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Simulation in Model Based Systems Engineering: Estimating Robot Range and Battery Performance

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Abstract: The DAF has begun incorporating robotic systems, like the Ghost Robotics Vision-60, into base defense and security operations including perimeter patrol, surveillance, detection, and emergency response. However, the variable performance specifications of max range and battery life pose challenges to determining operational requirements such as the number of robot units, capabilities achieved through accessories, support equipment, and total program cost. This presentation discusses a project in Model-Based Systems Engineering used to develop a tool that supports robot implementation in base defense plans. The key feature of the tool is a simulation that estimates robot range based on factors including distance patrolled, changes in elevation, local weather, battery capacity, and recharge rates. Using data from publicly available mapping software, the model output has the potential to support security forces squadrons in procuring and employing robots at any base worldwide.

Keywords: MBSE, Modeling, Systems Engineering, Robotics

1. Introduction

Recent advances in microelectronics processing power, sensor and communication capability, artificial intelligence, and low-cost components have enabled a revolution in drone warfare on air, land, and sea. Nowhere is this more evident than the battlefields of Ukraine enterprising soldiers and citizens are building thousands of cheap drones each month with devastating, and cost-effective, results on Russian armor and personnel (MacDonald, 2024). The Ukrainian government has issued over 50 grants for Quadruped-Unmanned Ground Vehicle (Q-UGV) projects, and this matches trends in other countries, such as the United States. In this pivotal moment, both small startups (e.g. Ghost Robotics, Boston Dynamics) and large companies (e.g. BAE Systems, L3Harris) are producing military robots (MacDonald, 2024).

However, this explosion of military robotics is outpacing robust documentation and performance characterization that is essential for effective operational employment. One example is the Vision 60 Q-UGV, which Ghost Robotics has developed under several SBIR (Small Business Innovation Research) grants and deployed at multiple military bases across the continental United States. While customers in the Air Force have been successfully operating the Vision 60 for security forces missions, there is limited data available to help customers understand its range limitations, and performance under varying configurations, terrain, and environmental conditions.

The purpose of this project was to use Model-Based Systems Engineering (MBSE) techniques in order to develop a robust digital model of the Ghost Robotics Vision 60. As part of the modeling, the team developed a simulation-based tool that outputs operational metrics of the Vision 60 for optimal employment in base defense operations. Using MBSE as a methodology can streamline multidisciplinary efforts, particularly through digital modeling toolchains such as CATIA Systems Modeler, offering a contemporary approach over traditional methods. The MBSE approach enables integration of disciplines and discipline-specific software. The effort focused on development of structural, behavioral, and parametric diagrams that will help users of the Vision 60 more effectively employ the robot in new locations. Features of the model include a MATLAB integration tool that incorporates real world terrain data from commercially available mapping software as well as historical weather information. The model provides users with a graphical user interface (GUI) that allows them to estimate the range and battery performance of the robot. Data collected while operating the robot across varying terrain and temperature conditions informed the development of the model. Figure 1 shows the Q-UGV undergoing data collection.

Figure 1. The Ghost Robotics Vision 60 Q-UGV

1.1 Literature Review

The literature on MBSE covers topics such as its justification, current development states, and unresolved challenges. MBSE aims to replace document-based methods, offering benefits that provide completeness in modeling to understand systems as well as improved requirement communication and early defect detection (Carroll & Malins 2016). While Ghost Robotics develops the Vision 60 independently, the team was able to develop a model that incorporated requirements based on requirements acquired through interviewing of a security forces squadron. Additional literature emphasizes the importance of MBSE in modern engineering practices (Hart, 2015). Hart highlights key principles of MBSE, such as using models as a central artifact to manage system complexity and facilitating communication among stakeholders (Hart, 2015). The overview highlights the benefits of MBSE, including improved system understanding, enhanced collaboration, and more effective decision-making throughout the system development lifecycle (Hart, 2015). Under these premises, the highly collaborative nature of MBSE platforms enhanced the team's interdisciplinary perspectives over the duration of the capstone project. While MBSE is justified in its general implementation, the evolution of the methodology emphasizes its data-centric approach that enhances Systems Engineering with limited costs, offering reusability and improved design quality (Hart, 2015). In terms of tool-chain integration, MBSE can significantly enhance understanding of complex systems through its ability to link heterogeneous models and data, fostering a more comprehensive approach to systems engineering. Additionally, literature suggests that integration with various engineering tools, including possibly MATLAB and Python, is a key area of focus, aiming to streamline and optimize the systems engineering process through improved tool interoperability (Kiritsis et al., 2016). The team took advantage of the ease-of-integration that MBSE facilitates and explored the possibility of multi-software tools to achieve the objective of the project.

