Radar reflecting pavement markers for vehicle automation

Alexey Voronov[1], Johan Hultén[2], Johan Wedlin[1], Cristofer Englund[1]
[1]Viktoria Swedish ICT, Gothenburg, Sweden. E-mail: firstname.lastname@viktoria.se.
[2]Sentient+, Gothenburg, Sweden. E-mail: johan.hulten@sentientplus.com.

***Abstract*—Dependable and fail-safe control of autonomous vehicles requires multiple independent sensors for lane detection and positioning. From analysis of modern sensing technologies, we conclude that radars are underutilized for positioning, and that they might be an enabling technology for achieving safety requirements posed by the standard ISO 26262. To fully utilize the radar potential, we have conducted a pre-study of equipping infrastructure with radar reflectors. We estimate that such reflectors should be installed in the lane markings, about 20-25 meters apart and with some kind of identification. We propose to design and evaluate a combi-reflector based on the traditional cat's eye design, which will be detectable both by human drivers, radars and lidars. Furthermore, the combi-reflector can be equipped with a magnet for in-vehicle electromagnetic field sensor. From the redundancy evaluation performed, we conclude that the proposed solution increases the level of redundancy significantly. Therefore, the proposed solution could be an enabler for autonomous driving.**

I. Introduction

Accurate and dependable positioning is essential for automated and autonomous driving - just think of drifting into a wrong lane. Modern Advanced Driver Assistance Systems (ADAS) often include a Line Keeping Aid (LKA). However, with the transition to the autonomous driving, today's LKA will not be good enough, since it mainly relies on the camera detecting lane markings. Firstly, a camera is not a perfect instrument: it performs poorly in heavy rain, snow, fog; it can be blinded by oncoming light and reflection (although filters and High Dynamic Range imaging can help); image processing algorithms are not perfect and can misinterpret shadows and potholes for road marks. Secondly, lane markings themselves degrade with time, and if they are not refreshed often enough, they might be difficult to detect. Thirdly and most importantly, if the camera fails, LKA can no longer function, which would not be acceptable for a lateral control system of an autonomous vehicle. If today's LKA system fails, it just gives the driver a warning, and the driver is still there steering the vehicle. Autonomous systems do not have such a luxury, they have to be fail-operational or at least fail-safe, for example by performing a safe stop maneuver.

Different functions of the vehicle require different positioning data from the sensing system. Requirements for output from the sensing system differ between safety and driving comfort control: comfort control requires much more data for smooth motion planning, while safety control requires less data. However, if the data for comfort control are missing, nothing more dramatic than a rougher ride will happen, while data loss would be unacceptable for safety functions. Requirements for lateral and longitudinal control are also different. Lateral positioning is always important: the vehicle has to be properly positioned within a lane, since crossing the lanes would cause a hazard. Longitudinal positioning, on the other hand, is not always needed; it has to be accurate when approaching intersections, on and off ramps, zones with custom speed limits, traffic lights, stop signs, etc.; while on long stretches of highways longitudinal positioning is less important. These requirements are summarized in Table I.

To increase dependability and achieve a fail-operational level, a lane detection and positioning system requires multiple independent sensors complemented by a sensor fusion system. Section III provides an overview of the sensing technologies that are most widely used by automakers, as well as an overview of infrastructure elements that can be used by the road authorities to enable easier detection both by human drivers and by automated vehicle systems.

From the overview of available technologies we conclude that there is an unused capacity on the infrastructure side in the area of radar detection, which might provide the needed sensor redundancy for both lane detection and positioning. In Section IV we analyze the potential of *radar reflectors*, as well as propose a design of a *combi-reflector* that might be the successor of traditional cat's eyes reflector that could be visible to human drivers, radars and lidars. We also consider some special circumstances where the combined reflector will have to operate, like markings of temporary road works and accidents as well as withstand snow plowing.

Lastly, sections VII and VIII summarizes the conclusions and proposes potential next steps to improve sensing for automated vehicles.

II. System safety aspects for vehicle automation

Automotive Safety Integrity Level (ASIL) is a risk classification scheme defined by the ISO 26262 [1]. The ASIL requirements follow from risk analysis and safety goals of a potential hazard. There are four ASILs identified by the standard: A, B, C and D. ASIL D dictates the highest integrity requirements on the product and ASIL A the lowest.

To determine ASIL, each hazard is classified according to Severity (S), Exposure (E) and Controllability (C). ASIL may be expressed as ASIL = Severity × Exposure × Controllability.

Severity Classifications (**S**): S0) No Injuries; S1) Light to moderate injuries, S2) Severe to life-threatening (survival probable) injuries, S3) Life-threatening (survival uncertain) to fatal injuries.

