# Structured Paint for Road Digitization

Alejandro Badolato[1], Juan de Dios Sanz[2], Javier Agustín[1]

***Abstract*— A novelty feasible and affordable infrastructure adaptation for supporting ADAS is proposed. The adaptation consists in deploying 6mm high paint drops along the road that encode data in a similar way of the Braille system (the reading system for Blind). The track deployed along the center of the lane is black color and remains invisible to regular drivers. It encodes a univocal pseudo random code that digitizes every 10cm of road stretch. A linear array of Mm-wave radars installed in the under body of the vehicle along a transversal axis obtains a high-detail three-dimensional image of the surface's asphalt while the vehicle is moving and reads the encoded track. As a result, the vehicle is located with 1cm accuracy in a reliable, secure, and low-cost manner. This precise vehicle location is crucial for achieving a progressive Intelligent Speed Assistant (ISA) in urban scenarios, for improving reliability of the Automatic Lane Keep Assistance Systems (ALKS) and for supporting unmanned platooning.**

***Index Terms*— ADAS, LDW, ALKS, Smart Infrastructure, Radar Positioning System, Vehicle Localization, Unmanned Platooning, Vehicle perception**

## I. Introduction

PRECISE location and orientation of vehicles is a must for reliable Advanced Driver Assistance Systems (ADAS) and Autonomous Vehicles (AVs). Current ADAS and AVs typically rely on stereo optical cameras, GNSS, IMUs and LIDAR sensors for these purposes. Optical cameras can estimate the lateral displacement and the orientation of the vehicle into the lane by detecting the land markings. Unfortunately, the reliability of optical cameras for detecting land markings depends on a good retro-reflectivity of land markings and favorable sunlight conditions. Wet surfaces, bad maintenance of land markings, snow, fog or heavy rain can reduce significantly the reliability of camera detection. GNSS provides a global positioning but the lack of accuracy and the low availability due to the absence of a clear line of sight with the satellite constellation under certain situations make them unsuitable for vehicle guidance. IMUs can improve GNSS accuracy but this enhancement is not enough for guiding a vehicle safely. Most AVs developers are also relying on LIDAR and 3D maps for location purposes especially at urban environments. In these areas, GNSS accuracy is typically poor, but surroundings have a lot of recognizable objects like buildings or traffic signals that create a signature which is easy to identify. Once the vehicle has scanned the environment, the computer tries to match the 3D cloud detection with the 3D map stored in memory. When the match is achieved, the vehicle performs triangulations with known objects on the map and can determine its position and orientation precisely. However, generating 3D maps is very costly. The tasks of object identification and the pinpoint of these known objects that will be used for triangulation have to be done by operators. Furthermore, maps must be updated continuously due to a time-changing environment. As a result, these maps can only be available for a limited set of constrained areas. Under favorable weather conditions, LIDAR positioning is a reliable technique with few centimeters accuracy. Nevertheless, big size objects such as buses or trucks placed near the sensor can block LIDAR rays avoiding an appropriate environment scan. Ray blocking, snow, fog, or heavy rain significantly reduce LIDAR positioning reliability.

Infrastructure adaptation by deploying magnets on the road has been explored in the past for supporting AVs localization. This adaptation allows to measure the lateral shift from the center of the lane [1]. However, the proposed solution has been commercially discarded due to a high cost of implementation. Another solution where infrastructure is used as a reference for locating purposes has been exposed in [2-3] where a Ground Penetration Radar (GPR) has been used for reading a map of the soil. One of the difficulties of this method is that soil maps change in time due to the variable content of moisture.

In this paper we present a novelty method of vehicle positioning and orientation based on a simple infrastructure adaptation called Radar Positioning System. RPS consists in deploying a track of raised land markings (also known as structured paint) that encode information in a similar way of the Braille system (the reading system for blind). The track encodes a univocal pseudo random code that digitizes every 10cm of road stretch. This new road map provides a well-known reference to vehicles that does not change over time. A linear array of Mm-wave radars installed in the under body of the vehicle along a transversal axis obtains a high-detail three-dimensional image of the surface's asphalt while the vehicle is moving and reads the encoded track. As a result, the vehicle is located with cm accuracy in a reliable, secure, and low-cost manner. Furthermore, vehicle orientation against the

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longitudinal axis of the lane is achieved with few degrees error.

