Digital Twin for a Vehicle: ElectroBus Case Study

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Abstract

A Digital Twin is a virtual representation of a real dynamic system that can simulate its current conditions, predict its future behavior, and log valuable information about its internal operation and interactions with other systems. The unique capability of automatic bidirectional information flow between virtual and physical worlds and predictive analysis of Digital Twins are what make this emergent technology greatly innovative and of significant value. The objective of this case study is to implement a vehicle's performance Digital Twin concept on an electric passenger bus and analyze the technology's adaptability level, capabilities, scope, limits, and future improvements. This system incorporates a network of sensing devices mounted on the vehicle, a real-time simulation model, edge computing capabilities and the possibility of incorporating predictive maintenance models to determine remaining useful life of components. The Digital Twin is thought to have great value when it comes to gaining deep insight on the dynamic performance of the bus, analyzing energy waste, exploring determining factors of energy usage and monitoring the current and future state of the vehicle. All of this being possible through simulation technology, digital modeling, physical and virtual sensors, edge computing, Internet-of-Things networks, and Machine Learning algorithms.

Keywords
Digital twin, simulation, vehicle dynamics, case study, internet of things.

1. Introduction
Digital twins (DT) are an emergent technology which has seen a recent surge in use cases and applications in a variety of industries. Due to the benefits of developing DTs for specific applications, it a desirable method for gaining deeper insight and testing/validation of physical object or processes. By having a reliable and experimentable model as a virtual testbed, users can extract information about current inner operations of a real object or process, predicting its future behavior and even simulating what-if situations. In this sense, it is possible to develop high fidelity, comprehensive "Simulation Models allowing a simulation-based verification and validation throughout the whole lifecycle (of the physical twin)" (Dahmen and Rossman, 2018). Recent studies and use cases for DTs revolve in its majority on manufacturing and smart city applications. However, with the emergent trend of electrification and evermore complex mechatronic systems, there is an opportunity of developing DT concepts for automotive applications. This work presents the case study of the use of the DT concept of a vehicle applied on an electric bus (Electrobus). This bus was converted from and internal combustion engine (ICE) to a fully electric (EV) powertrain and is expected to become a vehicle with smart mobility and connectedness capabilities. Amongst these capabilities, is the DT concept of the bus which would serve as a way of monitoring its performance, having an experimentable model of the physical bus, being able to predict future performance behavior and making available for the driver and other users, deep insight on sustainability and performance analysis of the vehicle and its interaction with its surroundings. The DT of a vehicle was previously developed for the representation of a commercial ICE vehicle. The original test vehicle was the Mazda 3 2018 hatchback which is classified as a Class C mid-range road family car. For this work however, the DT platform was converted and adapted to run the simulation model of an electric bus and the focus of the data analysis was shifted towards sustainable mobility. The test vehicle for this work is a Class 6 (gross vehicle mass of approximately 10,000 kg) city bus modified and converted to an EV bus. The powertrain, body work and driver cab will be modified, but the chassis for the bus will remain the same. The result will be the capability of analyzing the performance of the bus in real-time and having a record of its performance through time. This will enable deeper insight of the inner behavior of the vehicle. This in turn will provide information for data-led decision

making in terms of maintenance, driving styles and the understanding of the energy consumption and environmental impact of an EV mass transportation service in Monterrey.

The DT is intended to be optimized for studies on the use of energy by the bus under different conditions, the dynamic performance of the bus and the impact it has on its surroundings. In this sense, working under the scope of the United Nation's (UN) Sustainable Development Goals (SDGs) was important to determine the objectives of the system and the focus of the DT. More on the SDGs in Section 1.1.

This research is of great value since it is one of a few publications made on performance DTs for vehicle models that, furthermore, analyzes the results and behavior of the physical bus under a sustainability and smart mobility framework. Additionally, the DT of the vehicle is intended to be able to generate, populate, and interact with the DT of an urban space. This concept of interacting DTs will demonstrate the scope of this technology and open possibilities for new implementations and developments in the subject.