Table I. FUNCTIONS AND BASIC REQUIREMENTS

Function	Safety	Driving Comfort
Lateral control (steering)	Keep within lane markings	Enough information for soft control (e.g. to straighten the curves)
Longitudinal control	Keep speed limits, stop at crossings, follow on and off ramps etc.	Enough information for soft control
Safe stop	Find appropriate safe stop space, even without GPS and camera	-

Exposure Classifications (**E**): E0) Incredibly unlikely, E1) Very low probability (injury could happen only in rare operating conditions), E2) Low probability, E3) Medium probability, E4) High probability (injury could happen under most operating conditions).

Controllability Classifications (**C**): C0) Controllable in general, C1) Simply controllable, C2) Normally controllable (most drivers could act to prevent injury), C3) Difficult to control or uncontrollable.

A. ASIL Assessment

In order to achieve a safety integrity level for the top hazard ”Losing Lateral Control”, severity, exposure and controllability must be evaluated according to ISO 26262, leading to:

- Severity: **S3** Life-threatening (survival uncertain) to fatal injuries
- Exposure: **E4** High probability (injury could happen under most operating conditions)
- Controllability: **C3** Difficult to control or uncontrollable

This combination of S3, E4, and C3 classifications results in ASIL D. This ASIL requires a fail-operational system, for which a system shut-off is not a safe state.

B. Decomposition

Lateral control means that both lateral position measurement and curvature control must both be valid. This decomposition reveals that both must have ASIL D for the system to be fail-operational.

In order to meet ASIL D for fail-operational systems, design patterns from the airplane industry can be an inspiration source. There, a design pattern for fail-operational solutions with similar level as ASIL D is a redundancy pattern where sensing information must come from at least three fully decoupled sources, each with at least ASIL B, as well as a voting scheme in order to find out which two to continue with if one fails. At this stage, we conclude that it is reasonable to believe that some level of redundancy is needed also for lateral position sensing of road vehicles.

III. SENSING TECHNOLOGIES

Today, vehicles use a combination of sensing technologies and *sensor fusion* to form vehicle positioning measures. Table II summarizes major sensing technologies and infrastructure aids they rely on. The rest of this section considers sensing technologies in more details.

A. Visible light and camera/lidar

Vehicles can rely on visible light through cameras for detection and objects in the infrastructure for reflection. The most widespread group of objects are those that reflect visible light, i.e. all road infrastructure created to be seen by human drivers. Examples of these are:

- Lane markings (ordinary, fluorescent, coloured)
- Snow poles
- Delineator posts
- Traffic barriers or guardrails
- Traffic signs
- Reflective pavement markers like cat’s eyes

Moreover, ranging devices like ultrasound and lidar can detect objects on the roadside, including buildings, trees, curbstones, which can be used as landmarks for positioning. These landmarks are visible to the driver, but are not specifically intended for positioning.

An important category of reflective devices are retroreflective safety devices (sometimes called retroflectors or cataphotes) that reflects light back to its source with a minimum of scattering. In a retroreflector, an electromagnetic wavefront is reflected back along a vector that is parallel to but opposite to the direction from the wave’s source.

There are several ways of designing retroreflectors, including corner reflectors, cat’s eyes and phase-conjugate mirrors. These will be examined below.

1) Corner reflector: A corner reflector is a retroreflector consisting of three mutually perpendicular, intersecting flat surfaces, see Figure 1, which reflects waves back directly towards the source, but translated. The three intersecting surfaces often have square shapes. Radar corner reflectors made of metal are used to reflect radio waves from radar sets.

Radar corner reflectors are designed to reflect microwave radio waves emitted by radar sets back towards the radar antenna. This causes them to show a strong ”return” on radar screens. A simple corner reflector consists of three conducting sheet metal or screen surfaces at 90° angles to each other and attached to one another at the edges, forming a ”corner”. This reflects radio waves back parallel to the incoming beam. The reflecting surfaces must be larger than several wavelengths of the radio waves to function [2].

2) Spherical reflector and cat’s eye: A spherical retroreflector, also called a cat’s eye, consists of a refracting optical element (a transparent sphere) and a reflective surface (a spherical mirror), arranged so that the focal surface of the sphere coincides with the mirror, see Figure 2 for an illustration.

Table II. MAJOR POSITIONING AIDS AND THEIR ADVANTAGES AND DISADVANTAGES.