## II. Road Digitization

Nowadays, structured paint is deployed worldwide in many roads for improving visibility in rainy conditions. 3D land markings have attached glass beads on their surface as shown in Fig. 1 which reflect lights in all directions improving retro-reflectivity. They are typically 25mm in diameter and 6mm high and are made of thermoplastic or cold plastic. Thermoplastic is a soft material and has the advantage that, when glass beads are removed and the retro-reflectivity is degraded, new glass beads can emerge from inside when the material is getting worn out. Cold plastic 3D paint drops are 90% plastic and 10% catalyst. When both are mixed, a chemical reaction is performed and in less than 5 minutes the paint drop gets extremely hard and is fixed to the asphalt. They can be applied at lower temperatures than thermoplastic ones, however, they are very hard and, when glass beads are gone, the cold plastic remains without wearing down and the glass beads from inside cannot emerge to the surface. Structured paint is currently printed by trucks at speeds up to 16 km/h.

**Fig. 1.** Structured landmarks and a two-component cold-plastic printing machine.

We propose to digitize the infrastructure by deploying an encoded track with cold-plastic structured paint along the center axis of the lane. Data is encoded in a row along a transversal axis of the road by associating different combinations of 3D paint drops to different logical levels as shown in Fig 2.

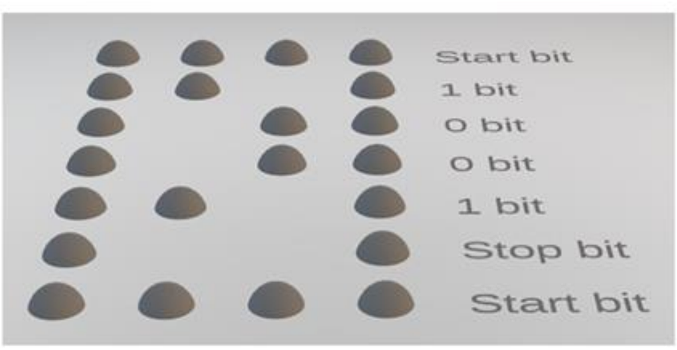


**Fig. 2.** Proposed encoding pattern.

While the inner columns encode the different logical levels, the outer columns provide a redundant clock signal. The paint drops are 45 mm in diameter and 6 mm high and the gap between two consecutive longitudinal or transversal axis is 90 mm. In this way, the 4-column track is 315 mm wide. They can be of any color. However, we propose to deploy it in black color for remaining invisible to regular drivers and prevent any interference with other landmarks. In this way, regular drivers will only perceive a slight noise when changing the lane.

The track is composed by a unique sequence of codes where every code corresponds to a stretch of few meters long. Once a complete code is read, the vehicle is located with cm accuracy and well oriented. Then, the position is updated on each bit every 9 cm if reading is according to the expected sequence recorded in memory.

To avoid repeated codes, an appropriate addressing size must be defined. Earth surface, including oceans, and poles, is 510.1 million of square kilometers. According to (1), every square cm of the Earth surface can be univocally encoded by using 63 bits.

$$Log_2(510{,}1 \cdot 10^6\ km^2) = Log_2(5{,}1 \cdot 10^{18}\ cm^2) = 62 \qquad (1)$$

Considering that roads are only a small portion of the Earth surface, 64-bit word length can address the complete lane network worldwide. A single 64-bit code is deployed along a 6 meters lane stretch which corresponds to an area of several squared meters. This means that there will be also enough spare codes available for re-asphalt tasks and future infrastructures.

To simplify the deployment, a pseudo random code will be printed in the surroundings of the central axis of the lane. Every printing truck will be provided with a unique pool of codes and will print those avoiding repeated codes. Once the lane is adapted, a vehicle with calibrated odometry will run over the track and will generate a road map storing the code sequence and the shape of the road thanks to data from the encoders of the wheel and the steering wheel and a GNSS receiver. The potential misalignment of the track respect the central axis of the lane will be also detected by optical cameras and stored as part of the roadmap. This road map information is low-weight data, and the global lane network would fit in a single flash memory. Unlike GPR or Lidar roadmaps, it will remain stable and will not change in time. If the infrastructure is modified, new available free codes will be used.

