1. Introduction

1.1. Autonomous Vehicles

Transportation has played an important role in the human history, evolving from the invention of the rotary wheel to the modern road cars. The invention of fuel engines in the last century marked a significant revolution, impacting faster goods transportation and extending to civilian life with the introduction of road cars. This period also witnessed the development of proper road infrastructures to accommodate the advancements in vehicle performance.

The fourth industrial revolution mark a start of new era where intelligent systems-controlled machines are developed which reduces the manual errors and enhancing performance. The automotive industry is also undergone this transformation with various intelligent driver assistance systems like Advanced Driver Assistance Systems (ADAS) which not only reducing human effort in driving but also ensuring safety. Engineers and scientists globally are working to enhance the capabilities of intelligent systems, aiming for complete autonomous driving, eliminating the need for human guidance.

The concept of autonomous driving dates back to 1926, with the development of a radio-controlled car in New York City. In 1960s, the Transport and Road Research Laboratory in the United Kingdom laid magnetic cables beneath the road, serving as a path detection tool for self-driving cars and tested its performance. Later, in 1995 Mercedes Benz achieved a significant milestone with the development of first self-sufficient autonomous vehicle, a retrofitted Mercedes S class equipped with efficient cameras and exclusive processors for parallel computing. This vehicle reached a maximum speed of 175 kmph, covering 1500 kms from Munich, Germany, to Copenhagen, Denmark, performing various manoeuvres in traffic without human assistance. In the late 2000s, carmakers like Toyota and Volvo, along with tech companies such as Google and Waymo, developed their prototypes of Autonomous Vehicles (AVs).

The parallel advancements in the field of Artificial Intelligence and efficient hardware accelerated research in self-driving technology. Notably, improvements in cameras and GPUs facilitated fast and efficient processing, while intelligent algorithms like neural networks laid the foundation for Autonomous Vehicles (AVs). In 2014, Tesla Motors launched Model S, a semi-autonomous driving car. This vehicle featured a various assistance feature, including lane detection, autonomous braking and parking, and speed limit recognition using computer vision. Tesla's entry into functional semi-autonomous driving represented a notable advancement in the field. During the same year, the Society of Automotive Engineers (SAE) had drafted a 6-level taxonomy for autonomous driving. This framework provided a standardized and structured classification system for assessing the level of autonomy in vehicles. Recognizing the growing impact of autonomous driving, several countries, including the United States of America, the United Kingdom, and Japan, made decisions to formulate laws addressing autonomous driving in the next few years. Various leading car manufacturers, including Mercedes Benz, BMW, and Volvo, have introduced their commercial fully or semi-autonomous production vehicles. They are continually enhancing their automation levels, as classified by the Society of Automotive Engineers (SAE). For instance, in 2022, Mercedes Benz achieved SAE Level 3 automation with its S-Class and EQS models, equipped with advanced driving technologies like an automated lane-keeping system. However, Tesla Motors has been a leader in this field, showcasing superior performance.

The SAE J3016 classifies autonomous vehicles into six levels, ranging from fully manual driving to fully automated systems [1].

|  |  |  |
| --- | --- | --- |
| Level 0 | No driving automation | This level involves no driving assistance system, and the entire driving process is manually controlled. |
| Level 1 | Driver assistance | Vehicles at this level feature a single automated system under the driver's supervision. |
| Level 2 | Partial driving automation | Multiple automated systems, such as automated steering and braking, work simultaneously under the driver's attention. The driver must be ready to take control at any moment. |
| Level 3 | Conditional driving automation | This level involves a system with an intelligent algorithm capable of making decisions like overtaking navigation. However, human attention is still required. |
| Level 4 | High driving automation | At this level, the vehicle can make optimistic decisions in the event of a failure, reducing the need for human interaction. This level is often suitable for confined areas or regions |
| Level 5 | Full driving automation | Here, the vehicle can perform all driving tasks without human interaction, comparable to an experienced human driver. |

Table1: Levels of driving automation defined in SAE J3016

Driverless vehicles find applications not only in passenger cars but also across various areas like shuttling people on campuses, moving goods in warehouses, and in military operations. Especially in industries, these automated machines could transport goods across the premises which save time and minimize human error. However, ensuring their safety of operation is crucial especially when it comes to road cars. Governments worldwide are creating regulations for autonomous mobility. Moreover, vehicle manufacturers are enhancing hardware and software while conducting extensive testing to ensure safety and prevent failures.

1.2. Simulators

Simulators imitate real-world systems, replicating their dynamics and features. They come in different types: software, hardware, or a mix of both. These systems replicate various functions, interacting with users, taking inputs, and providing feedback to the users. For example, driving simulators create visual environments and hardware setup for driver training and testing, Which takes control commands from users and update their states. Simulators can be classified based on various features Some of the examples are

Based on Time

Discrete Event Simulation: Each step happens at distinct intervals, which are mapped to specific durations. Driving simulators fall into this category, where observation states change at each step. The time duration of a single time step is defined by required precision.

Continuous Simulation: In this type of simulation, time moves continuously without distinct steps, backed by differential equations. These are useful for modelling continuous events like microbe growth in biology.

Based on Stochasticity:

Stochastic Simulation: This type of simulation introduces a controlled amount of randomness within sensible limits in the parameters. It's helpful for studying systems with random noise, like analysing daily usage patterns on a social media site.

Deterministic Simulation: These systems operate using deterministic algorithms without any randomness. They're commonly applied in engineering. The outcomes of these simulations remain consistent and reproducible for a specific set of parameters.

