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OpenCRG Models From Different Data Sources to Support Vehicle Simulations

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ABSTRACT Digital twins of road surfaces support multiple engineering applications. Remote sensing technologies provide information from the entire surface of the pavement by high accuracy point clouds. Pavement errors and differences from designed geometry can be detected and assessed using such datasets, while OpenCRG models derived from point clouds support transportation applications. High-resolution CRG (Curved Regular Grid) models enable analyzing vehicle suspension systems in vehicle dynamics simulation environments. Furthermore, such models also support creating the digital twins of vehicle suspensions and improve the development and research of models related to vehicle dynamics. The paper presents how the suspension digital twin was obtained applying a genetic algorithm and how it was assessed. The quality of raw data and that of the derived methods are analyzed in the case of multiple mapping technologies (terrestrial, mobile, and aerial laser scanning). CRG models were created from all datasets, and their applicability was investigated to support vehicle simulations with high accuracy demand. Other important vehicle-related use cases are also mentioned in the paper.

INDEX TERMS Road geometry, point clouds, laser scanning, OpenCRG.

I. INTRODUCTION

Digital representation of roads or selected road segments supports multiple engineering applications. While maps describe the topology of road networks, road surface models enable sophisticated analyses. Civil engineers use road surface models to assess pavement damage and to support reconstruction design. Vehicle engineers require high density and accurate surface models to support vehicle dynamics simulations. As simulation techniques evolve in research and the vehicle industry, digital twins (highly detailed copies) of EGO (the vehicle under test) vehicles are required. Scenario-based development, testing, and validation is an essential direction for securing automated driving, which involves novel research projects [1]. Entering the field of vehicle

dynamics requires not only the exact replication of the vehicle itself but the primary source of excitations to vehicles, the digital twin of the road surface. Simulation of dynamics requires the highest accuracy of the road surface to precisely calculate reaction forces at the tires' contact and consider rolling resistances on various surfaces [2]. Winkler *et al.* [3] analyzed the road-vehicle interaction with the help of CRG (Curved Regular Grid) models. Yavvari *et al.* [4] created a road surface-aware algorithm for automated driving using Open CRG. Before the release of CRG, road surface modeling was done by mathematical solutions and approximations, which ruled out the possibility of creating a model from an exact road surface. Zhang *et al.* [5] created 3D road surface models in the time domain with the help of power spectral density. Oniga *et al.* [6] combined the quadratic and the planar road models to support driving assistance systems. Weifeng *et al.* [7] created road surface models based on

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white noise filtration. Road surface models can be obtained multiple ways, but the most accurate ones can be derived by point-cloud based data acquisition technologies. Currently, point clouds are the general outputs of camera based systems, using photogrammetric data processing algorithms. However, image based solutions highly rely on the texture of the surface to be surveyed, since the algorithms need to detect common points (tie points) between image pairs. Road surfaces are typically homogeneous; pavement survey requires active remote sensing technologies, such as laser scanning. Laser scanners can be mounted on moving platforms (usually on vehicles), such Mobile Mapping Systems (MMS) are capable of rapidly surveying extensive areas. Chiang *et al.* [8] gave an overview of mobile mapping systems, including sensor fusion, development of carrying platforms, and in-/outdoor applications. The paper discusses future perspectives, e.g. creating HD maps and autonomous mapping. Kalvoda *et al.* [9] assessed MMS data using total station and GNSS surveys as reference. They focused on two data groups; terrain points and above terrain points. Toschi *et al.* [10] presented a methodology to evaluate the accuracy of a Riegl VMX-450 MMS applying non-parametric statistical models in order to achieve a robust estimation of error dispersion. They used TLS and photogrammetry data as references. Laser scanners can also be integrated into an Unmanned Aerial System (UAS) ensuring extreme flexibility and data acquisition speed. Salach *et al.* [11] investigated the digital terrain models derived from UAV (Unmanned Aerial Vehicle) photogrammetry and UAV LiDAR. The test area was covered by vegetation; they proved how effectively the elevation model can be derived from laser scanned data sets. They used GNSS RTK survey, and previous airborne laser scanned data as reference. Sofonia *et al.* [12] discussed the effects of flight parameters on the UAV LiDAR data sets. They concluded that altitude has the highest effect on accuracy, while ground sampling distance shows a correlation with the combination of the Sampling Effort Variable (SEV) and Effective Density Rate (EDR) defined by the authors. For some particular applications, the accuracy and point density (point spacing) provided by MMS is not sufficient (the movement of the platform has to be continuously measured); therefore the usage of Terrestrial Laser Scanner (TLS) is recommended. Commercially available laser scanners capture point clouds with high density (point spacing is around 1mm@10m) and high accuracy (around 2 mm for phase based scanners) [13]. Some top-of-the-line scanners are even capable of reaching 1 mm ranging accuracy. In order to effectively create data sets prepared for simulation applications, pre-processing is needed that involves selecting the area of interest, noise removal, and classification of road points. Extracting road surface points from point clouds is a rather complex procedure. Yadav and Singh [14] showed potential solutions using MMS point clouds acquired on rural roads with pavement edges difficult to be identified (no raised curb). They propose a 2-stage method; first planar ground surfaces are extracted, then, secondly, they assess