The length of European lane-network, including highways, main and secondary roads, is about 5,265,000 Km. Considering a printing speed of 16 km/h, 50 trucks working 24 hours/day and 365 days/year can encode the complete lane network in less than 1 year. However, this is not a realistic number. Infrastructure adaptation will take much more time, but a progressive approach can be tackled starting at principal highways and main roads.

The costs of painting the encoded track are negligible compared with the costs afforded by infrastructure operators in maintenance tasks. Due to the encoded track is deployed along the center axis of the lane and to the extreme wear resistance of two-component cold-plastic 3D paint drops, they will last, at least, more than 15 years. In this sense, no maintenance is expected since re-asphalt tasks should be required first. Small errors on the track are not an issue due to the decoding algorithm of the sensor has the advantage of reading a known sequence.

## III. READING A DIGITIZED ROAD

The encoded track can be read by onboard sensors able to obtain a 3D image of the road surface while the vehicle is moving. Time of Flight sensors like lidars, infrared cameras or mm-wave radars are suitable for this purpose. Optical cameras equipped with AI processing can also decode the 3D landmarks.

TABLE I
SENSOR TRACK-READING CAPABILITIES COMPARISON

| | Range accuracy | Scan time | Sunlight reliability | Dust reliability | Low cost |
|---|---|---|---|---|---|
| Optical | - | ✓ | ✓ | ✓ | ✓✓✓ |
| Lidar | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓ |
| Infrared | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ |
| mm-wave radar | ✓✓✓ | ✓✓✓ | ✓✓✓ | ✓✓✓ | ✓✓ |

Radar sensors have many advantages for reading the encoded track in comparison with other sensors. Radar signal is reflected over any type of surface even on those that present a low optical retro-reflectivity or are covered by dust. Furthermore, radar reliability does not depend on light conditions and works well under heavy rain or fog conditions. These properties make radars ideal for non-clean outdoor environments. Radars in the millimeter band [30-300GHz] have been typically used for space exploration and security applications [4-7] due to a high cost of components. Thanks to the technological advances, low-cost sensors embedded in a single chip are currently available in the market enabling multiple new applications. Nowadays, Continuous Wave (CW) mm-wave radars are especially used in the automotive sector [xx] for environment sensing. They are classified for short, medium, and long-range detection depending on the distance to the target. Typical numbers for short, medium, and long range are 1m, 15m and 150m respectively. The detection of the 3D paint drops is considered as ultra-short-range application since the typical distance from the under body of the vehicle to the asphalt layer is about 15 cm. This short distance is challenging for a CW radar due to the electromagnetic coupling existing between the TX and the RX antenna that increases the noise floor near to zero Hz. To deal with this limitation, ultra-wideband radars must be used.

A first radar sensor prototype has been developed by using four 120 GHz radar frontends [8]. Each radar transmits 15 GHz of bandwidth every 100 us for measuring the distance to the floor with mm accuracy.

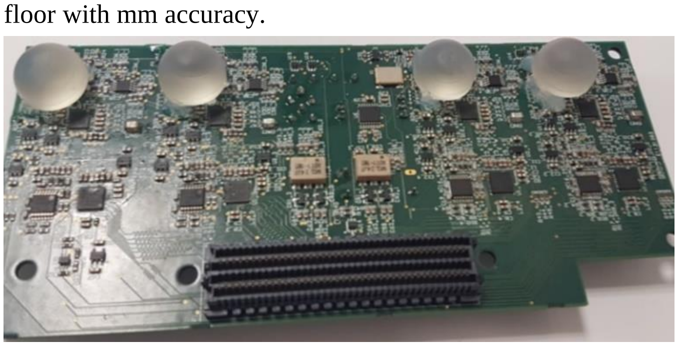

**Fig. 3.** Four-radar sensor prototype

At mm-wave frequencies, plastics are permeable and, it is possible to use them for constructing lenses [9]. A 15 mm diameter lens attached to each radar chip, has shown in Fig. 3, provides an aperture of 6 degrees resulting in a 1 cm diameter circular scanning spot over the floor. In this way, when a radar sensor is pointing over a 3D paint drop, the measured distance is reduced by 6mm. The prototype has been installed in the underbody of an electrical toy-vehicle scaled 1:4 from real dimensions which has run over a track made with 6mm high paint drops. Each channel includes a radar frontend, a PLL for signal generation, an amplifier, and an analog to digital converter. The purpose of this experiment is to demonstrate the ability of the radar sensor for reading a two column 3D paint drops.

