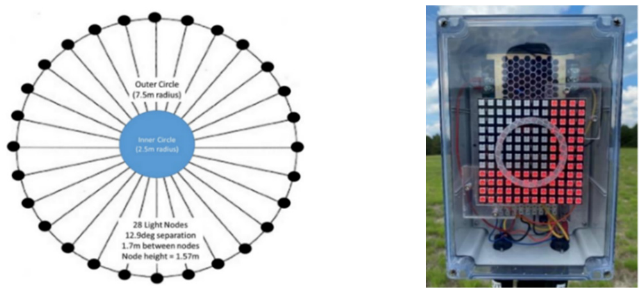

Figure 1: TSS Test Layout and Light Box Target Presentation. (S. Brown et al., 2022)

Soldiers stand centered in the inner circle while engaging targets. Light node targets are scaled to simulate shooting from 75 meters away. Each target can display three different modes: dormant, threat, or non-threat. Figure 1 is a diagram of the TSS configuration from above and shows an example of a threat. Testing is conducted in six successive segments, presenting targets in different densities throughout the 40 to 80-second segment. A mix of threat and non-threat targets are presented. Shot data from the FN Expert™ is used to calculate marksmanship lethality through the FN software. The FN devices connect to the laptop software via Bluetooth and light box nodes are connected together and back to a main hub via wired components (S. Brown et al., 2022). Upon completion of the test, each Soldier can view their scores and receive detailed feedback on their ability to effectively identify and engage targets.

1.4 Literature Review Findings

The Soldier Center team noted flaws within the TSS configuration that limited utility of the system in certain experimental scenarios. While detailed marksmanship results are available post-simulation, users do not receive instantaneous shot accuracy feedback during the simulation tasks. The intermingling of commercial off-the-shelf (COTS) and Soldier Center subsystems does not currently allow for cross-communication. Additionally, the current version of TSS does not provide the ability to match shots to target numbers; while accuracy data of an individual shot is always captured, there is no means to determine which target is being engaged at the time of trigger-pull. To address these issues, the research team focused on three areas: (1) the TSS's realism, (2) the best way to provide real-time feedback to Soldiers, and (3) the method for the TSS components to communicate shooter feedback.

The existing TSS relies on an accurate recreation of the form-factor and feel of an M4 rifle. The weight of the rifle should be kept between 3.3 and 3.8 kg to simulate carrying and aiming an actual M4 (Cheng-Kang & Yung-Hui, 1997). The M4 used for the TSS is approximately 3.6 kg, which falls within that range. The rifle must also have approximately the same dimensions as a real M4, which currently holds true. Additionally, the Soldier Center has mimicked the feeling of firing a rifle with simulated recoil (S. A. T. Brown & Mitchell, 2017). If components are added to the re-designed rifle for the purpose of giving real-time feedback, the weight or dimensions may change, exceeding the recommended tolerance for the weapon.

To maximize realism, it is important to consider the means through which Soldiers are given real-time shot feedback. One of the main issues with the existing system is that there is no live feedback mechanism that informs the shooter of whether they defeated the threat (or non-threat). The literature strongly suggests that the brain can pull a greater response from a cross-modal stimulus (i.e., incorporating multiple senses) than it would from two similar but unimodal stimuli. There are limits to this phenomenon known as multisensory integration (Calvert & Thesen, 2004). The Principle of Inverse Effectiveness stipulates that if too many stimuli are presented, reaction time will instead decrease (Privitera, 2023). If one stimulus is much stronger than the other or if too many stimuli are used, any attempt to minimize positive identification and feedback reaction times could backfire. As a result, it was decided to limit the shooter feedback methods to only two modes.

The system's method of communication is extremely important for giving the TSS flexibility and maintaining realism. Feedback needs to be immediate. After reviewing the literature, the research team considered Bluetooth, ZigBee, wired, and radio frequencies as options and ultimately decided on Bluetooth due to its ease of use and interoperability within existing wireless networks (Challoo et al., 2012).

2. Methodology

The Systems Decision Process (SDP) is a highly iterative problem-solving approach that focuses on creating value for the stakeholders and decision maker in the system solution. This process consists of four phases: (1) Problem Definition, (2) Solution Design, (3) Decision Making, and (4) Solution Implementation (Parnell et al., 2011). Each of these phases has its own distinct steps and outputs. The SDP also considers the environment that the system will operate in and the possible issues that could arise in this space (Parnell et al., 2011).

