A Visible Light-Based System for Automotive Relative Positioning

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Abstract—This paper details a simple relative positioning system based on phase-shift measurement with the vehicles light-emitting diode headlamps and taillights. A simulation study of this system is carried out in a realistic environment. It shows that the longitudinal measurement resolution is 12.4 cm over 18 m whereas the lateral distance can be estimated with a resolution of 22.6 cm over 3.5 m with a refresh rate of 2 kHz.

Keywords—range-finding sensor; positioning; automobile;

I. INTRODUCTION

Range-finding sensors are becoming increasingly common on new automobiles. They provide useful information to the vehicle concerning its surroundings and are a cornerstone on the road toward full automation. They can already provide partial automation, as in highway platooning. In this emerging use case, a leading vehicle (LV) is followed by following vehicles (FV) able to adjust automatically their trajectory using, among others, vehicle-to-vehicle (V2V) relative positioning [1]. To perform this function, each vehicle can use several technologies such as radars and lidars, which provide long range and high-resolution measurement but are also very sensitive to interferences [2], [3]. Global positioning systems (GPS) can also be used but do not provide enough accuracy and do not work when the satellites are out of sight.

Consequently, in [4], we have proposed for the first time a sensor based on phase-shift measurement that uses the light-emitting diodes (LED) headlamps and taillights of the vehicles to measure the V2V distance in highway platooning configurations. However, this system, called visible light rangefinder (VLR), is only able to measure the V2V longitudinal distance, which means relative positioning is not possible. Such a function would be useful, for instance when a vehicle joins or leaves a platoon from the side. However, it could also be used in other applications such as positioning of boats or in robotics.

In this paper, the concept of VLR is thus extended to support both longitudinal and lateral distance measurement and thus enable two dimensional relative positioning of vehicles in a highway platoon. The working principles of the VLR are first recalled and its extension for positioning purpose is detailed in Section II. Then, in Section III a simulation study of positioning VLR is carried out. The simulation model used is first presented. Then, the longitudinal and lateral range-finding performances are evaluated. It is shown that the longitudinal distance measurement resolution is 12.4 cm over 18 m whereas

the lateral resolution is 22.6 cm over 3.5 m, with a refresh rate of the measure of 2 kHz. Finally, conclusions and future works are listed in Section IV.

II. THE VISIBLE LIGHT RANGEFINDER

A. Working Principles of the VLR

The VLR ensures V2V range-finding according to the principles detailed on Fig. 1.

Fig.1: Block diagram of the VLR.

First, the FV emits a square signal s_e at frequency f_e by driving, with an emitter circuit, one of the headlamps. After free-space propagation, the optical signal transmitted is collected by a photodiode (PD) on the LV and turned into an electrical signal s_p . It is then processed by a receiver in order to recover a square signal $s_{p'}$ of frequency f_e .

This signal is emitted by the LV, with one of its LED taillights, toward the FV. Therefore, the LV acts as an active reflector of the signal sent by the FV. After free-space propagation, $s_{e'}$ is collected and reconstructed using the same process so that a square signal s_r of frequency f_e is retrieved. Due to the return-trip time-of-flight, s_r has with s_e a phase-shift ϕ partly proportional to the inter-vehicle distance d_x .

Both signals are first converted, through undersampling of factor r at frequency $r \cdot f_e / (r + 1)$, into signals s_{eh} and s_{rh} of lower frequency $f_i = f_e / (r + 1)$ but identical phase-shift ϕ . This phase-shift is then estimated using the classical auto-digital phase measurement technique [5]. This technique measures the width of a phase-shift pulse, obtained by XOR combination of one period of s_{eh} and s_{rh} , by counting the number of clock ticks M of frequency f_{clock} it can contain. From M and the light velocity c , the VLR can then provide an estimation d_{VLR} of the V2V distance using:

$$d_{VLR} = \frac{c}{2} \cdot \frac{M}{(r + 1)f_{clock}}. \quad (1)$$

B. The Positioning VLR

With reference to Fig. 2, if the VLR just described uses light/PD pairs placed at points FV_L and LV_L , it will only be able to measure the distance d_L , which is not sufficient to estimate the relative position of the vehicles.

Fig.2: Geometrical configuration of the platoon, with d_x , ϕ_x and ψ_x denoting the different distances, irradiance angles and incidence angles.

Now if the FV also detects the signals s_e , sent back by the LV with a second PD placed at point FV_R , it will be able to estimate the distance d_R . Assuming both vehicles remain on parallel longitudinal axis, the FV can thus estimate the coordinates of its point $FV_L = (x_{FV_L}, y_{FV_L})$ using:

$$x_{FV_L} = d_x = \sqrt{\frac{d_L^2 + d_R^2 - \ell^2}{2}}, \quad (2)$$

$$y_{FV_L} = \sqrt{d_L^2 - x_{FV_L}^2}. \quad (3)$$

In practice, if the vehicles do not have parallel axis, these equations are not valid anymore. However, in highway platooning, the curve radius are so large compared to the V2V distance that we can consider this condition is verified.