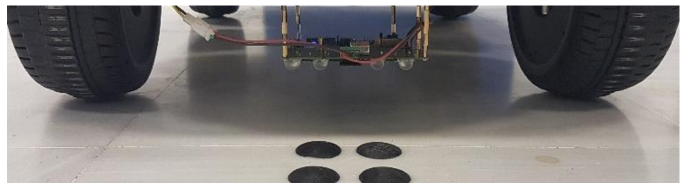

**Fig. 4.** Experiment setup.

Those columns are read by the inner radars of the sensors. The outer radar sensors are used to detect the misalignment. It can be noticed that 2 paint drops of the track, one in the middle and one at the end of the track, are slightly misaligned.


**Fig. 5.** Encoded track with two misaligned paint drops.

Fig. 6. shows the 4 radar profiles obtained after some signal processing. This signal processing basically consists in a digital low pass filter, a FFT transform, a peak detection in the Power Spectrum Density corresponding to the distance of the target and an additional filtering. It has been implemented in a FPGA for real time processing. Due to the vehicle is progressively increasing the speed, the square pulses corresponding to a 3D paint drop detection are getting narrower in time. It can also be noticed that, when the vehicle is running over a misaligned paint drop, the inner radar does not detect it but the outer one.

**Fig. 6.** Filtered radar profiles of the 4 channels

This prototype would be suitable for being implemented into a low speed AGV. In this way, the AGV could follow the track and, in case of one of the outer radars detect a misalignment, it can provide real time feedback to the steering control for its correction. However, a car running at high speed cannot precisely follow the track. To deal with potential misalignments, a linear array of 32 radar sensors deployed along a transversal axis of the vehicle is proposed as shown in Fig. 7. The gap between sensors is 2.5 cm and the size of the array is 77.5 cm. Hence, every time the encoded track is located between the 2 front wheels of the vehicle, the track can be read.

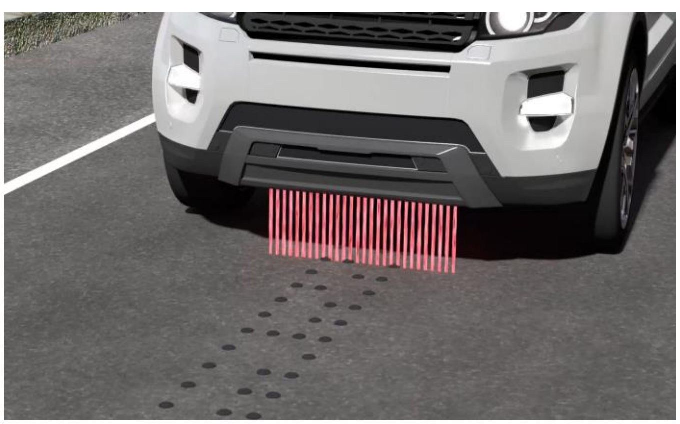
**Fig. 7.** Proposed 32-element linear array.

To simplify the hardware and the cost of the new sensor, a different radar chip that works in the [60-64] GHz band has been used. Each of the 32 channels of the linear array is implemented in a IWR6843AOP radar chip from Texas Instruments. The device is embedded in a FCBGA 15 x 15 $mm^2$ and includes an analog to digital converter and a hardware accelerator for implementing the real time digital signal processing. Due to the limited bandwidth, the minimum range is 0.4 meters which is challenging for the optic design to achieve a 1 cm in diameter circular scanning spot over the asphalt but also for the available space in the underbody of the vehicle. To solve these limitations, a different optic approach has been done. Each radar uses a plastic lens attached to the surface of the chip but, instead of pointing to the floor, the radar is rotated 90 degrees for illuminating an ellipsoid reflector 20 cm far has shown in Fig. 8. The radar sensor and the scanning spot are both focuses of the ellipsoid.