2.1 Problem Definition

The first phase of the SDP contains three parts: research and stakeholder analysis, functional and requirement analysis, and value modeling. These steps are conducted at the beginning to ensure that all system requirements are met, and that the solution is successful from the stakeholder's perspective (Parnell et al., 2011).

Stakeholder analysis is used to help fully frame and understand the problem that is being presented while also determining the needs, wants, and desires of stakeholders for the system. This step is crucial to develop a system that maximizes value for decision-makers while providing useful insight into potential solution designs (Parnell et al., 2011). To this end, the researchers conducted an initial client meeting with the Soldier Center team to codify what the stakeholder valued in a new TSS system design. In this phase, the initial problem statement emerged: *What is the best way to provide an accurate hit-or-miss feedback system to Soldiers engaging in simulated fire team marksmanship?*

To investigate, the team engaged in a value modeling procedure which has become popular for multi-objective decision analysis (Parnell et al., 2011; Braun et al., 2022). Requirement analysis began with the building of a functional hierarchy (Figure 2). This diagram defines the characteristics of a suitable system and ways in which decision criteria are to be measured. The fundamental objective was that the TSS needed to provide feedback to Soldiers with every shot. The objective was split into three functions: (1.0) provide quick and accurate shot feedback, (2.0) maintain realism, and (3.0) enable scope expansion.

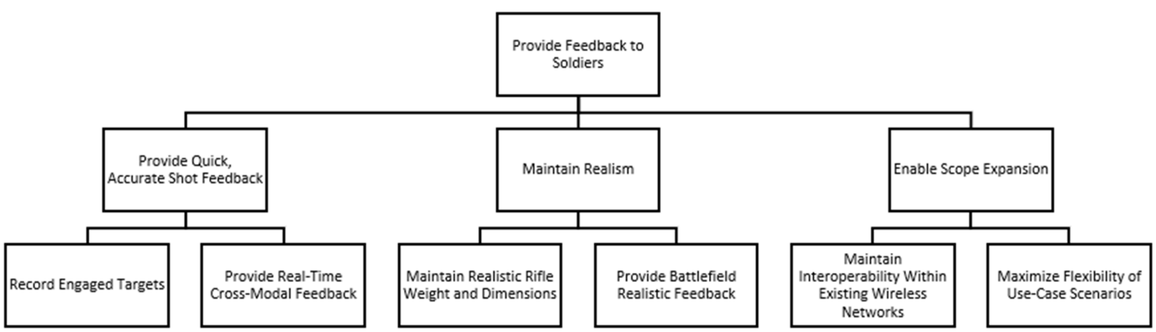

Figure 2: Functional Hierarchy (i.e., Qualitative Value Model) for the TSS shooter feedback system.

Table 1: Value Measure Description Table (Quantitative Value Model)

Objective	Definition
Minimize Design Complexity	The complexity of the electrical design and associated difficulty of assembly.
Minimize Relay Time	The time for the system to communicate with the software.
Maximize Interoperability	The ability for the system to be used and adapted for scope expansion (research and training tool).
Maximize Display Accuracy	The distance between shot placement and shot feedback location.
Maximize Soldier Comprehension	The time required for soldiers to see and establish PID (engagement time not included).
Minimize Weight Discrepancy	The difference in weight between usual soldier LBE and the system.

The sub-functions serve as assessment criteria for each system design in latter phases of the SDP. A quantitative model of system performance follows. Table 1 lists the full set of technical performance measures. At the conclusion of the Problem

Definition phase, a redefined problem statement is necessary: *The TSS must provide Soldiers with quick, accurate feedback while maintaining realism and enabling future use case expansion.*

2.2 Solution Design

In the idea generation phase, ideas are created and refined into alternatives, which are then screened for feasibility. The primary methodology for idea generation of the *physical* TSS components was the Zwicky Morphology, a matrix with combinations of components to generate solutions (Parnell et al., 2011). Unique options were listed for *feedback type*, *connection type*, and *power sources* for the system, then merged into feasible combinations of options to generate alternatives. This technique minimized the likelihood of reverting to Solution Design to generate suitable options later in the process.