1.1 Objectives

DT systems are complex and often hard to implement due to a variety of limitations and challenges. Amongst, these challenges, the most common are costs related to implementation (hardware), interoperability of platforms and devices, and a great investment when it comes to staying up to date with the development of enabling technologies such as IoT, ML and edge computing. The developed system for a performance and urban space DT is expected to be put to test in a real situation where these challenges and limitations can be documented, explored, and targeted in the most efficient way. The vehicle is expected to generate and populate the urban space DT using IoT sensing devices, edge processing and modeling and simulation software. The main objective of this work is to demonstrate the implementation of a DT for a vehicle and its interaction with the generated DT of an urban space. This type of DT interaction demonstrations is of great value to developing the DT concept and proposing the methodology for their design and development. This first step of the project will provide a framework and baseline to work with this type of technology which effectively contributes to the standardization and widespread design of DTs.

For the design and implementation of this DT concept under the framework of sustainability, UN's SDGs were consulted. This work's objectives have been aligned with some global issues as presented by the following goals:

- **Goal 3** – To ensure healthy lives and promote well-being for all at all ages.
  - Through the implementation of urban and vehicle DTs, one can perform studies and analysis of an urban space in terms of security, infrastructure, accessibility, open spaces, etc. to determine living standards and community perceptions.
- **Goal 9** – To build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.
  - The digital representation of an urban space may showcase the evolution of a community and effectively gather historical information on variables such that a deeper insight of the space is available. This level of insight may improve city planning, logistics and help understand city perceptions.
- **Goal 11** – To make cities and humans settlement inclusive, safe, resilient, and sustainable.
  - According to the UN, "as of 2020, 16% of the average global share of urban areas was allocated to streets and open public spaces. This is short of the 30% streets and 10-15% public open spaces target" and "as of 2019, only half of the world's urban population have convenient access to public transport. Convenient access means residing within 500 m walking distance of a bus stop/ low-capacity transport system and 1000 m of a railway or ferry terminal" (Department of Economic and Social Affairs, 2021).

2. Literature Review

Literature reviews are an important step when it comes to staying up to date with the most recent advances in technology and other subjects. It is an unbiased approach to evaluating the state of the art (SoA) of a certain technology with evidence of recent applications, implementations, research, and patents. There exists a variety of methodologies to performing and writing literature reviews, however that which aligns with a systematic approach to such research is desired to eliminate any kind of bias that might exist. A systematic-like review (SLR) is one that aims to "collate evidence that fits pre-specified eligibility criteria to answer a specific research question. They aim to minimize bias by using explicit, systematic methods documented in advance with a protocol" (Higgins and Thomas, 2021). These authors present a methodology for SLRs that include the following steps.

1. Identifying answerable questions
2. Developing a protocol
3. Conducting systematic publication searches
4. Selecting studies to include
5. A comprehensive revision
6. Extracting and synthesizing information
7. Writing and publishing the review

In accordance with the outline methodology, the following questions were determined for this SLR. *RQ* represent the research question and *SQx* represents the sub questions.

- RQ: What is the SoA of DT technology in implementation applications?
- SQ1: What are the current challenges of implementing a DT-based system with current technology?
- SQ2: What are the enabling technologies and their use trends for DTs?

Figure 1 presents the protocol, systematic publication search and selection criteria for the studies to include. For the systematic search, databases such as MDPI, Research Gate, IEEE Xplore, Science Direct and ProQuest were used for selecting an initial set of 110 publications that were then collated using the selection criteria. Afterwards, the remaining set of publications were revised.