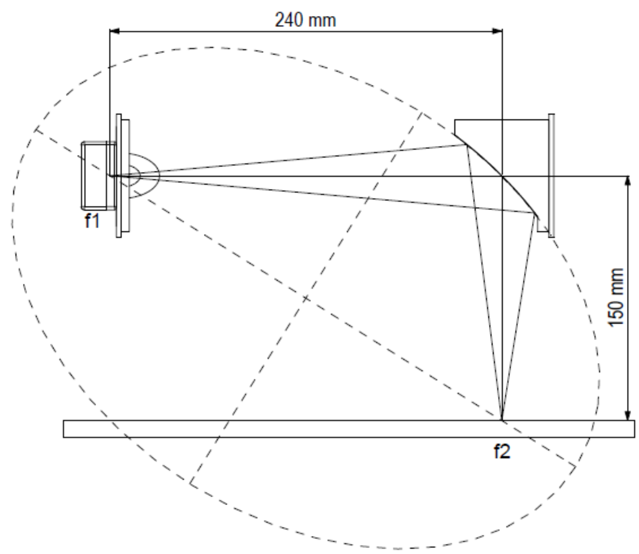

**Fig. 8.** Ellipsoid reflector.

With this scheme, the distance from the radar to the asphalt is increased to 0.5 meters while the spot over the asphalt is smaller than 1 cm in diameter. Fig 9 shows the evaluation board of the IWR6843AOP with a 3D printed plastic lens attached to the surface of the chip. It can be noticed that the lens has been cut in both sides with a vertical plane for the required 2.5 cm gap between two consecutive radars of the 32 elements linear array.

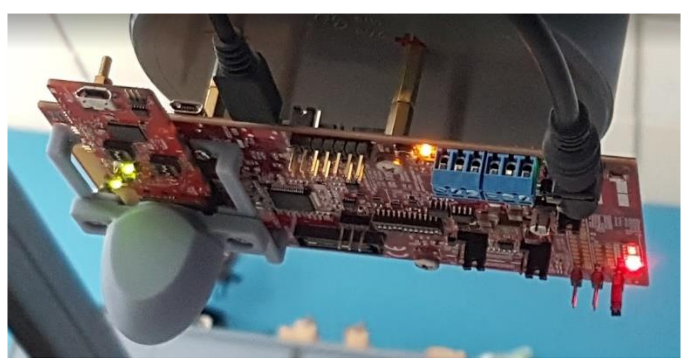
**Fig. 9.** IWR6843AOPEV attached to a DCA100 data acquisition board.

A 75 mm diameter PVC pipe has been used for placing a single radar and the reflector in their appropriate position and several tests have been successfully performed has shown in Fig. 10.

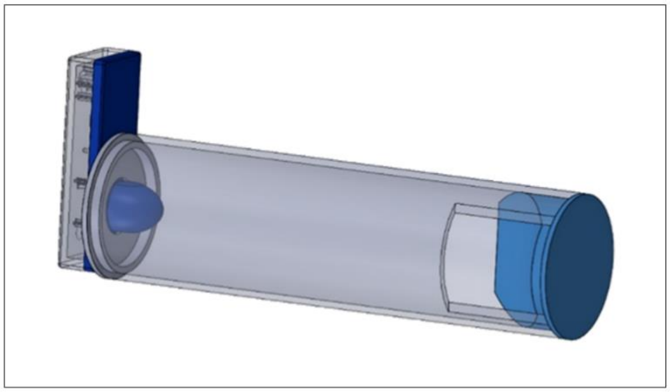

**Fig. 10.** Focusing optic for the IWR6843AOPEV

The radar measures the distance to the asphalt every 30 µs and obtains a high-detail profile of the ground at every millimeter while the vehicle is running at 120 km/h. When the radar is pointing to a paint drop, the measured distance is reduced and a loss of power is detected due to a non-flat surface of the target.

**Fig. 11.** IWR6843AOPEV sensor tested in real scenarios.

## IV. First Pilot in Real Scenarios

For testing the RPS in real scenarios, a 32-element linear-array must be developed, and few decameters of infrastructure must be adapted. In this way, a first pilot is currently being developed in Leon City (Spain). The encoded track has been painted in green color for also signaling a bike lane.