Users can tweak these parameters to test and tune the results of the system. Usually, simulations help to find the optimal parameters and it have diverse applications, for events spanning millions of years to nanoseconds. Simulations play a vital role in result analysis, safety engineering, and design processes. They save significant time during testing and can enhance the testing outcomes. For instance, testing the driving of an autonomous car for 10,000 km in the real world demands a lot of time and resources, whereas using a simulator significantly reduces this timeframe. However, there's often a discrepancy between the real world and simulations, which might lead to errors in analysis. In fields like machine learning and robotics, it contributes a crucial role. One of the three paradigm of Machine learning is reinforcement learning where a virtual agent within a simulator takes diverse actions under various conditions and learns from the feedback provided. In robotics, algorithm which drives the robots are trained using simulation for tasks like localization, pick and place, faulty detection…

1.3 Problem Statement

1.3.1 Lack of system of comparison

In the growing domain of autonomous vehicle research, simulator plays a significant role in the process of development such as algorithm training, performance evaluation across diverse environments and comparison of method. There are numerous simulators, varying in types and functionalities, available in the community for direct or indirect use in research works. In addition, the domain of self-driving vehicle research itself is broad, includes distinct applications such as indoor robots, industrial autonomous vehicles (AVs), on-road vehicles, and semi-autonomous vehicles. Each application requires a unique simulator tailored to its specific requirements.

The challenge arises due to the diversity among these simulators and their requirements, each comes with its own set of advantages, features, and limitations. Consequently, comparing and selecting the most suitable simulator becomes a complex task. For instance, a simulator might perform well in numerous aspects, yet fail to simulate a crucial sensor required by a user, making it unsuitable for that specific application. Conversely, another simulator might lack certain features but could be better suited for the user.

The aim of this thesis is to establish a concrete set of metrics for comparison purposes. The proposed metric will be generic and adaptable to individual user preferences. Users will have the flexibility to adjust the importance of criteria based on their requirements and they are universally applicable across all types of autonomous vehicle simulators. Through this systematic approach, users could able to assign personalized ratings to simulators, facilitating informed decision-making in selecting the most suitable simulator according to their preferences and needs.

1.3.2 Simulators Based on Generative AI

Generative AI had gained momentum in recent years, continuously improving its performance. This field primarily uses deep neural networks, trained on any provided data, learning its distribution. These trained models can generate novel, meaningful data samples which are not present in the training set but similar to it.

In the domain of autonomous vehicle simulators, rendering new scenarios and environments is a one of its objectives. This feature enhances its suitability for algorithm testing across diverse environments, potentially improving the model’s performance. It’s also important that these new scenarios closely resemble real-world features while being meaningful and plausible.

Sensors in Autonomous cars play a important role in understanding the real world where the vehicle navigates. These vehicles utilize data from various of sensors such as cameras, LiDAR, and radar to perceive their surroundings. The second part of this thesis aims to design and develop a simulator driven by a Generative AI model trained on real-world sensory data. The expected outcome is the generation of new, meaningful sensory data can effectively represent diverse and realistic environments. The simulator will operate on discrete time steps, ensuring that the generated data remains relative to preceding time steps.

2. Literature Review

This chapter explores different works related to the topic. The initial section examines the existing state-of-the-art autonomous vehicle simulators. The second part provides a summary of previous methodologies used to define a comparative metric for evaluating autonomous vehicle simulators. The last part of this chapter discusses about the different types of Generative Adversarial networks (GANs), a type of Generative AI algorithm utilized in this thesis.

2.1 State-of-the-Art Simulators

Numerous simulators are available in the market, but this section analyse some relevant and popular simulators and highlighting their advantages, limitations and applications.

2.1.1 CARLA

CARLA, (Car Learning to Act) is an open-source software developed collaboratively by the Computer Vision Centre (CVC) and the Barcelona Supercomputing Centre (BSC) in partnership with the Toyota Research Institute. It is primarily designed for autonomous driving research and development, which features diverse and realistic environments, various climates and wide range of sensors. CARLA operates on a server-client architecture, built on Unreal Engine 4 and utilizing the OpenDRIVE standard 1.4 to define roads and urban settings. This unique structure allows the server to manage physics of simulator and computation while enabling user to communicate the server through C++ and Python APIs, providing scalability.

A notable feature of CARLA is its seamless support for developing, training, and validating machine learning algorithms. Researchers had experimented various algorithms like modular pipelines, imitation learning, and reinforcement learning within this simulator [2]. Leveraging Unreal Engine 4, CARLA offers high-quality, realistic rendering of environments. Figure 1 showcases scenes from the simulator in different weather conditions. Additionally, it supports an array of built in sensors such as camera, LiDAR and provides the user with various metadata, and ground truth. Moreover, CARLA offers access to diverse digital assets (actors, buildings) within the environment, meticulously designed to maintain a high level of realism [2]. However, it currently offers support for only two pre-defined urban maps covering 2.9 km and 1.4 km, which limits its diversity and generalization capabilities.

Figure1: Scenes from the CARLA simulator in different weather conditions.

2.1.2 LGVSL

LG Silicon Valley Lab (LGSVL) is an open-source simulation engine developed by LG Electronics. It utilizes the Unity gaming engine to render photorealistic environments and taking advantage of technologies like the High-Definition Render Pipeline (HDRP) from Unity.

This simulator is developed in two parts: the Simulation Engine and the User Autonomous Driving (AD) Stack [3]. The Simulation Engine, a customizable open-source platform, receiving its inputs from AD stack and simulate the environment, sensors, and vehicle dynamics. The AD Stack comprises three major layers: Perception, Planning, and Control, offering various user-configurable functionalities. The AD Stack and the Simulation Engine is connected through communication bridge interface, such as Cyber RT, ensuring seamless integration [3]. While the simulator comes with various default sensors including cameras, LiDAR, and Radar, its unique feature lies in its adaptability. Users can build and configure their own sensors and importing models of real-world sensors as plugins. For instance, the plugin for Velodyne VLP-16 LiDAR replicates point cloud generation similar to its actual counterpart [3]. These sensors' data and its mounting positions are defined through JSON-formatted text, simplifying their utilization. Figure 2 showcases the array of default sensors available within this simulator.