Three design alternatives were proposed to meet system requirements. Solutions 1 through 3 are depicted in Figure 3. Each of the three solutions provide a visual and auditory feedback to the shooter, which can be programmed into the light node target as a color-change or shape-change.

Candidate Solution #1 uses internal IR receivers mounted between every four LEDs of the target (Figure 3, left). This design detects muzzle orientation; the continuous IR beam from the FN Expert triggers one or more of the IR receivers when the beam points within a target's boundaries. The IR receivers then communicate via Python script, and the target number is recorded during trigger pull. FN Expert emits noise and the light target changes color or shape to alert the shooter of a hit. This design requires external hardware (121 diodes per target) and modification to the existing Python code that governs TSS.

Candidate Solution #2 also uses IR receivers to determine target number but has external modification instead of internal IR receivers. The target has a ring mounted on the shooter side with IR receivers mounted around the edge (Figure 3, center). This design requires external hardware (24 diodes and a ring per light box) and modification to the Python code. This would provide the same hit-or-miss feedback as Candidate Solution #1 but without the accuracy provided by an array of sensors.

Candidate Solution #3 involves a significant redesign on the TSS. This design attaches a Raspberry Pi computer and a camera module onto the rifle. Light boxes are labeled with designators made of white and black tape (Figure 3, right). An IMU attached to the rifle commands the camera to continuously take pictures in muzzle direction. The Raspberry Pi camera uses image recognition machine learning to classify targets at trigger pull. The Raspberry Pi uses black crosses in the corners of the light box to orient itself and uses the numbers in the upper right-hand corner to discern which target the rifle is aiming at. Hits and misses are adjudicated with a feedback loop to the main computer. FN Expert emits noise and the light target changes color or shape to alert the shooter of a hit. Adding these components to the M4 adds non-negligible weight.

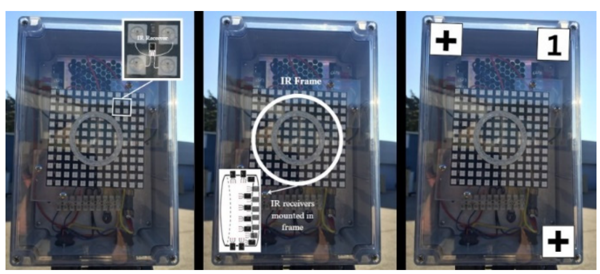

Figure 3: Candidate Solutions 1-3 (left to right).

2.3 Decision Making

The decision-making phase of the Systems Decision Process contains three subtasks: solution scoring, sensitivity analysis, and value-focused thinking. Here, the systems engineer must provide all necessary information and analysis towards recommended solutions to the decision maker.

The solution-scoring subtask begins by inputting raw data for each evaluation criterion, which is then converted into value scores using respective value functions. The stated importance of each value measure (by the stakeholder) is captured as a multiplicative and normalized factor known as "global weight"; higher weight represents more importance to the decision. After collecting values scores for each criterion, total value scores are generated using an additive value model equation as seen below in Equation 1.

$$V(\mathrm{x}_j) = \sum_{i=1}^{n} \left[w_i \times v_i(x_{j,i}) \right] \tag{1}$$

In Equation 1, $V(x_j)$ represents the total value score of the j^{th} candidate solution, n represents the number of value measures (decision criteria), w_i is the global weight applied to the i^{th} value measure, $v_i(x_{j,i})$ is the value function that assesses the j^{th} solution on the i^{th} value measure (where $x_{j,i}$ is the raw data).

To help stakeholders understand the impact of their preferences on the value model's output and mitigate unnecessary risk associated with the uncertainty of system design parameters, sensitivity analysis was conducted as seen in Curran et. al (2018). Sensitivity analysis displays changes in total value scores for each candidate solution based on changes in swing weights for each value measure. If any candidate solution's relative value ranking were to change based on an individual swing weight, this value measure would be considered sensitive, and the stakeholder would be informed.

3. Analysis & Discussion of Results

3.1 Swing Weights

A swing weight matrix (Table 2) assigns value scores (0-100) to each criterion based on importance to the stakeholder and variation in measurements. Global weights (Table 3) result from the normalization of swing weights (0-1 scale).