Detectable objects	Sensor	Advantages	Disadvantages
Painted lane markings	Camera, lidar	Cheap and simple	Degradation of lane markings. Camera performs poor in snow, rain, fog, backlight
Snow Poles	Camera	Cheap, work in snow	Easily displaced; not applicable on multi-lane roads; camera problems
Traffic signs	Camera, lidar (and potentially radar)	Exist in many places, provide rich information to the driver	Too few; require text recognition; camera problems
Cat's eyes pavement markers	Camera	Cheap, visible in darkness	Not visible during daytime; camera problems
Guardrails	Camera and radar	Provide passive safety	Not applicable on multi-lane roads
Delineator posts	Camera and radar	Cheap, steady	Not applicable on multi-lane roads
Landmarks (buildings, trees etc)	Lidar, stereo camera, camera + structure from motion	Big amounts of data available from a laser scan	Change often (can be outdated); require complex algorithms
Positioning + 3D map	RTK GPS + HD Map	Provide lateral and longitudinal position	Often changing (can be outdated); Dependency on GPS/GLONASS which can be scrambled
Magnets	Hall-effect sensor	Work in snow; do not distract the driver	Require new equipment and cannot be used by non-equipped vehicles; sensitive to electromagnetic noise
RFID	RF readers	Rich information	Requires new equipment and cannot be used by non-equipped vehicles; Uncertain lifespan and weather protection
Radio Communication	WiFi, Bluethooth etc	Cheap	Short-range, requires many active beacons/anchors
Dead-reckoning	Gyro, Accelerometer, Odometer, known starting position	Self-contained	High error accumulation rate
Radar reflectors (this study)	Radar	Many vehicles already have radars	Accuracy; New algorithms

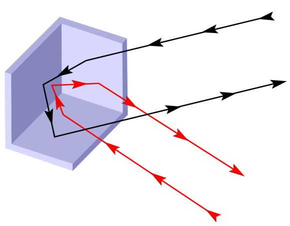

Figure 1. A corner reflector, consisting of three flat reflecting surfaces at right angles, and two rays coming from different directions and reflected by the corner reflector. Each ray is reflected three times, one from each surface.

If a single homogeneous sphere is used, its material should have a specific (high) refractive index. In that case, the sphere surface itself (even without an extra mirror coating) behaves as a retroreflective mirror. However, since back-side reflection for an uncoated sphere is imperfect, usually a metallic coating is added to the back half of retroreflective spheres to increase the reflectance. An alternative form uses a normal lens focused onto a curved mirror rather than a transparent sphere; this type has smaller range of incident angles over which it retroreflects.

Figure 2. Left: Spherical retroreflector and reflection of three light rays. Center and right: Cat's eye glass body and principle of operation (back face is mirror-coated). Image credits: [3], [4]

Cat's eye is also a name of a retroreflective safety device used in road marking, see Figure 3 for an illustration. It was the first in a series of raised pavement markers. It consists (in its original form) of two pairs of spherical retroreflectors (reflective glass spheres) set into a white rubber dome, mounted in a cast-iron housing [5], [6]. A cat's eye has a flexible rubber dome which is occasionally deformed by the passage of traffic. A fixed rubber wiper cleans the surface of the reflectors as they sink below the surface of the road. The rubber dome is protected from impact damage by metal 'kerbs', which also give tactile and audible feedback to wandering drivers.

Figure 3. Cat's eye pavement marker.

3) Phase-conjugate mirror: A much less common way of producing a retroreflector is to use the nonlinear optical phenomenon of phase conjugation [7], [8]. This technique is used in advanced optical systems such as high-power lasers and optical transmission lines. Phase-conjugate mirrors require a comparatively expensive and complex apparatus, as well as large quantities of power (as nonlinear optical processes can be efficient only at high enough intensities). However, phase-conjugate mirrors have an inherently much greater accuracy in the direction of the retroreflection, which in passive elements is limited by the mechanical accuracy of the construction.

B. Radar

A radar wave, being an electromagnetic wave just like visible light, can detect reflective devices, like radar corner reflectors or a radar cat's eye. A radar corner reflector, as shown in Figure 4, is analogous to the aforementioned corner reflector reflecting visible light, and a radar cat's eye is analogous to the aforementioned cat's eye reflector reflecting visible light, with the difference that the reflecting material is such that it reflects radar waves. As mentioned above, the reflecting surfaces must be larger than several wavelengths of the radio waves to function. For automotive radars working at 77 GHz the wavelength is less than 4 mm.

Figure 4. Example of a corner reflector used for radar testing. Image credit: [9].

A special type of a radar reflector can be made from a *Luneburg lens*. It is a sphere in shape, usually composed of concentric dielectric shells with specially-selected dielectric constants for each shell. The rear surface of the sphere is metallized. The radar energy is focused on the rear surface and is reflected back to the source [10], [11]. This reflector has a wider angle coverage and smaller physical size than a corner reflector, but it is heavier and more expensive.

Radar reflectors are used widely for radar evaluation, in maritime applications like on buoys and for non-reflecting vessels like wooden and plastic boats and kayaks [12], [13], as well as in aerospace, for example for military drones and decoys [14].

C. Magnetic material

A road surface can have magnetic materials installed, like small magnets milled into the road surface. The California PATH research program evaluated this solution [15], [16], [17], [18], and a similar technology was also investigated in Sweden [19], [20]; one of the conclusions made was that electromagnetic noise might be a big issue. Another disadvantage is that magnet installations are difficult to change, being buried in the road surface.