**Fig. 12.** Adapted infrastructure in León City.

The first stretch is 1,200 meters long and it has been printed at 6 km/h. Each 3D landmark consists in a 50x50x6 $mm^3$ thermo-plastic parallelepiped. It can be noticed that, due to the presence of shadows in the edges of each parallelepiped, the encoded track can be easily read by using a dashcam or a mobile phone camera with some AI processing. This approach will allow to precisely determine the position and the orientation of the vehicle every few seconds. However, for reading in real time every encoded row of the track, a radar sensor must be used. In this way, several public buses will be adapted with the appropriate radar sensor. In a first stage, the sensor will not interact with the vehicle and the collected data will be used for fleet monitoring purposes. In a second stage, A Driver Machine Interface will be installed for supporting the driver for an accurate stop at stations. In a third stage, the sensor will limit the maximum acceleration of the vehicle, according to the actual position, for minimizing pollutant emissions.

## V. RPS in Snowed Environments

Snowy environments are the worst possible conditions for ADAS and AVs. When road markings are covered by snow, optical cameras cannot detect them. Lidar rays are bounced on snowflakes generating false alarms on obstacle detection and reference objects for triangulation in 3D maps change its shape [10]. GNSS signa0ls are reflected on snowed surfaces causing loss of accuracy. Snow is also challenging for mm-wave radars for reading information encoded on the road with 3D paint-drops. RPS sensors cannot penetrate snow, and this means that they cannot read 3D paint drops covered by snow. Although snow is challenging for ADAS and AVs and requires extra measures to deal with, fortunately, most of the accidents that happen under these conditions are not critical since vehicle speeds are typically low. This means that snowed environments should not be a priority when facing traffic accidents reduction at short or medium term. However, ADAS and AVs must tackle snow issues. For dealing with RPS into snowed roads, a snow-plow robot equipped with an additional circular sweeper must be used first for removing the snow over the track. The robot will act as a platoon leader adapting the speed of the convoy for ensuring an appropriate cleaned track and informing the rest of the vehicles that they can follow it. In worst case, the guidance system will work safely by reading only 6 meters of the encoded track every 200 meters which means less than 4% of the track in this stretch.

## VI. Applications

Precise vehicle location and orientation obtained by RPS reading enables multiple new applications and improves the reliability and the availability of the current ADAS systems. In this section, we present some of them.

### *A. Reliable Automatic Lane Keep System*

The main advantage of such precise vehicle orientation and location is based on the ability for solving the problems related with the handover at level 3 SAE systems. When a Level 3 vehicle is running at high speed and the perception of the land markings fails, the driver must take the handover immediately. However, a driver that is not paying attention requires more than 5 seconds to identify the situation and react properly [11]. Thanks to a precise starting point and thanks to a recorded shape of the road stored in memory, when perception fails, the encoders of the wheels and the steering wheel in combination with IMU and GNSS data can be used for maintaining the vehicle into its lane along 200 meters [12-13]. This safety distance can be used for recovering perception while reducing the speed. Furthermore, it will provide enough response time to the driver for an appropriate handover. In worst case, it can be used for stopping the vehicle in a safe stop area.

### *B. Target-Vector Data Sharing between Vehicles*

Nowadays, a vehicle is able to detect a target, to measure the range and the angle of arrival and even to classify it. However, this data, when shared between vehicles, has limited trustworthiness due to uncertainty in the position and orientation of both vehicles, transmitter and receiver [14]. RPS provides a global reference system and, when both vehicles are properly pinpointed and oriented, the target vector can be transferred from one vehicle to another. Extending this idea, vehicle perception can be improved exponentially by using data gathered from multiple vehicles running into its neighborhood.

### *C. Progressive Intelligent Speed Assistance*

Intelligent Speed Assistant (ISA) uses GNSS and stored roadmaps as well as optical cameras for detecting speed-limit traffic signs [15]. In case of over speed, ISA will warn the driver. However, ISA is not reliable due to the lack of accuracy or availability of GNSS under certain conditions or due to unread traffic signs that are blocked by other big vehicles near the cameras. RPS can be an extra source of data for locating the vehicle enhancing ISA reliability. Furthermore, RPS allows the possibility of adjusting a different speed limit every 10 cm of road stretch instead of current constant speed limits. In this way, precise speed curves can be defined in sensible areas such as pedestrian crossings or dangerous areas. In addition, maximum accelerations curves according to the position can be defined to prevent inappropriate patterns that results in an excess of pollutant emissions.