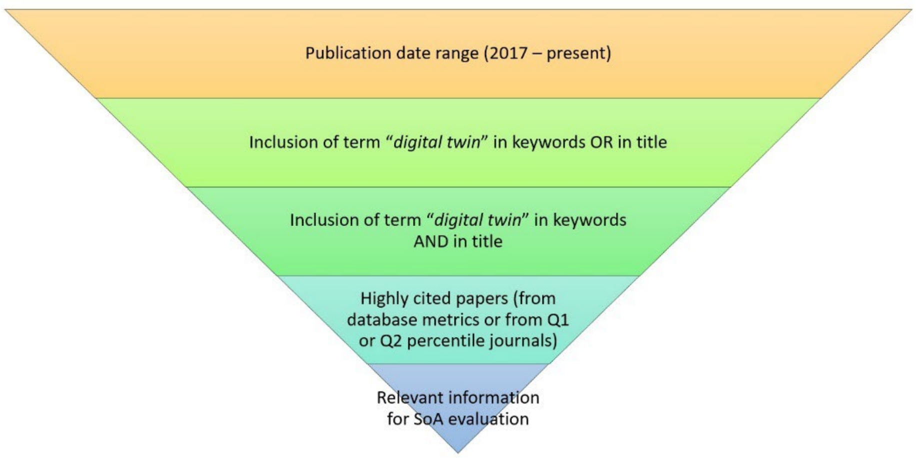

Figure 1. Protocol and selection criteria for SLR.

It was found that there currently exists no well defined or universally accepted definition for DTs. According to Sharma et al. (2020), "this lack of standards impedes the widespread design, implementation and adoption of this technology". In this sense, this work aims to contribute to the standardization of the DT concept and definition. It is a challenging task due to the wide variety of applications and use cases for this technology, but through more thorough reviews and publications, a well-defined definition is possible. Evans et al. present a maturity spectrum index for the evaluation of DT application maturity in terms of its integration and connectivity capabilities. Table 1 presents this spectrum index.

Table 1. DT application maturity spectrum (Evans et al.)

Maturity element (logarithmic scale of complexity and connectedness)	Defining principle	Urban space outline usage
0	Reality capture (LIDAR, drones, photogrammetry, plans, etc.)	Existing as-built digitalization
1	2D maps/system or 3D model	Space coordination and model

2	Connect model to persistent (static) data, metadata and BIM stage 2	Asset management, life cycle monitoring, simulation experimentation
3	Enrich with real-time data	Real-time life cycle monitoring
4	Two-way data integration and interaction	Remote and immersive operations, control physical from the digital
5	Autonomous operations and maintenance	Complete self-governance with total oversight and transparency

This work aims to reach the level 3 maturity level where real-time dynamic information is used to enrich the simulation and models. However, there exists certain restriction and limitations to the widespread adoption and implementation of DTs. Parrott and Warshaw (2017) argue that "many companies found that the connectivity, computing, data storage, and bandwidth required to process massive volumes of data involved in creating digital twins were cost-prohibitive". Other limitations include the complex task of modelling evermore complex mechatronics systems and staying up to date with enabling technology advancements such as Machine Learning, Big Data, IoT, and communication systems. Deloitte Tech Trends (2020) present the fact that developments in simulation and modeling tools, IoT device conectivity, expanded bandwidth and better computing architectures will enable DTs to become a predominant tool for companies and governments.

In terms of the classification of DTs, Juarez et al. (2021) propose three classes regarding integration levels:

- Digital Model: virtual representation of a physical subject with no automated flow of information from physical to virtual worlds.
- Digital Shadow: Virtual representation where there is a unidirectional flow of information usually from physical to virtual world.
- Digital Twin: Uses a bidirectional flow of information scheme to enable the management and monitoring of the object's life cycle.

Singh, et al. (2021) propose a three-level hierarchy classification: the basic level is the Unit Level where DTs represent single objects, materials, etc. In the System Level, physical twin could be a production process or a complex object's lifecycle and finally a System-of-systems (SoS) level where there is product of process life cycle management.

Some recent applications of DTs for the automotive industry include estimating the battery state of electric golf vehicles (Merkle et al., 2021), a study of DT potential applications in EV technologies (Van Mierlo et al. 2021), DT concepts for electric powertrain applications (Rodríguez et al., 2021), automotive validation methodologies using DTs (Szalay, 2021), an even the simulation and monitoring of vehicle sensors (Tavakolibasti et al., 2021).

3. Methods

DTs as presented by Campos-Ferreira et al. (2019) are made up of three main components: a physical world, a digital world, and the connectivity that allow bidirectional flow of information amongst both worlds. In this sense, the DT for the Electrobus is designed following this concept where the physical world is represented by the physical vehicle, the digital world integrates the digital model, simulation and visualization platforms, and the connectivity component is enabled by the communication capabilities amongst physical and virtual world. The overview of this work's vehicle DT is presented in Figure 2. More detail on the devices and methods for each component are listed on Sections 3.1-3.3.