2. Methodology

The focus of this project was to build a digital model of the Vision 60 robot using CATIA Magic System of Systems Architect (CATIA), which allows a coherent demonstration of system capabilities, requirements, and use cases. Before modeling began, the team completed interviews with security forces airmen and collected observational data of operations in the Base Defense Operations Center. These studies informed development of multiple diagrams in the model including

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requirements, use cases, activities, and creation of an operational view (OV-1) for the system. Additionally, the model includes a block definition diagram and internal block diagrams that define the structure of the Vision 60 robot. Much of the model development focused on a robust simulation featuring MATLAB integration, which enables operators to predict the robot's range and battery performance given terrain and weather inputs. MBSE was necessary for this project as creating simulations for complex systems requires complex understandings of components and needs that said system would have. Further, the systems modeling approach allows a holistic view of the system in simulation and allows consideration of more than one system component in affecting performance.

To create the battery and range performance simulation, the team developed a test matrix that focused on performance in varying terrain and weather conditions. From initial pilot testing, the team found that distance, slope, and ambient temperature have the most significant impact on range and battery performance. The team accomplished further detailed testing in which the robot demonstrated performance over multiple trials with battery data collected on 100-meter intervals. During these trials, the incline varied from -4.2%, 0%, and 4.2%. The team also conducted testing in 75°F and 37°F temperature conditions, which local weather limited. The team used the data to inform the parametric equations that estimate battery life and range.

A key feature of the range and battery performance simulation is integration with real world terrain and weather information. A commercially available mapping tool called CalTopo provided all terrain data. This tool allows an operator to map a route for the robot and export the route as a comma separated variable (CSV) file that breaks down the route into shorter legs capturing both the distance and change in elevation. Additionally, the developed simulation pulls historical weather data from an application called OpenWeatherAPI. This feature was set up to capture both average temperature and the standard deviation by month, which enabled the simulation to run as a Monte Carlo as performance can be highly variable across weather conditions. To judge the success of this simulation, team conducted verification testing after simulations to find what percent error existed between the simulated results and the actual operational data that the team would receive. The team derived this percent error from expected battery draw over a route and the actual battery draw over that same route.

3. Results

3.1 Model Development

Figure 2 below is the OV-1 diagram or the Operational Viewpoint. The diagram highlights potential users and information transfer, indicating operational use. Specifically, this figure demonstrates how different actors engage in typical use cases of the Vision 60 at USAFA.

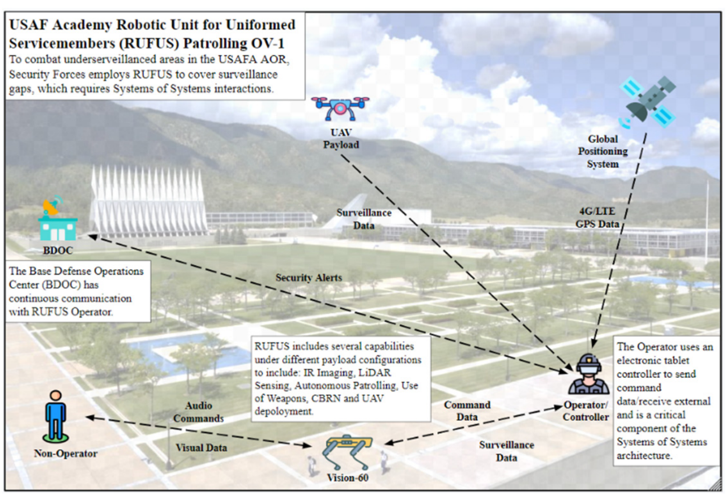

Figure 2: Operational Viewpoint (OV-1)

Effective Systems Modeling Language (SysML) interpretation and navigation is essential for MBSE methodology. Figure 2 compares the CATIA modeling system requirements, highlighting the differences between the inherited non-standard organization and modern SysML organization methods. The updated requirements offer better organization with top-level categorization and detailed breakdowns for each requirement. The team updated requirements through looking over the past year's requirements, filtering through them by talking with Ghost Robotics and Security Forces, and setting requirements based on the overall end goal. Stakeholder requirements linked to the power subsystem, which MBSE connectivity enhanced. The power subsystem was a priority requirement for this analysis due to the fact the team's goal was to optimize and determine battery life under operational use for the robot. Additionally, they include accurate data and estimates while eliminating irrelevant requirements for the team's research.