the global road properties, i.e. topology, smoothness, and the surface's radiometric response to the laser beam. Boyko and Funkhouser [15] developed an automatic method to separate road surfaces in urban environment. Their solution is based on approximate road network map data, and enables information extraction from non-structured point cloud; it requires dense sampling and low noise to detect curb features. Balado *et al.* [16] presented a procedure that segments a road network in MMS data using deep learning algorithms. Miyazaki *et al.* [17] proposed a line-based region growing method to detect planar structures with precise boundaries, such as road surfaces. They were able to detect more than 98% of the curb points. The OPENX standard family of ASAM (Association for Standardization of Automation and Measuring Systems) incorporates the standard systems relevant to vehicle simulations; it has two static contents, OpenDrive and OpenCRG and also contains OpenSCENARIO for the description of dynamic content of driving and traffic. OpenCRG is the focus of the current paper. OpenCRG is a file format and source code for a detailed description of road surfaces; such detailed models can support tire/vibration/suspension/driving simulations. OpenCRG represents the first (Street Layer) of the PEGASUS 6-Layer Model [18]. CRG stands for Curved Regular Grid, it describes the road surface in a regular grid along a reference line, typically the centerline of the road. The main advantage of the CRG model is the high memory efficiency and the low computation time that are relevant factors when using the model in a simulation environment. Su *et al.* [19] derived OpenCRG models from MMS data; their proposed modeling procedure is demonstrated on a real highway data set. The first step is focusing on extracting 2D geometry. The data is divided by road geometry (straight or arc), then an irregular grid is defined to all segments that contains the elevation values. As a next step, a regular grid is interpolated, finally, the CRG files are created. Ori *et al.* [20] showed, by using Matlab OpenCRG tools and GUI maker, how a spatial road surface with a pothole can be simulated with variable geometric parameters (road length and width, location and dimension of pothole). Schwab and Kolbe [21] investigated system development and testing challenges of automated driving. They defined lane-level spatial road model requirements and revealed the shortcomings of current standards. Barsi *et al.* [22] derived the OpenCRG model from a TLS survey of a straight road segment and emphasized how the TLS technology enables creating high accuracy, high-resolution elevation models. The research gap our paper intends to fill is as follows: different types of point clouds with different levels of quality (e.g. point spacing, ranging accuracy, noise) can be the basis of CRGs. Particular vehicle applications, such as vehicle dynamics simulations, require high density, high accuracy CRGs, while others have lower demands. Such requirements have a direct effect on what technology is to be used and what data acquisitions parameters have to be applied. Time of data acquisition and processing

highly depends on the technology and on the raw data set, reasonable management of resources is necessary to achieve optimal workflow. Our paper discusses the data acquisition methods and the resulting datasets, focusing on their further processing that leads to CRG models. The paper is structured as follows. Section II describes the method to gather data for modeling road surfaces with various instruments. It presents the ZalaZONE Proving Ground's braking platform measurements in subsection II-A. The workflow of the OpenCRG model realization is described in subsection II-B. Subsection II-C describes the automation of the calculation for speeding up the procedure. Subsection II-D presents the results from the different technologies. Section III demonstrates a use case for the created OpenCRG road surface models in the automotive industry and mentions other potential applications. Conclusions are summarized in section IV.

II. ROAD MODELING

Due to technological limitations, there is always a difference present between the designed and the as-built surface. These discrepancies are generally not relevant in everyday practice. Current asphalt finisher machines ensure sub-centimeter accuracy. However, there are some roads where a millimeter-level survey is needed, such as in the case of a test track. We carried out investigations for point clouds from different sources to demonstrate the OpenCRG modeling capabilities; the instruments that provided the point clouds are Surphaser400 TLS, Leica Pegasus 2 MMS, DJI Phantom 4 RTK UAV (imagery), YellowScan Mapper laser scanner mounted on DJI Matrice 210-v2 UAV (LiDAR). MMS data was processed in Leica Pegasus:Manager environment. The 5 swaths of UAV Lidar data were processed by OxTS Navsuite and Scanfly Smart Processing Lidar suites, while Pix4D was used for UAV imagery processing (78 images; 5472×3648 pixels each).