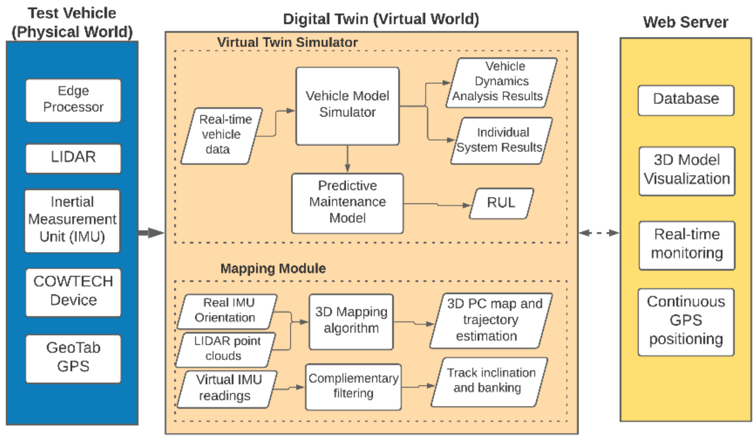

Figure 2: Architecture for vehicle DT.

3.1 Data Acquisition

To collect the necessary data to successfully run the digital model of the vehicle, a wide variety of methods and sensing devices were used. For instance, there is a need of static data represented by the technical specifications that characterize the vehicle and dynamic data which is given by a set of sensors and device that gather information in real-time. For the technical specifications of the vehicle, various parameters were used to define the different systems and dimensions of the model. For example, information about the body dimensions, nominal values for the motor, aerodynamic performance of the chassis, and tire specifications. Some of the most valuable information is given in the Table 2.

Table 2. Electrobus vehicle technical specifications.

Category	Specification	Value	Units	Comments
Body	General dimensions	[10.34, 2.36, 3.43]	[m, m, m]	Length, width, height
	Nominal vehicle weight	10,000.00	[kg]	Minimum functional systems only
	Expected max weight	15,000.00	[kg]	With passengers and extra systems.
	Wheelbase	4.75	[m]	-
	Expected number of seats	44	-	-
Tires	Type	275/80 R 22.5	-	-
Drive train	Motor max power rating	356.20	[kW]	-
	Battery power rating	500.00	[kW]	-

For the dynamic data aspect of the data acquisition network, a set of sensing and ranging device connected to an edge processor and mounted directly on the vehicle itself are used. A complete list of the devices and their use if presented in Section 4.

3.2 System Modeling

For the vehicle model and simulation, the software Matlab and Simulink are currently being used. These platforms present great interoperability with other software and it allows to create a tailored-made model and simulation environment for our work. It’s capability of hardware deployment with NVIDIA processor through Compute Unified

Device Architecture (CUDA) (MathWorks Inc, 2021) is also a desirable aspect. This way, all models and script from Matlab/Simulink may run on the edge processor.

For the vehicle model itself, a high-fidelity model is expected since there is a need to represent the physical vehicle's behavior and inner operations as accurately and precisely as possible. There are many approaches to vehicle and system modelling; however, for this work, a multisystem, parametric, and data-driven model was designed. This way, the model is connected to external input from real sensors for the data-driven aspect and is parametrized using the technical specifications and technical approximations. According to Aivaliotic et al. (2019), there are three modelling levels: "black (without any knowledge of the internal operation), grey (theoretical data are used to complete the model), and white boxes (fully described component)". In this sense, the model is designed mostly in grey and black box levels. The most crucial systems were modelled in such a way that most parameters are editable.

3.3 Connectivity

To enable connectivity between worlds, an network of IoT devices was design and implemented to allow each to communicate with each other and with the digital world. Although the data acquisition network and the digital world are connected through physical cabling, connectivity of the edge processor to an external web server is performed through wireless data streaming and communication. In this sense, various communication protocols and methods are used such as serial communication, Ethernet, application programming interfaces (APIs), etc. Furthermore, the external web server is used to live stream information from the vehicle, display graphic results to an end user and serves as a database storage system. More on the wireless communication and web server design is explained on Section 5.

