Unmanned Ground Vehicle Simulation with the Virtual Autonomous Navigation Environment

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***Abstract*— Unmanned and autonomous ground vehicles have the potential to revolutionize military and civilian navigation. Military vehicles, however, present unique challenges related to autonomous navigation that are not encountered in civilian applications. These include a high percentage of off-road navigation, navigation in hostile environments, navigation in GPS-denied environments, and navigation in urban environments where little data regarding road networks are available. These unique challenges require a deliberate approach for developing robust, reliable autonomous and unmanned systems that features extensive testing for performance and safety features in a wide variety of environments and conditions. In order to enable this approach, we have developed a computational tool for simulating and predicting the performance of unmanned and autonomous ground vehicles in realistic environmental conditions. This tool, the Virtual Autonomous Navigation Environment, will be discussed in this paper.**

***Keywords*— Autonomy, Unmanned Ground Vehicle, Simulation**

I. Introduction

This paper presents an overview of the Virtual Autonomous Navigation Environment (VANE), a simulation software for predicting the performance of unmanned and autonomous ground vehicles. The VANE integrates high-fidelity, physics-based sensor simulations with realistic vehicle dynamics and terrain and environment simulations to provide a complete picture of the factors influencing the performance of unmanned systems. While several robotics simulators exist, most lack the physics fidelity to accurately capture the influence of environmental conditions on the performance of the mobility platform (vehicle) and the sensors that enable autonomous operation. For this reason, simulation has typically been used only for early development and debugging in robotics applications. However, for robotics to gain widespread use and acceptance in military operations, simulation must be used throughout the process of design, development, testing, and deployment of the robotic system. This paper will show how the VANE is being used to enable this process with physics-based simulation.

II. Background

Modeling and simulation (MS) of off-road ground vehicle mobility has long been used to support the design, development, testing, and deployment of military ground vehicles. While the earliest tools used field-tested vehicle performance metrics to determine operational mobility [1], later tools developed simulation of vehicle performance that could be used as input into these analyses [2]. The utility of these MS tools for predicting the off-road mobility performance of *manned* ground vehicles is evidenced by their continued use over several decades. In particular, the capability of these models to predict soft soil performance [3],[4] provides a unique and necessary capability for military ground vehicles. Despite this apparent utility, these and other tools fail to adequately predict the performance of *unmanned* ground vehicles. This is because the limiting factor for the performance of autonomous systems is typically not the dynamic capability or off-road mobility of the platform, but rather the sensing used by the autonomy system and the algorithms employed to process the sensor data. In order to address this shortcoming in existing mobility models, a simulator that accurately captures the influence of sensors and the environment on robotic performance is needed.

There have been several simulation tools developed for robotics in the last decade. Foremost among these are USARSIM [5],[6] and Gazebo [7]. A 2009 review designated these tools “Robotic Development Environments,” or RDE [8]. This naming convention is appropriate, because these tools are designed with the robotic developer as the primary user and have several features that make them convenient tools for robotic developers. In particular, Gazebo’s integration with the Robotic Operating System (ROS) provides a convenient environment for the rapid development and prototyping of robotic systems.

More recently the Autonomous Navigation Virtual Environment Laboratory (ANVEL) [9] has been gaining popularity among developers of military ground robotics because of its ease of installation and use, open architecture, and features for creating highly detailed digital terrains. In order to be most useful for robotics developers, these tools all simulate the robot in *real-time*, enabling integrated hardware-in-the-loop simulations (HITL) for developing robotic systems. However, this real-time simulation comes at a cost; namely, it limits the fidelity, physics, and realism of the sensor, vehicle, and environment simulations. While this lack of realism is typically not a concern for robotic developers, realism and model validity is of primary importance for testers and evaluators of robotic capability.

In order to meet the needs of the test and evaluation (T&E) community for robotics, a different approach is needed. The VANE does not require real-time simulation - instead, the VANE uses the most realistic physics simulations for the physical processes impacting the robot, ensuring that the simulation is both realistic and predictive. The following sections briefly introduce the VANE and the simulation approaches used for all of the subsystems simulated by the VANE.

III. VANE Overview

Development of the VANE began in 2008 with an initial focus on the utilization of high-performance computing (HPC) [10]. The first four years concluded with an initial implementation of an integrated simulation vehicle dynamics, mobility, terrain, and sensors [11]. Since that time, additional capability has been added to the VANE to include the influence of weather and to add new terrains and terrain features to the simulation. The following few sections give some details about the models comprising the VANE.