A. MEASUREMENT AT ZalaZONE PROVING GROUND

A new automotive proving ground, called ZalaZONE Proving Ground (<https://ZalaZone.hu/en/>), was constructed in Hungary, near the city of Zalaegerszeg. This test track is specially designed to be capable of serving technological testing and proving processes of fully or highly automated vehicles. The more, the mission of ZalaZONE is not limited to pure commercial use. It is also a major goal to lay the foundation for research and innovation activities in national and international cooperation with universities, research centers, and industrial participants [23]–[25].

The braking platform (Fig. 1) is brand new and one of the best in Europe. The braking surfaces are separated into 8 different lanes: a chessboard surface, high friction, low friction, blue basalt, asphalt ($\mu = 1$), polished concrete, asphalt ($\mu = 0,8$), and an aquaplaning basin. These characteristics allow braking maneuvers, needed for both vehicle dynamic and ADAS/AD tests (Advance Driving Assisted Safety / Autonomous Driving).

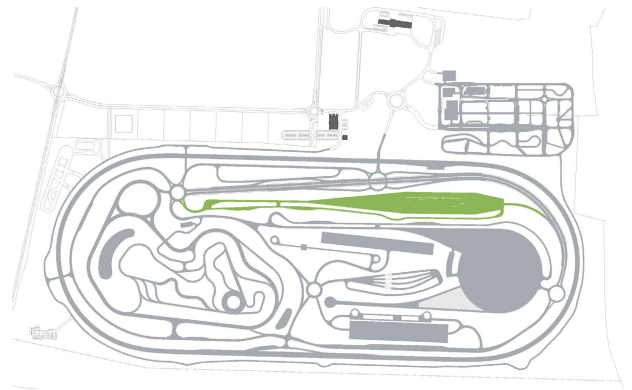


FIGURE 1. Braking platform at ZalaZONE proving ground (source: www.avizalazone.com/testing-and-track) (green colored).



FIGURE 2. TLS survey-surphaser 400 laser scanner (aquaplaning basin).

Test tracks, especially special track units, e.g. braking platforms are to be surveyed with extreme accuracy and resolution in order to assess their geometry. Laser scanning of the aquaplaning track has been carried out; the track starts and ends with a slope, and its basin is a 180 m long straight and horizontal segment that can be inundated by water. Surphaser 400 was used for the survey that has 1 mm ranging accuracy (Fig. 2). Evenly distributed sphere markers were used as tie points that enabled to join the point clouds captured from the different scan positions. Since 200 m long segment was surveyed, selected tie points were used as ground control points and were continuously measured by the total station that ensured rigid network geometry and enabled transforming the point cloud to the local coordinate system (georeferencing).

Besides creating the CRG model, the longitudinal section (Fig. 3) and cross-sections in every 5 meters have been derived. The results show the differences compared to the “as-designed” model. The captured point cloud enables obtaining a deviation map that shows minor discrepancies and demonstrates the global quality of the road segment. (Fig. 4)

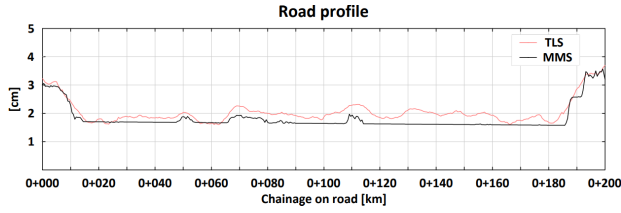


FIGURE 3. TLS-MMS longitudinal section (aquaplaning basin).

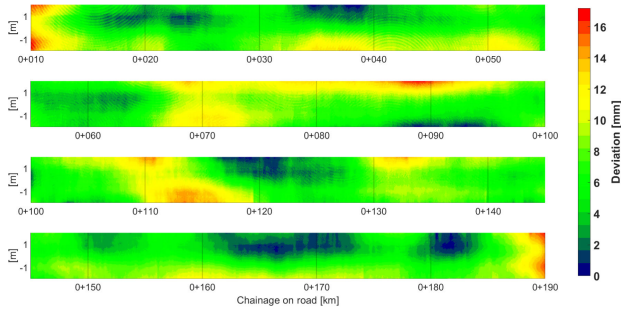


FIGURE 4. TLS-Designed deviation map [mm] section 0+010.00-0+190.00 km (aquaplaning basin).

B. DERIVING OpenCRG - WORKFLOW

Prior to OpenCRG modeling, the main task is to derive the axis of the particular road or lane segment. This can be stored in OpenDrive. The structured elevation data of OpenCRG are in a coordinate system perpendicular to the axis. Automatic extraction of lane information can be carried out considering certain constraints, e.g. by border signs of the lanes. This was not available in the discussed case, but, since the source point clouds were georeferenced and the designed geometry was known, the track geometry had been derived. Knowing the length and width of the area of interest, the point cloud segment to be investigated can be extracted. The method of CRG modeling depends on the horizontal track geometry; different calculations are needed for straight and curved segments.