4. Data Acquisition

For the data acquisition network, a total of 5 devices and an edge processor were used. All the sensing devices are mounted directly on the vehicle itself to reduce the amount of data being transmitted wirelessly and in real-time since this presents a challenge with current communication technology. Table 3 details the use and data gathered from each device.

Table 3. Devices used in data acquisition network

Device	Use	Data acquired
COWTECH device	Real-time information directly from the car's controller area networks (CAN) bus.	Vehicle speed, engine RPM, battery state of charge (SoC), steering wheel position, throttle/brake commands, tire pressures.
Inertial Measurement Unit (IMU)	Real-time information from car's dynamic behavior.	Accelerometer, gyroscope, magnetometer.
Light Detection and Ranging (LIDAR) sensor	Offline 3D mapping of surrounding area and trajectory estimation.	Point cloud data.
Geotab Device	Real-time geolocalization.	GPS coordinates.
Camera	Real-time object detection using Machine Learning (ML) algorithm.	Video frames.

For this work's system and architecture, the LIDAR, IMU and camera are used to gather information for the creation of the digital model of an urban space and effectively enable its DT. Specifically, the LIDAR is meant to be used for digitalization of spaces in terms of dimensions and objects. The IMU is meant to be fused with LIDAR information to produce an accurate and precise vehicle trajectory estimation that may be used for deeper mobility and infrastructure studies. The camera is used to detect objects throughout the vehicle's trajectory. This information, paired with GPS information on the detected object may generate valuable information for mobility infrastructure and civilian density studies.

Lastly, information from the devices reaches the central edge process which is a Jetson Xavier Developer board from NVIDIA. This processor is built to run Linux and have deployed applications from software like Matlab, Simulink, Python code, etc. It is also optimized to run Machine Learning vision and navigation algorithms in the most efficient way. All the devices are meant to be mounted on the vehicle. The specific location for each device may vary; however, it is important to have the LIDAR and IMU devices mounted as closely as possible to the vehicle's center of gravity to avoid any bias or drift form their measurements. Furthermore, the camera needs to be mounted on the front part of the vehicle where its field of view (FoV) is not blocked.

5. Results and Discussion

The proposed system is still under development; however, important advances on the development and implementation of some systems is already taking place. For instance, the mapping system is currently being tested to provide insight on its accuracy and precision. The digital model and its connection to the physical vehicle is also being developed, however, some advances on the modelling of the Electrobus with the associated companies is being made on a steady pace. Some other options for software and modeling techniques are also being explored but more information is provided on Section 5. Some current results presented in this section include the web server design, the mapping system design and experimentation advances as well as the IoT architecture development.

After having tuned the parameters of the LIDAR mapping module, an experimentation process was used to test the system under different conditions to evaluate and validate its performance. In this sense, an experimentation scenario was generated where the objective is to test the effect that the vehicle's speed has on the precision and accuracy of the 2D map and the estimated trajectory. Also, the effect of surrounding dynamic objects (moving vehicles, people, animals, etc.) is to be evaluated. For this scenario, a straight street (Avenida Fundadores) with little elevation was chosen. The experiment consists of driving at a constant speed three times. Then changing the speed (20 km/h, 40 km/h and 0-60-0 km/h) and evaluating if there is a difference in percent error with respect to the Google Maps trajectory distance estimation. Comparison of distance estimations is performed for each set of takes at the same speed and estimations at different speeds effectively evaluating both precision and accuracy. The results and evaluation of this experiment are shown in Section 5.1, Table 4.

To achieve more accurate error values, a stricter control of the travelled distance is necessary. For instance, ensuring that every take of the experiment consists of the same real distance. This will be achieved by using a Garmin device to calculate real distance and altitude and having start/stop marks on the road to ensure every take starts and ends in the same place. Also, additional testing is required to evaluate the LIDAR-IMU fusion algorithm.

5.1 Numerical Results

The following table present the results of the LIDAR mapping module experimentation. In the row "Distance", the estimated trajectory distance by the system is presented. Table 4 shows that the average percent error for distance estimation is 1.80% (translates to an average error less than 5 m) which as a positive result that shows a level of high definition of the mapping module. The expectation for the experimentation of the LIDAR-IMU fusion algorithm is that this error will be reduced to approximately 1.00% (less than 2.75 m average error). Additionally, GPS coordinates may be added to the system in the future to further decrease the error and enable other functionalities to the system such as live GPS tracking of vehicles within the urban space DT (effectively achieving interaction between both DTs).