A. Sensors

Sensors are simulated in VANE with a computationally parallelized physics-based ray-tracer [12]. The ray-tracer is fully spectral, with user defined spectral bands. The ray-tracer is used by a variety of sensor types to query the digital terrain, which will be discussed in Section III-B.

1) GPS and Inertial Sensors: Localization and inertial sensors are some of the most important for ground robotics. These include GPS sensors and accelerometers. GPS sensors in VANE are simulated using ray-tracing to determine the location of each GPS satellite and if it is blocked or in view. Multi-path signals are also calculated for each satellite using the ray-tracer. This introduces errors frequently called GPS "pop," which can appear as a sharp change in the position reported by the GPS. Additionally, atmospheric errors caused by the ionosphere and troposphere are simulated. Finally, the ranges simulated by the ray-tracer are input into a trilateration algorithm to calculate position. This method reproduces all the important sources of error in GPS, resulting in a realistic error distribution compared to random noise or other error models.

The accelerometer model takes accelerations calculated by the vehicle dynamics module as input and applies error functions to simulate the "measured" acceleration. The errors include accelerometer drift and bias. More technical details about the error functions for both the IMU and GPS function are given in [13].

2) LIDAR: The VANE LIDAR model uses ray-tracing to simulate each laser pulse. Errors are introduced in real LIDAR measurements due to the finite size of the beam, resulting in edge effects, mixed pixels, and inaccurate distance returns from surfaces at oblique angles such as road surfaces. The VANE simulates these effects by using a diverging bundle of rays to a capture the important properties of the beam [14]. The LIDAR model accepts the beam divergence properties, scan pattern, laser wavelength, and timing parameters as input. An example of a LIDAR point cloud generated in the VANE is shown in Figure 1.

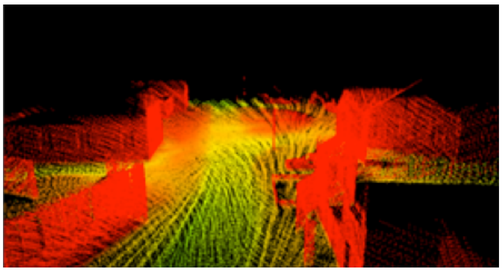

Fig. 1. A LIDAR point cloud generated by a VANE simulation.

3) Camera: The VANE camera model also uses high-fidelity ray-tracing to generate photo-realistic synthetic imagery. One important source of error in camera simulations is lens distortion and blur. VANE implements lens distortion by using camera model parameters that can easily be measured with the MATLAB camera calibration toolbox [15]. Additionally, the VANE camera model implements blur by oversampling each pixel according to the relative motion between the camera and the scene and taking into account the shutter speed of the camera. The VANE also allows the user to define camera parameters such as the gain and range compression factor. An example of the quality of the camera model is shown in Figures 2 and 3, which compare a real digital image and a camera simulation from the VANE.

Fig. 2. A reference image for a VANE simulation taken with a Sony XCD camera.

Fig. 3. Simulated image from the VANE for comparison to Figure 2

B. Environment

The geometry of the environment in VANE is represented as triangular meshes and material files defining the properties of each triangle. Additional atmospheric and environmental properties can be defined by the user. Since VANE leverages HPC assets, very large and detailed environments like the one shown in Figure 4 can be simulated. Additionally, dynamic actors and animations like humans and vehicles be scripted as input into the VANE in order to predict how the robot will respond to their behavior.

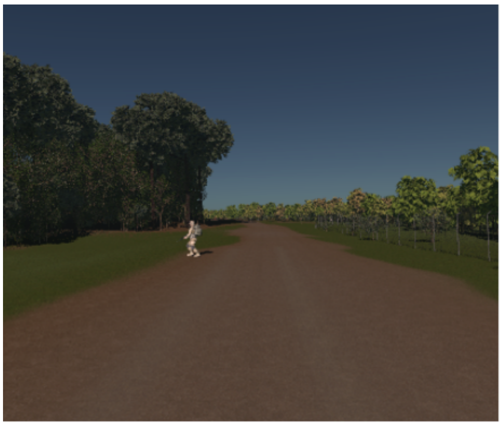

Fig. 4. Example of a highly detailed scene for robotics simulation enabled by VANE's use of HPC.

1) Reflectance Modeling: VANE uses detailed and realistic material models to predict the reflectance properties of materials. Material properties are measured with a spectrometer such as the ASD Handheld or similar device, and reflectance spectra are encoded in the material file for each triangle. Additionally, the parameters for the bidirectional reflectance distribution function (BRDF) are encoded in the material file. There are two BRDF models available in VANE. For visible band images and LIDAR, VANE uses the cosine lobe model [16], [17] to calculate the diffuse and specular reflectance components.