In the case of straight road segments, the procedure of creating the CRG model is as follows. Since curvature is 0 in this case, the start and endpoint coordinates and road width are the only required parameters of the particular road segment. Additionally, two parameters defining the grid spacing are needed, the default OpenCRG values are: $u_{inc} = 0.01$ m, $v_{inc} = 0.01$ m. Therefore the grid is defined parallel to the road axis with “ u_{inc} ” distance, and perpendicular to the road axis with “ v_{inc} ” distance for the entire road segment. The steps are as follows: let “ x ” be a row vector that goes from 0 to the end of the road axis with an increment “ u_{inc} ”, and let “ y ” be a column vector that goes from negative half of the road width to the positive half of the road width with an increment of “ v_{inc} ” (Eq. 1).

$$x = [0, u_{inc}, 2 u_{inc}, \dots, i u_{inc}], \quad i = \frac{|u|}{u_{inc}},$$

$$y = [-\frac{v}{2}, -\frac{v}{2} + v_{inc}, -\frac{v}{2} + 2 v_{inc}, \dots, j v_{inc}], \quad j = \frac{|v|}{v_{inc}}. \quad (1)$$

Two matrices, “ X ” and “ Y ” are composed by the vectors; rows of “ X ” are the “ x ” vectors, while columns of “ Y ” are the “ y ” vectors. In order to make the grid’s “ x ” rows parallel to the road axis, rotation is to be applied. The rotation angle is the angle between the “ u ” vector and the x axis. The origin of the vector is the starting point of the road axis. Finally, the array is translated by the origin of the road axis (Eq. 2).

$$\alpha = \text{atan2}(y_1 - y_0, x_1 - x_0)$$

$$X' = X \cos \alpha - Y \sin \alpha$$

$$Y' = X \sin \alpha + Y \cos \alpha \quad (2)$$

where:

$$x_0, y_0 = \text{axis start}$$

$$x_1, y_1 = \text{axis end}$$

Elevation values have been interpolated to the grid points applying the road surface model; options are available for linear, nearest neighbor, or cubic interpolations. Elevations have been computed by linear barycentric interpolation. Elevation can be interpolated in one triangle of the mesh model by the center of gravity coordinates (Eq. 3).

$$w_1 = \frac{(y_2 - y_3)(x_p - x_3) + (x_3 - x_2)(y_p - y_3)}{(y_2 - y_3)(x_1 - x_3) + (x_3 - x_2)(y_1 - y_3)},$$

$$w_2 = \frac{(y_3 - y_1)(x_p - x_3) + (x_1 - x_3)(y_p - y_3)}{(y_2 - y_3)(x_1 - x_3) + (x_3 - x_2)(y_1 - y_3)},$$

$$w_3 = 1 - w_1 - w_2,$$

$$z = z_1 w_1 + z_2 w_2 + z_3 w_3. \quad (3)$$

where:

$$w_1, w_2, w_3 = \text{weight values}$$

C. AUTOMATION OF THE CALCULATION

This work phase has been automated in order to speed up the interpolation procedure. Our software routine needs only the parameters as follows: road surface model location, start point, endpoint, road width, file saving route, and the default values of $u_{inc} = 0.01$ m, $v_{inc} = 0.01$ m. Road curvature and arc centerpoint are known; to create the curved grid, the angle between the start and endpoint is to be calculated (Eq. 4). Grid definition is based on polar coordinates; origin is set to the origin of arc, then the angle of “ ϕ ” is to be defined that results in “ u_{inc} ” arc length along the road axis (Eq. 5).

$$\theta_{min} = \cos^{-1} \frac{y_{P1} - y_{PO}}{R}, \quad \theta_{max} = \cos^{-1} \frac{y_{P2} - y_{PO}}{R}. \quad (4)$$

where:

$$PO = \text{arc origin}$$

$$P1, P2 = \text{start point, endpoint}$$

$$\theta_{min}, \theta_{max} = \text{min. and max. angle}$$

$$\phi = \frac{u_{inc}}{R} \quad (5)$$

where: “ ϕ ” angle, “ R ” radius “ u_{inc} ” arc length

With “ ϕ ” angle value and its multiplication, the road segments in “ u_{inc} ” distance can be defined. Then the

segments parallel to the road axis are to be derived that are in “ v_{inc} ” distance (and its multiplication) along “ s ” road width. Polar coordinates of points stored in matrix “ A ”:

$$r = [R - \frac{s}{2}, R - \frac{s}{2} + v_{inc}, R - \frac{s}{2} + 2 v_{inc}, \dots, R - \frac{s}{2} + i v_{inc}],$$