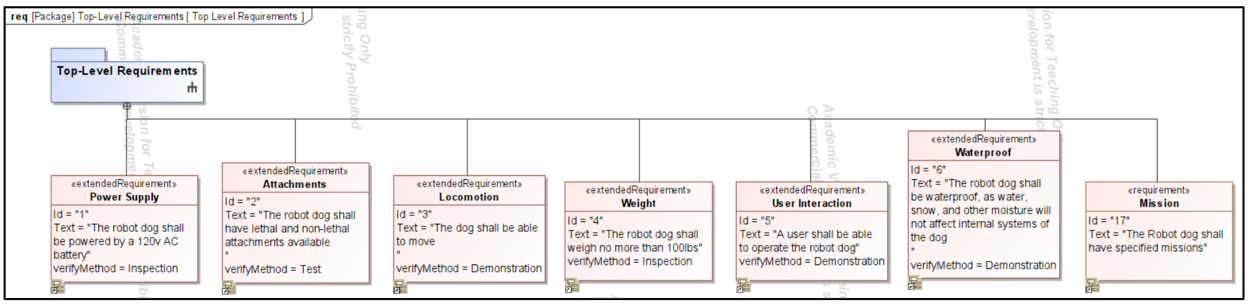

Figure 3. CATIA Model Old (Top) to New (Bottom) Requirements Comparison

3.2 Battery and Range Performance

Table 1 displays the average results over three weeks of testing. Each equation developed below references the different tests and averages of both distance and test battery draws.

Table 1. Straight Line Battery Draw

Distance Traveled (Feet)	Average Percent Draw Through All Tests	Temperature At Test	Category
367	-2.67%	75 F°	Incline Uphill
367	-0.4%	75 F°	Incline Downhill
367	-1.2%	75 F°	Straight Line
367	-0.85%	37 F°	Straight Line

After collecting the initial incline/decline data, the team developed a linear relationship with a slope of 0.09149 and a Y-intercept of 0.03726 where the average battery drop can be determined by inputting the degrees of incline. Equation 1 depicts this relationship.

$$y = 0.09149x - 0.03726 \quad (1)$$

The tertiary tests on straight-line at 75°F results showed a battery drop of 0.3726% every 367 feet based on the average of the percent draw of the average distance walked. Thus, the team could use this standard battery drop for every 367 feet that the robot would walk in the simulation given no incline or decline at all.

Finally, the team took the same straight-line tests as above at a cooler temperature of 37°F to compare the effect that temperature has on the battery draw of the robot. This team only tested the straight-line scenario as it had the most reliability and least variability in testing results. Thus, this temperature coefficient was determined to be more accurate as there were fewer independent variables to consider, and we could more accurately focus on the temperature variable. In addition, limited changes in temperature in the Colorado Springs area prevented further testing on intermediary temperatures between 37 and 75 Degrees Fahrenheit. With this newly collected temperature data, the team developed another linear equation to determine how far the robot could walk at any given temperature the equation has a slope of 0.0033 and a Y-intercept of 0.1265 where the average battery drop can be determined by inputting the temperature. Equation 2 depicts this relationship.

$$y = 0.1265x - 0.0033 \tag{2}$$

The two equations above combined within MATLAB resulted in a single equation, multi-variable model. As the initial battery equation assumed a temperature of 75 Degrees Fahrenheit, the team multiplied Equation 2 by the battery draw equation to get a more accurate slope according to not only terrain and incline, but also changes in temperature.

3.3 Model Validation

The team validated the model on campus at the United States Air Force Academy. A route was selected on the Santa Fe Trail which runs over 7 miles from North to South through the base. First, members of the team generated a route on this trail using the CalTopo software and exported as a CSV file. Next, the team used OpenWeatherAPI to gather historical weather for the last 3 years. The team imported the information into the MATLAB file and ran the simulation 1000 times as a Monte Carlo. Figure 4 presents the outputs and depicts the percent battery draw and the distance traveled on each trial. The data shows no trials walking greater than 6 miles or less than 4.2 miles. The battery drawn all shows nearly 100% battery drawn because the trail of interest is greater than any one Vision 60 would be able to walk on one charge.