Table 4. LIDAR mapping module experimentation results.

	40 km/h				**20 km/h**				**0-60 km/h**	**Total**		
Category	1	2	3	Avg.	1	2	3	Avg.	1	Avg.	Variance	Standard Deviation
Distance [m]	315,73	286,08	248,95	283,59	237,17	264,43	254,51	252,04	260,21	266,73	594,64	24,39
Rise [m]	37,50	36,54	35,00	36,35	35,33	43,87	32,45	37,22	31,32	36,00	14,35	3,79
Predicted Dist. (Google Maps)	322,00	290,55	253,79		239,39	270,53	259,06		266,12			
% Error	1,95	1,54	1,91	1,80	0,93	2,25	1,76	1,65	2,22	**1,79**		
RMSE										**5,08**		

Apart from the percent error and RMSE values, this initial experiment was significant in the sense that it demonstrated that dynamic objects have very little to no effect on the precision of the system. This is mostly because the near distribution transform (NDT) distinctive feature registration (DFR) algorithm only register distinctive and static features throughout LIDAR frame readings. This means, that the algorithm ignores dynamic object such as cars and people. With these results, one can also conclude that speed and acceleration have little effect on the precision of the system. This is more evident with the 0-60 km/h take which shows and increase of percent error. The expectation is that the LIDAR-IMU fusion algorithm will help reduce this effect attributed to fast movements of the sensor. This due to the fact the IMU gyroscope might reduce the drift effect in LIDAR data.

5.2 Graphical Results

After processing LIDAR data, the accumulated PC map is generated. Figure 3 portrays the result of one of the Scenario 1 data takes (left) and the Google Maps distance estimation (right). As mentioned earlier, for future experiments and more accurate results, a Garmin device will be used to set true values of distance and altitude. The result from the current mapping module is a 2D map and a 3D trajectory estimation, however, after being processed with ArcGIS, the system will yield HD 3D visualizations of urban spaces and more accurate vehicle trajectory estimations.

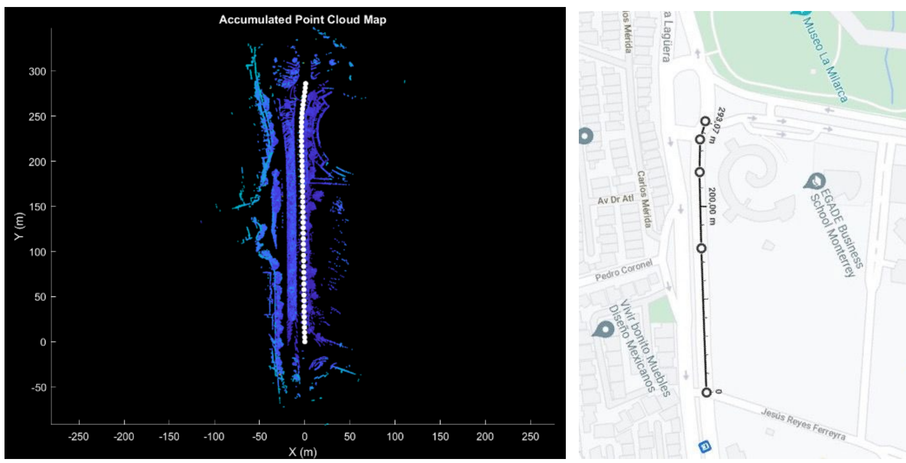

Figure 3: LIDAR mapping module result from an experiment in Avenida Fundadores (1.8% traveled distance error).

Apart from the experiment, the system was also tested with single takes (no experimental control) on more complex trajectories. Figure 4 is an example of a take where the vehicle travelled through a neighborhood with more elevation differences, speed bumps, sharp turns, and some dynamic objects (people).

