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Model-Based Systems Engineering (MBSE) a Ghost Robotics Vision 60 Q-UGV for Future Power Systems and Emerging Military Requirements

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Abstract: This paper presents the use of Model-Based Systems Engineering (MBSE) to model the Ghost Robotics Vision 60 quadrupedal unmanned ground vehicle (Q-UGV) and guide future decision making for military engineers and leaders. The Catia Magic System of Systems is used to model both internal and external interactions with the system, including power drawn from those processes and interactions. By connecting this model to a MATLAB-based program, a holistic model for the Vision 60 is created, which can be modified, improved, and better understood early in the design phase. One application of our work is to help predict and analyze power drawn from various attachments and internal processes to predict future performance in a military context. The results of this study provide insights into the design of future power systems, especially as attachments are added to the robot, and demonstrate the potential of MBSE modeling for complex systems in military contexts. Finally, this paper verifies the potential implementation of MBSE within the Department of Defense (DoD) to maintain an advantageous position over adversaries in the current digital transformation.

Keywords: Robotics, Model-Based Systems Engineering, Ghost, Q-UGV, Technology

1. Introduction

The use of robots in defense and industry is becoming ubiquitous. Among the various types of robots being used, quadrupedal unmanned ground vehicles (Q-UGV) have gained popularity due to their versatility and potential to expand human capabilities in safe and effective ways. For example, Q-UGVs have been used by the Army for tasks such as clearing buildings and identifying potential threats. The Army's Maneuver Center of Excellence has deployed the FLIR PackBot EOD robot and the General Dynamics Mission Systems (GDMS) for reconnaissance and bomb disposal (Grizzle, 2018). Law enforcement agencies have also used Q-UGVs to search for missing persons or suspects (Holt, 2020). These robots also have potential in disaster response scenarios, where they can be used to locate survivors and assess damage (Kusaka, Miyawaki, & Nakamura, 2020). Additional applications for Q-UGVs include guiding visually-impaired people (Due, 2023), surveillance (Hougen et al., 2000), and companionship (Banks et al., 2008; de Visser et al., 2022).

This paper focuses on the Ghost Robotics Vision 60 Q-UGV (Figure 1). The Vision 60 is a mid-sized high-endurance, agile and durable all-weather ground drone designed for use in a broad range of unstructured urban and natural environments for defense, homeland and enterprise applications. The can carry a variety of payloads including electro-optical sensors, robotic arms, as well as lethal and non-lethal weapons. The Vision 60 is powered by a 1,250 Wh lithium-ion battery with an advertised range of 10 km, though the true range and operating time are highly dependent on mission profile (e.g. payload weight, power requirements of accessories, moving speed) and environmental factors. As organizations, including special operations forces, law enforcement, and public safety, begin to make use of these robots it is essential that they understand how the mission profile and environment impact range and operating time as this can influence the number of robots required or the utility of the robot for a specific mission.

Figure 1. The Vision 60 on a walk at the United States Air Force Academy

One approach to a developing a better understanding of the Vision 60's power requirements under a variety of conditions is model-based system engineering (MBSE). MBSE is the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases (INCOSE). Rather than reliance on documentation, MBSE focuses on the creation of domain models to capture the structure and behavior of a system of interest. This enables system engineers to characterize the system, specify and design new systems, evaluate a system, train users, and sustain the system over its lifecycle.

This project is an application of model-based systems engineering (MBSE) in order to develop a tool that can help users predict Vision 60 power requirements given a specific mission profile. The models developed as part of this project include system requirements, structure, and behavior. The components of this model allow for the simulation of battery state and power draws under a variety of configurations and mission profiles, which can help predict the robot's capabilities in real-world scenarios. MBSE can serve as a powerful tool to identify potential problems, test different scenarios, and optimize the system design before committing to implementation. Application of MBSE in this project provides a comprehensive understanding of the system and inform decision-making. This paper describes the development process of this model and its potential applications beyond the Vision 60.