Figure 2: Different types of sensors. Left (top to bottom): Fish-eye camera,LiDAR, Radar; Right (top to bottom): Segmentation, Depth, 3D Bounding Box.

A distinguishing aspect of this simulator is its capability to incorporate real-world maps to construct virtual environments within the simulator. Map formats like Lanelet2, OpenDRIVE, and Apollo 2 HD map can be imported and used as the virtual environment. This features of LGSVL appeals to engineers of automakers and making it a highly suitable tool for their research.

2.1.3 SUMMIT

SUMMIT (The Simulator for Urban Driving in Massive Mixed Traffic) is an open-source simulator developed as an extension of the CARLA simulator [2], inheriting its physics and visual realism. Unlike many other simulators that predominantly which simulate rule-based traffic with minimal randomness, SUMMIT stands out for its ability to replicate the aggressive and chaotic nature of real-world traffic. This distinctive feature attracts users interested in training and testing algorithms for vehicles navigating unregulated traffic scenarios. SUMMIT employs the 'Context-GAMMA', a velocity-space optimization crowd behaviour algorithm [4] to simulate traffic behaviour geometrically and topologically. Additionally, it utilizes real-world maps from OpenStreetMap, extracting features such as roads, sidewalks, and roundabouts which are incorporated into the simulator, enabling the replication of real-world maps. An illustrative example can be seen in Figure 3, which showcases the comparison between a real map and its counterpart with unregulated traffic behaviour in SUMMIT at the Magic Roundabout in England.

Figure3: Scenes in the real world and corresponding scenes in SUMMIT

SUMMIT's utilization of real-world maps, combined with CARLA's visual realism and the simulation of chaotic traffic behaviour, significantly enhances its capabilities and making is a best option for inroad commercial autonomous vehicles research.

2.2 Comparative Study on Simulators

This section examines notable studies that compare existing autonomous vehicle simulators and summarizes their approach and results.

In Guan Yang et al. work (2021), "Survey on Autonomous Vehicle Simulation Platforms," [5] the team extensively researched different autonomous vehicle simulation platforms. The objective of a simulator is broken down into five parts: Static environment simulation, Dynamic environment and behaviour simulation, Traffic flow simulation, Sensor simulation, and Vehicle dynamics simulation. They also established a taxonomy for existing simulators, categorizing them into Point Cloud-based and 3D Engine-based platforms. Point-based simulators, such as CarCraft from Waymo and Apollo from Baidu, reconstruct the environment based on simulated sensor data. Figure 4 displays the map from Apollo, a point-based simulation platform. On other hand, 3D engine-based platforms, like PanoSim, utilize gaming engines like Unity and Unreal to render environments following laws of physics (Figure 5).

Figure 4: Scene from Apollo simulator

Figure 5: Scene from PanoSim simulator

They further created a table comparing some of popular and relevant simulation platforms and their features [5] (Figure 6).

Figure 6: A Comparison table of various simulator

Although this table aids in comparing simulators roughly, it doesn’t compare sufficient features for making a concrete decision, and lacks a single metric defining the level of usability of the simulator for a user. While the categorization of simulators is provided, a clear comparative method among simulators is not clearly defined.

In Md Salman Ahmed et al.'s work (2016), an extensive study on connected vehicle simulators was presented [6]. The focus was on the domain of connected vehicles, including vehicle-to-vehicle and vehicle-to-server communication. The paper assessed several simulators based on their memory consumption, computing environment (Sequential or Parallel), and the number of vehicles they could handle. However, these results are specific to the connected vehicle domain and may not be applicable to other types of autonomous vehicle simulators effectively.

2.3 Generative Adversarial Networks

Generative adversarial networks (GAN) mark a significant advancement in the domain of Generative AI, first introduced in 2014 by Goodfellow et al. in the paper "Generative Adversarial Networks" [7]. Since then, GANs have gained substantial momentum in the field of Generative AI especially in image generation. This section discusses some noteworthy works within the domain of GANs.

2.3.1 VGAN (Video Generative Adversarial Network)

VGAN, developed by Carl Vondrick et al. [8], specializes in generating videos with its scene dynamics. The model is capable of generating videos up to a second at full frame rate. Its training involves over 2 million pre-processed videos sourced from the internet, categorized into four distinct groups: golf courses, hospital rooms, beaches, and train stations.

The architecture of VGAN employs a standard Generator-Discriminator structure. The generated video is segmented into two features: foreground and background, assuming a fixed camera resulting in a static background. The generator comprises two network streams dedicated to foreground and background, respectively. The foreground stream consists five layers of 3D spatiotemporal convolution layers (time x width x height), which upsamples the information from a low-dimensional latent code z, sampled from a standard normal distribution. A masking layer 'm' is introduced before the final layer, outlining the pixels of objects in the foreground. Meanwhile, the background stream utilizes five layers of 2D convolution layers (width x height), responsible for generating a background 'b'. The background stream uses 2D convolution layers as the background is assumed to be same for all the generated frames. The synthesis of foreground and background follows the equation

m@f+(1-m)@b

The resultant video, comprising 32 frames with dimensions of 64x64, is generated from a 100-dimensional latent code sampled from a normal distribution. The Discriminator is designed for two primary objectives: classifying realistic scenes and recognizing plausible and smooth motion between frames. It mirrors the architecture of the foreground stream of generator with a five-layered spatiotemporal convolutional setup, employing downsampling instead of upsampling. The final layer outputs a binary classification (real or not). Batch normalization and ReLU activation functions are used after every layer in both the generator and discriminator.