D. Satellite system

Exact knowledge of absolute vehicle position and coordinates of the road can also provide information about relative position of the vehicle in the lane. Absolute positioning can be achieved through satellite navigation systems, including Global Navigation Satellite System (GNSS) like GPS, GLONAS, Galileo and BeiDou, or Regional satellite navigation systems like the Chinese BeiDou-1, Indian Regional Navigational Satellite System (IRNSS) and Japanese Quasi-Zenith Satellite System (QZSS).

The accuracy of GPS positioning can be improved using Real-Time Kinematic (RTK) corrections from fixed base stations. For example, in Sweden Läntmäteriet has a network of more than 400 base stations and provides a service called SWEPOS with RTK corrections distributed from relevant stations over mobile broadband connections.

E. Other positioning systems based on radio communication

Systems based on Ultra Wide Band communication, Bluetooth, WiFi and other technologies are popular today for indoor navigation, 3D motion tracking and Real-Time Location Services [21]. Commercial examples include Pozyx Labs, DecaWave, Xsens, SenionLab, Combain, and many others, including more than 50 members of InLocation Alliance. In theory, similar systems on a larger deployment scale can be used even for vehicle positioning.

F. Dead-reckoning

Dead-reckoning is the process of calculating an object's current position by using a previously determined position and extrapolating that position based upon known or estimated speeds over elapsed time and course. Inertial navigation systems, often based on gyroscopes and accelerometers, belong to this category. A vehicle's odometer is another example of a device used for dead-reckoning.

G. Map data as a virtual sensor

To achieve good driving comfort it is important to know the road curvature, inclination, surface quality etc. Road information can be sensed from the vehicle, but it might then be too late to react. Much better would be to receive road information in advance by means of a ”virtual” sensor like map data. To use the map data, the vehicle of course must know its own position. However, map and road information can be used for positioning, for example by matching observed environment objects to the map.

There exist commercial providers of High-Definition (HD) 3D map data. For example, HERE provides HD Maps with 10-20 cm resolution [22].

H. Example of vehicle equipment

As an example, modern vehicle equipment for sensor fusion typically include the following sensors: Forward-looking wide-angle radar; Stereo camera + camera + infrared camera (night vision); Ultrasound sensor; High-definition (HD) map + multi-Constellation GNSS system + RTK correction service; Vehicle-to-Vehicle and Vehicle-to-Infrastructure communication; 9 degrees of freedom Inertial Measurement Unit (9-DOF IMU) with accelerometer + gyroscope + magnetometer/compass; Odometer, dynamically calibrated for the current wheel radius.

IV. Proposed solution

In order to increase the level of redundancy as discussed in Section II, we propose a new type of cat's eye pavement marker that reflects the following type of signals:

- visible light
- laser from a lidar
- radar signals

This *combi-reflector* may also incorporate a LED light and a magnet for additional visibility by human drivers and by in-vehicle electromagnetic field sensors. The reflectors should be placed in the lane edges, in line with the lane markings (positioning in the middle of the lane would create obstructions for two-wheelers, and positioning away from the road might be impractical to occlusions on multi-lane roads). The longitudinal distance between the reflectors should be approximately 20 meters (see below), and small variations in that distance can be used in order to encode the longitudinal position of the vehicle, see Section V below.

Readings from combi-reflectors can be used for absolute positioning based on the following data:

- GPS, giving an approximate absolute position
- Cloud map data information, for detailed road map,
- Coding theory, to decode a pattern that is sensed from the devices described above (the coding theory as well as alternative patterns are described in detail below), that can be used together with the GPS and map to form a high resolution absolute position.

And finally, dead reckoning from a known position in a known environment is yet another source for absolute positioning.

A. Requirements and assumptions

Given the typical width of a vehicle (ca. 2 m [23], [24], see also Figure 5 below), and a typical lane width (ca. 3 m, [25]), the vehicle should be positioned in the center of the lane with an error of no more than ±0.5 m.

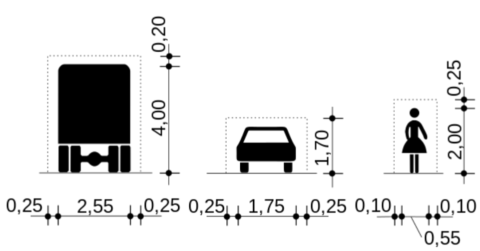

Figure 5. Assumed vehicle widths and heights in European road design (in meters).

We assume that the absolute positions of the reflectors are known and available for downloading from the cloud. We further assume that those positions have errors of max ±0.1 m, at least in the lateral direction. The positions can be obtained for example using high-precision GPS RTK system, and kept up to date in a database at the road administration.

We assume that the radar angular error is max ±1°, and that the radar distance error is max ±0.1 m for distances up to 10 m, as can be seen in Figure 6. With 60° opening angle and 3 m lane, the lane markings are just 3 m away from the radar positioned in the vehicle front.