Fully spectral reflectance and polarization is calculated with the He-Torrance model for polarized reflectance [18], [19]. This model uses the surface roughness properties and the index of refraction to calculate the specular and diffuse reflectance and the polarization of the reflected light. In addition, the VANE employs a realistic reflectance model for water surfaces that uses Fresnel theory to reproduce the unique angular reflectance properties associated with water surfaces, as shown in Figure 5.

2) Weather and Dust: Snow and dust are simulated in VANE using a particle system, while rain is simulated using a random mask generator [20]. Both methods interact with the ray-tracer using physics-based models, resulting in realistic signatures for both the camera and LIDAR sensors. An example of rain being simulated in VANE is shown in Figure 6.

For LIDAR sensors, predicting the influence of dust and smoke is somewhat more complex that simply rendering the color. This is because the LIDAR acts as both the source and receiver, and the two-way radiative transfer must be calculated. The VANE employs an empirical model, based on field and laboratory measurements, for calculating the probability of LIDAR return from dust [21]. An example of a simulated dust cloud in VANE is shown in Figure 7.

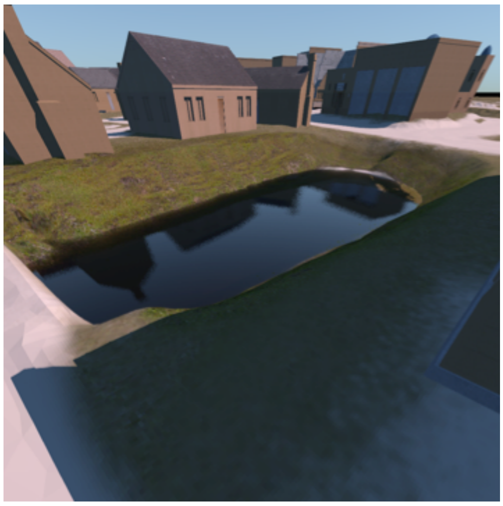

Fig. 5. Example of reflection from water surface simulated in VANE.

Fig. 6. Simulation of rain in VANE.

Fig. 7. Simulation of vehicle generated dust in VANE.

3) Atmosphere: The propagation of light through the atmosphere is an important aspect of simulating both LIDAR and cameras. VANE uses two models to simulate atmospheric properties. For the visible and near-infrared (NIR) band, VANE uses the Hosek-Wilkie sky model [22], a physics-based radiative transfer model that accounts for aerosol and water vapor content to produce realistic reddening and haze. These conditions are user-definable in VANE. For infrared wavelengths the VANE uses the National Renewable Energy Laboratory implementation of the Bird solar spectral model [23] to calculate the direct and diffuse downwelling irradiance on the simulated scene. An example of hazy atmosphere simulated with the Hosek-Wilkie model is shown in Figure 8.

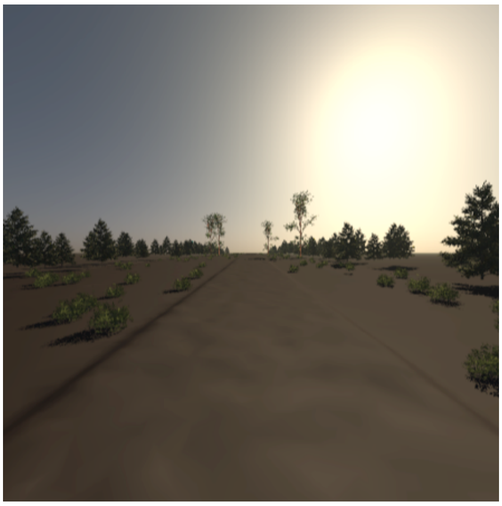

Fig. 8. A hazy atmosphere simulated in the VANE.

C. Vehicle

Vehicles are simulated in VANE using the Computational Research and Engineering Acquisition Tools and Environment - Ground Vehicles (CREATE^{TM}-GV) software. CREATE^{TM}-GV is one of several codes developed by the US Department of Defense High Performance Computing Modernization Program under the CREATE^{TM} program, which includes ships, air vehicles, and meshing, in addition to ground vehicles [24].

CREATE^{TM}-GV uses the Chrono multi-body dynamics engine to simulate vehicle dynamics [25], the Powertrain Analysis and Computational Environment (PACE) [26] to simulate the powertrain, and the Ground Contact Element (GCE) implementation of vehicle-terrain interaction (VTI) algorithms [3] for tire-soil or track-soil interaction. These cutting edge models utilize the best available government owned software for simulating vehicle mobility performance. An example of a Chrono simulation is shown in Figure 9.