The VGAN is trained using Adam optimizer with a batch size of 64. Results demonstrate the model's ability to generate videos with a sharp background and a slightly blurry foreground. While the resolution of the foreground might be blurred, the motion of the generated foreground are convincing. However, the user had no control over the content of generation. Figure 7 illustrated the frames of various generated videos.

Figure 7: Videos generated using VGAN

2.3.2 ImaGINator

ImaGINator is a conditional Generative Adversarial Network (GAN) developed by Yaohui Wang et al [9]. Its primary aim is to produce human videos depicting various expressions. Unlike VGAN [8], this model generates videos conditioned on specific class labels for expressions for example smiling, jogging... The model is designed to segment the generated video into spatial and temporal parts.

ImaGINator comprises a generator and two discriminators. The generator adopts an encoder-decoder architecture with skip connections. It takes a static image featuring a person's face as input and encodes it into a latent vector 'p'. In addition, this vector is concatenated with one-hot encoded class label c, representing the expression, and random noise sampled from a standard normal distribution. This fusion embeds spatial (p) and temporal information (c) into the latent vector. The decoder, structured as a (1+2)D convolution layer, explicitly separates temporal and spatial information. It mirrors the dimensions of the encoder's architecture and had skip connections from encoder, ensuring that each decoder layer retains embedded spatial details from the corresponding encoder layer. Moreover, the embedded class label vector is integrated into every decoder layer, ensuring the preservation of temporal information throughout the model. The generated video consists of a fixed number of frames and the last layer of the generator outputs an image with all the frames.

Two discriminators serve distinct purposes: 'Di' evaluates individual frames of the generated video to classify real from fake based on appearance, while 'Dv' examines the sequence of frames alongside the class label to classify the dynamics within the frames as real or fake. The Generator is optimized on the combined loss function from both discriminators and a reconstruction loss for corresponding frames. Each discriminator's loss function optimizes the weights of corresponding discriminator. The ADAM optimizer with the same learning rate is used across all generator and discriminator components.

Evaluation metrics such as Frechet Inception Distance (FID), Peak Signal-to-Noise Ratio (PSNR), and Structural Similarity Index Measure are used to evaluate the performance of the generated videos and to monitor the training progress. Figure 8 provides a visual representation of the frames within the generated video.

Figure 8: Frames of the video generated using ImaGINator

The model was trained on various widely used datasets like MUG Facial Expression Dataset [13], NATOPS Aircraft Handling Signal Dataset [14], Weizmann Action Dataset [15], and UvA-NEMO Smile Dataset [16]. Comparative analysis shows the superior image quality compared to VGAN. Furthermore, the model's ability to control the content of generated videos using class labels holds significant potential across various applications.

2.3.3 MoCoGAN

Motion and content decomposed GAN (MoCOGAN), a Video Generation GAN introduced by Sergey Tulyakov et al. in 2016 [10], operates on a unique architecture that segments videos into Content and Motion. This segmentation allows the model to sample inputs separately from the Content and Motion subspaces (unsupervised). Notably, this architecture enables the model to generate videos depicting the same content with different actions or the same action with different content. While designed for shorter video durations, MoCOGAN doesn't require a fixed length for the generated videos. Given the shorter duration, the video's subject is assumed to remain constant.

The model comprises four networks: a Recurrent Neural Network (Rm), Generator (G1), Image Discriminator (Di), and Video Discriminator (Dv). The Generator sequentially produces frames by taking a latent image Z as input, containing zc and zm. The random vector zc represents the video's content and is sampled from a content subspace, remaining constant throughout the video as the subject remains unchanged. On the other hand, the latent vector Zm, which determines the motion trajectory of the subject, and it is recursively outputted by Rm by sampling from a motion subspace at each timestep.

The Rm's parameters are learned during training, as not all motion trajectories are physically possible. The generator G takes Z (combination of Zc and Zm) and generates video frames sequentially. The Image Discriminator assesses frame quality, while the Video Discriminator evaluates subject motion in the video. The RNN is trained exclusively on the Video Discriminator loss, while the entire Generator network is trained on the combined loss of the discriminators.

The model's training utilizes the Weizmann Dataset [15] and Tai-Chi Dataset [17], and its performance was assessed using the Average Content Distance (ACD). Visual representations in Figure 9 depict video clip frames generated by the MoCoGAN model.

Figure 9: Frames of video generated by MoCoGAN

Notably, MoCoGAN had outperformed VGAN [8] and TGAN in image quality within the videos and offers the flexibility of generating videos of varying lengths. However, it lacks direct control over content creation like ImaGINator as content is randomly sampled from the content subspace

2.3.4 Pix2pix GAN

Pix2Pix, introduced in 2016 by Philip Isola et al [11], is an image translation technique using Conditional GANs. Image translation involves transforming images from one domain to another, such as converting grayscale images to colour images. In [12], the method was applied to translate satellite terrain images into Google Maps style images.

The structure of the conditional GAN resembles that of a Normal GAN, comprising a Generator and a Discriminator. In [12], the generator adopts an encoder-decoder architecture, where the encoder consisting of blocks that include a convolution layer, Batch Normalization, and ReLU activation function. The decoder mirrors the encoder, employing skip connections (known as U-Nets) between corresponding layers to retain information and prevent loss during transmission through bottle necks [11]. The Generator takes an image from the input domain and produces an image in the target domain. On the other hand, the Discriminator intakes the paired images from both domains, uses standard convolutional layers, converging in a final layer that determines the given image (real or fake). Using PatchGAN, the Discriminator segments images into 70x70 patches and performs binary classification for each patch, this makes the discriminator suitable for any given image size.