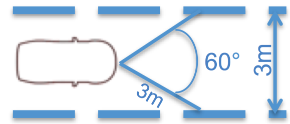

Figure 6. Lane width and radar distance to the lane marking.

Given the assumptions above, the vehicle can determine its relative lateral position on the lane within ±0.2 m, which fulfills the requirement of max ±0.5 m. However, the reflectors are placed only at discrete positions on the road. Between detecting reflectors, the vehicle accumulates an error. How dense should we then place the reflectors so that the error does not become too large? On one hand, reflectors should be placed as close to each other as possible to give as much information as possible. On the other hand, they should be placed as far apart as possible to cut the costs of manufacturing, installation and maintenance. The next subsection estimates the longest distance that can be used between the reflectors and still enable safety functions.

B. Longitudinal distance between reflectors

Given the best knowledge of the vehicle's relative position from the radar reflector (±0.2 m), and the largest error the vehicle can afford without violating the lane limits (±0.5 m), how far the vehicle can travel until it accumulates a lateral course deviation of 0.3 m? We assume here that we can not rely on GPS or camera signals, but we can still rely on IMU, odometer and steering angle sensor. The vehicle then accumulates 0.3 m of lateral deviation after about 25-30 m of (longitudinal) driving (source: interviews with vehicle control engineers and prior experience from test tracks).

This can also be illustrated as reducing the uncertainty of the relative lateral position with help of the detected reflectors. When a reflector is detected, the uncertainty is small. Then uncertainty grows, until the next reflector is detected, at which point uncertainty becomes smaller again, see Figure 7.

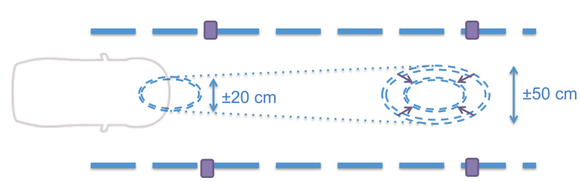

Figure 7. Uncertainty reduction illustration. After detecting the reflectors, the uncertainty is small. It then grows until the next reflector is detected, when the uncertainty is again reduced.

To keep the vehicles within the limits outlined above, the reflectors have to be positioned at max 25 meters relative distance from each other. Even though this might be too far for comfortable driving (which would require at least one-fifth of that distance), we consider radar reflectors as a backup solution, for the vehicle to remain fail-operational in case of simultaneous camera and GNSS failures.

Another consideration may be to increase the density of the reflectors in the curves, both to highlight to the driver that it is a hazardous road segment, and to allow the sensor system to make better positioning.

Yet another possibility is to encode the longitudinal position of the vehicle by slightly varying the distances between the reflectors, see next section.

C. Special circumstances

Special care must be taken for special circumstances like temporary changes in the road due to the roadwork or accidents. Another very important issue is snow, and how reflectors can be used together with snow plows.

1) Roadwork, accidents and manual driving zones: In cases where it is not applicable to drive in automated mode, reflectors can be used to indicate the beginning of such a zone. It might be a rubber road mat with multiple reflectors installed across the whole mat, similar to the reflectors in Figure 8. Such temporary mats can be used by police and rescue services in the area of an accident. Such mats should be placed well in advance of the manual driving zone, to allow transfer of control to a manual mode or to perform a Safe Stop in a specially designated zone.

Figure 8. Multiple raised pavement markers.

2) Warning triangle: Today, in case of an accident, a warning triangle is deployed to warn other drivers in advance and make the accident zone safer. Such warning triangles are normally visible by both human drivers and by cameras/lidars. However, it is possible to add radar reflecting features to the warning triangle to enable also radars to pick up the warning signal.

3) Snow: Raised Pavement Markers with (ordinary) retroreflectors exist in snowplowable variants, and are used widely in the USA [26], [27], [28], [29], [30], [31] and Canada [32]. Both raised and recessed variants exist [33], [34], [35].

Plowable pavement markers compare favourably with delineator posts, since the latter can not be plowed, as illustrated in Figure 9.

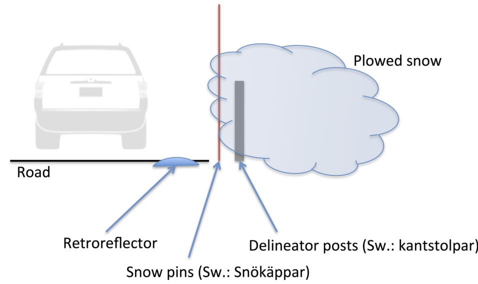

Figure 9. Comparison of retroreflectors with delineator posts.

V. Longitudinal identification

Knowledge about the vehicle's longitudinal position on the road is important when approaching intersections and on- and off-ramps, as well as when performing a Safe Stop, which requires identification of a parking space or a free space on the road shoulder to safely stop the car, in case the vehicle can not proceed with autonomous drive and the driver is not available to take over the control.