$$i = \frac{|v|}{v_{inc}},$$

$$\theta = [\theta_{min}, \theta_{min} + \varphi, \theta_{min} + 2\varphi, \dots, \theta_{min} + j\varphi],$$

$$j = \frac{\theta_{max} - \theta_{min}}{\varphi},$$

$$A = \begin{bmatrix} r_{11}, \theta_{11} & \dots & r_{i1}, \theta_{i1} \\ \vdots & \ddots & \vdots \\ r_{1j}, \theta_{1j} & \dots & r_{ij}, \theta_{ij} \end{bmatrix} \quad (6)$$

if “ r ” is evenly divisible by “ v_{inc} ”, and, if “ θ ” is evenly divisible by “ φ ”.

Polar coordinates then can be transformed to cartesian coordinates:

$$x = r \cos \theta, \quad y = r \sin \theta,$$

$$A = \begin{bmatrix} x_{11}, y_{11} & \dots & x_{i1}, y_{i1} \\ \vdots & \ddots & \vdots \\ x_{1j}, y_{1j} & \dots & x_{ij}, y_{ij} \end{bmatrix} \quad (7)$$

From here, the interpolation is the same as explained previously; “ z ” elevation values at “ x ” and “ y ” coordinates can be calculated on the mesh model by linear barycentric interpolation. Inputs of the interpolation routine are: road surface model location, start point, endpoint, arc origin, road width, file saving route, and the default values of $u_{inc} = 0.01$ m, $v_{inc} = 0.01$ m.

D. ASSESSING THE DERIVED MODELS

Such OpenCRG models represent both the potential and the risk factors of the different technologies. TLS provides high density and high accuracy point clouds (Fig. 5), but acquiring and processing data is rather time-consuming; it cannot be considered as an effective technology for surveying long road segments. On the other hand, MMS and UAV capture the geometry of huge areas rapidly, but with lower accuracy; the application requirements define which technology is the appropriate one in the particular case. The point density/spacing of the investigated MMS dataset does not meet the accuracy requirements of the vehicle dynamics simulations of which objective is to derive the digital twin of the vehicle’s suspension system (Fig. 6). UAV laser scanned point cloud and that of derived from UAV imagery has about 1 cm noise which is expected but post-processing is needed (e.g. smoothing) to obtain surface models adequate to vehicle simulations with less accuracy demands (Fig. 7, Fig. 8).

III. USE CASE EXAMPLE FOR AUTOMOTIVE INDUSTRY

The automotive industry relies more and more on sophisticated testing and validation methods like Vehicle-In-the-Loop (VIL) [26] and Scenario-In-the-Loop (SCIL) [27], where the line between reality (real hardware and test

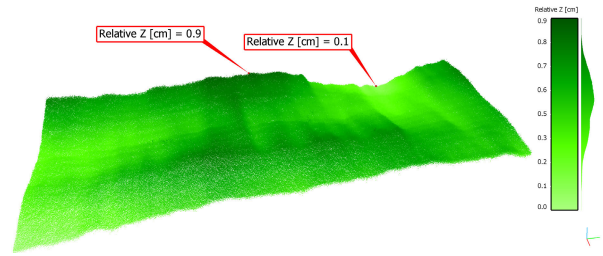


FIGURE 5. TLS point cloud detail.

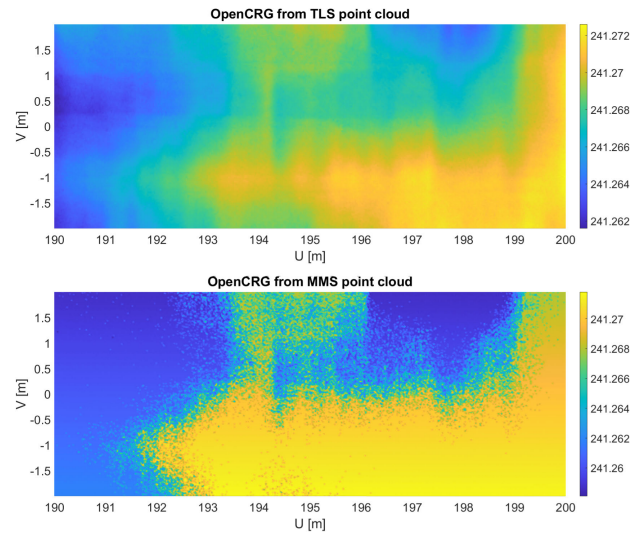


FIGURE 6. OpenCRG from TLS and MMS point cloud (aquaplaning basin).