Training involves computing the reconstruction loss between the generated image and the target image. The generator's gradients are optimized to minimize this loss. The composed model training combines the Discriminator loss and the reconstruction loss using a weighted sum for gradient update. The dataset used for training, consisting of 1097 paired images of satellite and Google Maps images. Each image is pre-processed and rescaled to 256X256 pixels before training. Figure 10 illustrates the satellite images and its corresponding google map image and generated image.

Figure 10: The satellite images and its corresponding google map image and generated image after 10 epochs

While image translation using this method has diverse applications, this method often requires paired datasets, which is difficult to obtain in most of the cases.

3. Framework for Comparative Study

The suitability of an autonomous vehicle simulator for a particular user varies significantly based on several factors. These factors include various aspects such as the intended application, sensor support availability, integration of real-world components like vehicles and maps, computational resources... Within this proposed method 73 such parameters are identified and these parameters collectively contribute to formulate a single score for each simulator. This score serves as a means for comparison between different simulators.

3.1 Comparison Parameters

The identified parameters are categorized into six broad classifications: Sensors, Actors, Environment, Vehicle, Framework, and Algorithm. Each parameter is evaluated using a scoring system ranging from 0 to 1 where 0 being worse and 1 is best. In cases of binary classification, where a feature's availability is assessed, the corresponding parameter receives a score of 0 if the feature is unavailable and 1 if it is available.

3.1.1 Sensors

Sensors serve as the tool to perceive the vehicle's surrounding environment. They play a crucial role in driverless vehicles by providing inputs to the algorithm, which determines subsequent actions of the vehicle. In autonomous vehicles, multiple sensors are commonly utilized simultaneously. It is important to accurately model and integrate these sensors within the simulator to mimic those employed in real vehicles. This part examines the various aspects of sensors that can be used within an autonomous vehicle simulator.

3.1.1.1 Default Sensors

The majority of simulators offer some default sensor models that are readily available for use. A simulator will receive a score of 1 for each sensors defined below if it offers support for it; otherwise, it will be assigned a score of 0.

a) RGB Camera

An RGB camera functions by translating the 3D environment within its field of view into a 3-channel 2D image (Red, Green, Blue). Refer to Figure 11 for an example of data captured by an RGB camera mounted on a vehicle. These images are valuable for understanding the surroundings, including aspects such as traffic lights, signage, and pedestrian crossings.

Figure 11: Image of vehicles surroundings captured by a RGB camera

b) Depth Camera

A depth camera captures a single-channel image embedding depth information. Each pixel in this image denotes the distance between the camera's mounting point and objects in the 3D environment it references. Figure 12 showcases an example data captured by a Depth Camera fixed on a vehicle. This data is commonly utilized to measure distances between the ego vehicle and other nearby vehicles.

Figure 12: Depth Image of vehicles surroundings captured by a depth camera

c) 3D Lidar

Unlike traditional cameras, the 3D lidar creates a 3D point cloud representation of the environment. Each voxel's position corresponds to a point on objects in the surroundings. This sensor projects laser beams and calculates positions based on time of flight. Figure 13 illustrates an isometric view of a point cloud generated by 3D lidar. However, factors such as fog or object texture can distort the energy of the laser signals. These sensors are occasionally affixed to a rotary motor to achieve a 360-degree scan around the device.

Figure 13: Isometric view of point cloud projection of surrounding captured by 3D Lidar

d) Radar

Similar to the 3D lidar, the Radar sensor maps the environment into a 3D point cloud. However, unlike the 3D lidar, this sensor uses electromagnetic (EM) waves instead of laser beams. Radars takes the advantages of EM waves such as covering longer distances and experiencing less distortion from external factors. Both the 3D lidar and Radar are utilized to project the surrounding environment in 3D data.

e) IMU Sensor

The Inertial Measurement Unit (IMU) sensor measures specific forces like acceleration and angular velocity. It provides information about the orientation and changes in position of the vehicle on which it is mounted on. IMU consists of sensing elements such as accelerometers and gyroscopes which aids in determining the vehicle's acceleration, change in direction, and rotation.

f) Semantic Information

Semantic Information isn't a physical sensor used directly in autonomous vehicles. Rather, it denotes a simulator's ability to offer semantic information about every object within the environment. This information typically includes the class or name of objects, such as trees, dogs, children, women, along with the coordinates of bounding boxes encapsulating these objects. Refer to Figure 14 for an illustration of the environment with bounding boxes and class labels of the objects. This information can be valuable in certain training algorithms like reinforcement learning, facilitating the provision of rewards and penalties.

Figure 14: Semantic Information of various object in environment with bounding boxes

g) Force Impact Sensor

This sensor measures the force experienced by a vehicle during impact with another object. This measurement directly correlates with the damage caused by both the vehicle and the object. Moreover, it can be utilized to assign weighted rewards and penalties.

h) Lane Detection or Infringement Sensor

Similar to Semantic Information, this feature isn't a physical sensor but provides information about driving lanes. This sensor reflects a simulator's capability to provide details about lane boundaries and the extent of infringement, indicated as the percentage of the ego vehicle's body overlapping the lane.

i) Fuel/Battery Sensor

This sensor monitors information regarding fuel or power consumption by the vehicle. As self-driving vehicles aim for efficiency, researchers worldwide continually work to enhance fuel efficiency of the vehicle. Therefore, it's crucial for a simulator to offer such data.

j) Vehicle Speed Sensor

A widely used sensor present in nearly all vehicles, it measures the vehicle's velocity. This sensor is particularly important when navigating in areas with speed limits, such as city roads or warehouses within the simulator.