Our assumption here is that the vehicle knows its rough position with about 1 km confidence interval, either from GNSS or from dead-reckoning. Thus we can focus on uniquely identifying the reflectors within a 1 km circle.

Moreover, while each reflector does not have to be uniquely identifiable, we can rely on the fact that the sequence of reflectors is unique. Suppose we have two types of reflectors, encoded as 0 and 1. Then we can arrange them in a sequence that will not repeat itself within our area of interest (1 km circle). The sequence can look like 010011010101001010. After detecting enough reflectors, the vehicle will know exactly where it is within the sequence (remember that both the sequence and the reflector positions are available from *the cloud*). Having more unique identifiers than just two will require much fewer elements to identify which part of the sequence they belong to. Coding theory and Information theory can be used to design the pattern, as well as to identify the minimum number of the reflector ids that have to be detected to be confident enough in the position within the sequence.

There are several approaches to identify the reflectors, including changing radar cross section, polarization, encoding position in the distances between the reflectors, adding additional camera-readable elements and putting several reflectors in a row laterally or longitudinally. We consider each of them below.

A. Radar cross section

Radar cross section (RCS) is the measure of a target's ability to reflect radar signals in the direction of the radar receiver, i.e. it is a measure of the ratio of backscatter power in the direction of the radar (from the target) to the power density that is intercepted by the target.

Informally, the RCS of an object is the cross-sectional area of a perfectly reflecting sphere that would produce the same strength reflection as would the object in question. (Bigger sizes of this imaginary sphere would produce stronger reflections.) Thus, RCS is an abstraction: The radar cross-sectional area of an object does not necessarily bear a direct relationship with the physical cross-sectional area of that object but depends upon other factors, such as material of the target, absolute size of the target, relative size of the target in relation to the wavelength of the radar, shape and orientation of the target and polarization of transmitted and received radiation with respect to the orientation of the target.

By varying the RCS of the reflector, e.g. by changing its material or shape, while keeping RCS big enough for easy detection, it is possible to assign a RCS-ID to each reflector, and a unique sequence of such RCS-IDs within the 1 km area of interest will uniquely identify the reflector.

B. Polarization

Polarization is a property of waves that can oscillate with more than one orientation. In an electromagnetic wave, both the electric field and the magnetic field are oscillating but in different directions; by convention the "polarization" of electromagnetic waves refers to the polarization of the electric field. The polarization of an antenna refers to the orientation of the electric field (E-plane) of the radio wave with respect to the earth's surface and is determined by the physical structure of the antenna and by its orientation. There exist polarimetric radars that can detect changes in polarization [36]. It might be a topic of a future work to investigate if it is possible to create a radar reflector that can introduce a change in the wave polarization detectable by an automotive radar.

C. Distance pattern

It is possible to use distance between two adjacent reflectors as an identifier. Instead of a constant 20 m distance, the distance can be chosen from 18, 20 and 22 m. Each distance will then be used for the encoding an unique id (e.g. 0, 1 and 2), and a sequence of ids can be used to identify each reflector in a sequence.

A potential drawback of varying the distance can be that it may distract drivers if it is noticeable. An alternative solution can be to put the radar reflecting component only in some, but not all, units. Then visually there will be an even pattern, while the radar will detect a non-homogeneous, coding pattern.

D. Camera-readable signs

It is possible to use camera-readable signs, or even QR-codes, to identify the longitudinal vehicle position along the road. Also the number of visible light reflector elements can be varied in the reflector unit to give it an identifier. However, these solutions will of course not work in case of a camera failure.

E. Reflectors formations

It is possible to put several reflectors together either along or across the road, or in some form of a pattern or formation. However, with radar resolution being quite limited, rather big distances between the reflectors, maybe 20 cm or more, will be required to distinguish different reflector units, thus making this solution not always practical. Moreover, variable amounts of reflectors will be visible to the drivers, which might distract them.

VI. Redundancy evaluation

As concluded in Section II, to make vehicle automation safe there must be a level of redundancy in the measurements of the vehicle lateral position. Table III provides a sketch of an analysis of the outlined vehicle sensing systems in combination with potential environmental problems, in order to determine how many systems remain unaffected by these problems. A "x" indicates that we expect that such an unaffected system may exist, however detailed analysis is outside of the scope of this study. Ultrasound sensors are excluded from the table since they are assumed to be too short-range for navigation, and IMU sensors for dead-reckoning are also excluded since their error accumulation rate is probably too high. However, dead-reckoning can be very valuable in combination with the other technologies.

Table III. Sensing principles and potential problems. "Radar" assumes presence of radar reflectors.