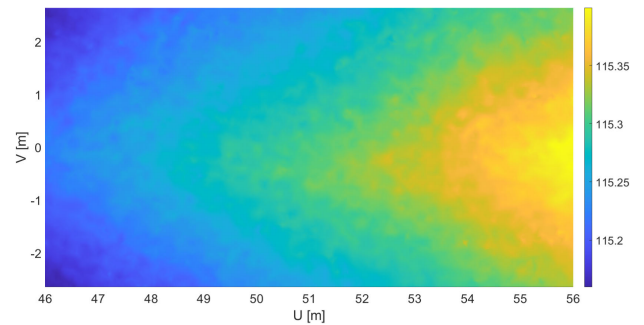


FIGURE 7. OpenCRG from UAV point cloud (Székesfehérvár).

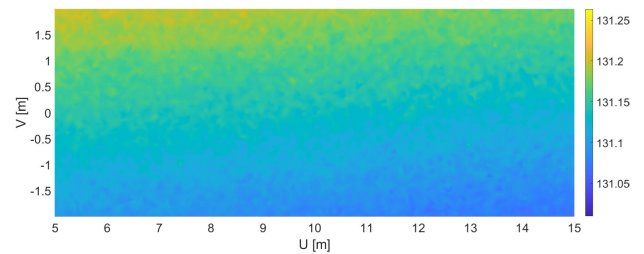


FIGURE 8. OpenCRG from UAV laser scanned point cloud (M0 highway).

vehicle) and virtuality (multiple co-simulation) is blurred during the development of highly automated vehicles. These techniques require so-called digital twins, which are the virtual representations of the targeted object in a test scenario. As these tests are commonly aimed at complex systems, not

only the main object (the tested vehicle) is required to have a digital twin, but the whole environment must be represented with an appropriate level of details regarding the primary goal of the test. The need for a high detail environment is especially true in vehicle dynamics or in tests where vehicle dynamics significantly impact test results. Creating these environments and the creation of realistic traffic needs sophisticated measuring solutions like the use of UAVs [28] to realize digital twins of the vehicles and the environment for co-simulations [29]. With the proposed method of creating OpenCRG of a chosen road, a high-quality digital twin can be realized of any particular road surface.

One use-case of the created OpenCRG can be to realize a decent digital twin of a particular vehicle’s suspension. Creating a digital twin of a vehicle suspension to represent an actual vehicle’s dynamics in the virtual world is challenging without disassembling the suspension itself for measurement purposes. As car manufacturers do not provide suspension characteristics and these characteristics are changing with the wear of parts, a method was designed [30] to discover these characteristic parameters with the help of a genetic algorithm running in Matlab interfaced with an industrial level automotive software IPG CarMaker [31].

The method is as follows: First, an actual measurement needs to be done, where the vehicle’s vertical accelerations are measured with high frequency while the vehicle drives on a bad quality surface or goes through something with a decent excitation for the suspension (e.g. a speed bump or a pothole). The recorded vertical acceleration must be processed to filter out measurement noises. This processed data is the reference signal for the genetic algorithm, which will run a CarMaker simulation in every iteration, where the virtual environment contains the same excitation as it was present in the real measurement. The characteristic points, tuned by the genetic algorithm, were constrained with specific values of forces to maintain reality and avoid crashing the simulation. The genetic algorithm can be run and fine-tuned until the required level of accuracy is reached. The genetic algorithm’s cost function was the Euclidean distance of the measured and the simulation result signal. Fig. 9 presents the operation of the genetic algorithm with IPG CarMaker.

The vehicle used for the method was a Ford Mondeo MkIV (2012) estate (facelift). It has a Macpherson type front suspension and a multi-link rear suspension. For optimal accuracy, the virtual vehicle in CarMaker was set up just like the actual vehicle, using its parameters, summarized in Table 1, even considering the weights of the driver and the passenger. The tire size of the simulated vehicle was also chosen to be identical to the EGO vehicle (205/60-16).

The created digital twin of the road can be used for the genetic algorithm to represent the real measurement’s excitation to the vehicle with a high level of detail. It is also an inevitable component for validating the resulting suspension characteristics. Fig. 10 depicts the simulation results where the suspension characteristics were discovered with the method (the tuning was done on a speed bump and

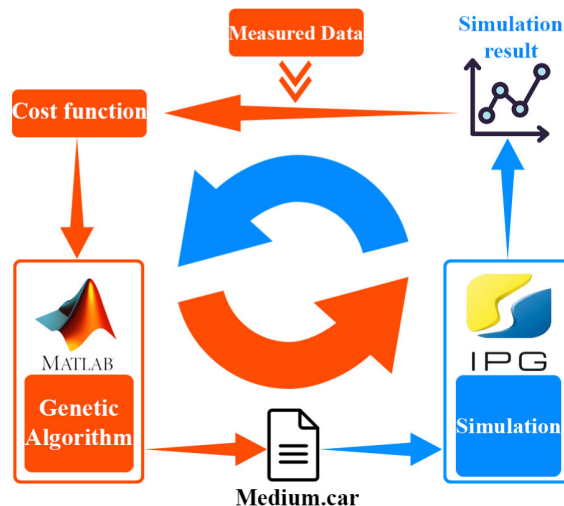


FIGURE 9. Loop of the genetic algorithm.