1.1 Client Organization

This project was carried out in partnership with several organizations including Ghost Robotics, the 10th Security Forces Squadron at the US Air Force Academy, and the US Air Force Security Forces Center. Ghost Robotics is a technology company that specializes in developing and building quadrupedal robots for customers, including defense contractors, technology innovators, and systems integrators, to build useful and scalable technology. The company's vision is to create a portfolio of robots of various sizes and capabilities that are tailored to specific environments and price points, serving both government and enterprise users. Ghost Robotics' provided us insight into their proprietary electronics, software stack, and control system for complex actuated systems for the purposes of this project. Our understanding of robot use cases was informed by members of the 10th Security Forces Squadron and documentation from the Air Force Security Forces Center. All stakeholders are considered to be beneficiaries of the models developed for this project.

1.2 Related Work

The development of robotic Q-UGVs for various applications has been extensively studied in recent years. Such systems have been developed and deployed for military and defense applications, including reconnaissance, transportation, search and rescue, CBRN exposure, firefighting, and armed attack and defense. Sanaullah et al. (2022) discussed the integration of cognitive systems in military and defense land-robots, highlighting ethical and integration limitations. Grizzle (2018) provided a case study on the FLIR PackBot EOD Robot, which is used by the US Army for explosive ordnance disposal. Hougen et al. (2000) presented a miniature robotic system for reconnaissance and surveillance, while Kusaka et al. (2020) surveyed disaster response robots, which includes robotic Q-UGVs.

Although no previous studies have used MBSE to model robotic Q-UGVs, there is related work. Mittal and Gillespie (2022) and Chavan and Brocanelli (2022) use model-based systems engineering to inform battery life improvement for autonomous mobile robots. Mittal and Gillespie discussed the use of model-based systems engineering to avoid unnecessary technology resulting from dynamic requirements. Chavan and Brocanelli focused on improving the battery life of autonomous mobile robot fleets, which is relevant to the development of robotic Q-UGVs for prolonged operation. Still, our work is novel in the MBSE of the Vision 60.

2. Design Methodology

Modeling the Vision 60 began with a structural model that included SysML Block Definition Diagrams (BDD), Internal Block Diagrams (IBD), and hierarchical representations of the system. The robot architecture, showing the composition, the links, and the interactions between the components, is described within the IBD. Following the structural modeling, behavior diagrams and SysML state machines were developed to model the interactions between the various parts of the system, serving as the first step to analysis. Once behavioral diagrams were established, simulations were executed using MATLAB integration as a part of a Simulation Configuration Diagram, with Graphical User Interfaces (GUI) developed to provide user-friendly functionality. The behavior models described with SysML state-machines provide an understanding of battery usage and broader system performance. Vision 60 components including the control system, power supply system, movement system, communication system, and accessories are contained in this model.

3. Modeling the Vision 60 Q-UGV

3.1 Structure

The structural models of the Vision 60 were developed with Magic Systems of Systems – CATiA, employing a SysML modeling approach. The Vision 60 Q-UGV physical system consists of multiple components including a chasis, processor, legs, actuators and sensors. The block definition diagram provides a more specific visual representation of the physical system and the interactions between its components (Figure 2). Additional system attachments were modeled in the BDD but are not depicted in the figure below. These include an infra-red sensor, additional LED lights, a robotic arm, and weapons including a gun and taser. The block definition diagram establishes a baseline for the system's interactions and definition of relevant parts and parameters, while the internal block definition diagrams facilitate the integration of flows within the model.