	Camera	Lidar	Radar	Magnets	GNSS+Map
Snow	(x)$^{1)}$	(x)$^{1)}$	(x)$^{1)}$	x	x
Rain			(x)$^{2)}$	x	x
Fog			x	x	x
Darkness	(IR) x	x	x	x	x
Backlight	(HDR) x	x	x	x	x
Scrambling	x	x	x	x	
EM noise	x	x	x		x
Tunnels	x	x	x	x	

$^{1)}$ For the alternative with a delineator post with the proposed device contents, the same performance as without snow can be achieved.
$^{2)}$ Radar works up to extreme weather conditions.

From Table III we conclude that radar reflectors add a valuable independent signal source that can tolerate many of the problems. Hence, radar reflectors add an important level of redundancy in the work towards vehicle automation.

VII. Conclusions

One conclusion from this work is that for vehicle automation, there must be a redundancy in the sensing principles for vehicle lateral position in order to make vehicle automation safe. In order to increase the redundancy for vehicle lateral position, we propose a new type of cat's eye pavement marker that reflects the following type of signals: visible light, laser from a lidar and radar signals.

This *combi-reflector* can also incorporate a magnet for additional in-vehicle electromagnetic field sensors. Furthermore, readings from combi-reflectors can be used for absolute positioning based on GPS, cloud map data information, and coding theory, to decode a longitudinal identification pattern that is sensed from the devices described above. And finally, dead reckoning is yet another source to further improve absolute positioning.

Another important aspect of the proposed solution is that the combi-reflectors are handled by the road authorities. This is especially important during *e.g.* road works.

The proposed solution increase the level of redundancy significantly, and hence there is a high potential to significantly improve vehicle positioning for vehicle automation. Therefore, the proposed solution can be an important step towards autonomous driving.

VIII. Future work

One of the most important steps is to evaluate a potential radar reflector with modern automotive radars. It is also important to verify the assumptions made in this study, including the angular resolution of the radars and distance errors. Radar sensitivity will dictate the Radar Cross Section of the reflector, which in turn will set its size. It is important to validate that the reflector will fit in a reasonably-sized pavement marker housing. Another question is whether radars can distinguish different sizes of reflectors to enable encoding of the reflector ID. The potential of using polarization to encode reflector ID should also be investigated. This work is suggested to be performed in collaboration with a radar supplier.

Design and construction of the combi-reflector is another very important step. The construction should be water-proof, since if water will be collecting in front of the reflector, it will influence the radar detection. The construction should also be snowplowable. Another important requirement is that it should combine different detection modes (radar, lidar, camera, human drivers, and potentially a magnet detector) in order to be a stepping stone and be usable also for non-fully equipped vehicles. This work is suggested to be performed in collaboration with some of the plowable pavement markers manufacturers.

In this study we estimated that the distance between reflectors should be max 25 m. This distance have to be verified in practical tests. In case the id of the reflector will be encoded in varying the distance between the reflectors, it is important to investigate whether this distance will be noticeable for the drivers and/or passengers of the vehicle, and if so, whether it will distract the drivers. If a sequence of reflector IDs will be used for longitudinal positioning, a study of the best sequence is needed. Another direction for a future work is to evaluate avionics design patters for ensuring safety and fulfilling the standards and regulations. A natural further step will then be to develop a proof-of-concept demonstrator, for example on a proving ground like AstaZero.

IX. Acknowledgements

This work was initiated by Sentient$^+$ and supported by the Swedish Transport Administration (Trafikverket).

References

[1] ISO, "ISO 26262 Road vehicles – Functional safety."

[2] J. Kraus and R. Marhefka, *Antennas for All Applications, 3rd ed.* McGraw-Hill, 2002.

[3] C. Lee, "Comparison of retroreflectors (Adapted). Licensed under CC BY-SA 3.0," 2014. [Online]. Available: https://commons.wikimedia.org/wiki/File:Comparison_of_retroreflectors.svg

[4] U. Seifert, "Cat's eye schema "Katzenauge2". Selfmade photo and drawing. Licensed under CC BY-SA 3.0," 2007. [Online]. Available: https://commons.wikimedia.org/wiki/File:Katzenauge2.jpg

[5] P. Shaw, "Improvements relating to blocks for road surface marking (patent GB436290A)," 1935.

[6] ——, "Improvements relating to blocks for road surface marking (patent GB457536A)," 1936.

[7] H. J. Eichler and O. Mehl, "Phase Conjugate Mirror," *Journal of Nonlinear Optical Physics & Materials*, vol. 10, no. 01, pp. 43–52, mar 2001.

[8] M. C. Gower, "Phase Conjugate Mirrors," *Physics Bulletin*, vol. 38, no. 6, pp. 220–222, jun 1987.

[9] Wikimedia Commons user:Elborgo, "Corner reflector (Own work. Licensed under CC BY 3.0)," 2007. [Online]. Available: https://commons.wikimedia.org/wiki/File:Corner_reflector.JPG

[10] F. S. Holt, *Comparison of reflective properties of corner reflector clusters and lundeburg lens reflectors*, ser. Instrumentation papers, 1966.