k) GPS

The Global Positioning System (GPS) is a geolocation sensor utilized for locating and navigation. It's one of the most common sensors found in commercial vehicles, essential for path planning both on roads and within closed environments. Regarding simulators, it's vital for them to provide information about the coordinates of the vehicle and its destination within global boundaries with respect to the simulator scale.

l) Visibility Sensor

Visibility while driving can be affected by various environmental factors like fog, smog, or pollution. It is a measure of the maximum distance at which objects can be clearly seen which plays a critical role in safe driving. For simulators, providing this information becomes crucial, particularly when simulating foggy conditions.

m) Other Vehicle Sensors related to Vehicle Dynamics

Conventional cars possess numerous sensors measuring various car properties such as tire pressure, parking aid, engine RPM. However, not all these vehicle sensors are typically utilized in autonomous vehicle research. An ideal simulator should offer the infrastructure to model any of these vehicle sensors when needed, quantifying its ability to define and provide data related to ego vehicle.

n) Other Environment Sensors related to Perception

This parameter denotes the user's ability to define sensors measuring environmental properties. These user-defined sensors could offer data regarding the car's surroundings, like the number of people/vehicles within the car's field of perception. For example, sensors like audio recognition for identifying priority vehicles, such as ambulance and fire-fighting vehicles, fall under this category.

o) Macroscopic Global Sensor

Another user-defined sensor, this provides information about the simulation world, not just the local area near the vehicle. Such a sensor could furnish global details like traffic conditions in specific sections of the map or future weather forecasts, which can significantly aid in path planning.

3.1.1.2 Multiple Synchronous Sensors

In autonomous vehicles, multiple sensors are commonly used simultaneously to enhance reliability and provide backup in case of sensor failure. Simultaneous data from multiple sensors provide more dependable information compared to a single sensor. An AV simulator's capability to handle multiple synchronized sensor models and provide their data becomes crucial. This parameter ensures the synchronized data simulated by multiple sensors at a given time corresponds to the same time step and is coherent with each other.

3.1.1.3 User-Defined Sensor Position and Orientation

The placement and orientation of sensors within a vehicle significantly influence their application. AV Engineers meticulously design the mounting points and orientations, especially when multiple sensors are used to avoid sensor blind spots. This parameter evaluates a simulator's capacity of enabling users to define sensor location and orientation with respect to the vehicle geometry.

3.1.1.4 Precision of Sensor Readings

Sensor precision refers to the smallest measurable change in a sensor's readings. This attribute applies to various sensor types and their measurements. The precision of a sensor varies based on application needs and accuracy required. An adaptable simulator should accommodate diverse levels of precision, allowing users to configure it for various sensor according to their requirements.

3.1.1.4 Real-Time Sensor Models

Some vehicle manufacturers develop unique in-house sensors with unique features. Simulators incorporating digital models of these sensors help users to retain their specific functionalities within the simulation. Additionally, providing digital models of popular sensors readily available in the market becomes advantageous. This parameter evaluates a simulator's capability to import real-time digital models of sensors and integrate them into the simulation environment.

3.1.1.5 User-Defined Sensors and Observers

In the dynamic field of autonomous driving, new sensor technologies are frequently emerging, and existing sensors undergo performance updates to better understand the environment. Within a simulator, users might have specific data of interest for their application or need to monitor certain aspects. The simulator's capability to enable users to define observers to monitor data or model new sensors becomes important to cope up with evolving sensor needs and user-specific requirements.

3.1.2 Actors

Actors within the simulator constitute the diverse objects forming the environment. These actors broadly categorize into stationary and non-stationary, with stationary actors maintaining fixed positions (e.g., buildings, trees, traffic signs) and non-stationary actors changing their positions during simulation (e.g., people, animals, moving vehicles). This part explores criteria of various parameter related to actors that influences the comparison.

3.1.2.1 Geometry

a) Predefined Scenarios

Environments for vehicle operation vary widely such as rural, urban, industrial… each possessing unique features and actors. For instance, observing a child is less likely in an industrial setting compared to seeing a cargo truck. This parameter evaluates a simulator's capability to offer presets of environments with appropriate actors corresponding to various scenarios.

b) Predefined Models for Actors

This parameter evaluates the simulator's ability to offer access to meticulously designed digital assets (actors) across various categories such as buildings, vehicles, people, and traffic signs. These models are preconfigured across various scenarios and ready for deployment within the simulator environment.

c) User-Defined Actors

Apart from the preconfigured libraries of 3D models, the simulator should allow users to import custom 3D models of actors while maintaining a standardized scale within the simulator. This feature can aid user to tailor the simulator for their use case. For example, develop a simulator for driverless vehicle in golf field demands integration of 3D models of golf carts and players.

d) Number of Actors and Spawning Location

The nature of an environment is influenced by the number of actors within it. Users should have the ability to adjust the number of actors and their location to configure the environment. For example, configuring the traffic density in a particular road by defining number and location of vehicles or placing specific objects like traffic light poles.

e) Recreation of Real-Time Models

Simulators should possess real-time 3D models of actors such as cars, buildings while preserving their physical properties like geometry and textures. This feature appeals to users working with real-time vehicles or entities.

f) Path/Destination of Actors

Configurability of the moving trajectories for non-stationary actors, allows users to define paths and destinations. Actors should also respawn in new locations when they move beyond environment boundaries. This parameter ensures this capability of a simulator providing flexibility in defining their movement patterns.

g) Context-Aware Spawning

Ensuring that the spawning or respawning of actors aligns with contextual reasoning. For instance, spawning more ambulances near hospitals demonstrates intelligent spawning based on context. This parameter evaluates the simulator's ability to spawn actors sensibly in relation to their surroundings.