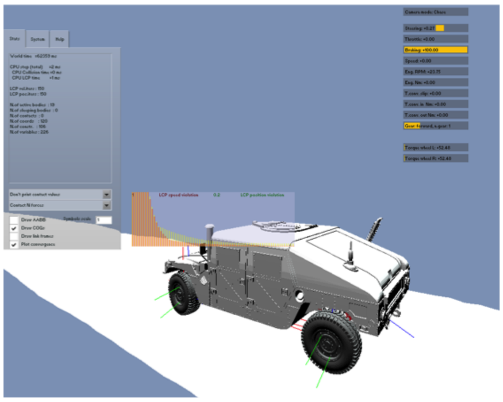

Fig. 9. Example of a ground vehicle simulation in CREATE^{TM}-GV

IV. Example Analyses

The VANE has been used to support several interesting analyses in the last few years. One interesting application for autonomous unmanned ground vehicles (AUGV) is reconnaissance in urban environments. Urban environments present several challenges to AUGV including intermittent GPS dropout, short line-of-sight, and the presence of traffic and other dynamic obstacles. The VANE was used in 2011 to conduct a simulation of a wheeled AUGV performing reconnaissance in an urban environment [27] using only GPS, accelerometers, and LIDAR sensors for navigation. Additionally, the VANE was used to predict the frequency and severity of GPS dropout caused by "urban canyons" in urban environments [28]. Figure 10 shows an example urban reconnaissance simulation conducted in the VANE. The Figure shows the VANE simulation being replayed in the ANVEL software, highlighting the capability of these two tools to share data. In particular, ANVEL can be used to interactively setup and replay VANE simulations.

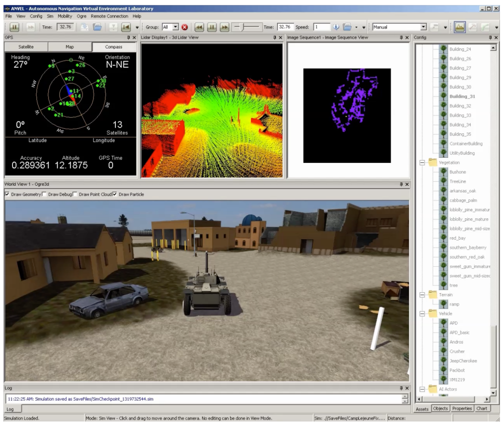

Fig. 10. VANE simulation of reconnaissance by an AUGV being replayed in ANVEL. The top left window is a replay of the simulated GPS, the top middle is a replay of the simulated LIDAR, and the top right is a drawing of the map being generated by the autonomous system.

More recently, VANE has been used for a variety of other interesting applications, including using VANE to train image processing algorithms with simulated data [29]. In that study, the VANE was used to simulate a 5 band multi-spectral imaging system in the visible to NIR wavelength bands. This work highlighted some of the physics features of the VANE that cannot be reproduced by Gazebo and USARSIM - in particular fully spectral ray-tracer for simulating cameras with unique filtering.

One of the more unique simulated experiments using VANE was a study of the effectiveness of biological algorithms in controlling groups of AUGV [30]. The work implemented algorithms that were developed by studying the movement and interaction of fish [31] on a group of AUGV and studied the coordination of the group as it responded to a disturbance.

The VANE was also recently used to evaluate the effectiveness of NIR camera systems in detecting a lead vehicle with an emitting "fiducial" marker on the rear bumper [32], as shown in Figure 11. The simulations employed a variety of terrains and environmental conditions to evaluate the effectiveness of this sensing system in all conditions, highlighting the need for a physics-based simulator in T&E activities. It will always be difficult to physically test the wide range of physical conditions and terrains that will be encountered in operational simulation. By using a physics-based simulation like the VANE, field testing can be augmented with many more environmental conditions than would be possible without simulation.

Fig. 11. VANE simulation to detect fiducial marker on rear bumper or AUGV.

V. Conclusion

This paper has presented an overview of the physics-based models that comprise the VANE, including the sensor, vehicle, and environment simulation models. Additionally, several recent applications of the VANE to real-world problems such as urban navigation, coordination of teams of AUGV, and sensor performance prediction were shown. Thes examples demonstrated the necessity of physics-based approaches for supporting the T&E of AUGV as a complement to real-time simulators aimed at the robotic development process.

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