[11] S. S. Vinogradov, P. D. Smith, J. S. Kot, and N. Nikolic, "Radar Cross-section Studies Of Spherical Lens Reflectors," *Progress In Electromagnetics Research*, vol. 72, p. 325–337, 2007.

[12] S. Luke, "Performance investigation of marine radar reflectors on the market," Tech. Rep. CR0704527, 2007.

[13] N. Springuel, P. Travis, and R. MacDonald, "Radar , Reflectors and Sea Kayaks : A Visibility Study," Tech. Rep., 2004.

[14] C. Liang, D. Streater, J.-M. Jin, E. Dunn, and T. Rozendal, "A quantitative study of Luneberg-lens reflectors," *IEEE Antennas and Propagation Magazine*, vol. 47, no. 2, p. 30–42, Apr 2005.

[15] J. Guldner, S. Patwardhan, H.-S. Tan, and W.-B. Zhang, "Coding of Road Information for Automated Highways," *Intelligent Transportation Systems*, vol. 4, no. 3-4, p. 187–207, 1999.

[16] H. Tan and B. Bougler, "Vehicle lateral warning, guidance and control based on magnetic markers," Tech. Rep. January, 2001.

[17] C.-Y. Chan and H.-S. Tan, "Evaluation of Magnetic Markers as a Position Reference System for Ground Vehicle Guidance and Control," California Path Program, Institute Of Transportation Studies University Of California, Berkeley, Tech. Rep., 2003.

[18] H.-S. Tan, F. Bu, S. Johnston, B. Bougler, W.-B. Zhang, and S. Sun, "Field Demonstration and Tests of Lane Assist/guidance and Precision Docking Technology," Tech. Rep. January, 2009.

[19] S. Sternlund, "Fordonspositionering med vägmagneter," Tech. Rep., 2014. [Online]. Available: http://www.trafikverket.se/contentassets/09a2b6a0c7c34586be74416d77db989e/04_fordonspositionering_vagmagneter_sternlund_140206.pdf

[20] A. Torin, S. Hellman, and M. Svensson, "Magnets in a carriageway part 2; magnetic background noise and markers pattern study," Tech. Rep., 2015. [Online]. Available: http://www.astazero.com/wp-content/uploads/2015/10/Bergman-%C3%85F_Magnets_in_a_carriageway_part_2_-_AstaZero_Researchers_Day_short_public.pdf

[21] A. Malik, *RTLS For Dummies*. Wiley, 2009.

[22] C. Lawton, "Why an HD map is an essential ingredient for self-driving cars," 2015. [Online]. Available: http://360.here.com/2015/05/15/hd-map-will-essential-ingredient-self-driving-cars/

[23] The Council of the European Union, *Council Directive 96/53/EC laying down for certain road vehicles circulating within the Community the maximum authorized dimensions in national and international traffic and the maximum authorized weights in international traffic*, 1996, no. L 235/59.

[24] F. H. Administration, *Federal Size Regulations for Commerical Motor Vehicles*, 2004.

[25] PIARC, *Taffic Lanes and Carriageway*, 2001, ch. Chapter 5.

[26] J. Pigman and K. Agent, "Evaluation of snowplowable markers," Tech. Rep., 1982.

[27] F. E. Walker, "Snow plowable pavement marker (patent US 4557624 A)," 1988.

[28] G. Behar, C. Mollett, B. Persaud, C. Lyon, A. Smiley, T. Smahel, and H. McGee, *Safety Evaluation of Permanent Raised Pavement Markers*. Transportation Research Board, 2004, vol. NCHRP, no. 518, 2.1.2.1.

[29] E. Stellfox, "Evaluation of Snowplowable, Retroreflective Raised Pavement Markers," Tech. Rep. April, 2004.

[30] K. Patterson and J. Fitch, "Evaluation and Comparison of Snowplowable Raised Pavement Marking," Tech. Rep., 2007.

[31] K. R. Agent and E. R. Green, "Evaluation of the Use of Snowplowable Raised Pavement Markers," Tech. Rep., 2009.

[32] J. Filice, "Study on Snowplowable Raised Pavement Markers," Tech. Rep., 2006.

[33] K. Hofmann and M. Dunning, "Evaluation of raised and recessed pavement markers," Tech. Rep., 1995.

[34] K. R. Agent and J. G. Pigman, "Evaluation of alternative Snowplowable Markers and Snowplowing Procedures," Tech. Rep., 2013.

[35] ——, "Time for recessed? Study Explores Different Ways to Plow Snow," no. February, p. 46–49, 2014.

[36] D. Giuli, "Polarization diversity in radars," *Proceedings of the IEEE*, vol. 74, no. 2, pp. 245–269, 1986.