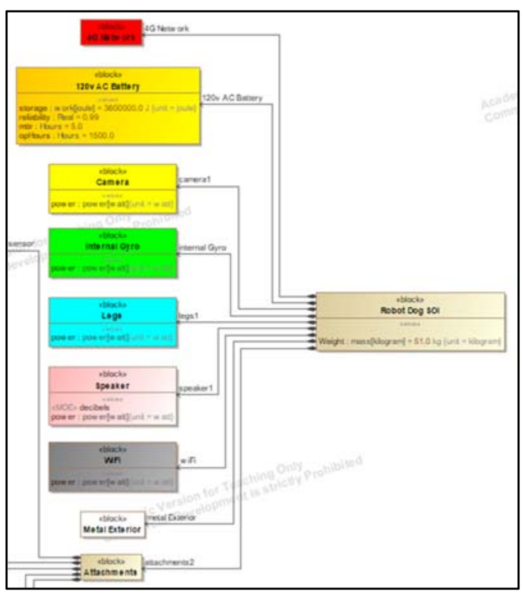

Figure 2. Block Definition Diagram of the Ghost Vision 60 Q-UGV.

The Vision 60 structure was further decomposed with internal block definition diagrams to facilitate the integration of flows within the model. These IBDs served as the foundation for establishing the behaviors required for simulation purposes. Through this approach, we were able to capture the complexity of the system and its interactions, allowing for a comprehensive analysis and evaluation of the model's performance. Moreover, the use of SysML modeling approach ensured that the model was accurately represented, minimizing any discrepancies and errors that may have arisen during the design phase.

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3.2 Behavior

After creating all the structural diagrams, we developed use cases based on documentation from the Air Forced Security Forces Center and conversations with the 10th Security Forces Squadron. Three specific use cases were identified for modeling in behavior diagrams: Patrol, Engagement, and Chemical, Biological, Radiological, Nuclear, and Explosive (CBRNE). These use cases were modeled as SysML behavior diagrams and they are briefly described below.

Patrol: When performing the patrol mission, the Vision 60 will autonomously follow a pre-mapped route along or within the base perimeter. This mission may require additional electro-optical sensors or other accessories. Operators will be able to monitor the robot while on patrol or receive updates from the robot when required.

Engagement: The engagement mission will occur when the robot interacts with an unknown human. In this use case, the Vision 60 will use features such as microphones, speakers, and cameras to communicate with any person of interest.

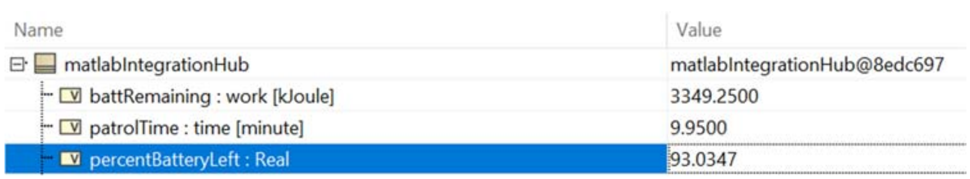
CBRNE: The Vision 60 Q-UGV will be used to sense and identify CBRNE threats. The robot will be equipped with sensors to detect any harmful agents and will be able to relay this information back to the security team.

3.3 Simulation

A mission profile of the Vision 60 was derived from the use cases described above and served as the starting point for a state machine used to simulate the robot's power usage. The output of this simulation is the percentage of battery remaining, the battery power remaining (joules), and mission duration. These results are achieved through an integration between CATiA and MATLAB. CATiA is used to set the robot configuration, mission profile, and power draw of the robot's components and MATLAB calculates the outputs based on the CATiA settings. Battery use data for the robot's subsystems was derived from existing code that is used to calculate a robot's battery life while in operation and through observations of battery percentage and voltage at 1 minute intervals over a 30 minute time period. The MATLAB equation is provided below:

$$[\text{Battery Capacity (Ah)}] / ([\text{Current (A)}] + [\text{Current Required by Each Subsystem (A)}]) * 3600 \quad (1)$$

Key features of the simulation include the ability to customize the distance to be travelled, configuration of the robot including robot weight and payload, as well as accessories including electro-optical sensors, robotic components, and weapons. In order to facilitate the use of our model by end-users, we developed a graphical user interface (GUI) that allows users to easily adjust the robot's configuration for the simulation. The estimate for walking 600 meters at a speed of 1 m/s with 0 kg weight provided the following output:



Name	Value
matlabIntegrationHub	matlabIntegrationHub@8edc697
battRemaining : work [kJoule]	3349.2500
patrolTime : time [minute]	9.9500
percentBatteryLeft : Real	93.0347

Figure 3. Simulation output for 600 m, 1 m/s, and 0 kg payload.