3.1.2.2 Behaviour

Behaviour of the actor within the simulator refers to the rules guiding actor actions, their responses to other actors, and environmental changes.

a) Predefined Rules

Simulators can define certain preset rules governing actor behaviour, such as traffic regulations in specific countries, readily available for use within the simulation.

b) User-Defined Rules

Allowing users to define specific behaviour patterns for actors within the simulator in addition to predefined rules, provides better customization options.

c) Distinguishable Behavioural Patterns

Simulators aiming to replicate real environments must simulate distinct behavioural patterns among actors. For example, distinguishing between the behaviour of an adult, a child, and a dog walking on a sidewalk. A simulator earns a score of 1 for this parameter if it is capable of accurately simulating these behavioural differences.

d) Sensitivity

Sensitivity refers to an actor's responsiveness or reaction to actions taken by other actors, including the ego vehicle within the environment. A score of 0.5 is given if actors respond solely to the ego vehicle, while a score of 1 is granted if actors respond to all fellow actors. This parameter evaluates the simulator's sensitivity to fellow actors' actions.

e) Level of Aggressiveness in Driving

The driving pattern varies among various parts of the world. Simulators should allow users to define driving patterns' aggressiveness using metrics like violations per kilometer driven or similar parameters. This parameter enables users to train and test in various driving conditions by defining custom behavioural patterns.

f) Reproducibility

Certain random behaviours exhibited by actors can elicit unique responses from the ego vehicle. The simulator should enable users to reproduce the same set of random actions performed by actors, known as seeding. This parameter evaluates the simulator's capability to reproduce a specific set of actions performed by actors for further analysis.

3.1.3 Environment

The simulator's environment includes the weather, terrains, maps, and conditions where the vehicle operates. This part explores various the criteria for various comparative parameters related to environment.

3.1.3.1 Pre-defined Libraries

This parameter assesses the simulator's capability to feature pre-designed environments consisting of diverse landscape and weather conditions. The simulator earns a score of 0.5 if it satisfies one condition and a score of 1 if it fulfils both.

3.1.3.2 User-Defined Environment

Simulator tools enabling users to define their own maps and various weather conditions enhance customization and adaptability, allowing for efficient simulation tailored to specific needs.

3.1.3.3 Real World Maps

The capability to import or utilize real-world maps within the simulator holds significant importance, particularly for developing commercial autonomous vehicles that directly navigate on real road. A simulator scores 1 if it facilitates user access to import or integrate real-world maps and associated features.

3.1.3.4 Photorealism

Photorealism is the concept of how closely a simulator's environment resembles the real world in appearance. Assessing photorealism is subjective, thus scored by users through visual inspection on a scale of 0 to 1. A simulator that closely replicates reality receives a higher score, while deviations affect the score inversely.

3.1.3.5 Variable Resolution

The ability to vary the level of detail in the rendered environment by adjusting resolution. Variable resolution provides flexibility, allowing users to balance computational resources against information accuracy. With lower resolution considerable computation resources can be saved but potentially losing detail and vice versa. This parameter checks the ability of a simulator which enables the user to vary the resolution.

3.1.3.6 Context-Aware Map Planning

The simulator-generated map should possess contextual coherence, ensuring that elements such as buildings, roads, and traffic lights correlate logically within the environment. This feature scores 1 when a simulator has the capability of generating contextually plausible maps.

3.1.3.7 User-Defined Scenarios

Allowing users to generate specific scenarios, such as road constructions or obstacles like fallen trees on roads, contributes to the simulator's versatility. This parameter is scored by its ability to facilitate user scenario generation.

3.1.3.8 Material Definition

The optical properties of environment materials can influence sensor data, impacting sensors like Lidar and Cameras. For instance, Lidar may fail to detect glass walls due to the laser beam passing through it rather than reflecting. This parameter evaluates the simulator's capability to enable users to define materials and texture of objects in the environment.

3.1.3.9 Variable Level of Sun Shades

Shades of the sun can influence significantly in replicating the time of day and weather ultimately impacting the sensor readings. This parameter refers to the simulator's ability to allow users to manipulate sun shades, considering factors like time of day and weather

3.1.3.10 Special Optical Features

Real-world optical phenomena like sun glare, mirage, dust, and fog can impact driver visibility and sensor data for driverless vehicles. Therefore, it's also important for simulators to model these features which impacts sensor data and subsequent vehicle actions.

3.1.3.11 Data Visualization and Analytical Tools

Simulator tools facilitating the display of various data and analyses during training and testing offer valuable insights to users. This parameter assesses whether the simulator allows users to define data visualization and monitoring tools, which could include sensory data from the vehicle, algorithm-related data, or annotations like bounding boxes and semantic truth.

3.1.3.12 Rendering

During testing, the quality of scene rendering aids in analysing algorithm performance. Users should have the ability to modify rendering parameters such as view angle and frames per second, ensuring adaptable display quality. This parameter evaluates the simulator's capability to offer configurable rendering options, earning a score of 1 if available.

3.1.3.13 Recording

Recording the training process allows users to analyse performance and playback sessions for future evaluation. This parameter accounts for the simulator's ability to record the training process alongside associated data, aiding users in comprehensive analysis.

3.1.4 Ego Vehicle

The agent vehicle, or ego vehicle, is the vehicle which is subjected to training or testing for autonomous driving within the simulator. This part explores various parameters evaluating the simulator based on the ego vehicle.

3.1.4.1 Vehicle Geometry

Vehicle Geometry refers to the dimensions and bounding box encapsulating the vehicle in the 3D environment. This parameter evaluates the simulator's capability to allow users to configure the geometry of the ego vehicle.

3.1.4.2 Wheel Geometry

This parameter involves the ability to modify suspension and steering system parameters of the ego vehicle within the simulator. Ensuring adherence to physics related to wheel geometry is important as it impacts driving performance significantly.