TABLE 1. Physical parameters of the vehicle.

Parameter	Value
Length	4837 mm
Width	1886 mm
Wheelbase	2850 mm
Weight	1575 kg
Front track	1588 mm
Rear track	1605 mm
Driver’s weight	80 kg
Passenger’s weight	70 kg

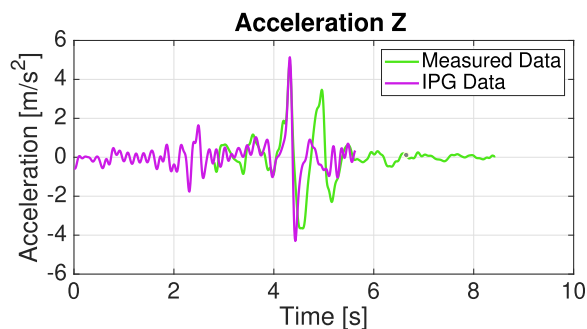


FIGURE 10. Measured and simulated vertical accelerations on a CRG road model.

not on the CRG), and the simulation was run on the OpenCRG road. A measurement was done on the same road where the OpenCRG was created for validation.

As results show, the method created a decent suspension characteristic (see Fig. 11 and 12), and the high-quality OpenCRG provides an excellent validation to compare the real-life measurement with the simulation. The genetic algorithm could be fine-tuned more to get even more accuracy.

Another test was done on two separate CRGs to create a comparison between two technologies for point cloud creation. The tuned vehicle’s suspension was tested on an MMS-based CRG and on a TLS based one. Simulations were done again in CarMaker with the same settings for both CRGs, and the maneuvers and route were identical. The

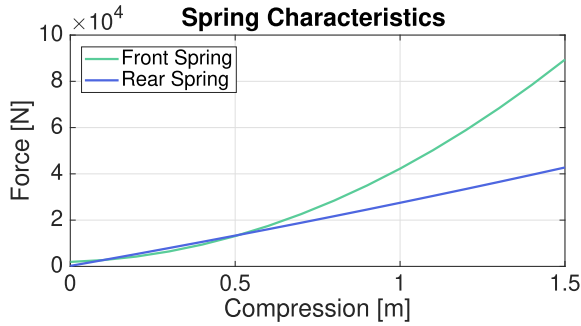


FIGURE 11. Spring characteristics generated by the genetic algorithm.

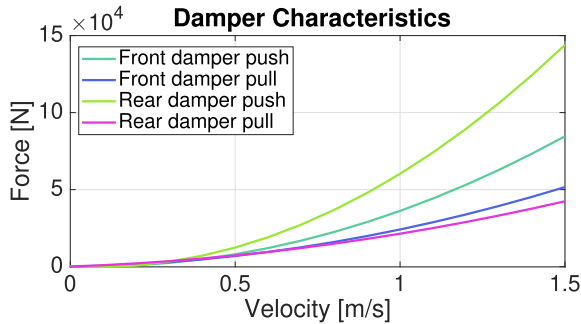


FIGURE 12. Damper characteristics generated by the genetic algorithm.

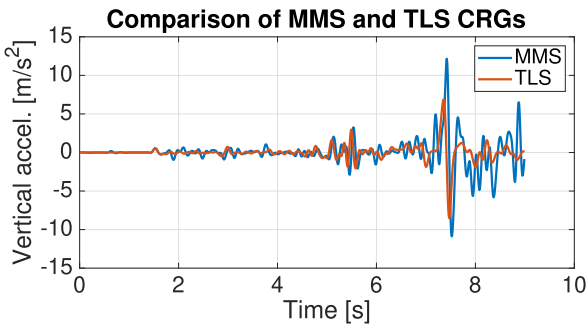


FIGURE 13. MMS and TLS based CRG simulations.

resulting accelerations from the road excitations are depicted in Fig. 13.

Results clearly show that the MMS CRG produces higher accelerations in cases where the excitation is easily identified. It also produces more oscillations on surfaces, where the TLS produced much lower values. The result is not surprising, as the TLS CRG has a higher resolution and lower noise. Such a difference can significantly impact simulation results as results proved it, especially in cases where the road surface has an even more significant impact on the output (e.g. vibration simulations). The difference between the two CRGs is even more conspicuous if the results are analyzed in the frequency domain. The power spectral density shows the difference clearly in Fig. 14.