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3.4 Validation and Limitations

Validation of the Vision 60 power and battery consumption model was performed through operation of the robot on a closed course while monitoring power system status. The robot was operated on a 600 meter course in walk (1 m/s) and run mode (3 m/s) over several trials in which payload was varied between 0kg, 5kg, and 10kg to generate an approximate equation for battery drain. We compared the results of these trials to the simulation prediction and found values that closely approximated reality, with trial time differing by seconds and slightly more power used than predicted by the model. Further statistical analysis of the results is pending the collection of a larger data sample.

During some running trials we found that the robot would overheat before completion of the course, resulting in the robot slowing its movements to allow the system to cool down. This behavior has not been captured in the model and is something that must be considered in the mission profile. Furthermore, the model does not capture environmental conditions such as the type of surface being walked on, temperature, altitude, humidity, and incline. A more complete model will need to consider these variables in order to ensure an accurate estimate that can be used for mission planning purposes.

The Ghost Robotics user interface currently provides the operator with a battery remaining percentage and operation time estimate. This is essential information for the operators and ensures they do not run out of power, but these calculations are updated in real time based on changing configurations of the robot. The result is that operation time estimates can change by an hour or more simply by switching from walk to run mode. This makes our approach more useful for mission planning, while the data provided to the user while in operation is better suited for real-time decision making.

4. Discussion and Future Work

The development of a model-based systems engineering (MBSE) approach provides a powerful tool for analyzing and optimizing complex systems such as the Ghost Robotics Vision 60 Q-UGV. The ability to create and simulate models of the system enables us to predict power draw, analyze different subsystems, and identify potential areas for improvement. Through the integration of our CATiA model with MATLAB, we were able to simulate the Vision 60's power draw with various weights, speeds, and attachments. We also developed a user-friendly GUI, which allows users to interact with the model and input their own constraints and requirements. This tool aims to provide value for Security Forces units around the Air Force and to assist Ghost Robotics in predicting power (and other) requirements as they serve a variety of their customers. The model can also provide future customers with data-driven insights that can be used to make informed decisions about how best to use the Vision 60 in different capacities.

This initial step in modeling power consumption of the Vision 60 with limited payloads while walking or running served as a foundation for significant capability growth. Operators of this robot can greatly benefit from mission planning capabilities that consider the robot's range limitations over varying terrain. This can help with patrol missions where users may need to plan for multiple robot coverage and need to consider the capabilities of each individual robot including periods of operation and charging. It is also essential to understanding the power demands of other use cases like engagement with unknown persons and CBRNE. Future work on this project will focus on modeling the effects of environmental conditions as well as the variety of accessories that are currently compatible with the Vision 60. Research is also underway to model the impact of flexible behaviors that allow the robot to conserve energy or even recharge. The ultimate goal of this project is to allow the user to draw a robot's route with map software then receive power consumption estimates based on chosen robot configuration and local environmental conditions.

In conclusion, the integration of CATIA and MATLAB provides a powerful tool for predicting the power draw of the Ghost Robotics Vision 60 Q-UGV. More broadly, the use of MBSE demonstrates the potential for digital transformation within the DoD. By creating and analyzing models of complex systems, we can gain insights into their capabilities, identify potential issues, and optimize their performance. This approach can be applied to larger systems, such as the coming changes to nuclear capabilities and 6th generation fighters.

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