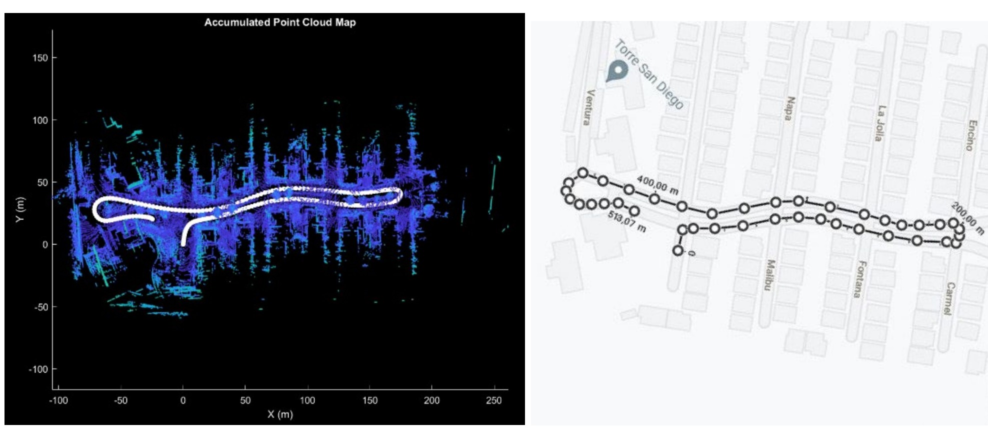

Figure 4: LIDAR mapping module result from take inside a neighborhood (Los Angeles, Monterrey).

5.4 Validation

The validation process is very important when it comes to evaluating and validating systems or models that represent real objects or processes. In our case, since the digital models are desired to produce calculations and conclusions on the behavior of their physical twins, these need to be as accurate and precise as possible to present the most real information as possible. For our system experiments, the validation process is carried out by comparing absolute true values to those output by our design system. In the case of the mapping module, distances and altitude is evaluated through percent error and RMSE calculations.

When the system and individual models are complete, the use of other validation techniques are necessary. For our work, the Grieve's Tests of Virtuality (GTV) will be performed to evaluate the ability of our models to mirror their physical twins. These GTV consists of three tests: sensory visual, performance, and reflectivity (Juarez et al. 2021) where the behavior similarity of both physical and virtual worlds is evaluated.

- Sensory Visual Test: A tester subject demands a movement either from the DT or the physical twin and if the tester cannot differentiate among the real system and the DT, this test is approved.
- Performance Test: The tester demands an action from both twins and if it cannot differentiate the performance among both, this test is approved.
- Reflectivity Test: The tester demands information on the current state of the object, if there is no difference between the data from the physical and virtual twin, this test is approved

6. Conclusion

The results and designed software for this work already has great value in terms of setting a baseline for the future development of the DT for a vehicle and for urban spaces. Implementation is still pending, however after the proposed validation techniques, system integration will be feasible, and implementation would be the next step. In this sense, the objective for the project is still to be reached. Some challenges and limitations have already been worked around. For instance, implementation costs due to the number of devices and software needed is a challenge to overcome. For this, open-source software and popular platforms were used and tailored-made designs developed. Other challenges like the complexity of interoperability amongst software was experimented. Matlab and Simulink were a solution option due to their facility to interact with other platforms.

With the current results, the system may already be classified in a maturity level 1 according to the DT maturity spectrum index. However, once the system is complete and once it is validated, a level 2 and even level 3 of maturity will be achieved. The static information and real-time information will come from the sensing devices mounted on the vehicle. This will also demonstrate the interaction between an urban space DT and a vehicle DT concept.

Furthermore, the current system may be classified as a SoS level hierarchy and an integration level of Digital Shadow. When the system is complete, the integration will be classified as a Digital Twin. A lot of work needs to be done with the interoperability and connectivity of platforms and devices. It is a special challenge when it comes to real-time data processing, and enabling technologies such as ML, Big Data, IoT and edge processing have a great role.

Future work will focus on connecting both physical and virtual world and performing experimentation to evaluate and validate individual systems. After this, implementation of the DT for Electrobus will be enabled.

7. Acknowledgements

For the development and implementation efforts, a total of 5 associated companies are involved. Tecnológico de Monterrey and this work's authors are currently collaborating with an automotive bus manufacturer, a bodywork manufacturer, a public transport agency, and two EV conversion companies.

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