Another advantage of the CRG is that multiple automotive software supports it by default (e.g. IPG CarMaker, Vires [32]), making it easy to import and just run the simulation. It is also possible to create a 3D object from the surface, allowing game engines like Unity 3D [33] or Unreal Engine [34] to apply the CRG, which is also more and more

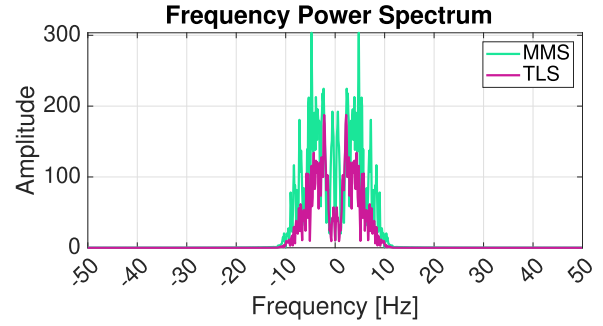


FIGURE 14. Spectral density of the MMS and TLS based CRG simulations.

widely used by the automotive industry for simulation and visualization purposes.

Many other use cases can benefit from the usage of CRGs, as there are situations where the most negligible oscillations caused by the road surface can have an impact on results (e.g. virtual image sensors on trucks, where the cabin has its own suspension and its dynamics are highly affecting sensor results, simulation of noises and vibrations).

The use cases are not limited strictly to testing and validation. Researching and developing new models can benefit from the high-quality road models created with OpenCRG. With the help of the designed road surface, engineers can further analyze and develop tire or suspension models [35] without using real hardware, relying only on highly detailed simulations.

It is also possible to extend the measurement of a road surface with artificial potholes or any additions to the road surface. Having precise models in a virtual environment can support testing algorithms responsible for road surface irregularity detection [36] without expensive hardware. By manipulating these OpenCRG models, engineers can further analyze any road irregularities affecting passenger comfort, suspension optimization, and ensuring optimal vehicle handling and safety. The created digital twin of proving grounds and other real-world roads can be also shared in various databases like SafetyPool [37] to provide high detailed models for scenario-based testing for engineers around the world.

IV. CONCLUSION

The investigations proved that cutting-edge data acquisition methods are capable of providing accurate, high-resolution point clouds that support vehicle dynamics simulations. Such simulation environments require CRG models as input that can be derived from point clouds. Point clouds are primary data outputs of multiple data acquisition technologies; current paper discusses terrestrial, mobile, and UAV laser scanning. All of these have different strengths and shortcomings, the application requirements determine which one is recommended to be used. Having a CRG available for vehicle simulations requires a complex workflow of which stages can be fully or partly automatized that enable achieving the required models rapidly with the highest accuracy. The created high-accuracy models can have a high impact on

many use cases. Such models can effectively support creating the digital twin of a vehicle suspension. The paper presented a method for digital twin realization of vehicle suspension characteristics relying on a genetic algorithm embedded in vehicle dynamics simulation and the validation with an OpenCRG model as a use case. The complex surface of the road can significantly affect the excitation of vehicle dynamics, and as a result, it can influence the results of a parameter tuning or validation. Comparing the MMS and the TLS based CRG roads showed that the higher resolution of the point cloud and the derived CRG road surface is highly beneficial for vehicle dynamics simulations. The lower resolution creates more noise than the higher, and the critical excitations lose power, while additional oscillations appear on smoother surfaces, which is significant in vehicle dynamics.

Due to remarkable interest from the vehicle testing experts, we intend to continue our research in this area. Regarding the road surface geometry, the future research is twofold: creating high accuracy point clouds from UAV measurements and increasing the level of automation of the point cloud processing. There is reasonable potential in enhancing geometric accuracy and reduce noise in point clouds acquired by UAV LiDAR systems; applying multiple ground control points, capturing overlapping LiDAR swaths. Point cloud processing development includes automated segmentation of road surfaces, selection of road axis, and deriving the CRG models.

The presented use case showed how important it is to have a high-resolution CRG for vehicle dynamics simulations or methods based on simulations, where the road surface is required. Future work on the use case can be an improved measurement, using sensors attached to each wheel. With such a sophisticated measurement, the genetic algorithms reference signal is much closer to the reality excited by the actual road surface, and the simulation will benefit more from the high-resolution of the created CRG.

As an important future task, the presented methods in this paper will be compared with other algorithms in the scope of performance, time- and space complexity with the analysis of the resulting accuracy.

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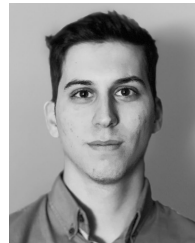
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