III. SIMULATION STUDY

A. Simulation Modeling and Parameters

The positioning VLR is now tested through simulations with Simulink. The distortions experienced by the signals between their transmission and reception are gathered in the free space optical channel model. If P_t is the optical power transmitted, then the average optical power received P_r will be $P_t = H(0)P_r$, with:

$$H(0) = \frac{(m+1)A_r}{2\pi d_x^2} \cos^m \phi \cos \psi, \quad (4)$$

where d_x , ϕ and ψ are the inter-vehicle distance, the irradiance angle and the incidence angle, A_r is the radiant sensitive area of the PD and m is the order of Lambertian emission, defined as $m = -\ln 2 / \ln(\cos \phi_{1/2})$, where $\phi_{1/2}$ is the semi-angle at half illuminance of the LED emitter [6]. Note that this equation is true as long as $\psi < \psi_c$, with ψ_c the field-of-view of the PD. Consequently, the signals produced by the PD will have an amplitude equal to γP_t , with γ the responsivity of the PD, and will also contain white Gaussian noise composed of shot noise of variance:

$$\sigma_{shot}^2 = 2q\gamma P_r B + 2qI_{bg}I_2B, \quad (5)$$

and thermal noise of variance:

$$\sigma_{th}^2 = \frac{8\pi k T_K}{G} \eta A_r I_2 B^2 + \frac{16\pi^2 k T_K \Gamma}{g_m} \eta^2 A_r^2 I_3 B^3, \quad (6)$$

where q is the electronic charge, B is the equivalent noise bandwidth, I_{bg} is the background photocurrent, equal to 740 μA in case of indirect exposition to the sunlight [7], I_2 is a noise bandwidth factor, k is the Boltzmann's constant, T_K is the absolute temperature, G is the open-loop voltage gain, η is the fixed capacitance of photo detector per unit area, Γ is the FET channel noise factor, g_m is the FET transconductance and I_3 is a noise-bandwidth factor. In practice most of these factors depend on the type of front-end preamplifier coupled with the PD. Here, field effect transistor (FET)-based front-ends are considered so the values used are taken from [6].

These values are listed in Tab. I along with the values of all the other parameters involved in the simulations. Note that the reconstruction of the signals received by both vehicles is performed by band-pass filtering, amplification and zero-crossing detection. Also note that the optical power P_t and the semi-angle $\phi_{1/2}$ of the headlamp and taillight have been chosen in order to have a luminous intensity in the reference axis of 5100 cd and 730 cd, as recommended in the international standards [8]. The frequency f_e is fixed at 4 MHz because of the limited bandwidth of most high-power LED and the other parameters are such that the refresh rate of the measure, given by $2f_e/(r+1)$, is 2 kHz.

TABLE I. SUMMARY OF THE SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
<i>General parameters</i>		<i>Filtering parameters</i>	
f_e	4 MHz	Order	4
f_{clock}	100 MHz	f_{LP}	4.05 MHz
r	3999	f_{HP}	3.95 MHz
<i>Headlamp parameters</i>		<i>Channel parameters</i>	
P_t	2 W	I_{bg}	740 μA
$\phi_{1/2}$	20°	I_2	0.562
<i>Taillight parameters</i>		B	10 MHz
P_t	1 W	T_K	298 K
$\phi_{1/2}$	20°	η	112 pF/cm ²
<i>Receiver parameters</i>		G	10
γ	0.5 A/W	Γ	1.5
A_r	50 mm ²	g_m	30 mS
ψ_c	55°	I_3	0.0868

B. Longitudinal Performances

First, the longitudinal performances of the positioning VLR are tested. Both vehicles are here considered aligned ($\phi_L = \psi_L = 0$) and separated by a distance $d_L = d_x$ that varies, by steps of 1 cm, from 5 m to 18 m, with 18 m the non-ambiguity range. One measure is taken at each step and the resulting distance evolution is given on Fig. 3(a): d_{VLR} is increasing linearly, closely to the real distance d_L . There is however a small offset induced by the processing delays on both ends. Since it remains constant, it can simply be removed. Fig. 3(b) shows then that the distribution of the remaining error is Gaussian-like with a standard deviation $\sigma_{long} = 6.2$ cm. If we define the measurement resolution as $\pm \sigma_{long}$, we can conclude that the longitudinal measurement resolution is 12.4 cm.

Fig. 3: (a) Evolution of the longitudinal distance measured by the VLR (blue curve) and of the true distance (red dashes) and (b) histogram of the resulting measurement error (blue blocks) with its Gaussian fit (red curve).

C. Positioning Performances

Then, the positioning capabilities of the VLR are evaluated. Here the FV stays at a fixed longitudinal distance of 6 m, which is an optimal V2V distance in platooning at 90 km/h [9]. The lateral distance varies from 0 m to 3.5 m by steps of 0.1 cm. One measure of d_L and d_R is taken at each step and (2) and (3) are then used to estimate the coordinates of the point FV_L . Fig. 4(a) shows the resulting evolution of these coordinates. The longitudinal coordinate remains very close to 6 m. The lateral coordinate, on its side, is sometimes constant over short ranges because the variations of d_L and d_R over these ranges are too small to be detected. However, its evolution follows the true value with small fluctuations highlighting the lateral measurement error. This error, which distribution is given on Fig. 4(b), is Gaussian-like with a standard deviation $\sigma_{lat} = 11.3$ cm, which means the lateral resolution can be defined as 22.6 cm.

IV. CONCLUSION

The concept of VLR, is here extended to support relative positioning of two consecutive vehicles. It enables, with a refresh rate of 2 kHz, longitudinal measurement over 18 m with a resolution of 12.4 cm and lateral measurement over 3.5 m with a resolution of 22.6 cm. Therefore, the system proposed takes good advantage of the automotive light sources, which first purpose is lighting and signaling, to provide an additional positioning solution that could be interesting, especially in platooning applications. This system

Fig. 4: Evolution of the lateral and longitudinal coordinates of the point FV_L estimated by the VLR and of the actual values by steps of 1 cm.

could however also be used in other applications such as positioning of boats or in robotics. Future works will consist in implementing and testing a real prototype in order to evaluate its true performances. Since both the FV and the LV use only one of their front or back lights, a joint use of VLR with visible light communication may also be investigated.

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