3.1.4.3 Real-World Models

This parameter assesses the simulator's feature of enabling the user to import and use of 3D models of real-world vehicles developed by vehicle manufacturers. This feature is important and timesaving for researchers from vehicle manufacturing companies.

3.1.4.4 Real-World Physics

This parameter is a check for the simulator's capacity to simulate various physical parameters associated with driving, including wheel slip, crash damage, and vehicle inertial behaviour. Accurate replication of these features is vital for developing algorithms for real-world on-road autonomous vehicles.

3.1.4.5 Input Commands

The driving algorithm generates action commands for the vehicle (e.g., acceleration, steering angle) based on observations. Configurability of input commands for every component within the ego vehicle is crucial to accommodate various algorithms. This parameter ensures the simulator's ability to configure input commands for the vehicle.

3.1.4.6 Other Components

Minor components like headlights and horns can have minor impact in driving. The simulator should allow users to model the intensity or impact of these components. This parameter evaluates the simulator's feature for adjusting the effects of such components.

3.1.5 Framework

The framework within which the simulator operates plays a crucial role in its versatility and usability. This part evaluates various comparative parameter related to simulator’s framework.

3.1.5.1 Cross-Platform Compatibility

This parameter assesses the compatibility of the simulator software across diverse operating systems, determining support for OS environments such as Linux, ROS, Windows, MacOS, and any other relevant OS. The simulator earns a score of 1 for each supported operating system from the listed ones.

3.1.5.2 Open Source

Evaluating whether the simulator or parts of it are open source, enabling users to tailor the simulator to their specific needs by importing components as plugins and developing customized software. A score of 1 is given if the simulator allows for such user-driven customizations.

3.1.5.3 Scripting Language Support

This parameter evaluates the breadth of scripting language support within the simulator, crucial for facilitating communication between users and the simulator. The assessment includes popular languages like Python, C++, C, R, Java, and other relevant scripting languages. The simulator earns a score of 1 for each supported scripting language from the listed options.

3.1.5.4 Scalability

This parameter evaluates the simulator's ability to provide various light versions to suit diverse user needs. Offering various individual light versions with unique features, alongside a comprehensive pro version encompassing all features, the simulator ensures adaptability to different user requirements. This feature contributes to making the software more streamlined and efficient for users by allowing them to opt for lighter versions catering to their specific needs.

3.1.5.5 Computational Resource Evaluation

In this study, the computational resource consumed by a software is calculated based on electrical energy consumption by a baseline system under maximum operation. The configuration of the baseline system and its power consumption at it maximum usage is tabulated in Table 2

|  |  |  |
| --- | --- | --- |
| Component | Model | Power Consumed (Appox.) |
| Processor | Intel i9 processor | 200 – 250 Watts |
| GPU | Nvidia RTX 3090 – 24 Gb | 400 Watts |
| RAM and ROM | 16 Gb and 500 Gb SSD | 15 Watts |
| Monitor | 27” 4K resolution Monitor | 50 Watts |
| Fan and other components |  | 25 Watts |

Table2: Baseline system configuration

The score is calculated by comparing the simulator's power consumption during operation against the maximum power consumption of the baseline system (approximately 750 watts).

The score for the computation resource consumed by a simulator A is given by

Score = 1 – (power consumed by simulator/ maximum power consumption by baseline system)

3.1.5.6 Community Support

Community support is crucial for public software, evaluating three streams: structured documentation, tutorials, and discussion forums. Each stream receives a score of 1 if available.

3.1.5.7 Distributed Computing

This parameter assesses the simulator's ability to execute multiple simulation instances on different machines, converging into a coordinated and coherent simulation system. In addition, training of Machine learning can be parallelized when a simulator supports GPU operations. This parallelization capability enhances efficiency by reducing runtime and increasing the number of simulation episodes within a given time.

3.1.6 Driving Algorithm

This section delves into the comparative assessment of the driving algorithm used to navigate the ego vehicle within the simulator, analysing various parameters critical to algorithm and associated data.

3.1.6.1 Data Exchange

The interaction between the algorithm and the simulation engine often occurs through communication channels like APIs or dedicated communication bridges. This parameter evaluates the presence of pre-defined communication plugins, scoring 1 if available.

3.1.6.2 Data Logging

Data logging involves collecting and storing simulation-generated data for future analysis. This parameter assesses the simulator's support for user-controlled data logging, scoring 1 if it aids users in logging specific data of interest.

3.1.6.3 Hardware in Loop (HIL)

The incorporation of real-time hardware, such as sensors and vehicle controls, within the simulator aids in testing hardware performance. This parameter evaluates simulator support for any hardware involvement during operation.

3.1.6.4 ML Libraries

Support for popular machine learning libraries like TensorFlow, PyTorch, and Scikit simplifies machine learning model training. This parameter assesses the simulator's compatibility with integrating such ML libraries, enabling users to utilize these tools within the simulator environment.

3.2 Methodology

This section outlines the process of deriving a single score for a simulator using the above-mentioned parameters. The scoring system comprises two main components which constitute to form the final scores: Base Score and User Weight

3.2.1 Base Score

Each simulator being compared will receive scores for all parameters on a scale from 0 to 1. This produces a base score vector for each simulator, usually given by the developers of the simulation software.

3.2.2 User Weight

Users assign weights ranging from 0 to 1 to each parameter based on the individual importance These user-assigned scores create a user weight vector that reflects the significance of each comparative parameter to the user.

3.2.3 Final Score

The final score, denoting the suitability of a set of n simulators S = (S1, S2, S3… Sn) for a specific user (U), is calculated using the dot product of the base score vectors of simulators S and the user weight vector of user U. This computation generates a usability score for each simulator, allowing users to assess and compare simulators based on their preferences.

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