### *D. Support for Unmanned Platooning*

Current unmanned platooning pilots are limited to 2 or 3 vehicles due to the difficulties for keeping long convoys into its lane [16]. The virtual engagement is coupled between two consecutive vehicles and suffer of a cumulative error that can make that a vehicle placed at the end of the tail will get out of the lane into a curve. For preventing this situation, the leader vehicle, which is the first truck of the platoon, would broadcast its RPS trajectory to the other vehicles. Then, the other vehicles of the platoon would precisely repeat the same trajectory of the leader.

### *E. Recharge while driving*

Typical safety gap between consecutive vehicles in manned and unmanned platooning is about 6 meters [17]. Precise vehicle positioning can reduce this gap to less than 1 meter if the wireless communication system used for sharing data between vehicles is replaced by a secure communication channel with Quality of Service (QoS). QoS channel can be implemented by using a similar helicoidal wire that the trucks use for transferring brakes and light signals from the cabin to the trailer. In this way, when the platoon leader starts breaking at high speed, safety gap is reduced in less than 1 cm when the vehicle follower starts to break with the same strength. The helicoidal cable that interconnects vehicles in the platoon can also be used for transferring energy between vehicles. Thanks to this capability, electrical platoon range can be increased when needed by coupling battery-load trailers.

### *F. Synchronized Traffic Flows in Urban Scenarios*

ADAS and AVs must work in a standalone manner for warranting a fast response but, most of the time, its movements would be controlled by a central host for improving mobility and prioritizing public transport and emergencies [18]. In this case, RPS can provide a precise positioning system will be required for scheduling vehicle movements appropriately.

### *G. Other Applications*

Structured paint for road digitization is also suitable for supporting tram signaling or outdoor Automated Ground Vehicles in controlled scenarios such as airports, factories, or harbors. It can also be used in railways for enabling an accurate breaking curve to trains. The breaking curve can be used at stations for a precise stop when Platform Screen Doors are deployed or for safety reasons in the surroundings of a buffer stop.

## VIII. Future Work

Next steps should be to demonstrate RPS capabilities in high-speed infrastructures such as main roads or highways. A study of the interaction of regular vehicles with the encoded track in these infrastructures should be performed. Also, an analysis of the maintenance costs and durability of the encoded track should be done to evaluate the convenience of a massive deployment of RPS. Finally, RPS reliability in snowy environments should be tackled.

## IX. Conclusion

Precise location and orientation of vehicles is a must for reliable Advanced Driver Assistance Systems and Autonomous Vehicles. Current solutions based on GNSS, IMUs, stereo optical cameras or LIDAR are not reliable enough under certain conditions. At high speed, safety may be compromised if land marking detection is not achieved. Dead-reckoning techniques can guide a vehicle safely along 200 meters by using the encoders of the wheels and the steering wheel and a pre-recorded roadmap. However, a precise starting point and vehicle orientation is required. A slight modification of the infrastructure is proposed in II for enabling precise vehicle positioning with cm accuracy and vehicle orientation with few degrees error. It consists in deploying black-color 3D paint drops along the center of the lane for encoding a pseudo random code in a similar way of the Braille code (the reading system for blind). This feasible and affordable adaptation remains invisible to regular drivers.

A 120 GHz radar sensor prototype for reading the encoded track at low speed is presented in III and a second prototype working at 60 GHz is proposed for developing a 32-elements linear array suitable for high-speed vehicles. First RPS pilot in real scenarios is shown in IV where 1,200 meters of lane stretch has been adapted for supporting public transportation. After six months, no interference issues with other road users have been reported. RPS limitations in snowed environments and a potential solution for dealing with is explained in V. Reliable ALKS, target-data sharing between vehicles for improving vehicle perception, support unmanned platooning or Intelligent Speed Assistant are some of the RPS applications shown in VI.

## Acknowledgment

We would like to thank to the Mobility Directorate from the Spanish Traffic Administration (DGT), the Spanish Transport Ministry (MITMA), Regional Government of Castilla y León and León Municipality for its support to RPS development.

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