Table 2: Swing Weight Matrix

Variation in ranges	Level of Importance: High	Level of Importance: Medium	Level of Importance: Low
High	Design Complexity 100		
Medium	Relay Time 80 Interoperability 70	Display Accuracy 60	Weight Discrepancy 50
Low	Soldier Comprehension 60		

Table 3: Global Weights

Objective	Swing Weight	Global Weight
Minimize Design Complexity	100	0.238
Minimize Relay Time	80	0.190
Maximize Interoperability	70	0.167
Maximize Display Accuracy	60	0.143
Maximize Soldier Comprehension	60	0.143
Minimize Weight Discrepancy	50	0.119
Total:	420	

3.2 Value Model and Sensitivity Analysis

Value functions were generated by listing the range of possible outputs for each value measure then determining the provided value (0-100) at each interval; stakeholder feedback yielded the resulting six value functions. Each alternative was scored by inputting raw data into the value functions to obtain value scores. Value scores were then combined based on their global weights to compare in the value vs. cost trade space. The recommendation was deemed to be not sensitive to changes in stakeholder preferences.

3.3 Value vs. Cost Trade Space

The value vs. cost trade space allows the stakeholder to visualize tradeoffs when accepting candidate solutions and transitioning to Solution Implementation. Each candidate solution yielded nine total points consisting of every combination of the lower bound, expected value, and higher bound for value and cost. This is presented as a rectangle on Figure 4 with the corners being High Value High Cost (HVHC), HVLC, LVHC, and LVLC.

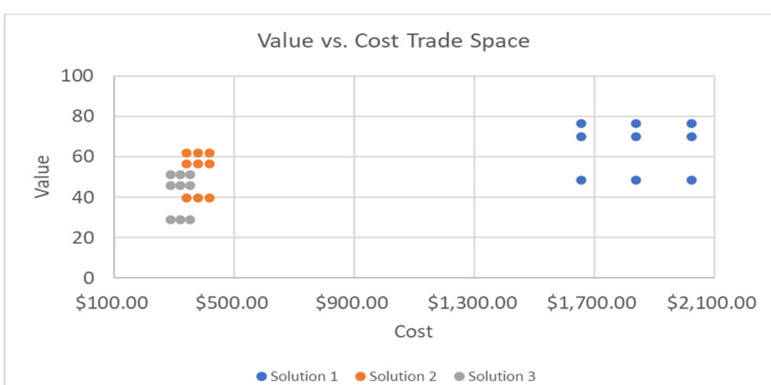

Figure 4: Value vs. Cost Trade Space

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4. Conclusion

A systematic systems-decision approach allowed the project team to effectively define the problem, innovate new solutions, and decide on how to implement real-time Soldier feedback. This was possible after a thorough investigation of the existing system and supporting literature. Using literature as a foundation, the project team was able to understand where alternatives could be implemented. Generating alternatives while staying within stakeholder requirements remained a challenge. This work demonstrates the benefit of taking a deliberate and quantifiable approach towards decision-making in the re-design of complex technological systems, especially when a significant human-system interaction is to be considered in the functional requirements.

Based on the team's findings, none of the candidate solutions can be eliminated from consideration. The Soldier Center approving authority has three options to consider: Solutions 2 and 3 which are similar in their value and cost, or Solution 1 which outputs significantly more value on average but at a much higher cost. Each candidate design delivers on the fundamental objective by providing two forms of feedback to shooters (visual and auditory). The literature review emphasized the importance of multi-modal stimuli for providing the best training value for Soldiers engaging in TSS experiments, which was incorporated into all three solutions. The researchers recommend the Soldier Center team reassess the project schedule and budget with the consult of the electrical engineer to come to a conclusion on best fit based on this research and the expertise of the electrical engineer.

The next step in this project is to conduct validation testing of Solutions 1, 2, and 3. Limitations of the light node target design are a constraint that must be worked through. A subject matter expert (i.e., electrical engineer) will assist with prototyping. Advanced experimentation will validate whether sufficient feedback stimulus is provided to the shooter in each of the candidate solutions presented. The system was re-designed with stakeholder requirements in mind; once produced and tested, the applied ergonomics team will be able to provide further input to the iterative SDP design approach.

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