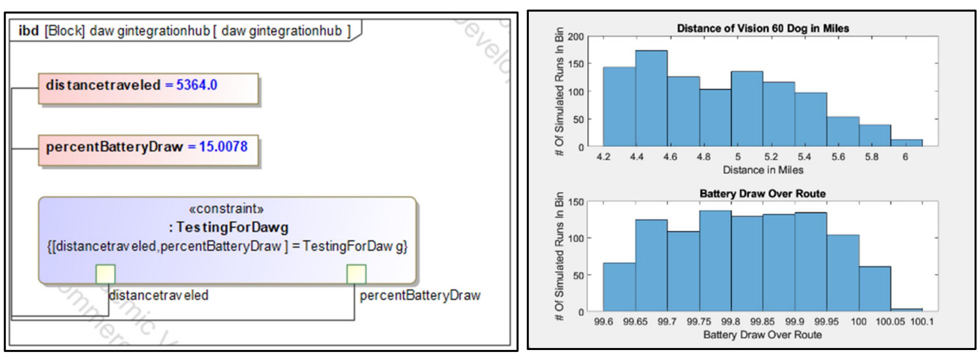

Figure 4: Experimental Modeling Results

The team validated the accuracy of the simulation by operation of the robot on the Santa Fe Trail over a 3 mile long mapped route. The Vision 60 robot walked this route 7 times and on each trial the actual battery draw had less than a 5% error. This percent error is sufficient to make a recommendation to a security forces squadron, however, the percent error the unit is willing to except when using this model is ultimately up to the commander.

3.4 Operational Recommendation

Using the data from the simulation, the team proposed an operational recommendation that considers predicted range and battery limitations. The simulation predicted that the robot would be unable to traverse the entire 7-mile distance of the Santa Fe Trail. Therefore, the team proposed two remote charging stations at 3.7-mile intervals. This distance was selected to keep each station equally spaced and below the 4.2 mile minimum range predicted by the simulation. The simulation also predicted that an individual Vision 60 would take 8 hours and 10 minutes, on average, to patrol the entire trail one-way with 1 hour and 10 minutes of downtime. Figure 5 depicts a final recommendation for the Santa Fe Trail patrol route based on our simulated results. The blue line depicts the base borders, while the red line depicts the Santa Fe Trail section the Q-UGV Vision 60 patrol route.

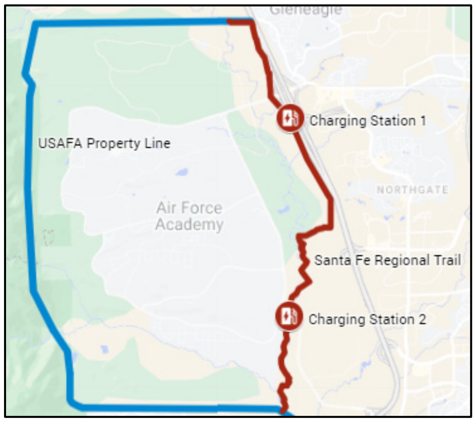

Figure 5. Resultant Map of the USAFA Property with Proposed Charging Station Locations

4. Conclusion

The team's objective was to build a tool that would aid in employing Ghost Robotics' Vision 60 Q-UGVs. The team used MBSE, additional mathematical simulation tools, and experiment designs to calculate the battery percentage drop of the vehicle under differing operational conditions. The Monte Carlo-based equations aided in the development of proposals, suggesting the number of robots and stations required to conduct a specialized patrol mission of an unsecured trail which is difficult for security forces to conduct constant operations. The research will be helpful for the refinement of operations research in providing Q-UGV capabilities to forward operating bases. The capability of implementing the Q-UGV 60 under different environmental factors and estimating battery drop will prove beneficial to security and planning operations in deployed environments. The limiting conditions of the research include snow, dirt, and other extreme weather. The team recommends for future research further data gathering, validation, and verification under other weather conditions and integration with other instruments. In particular, the Vision 60 has other configurations with long-range communication packages, CBRNE capabilities, LiDAR sensors, real-time kinetic positioning features (RTK), and weapon packages. Alternate configurations will almost certainly result in different battery drop rates due to the higher battery draw required for additional capability packaged. The team's work aids in mission planning and resource allocation, highlighting the importance of integrating MBSE and experimental methods in assessing unmanned ground vehicle systems for military operations.

5. References

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