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Sensor-Friendly Vehicle and Roadway Systems

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Abstract *– Sensor-friendly vehicle and roadway systems consist of complementary signal sensor and reflector or transmitter technologies, which provide information about the threat of a collision. These technologies can be composed into cooperative collision avoidance systems, which can supplement or replace single vehicle-based systems. Experiments were run on the four most promising technologies to determine their performance and reliability; the four technologies were passive license plates with enhanced radar return, roadside obstacle-mounted radar-reflecting corner cubes, fluorescent paint for lane and obstacle marking, and light emitting diode brake-light messaging. These technologies all focus on improving the signal-to-noise ratio of the collision avoidance sensor. We believe that experimental results indicate that further proof-of-concept refinements are needed, but, in general, these systems represent technologically sound, cooperative vehicle-roadway components and that sensor friendly systems could eventually translate into a significant benefit in terms of lives saved.*

Keywords *– vehicle, highway, roadway, safety, collision avoidance, sensor, radar, fluorescence, light emitting diode.*

I. INTRODUCTION

As a compromise between unaided and fully automated driving, we have been investigating the concept of sensor-friendly highways and roadways. In this paradigm, roadways, obstacles, and vehicles are fitted with easy-to-sense markers, and vehicles are equipped with simple sensors and driver-alerting systems. These complementary sets of markers and sensors attempt to improve on the poor reliability of single-vehicle based sensors, which have difficulty distinguishing stationary roadway infrastructure from a stationary vehicle. We describe tests and the results thereof for four sensor-friendly technologies. We believe that these technologies are the most developed and could be installed on vehicles and roadway infrastructure in the shortest time frame.

- Fluorescent lane-marking paint
- Roadside obstacle-mounted radar-reflecting corner cubes
- Radar reflection-enhanced license plates
- Vehicle-to-vehicle light emitting diode (LED) brake-light messaging

All four technologies focus on improving the signal-to-noise ratio accessible with inexpensive sensors. The two radar-based technologies reasonably presuppose that forward-looking radar collision avoidance systems will soon be standard equipment on new vehicles. The LED brake-light messaging technology reasonably presupposes that LED clusters will soon replace incandescent brake-light bulbs. Our experiments indicate that all four technologies are technically viable, and our analysis indicates that all four technologies are potentially economically viable, depending on how marginal costs will be tallied.

A motivating premise for investigating sensor-friendly vehicles and roadways (SFVR) is that near-term cooperative vehicle and roadside measures can enhance other autonomous collision avoidance systems (CAS) such as forward collision warning (FCW) and avoidance (FCA), or lane departure warning (LDW) or avoidance (LDA). This is based on the hypothesis that supplemental cooperative systems in the road or on other vehicles will allow driver-assist systems to perform over a broader range of traffic conditions and roadway geometries, e.g., including curved sections and bridge abutments. Hence, with SFVR, system availability and reliability of CAS could be enhanced. Then user acceptance, market penetration, and ultimately, safety benefits could grow more quickly than with autonomous versions of CAS. In the end, sensor-friendly systems could be a shortcut to CAS deployment.

II. PRELIMINARIES

In the past, we have investigated the limitations of autonomous sensing systems in the context of vehicle and roadway signature characteristics [1]. In the present study we emphasize how those limitations could be mitigated through the use of near-term cooperative approaches, both vehicle-to-vehicle and vehicle-to-roadway [2]. In addition to our technical studies, we have investigated economic issues, especially marginal costs and benefits of candidate sensor-friendly concepts [3], and social issues relevant to near-term deployment of this technology. We began by "brainstorming" about 20 potential cooperative technologies. On apparent technical, economic, time-to-deployment, and social acceptability grounds, we narrowed down the list to four systems, for which preliminary experiments are reported in this paper.

III. EXPERIMENTS & RESULTS

A. Passive License Plates

A passive license plate (PLP) with enhanced radar-reflecting cross-section (RCS) is constructed by overlaying a standard license plate with a visually transparent superstrate that has the desired directional reflecting properties in the radar frequency regime. The goal is to modify the RCS so that a vehicle's rear license plate is seen by the following vehicle's radar as a near-point source of uniform high reflectivity over a wide azimuth, e.g., +/-45 degrees. PLP technology thus addresses rear-end collisions. Vehicles equipped with forward collision warning (FCW) or forward collision avoidance (FCA) radar systems would be able to reliably pick out forward cars even in curves, in adjacent lanes, or in inclement weather (in which road spray reduces unenhanced radar cross-sections below the detection threshold).

Two sets of PLP tests were run: laboratory tests to verify the PLP design [4], and road tests to gauge PLP performance in the field. Two prototype designs were tested, PLP-001 and PLP-002. The PLP-001 design has facets at 45 degrees from the rear surface. These facets are set at 90-degree angle to each other. The PLP-002 design is an array of semi-circular vertical contours. In both types, the grooves are filled with a low dielectric filler material, creating a flat surface like a normal license plate. Both types (before filling with dielectric) are illustrated in fig IV. Reflectance was measured at 77GHz at the normal, 5, 10, 15, 30 and 45 degrees. Measurements were made before filling with dielectric, after filling, and after applying an overcoat of material that is highly reflective in the visible spectrum.

Emerging FCW/FCA radar designs typically operate at 77 GHz, so our PLPs were designed for this frequency. Our sensor uses a FMCW processor with a frequency modulation bandwidth of 300 MHz, employing a single transmitter and an array of four receivers. The vertical field of view of the radar is 3 degrees, and the horizontal field of view is 12 degrees. The processor outputs range, horizontal bearing and signal amplitude for each detected target. Using the receiver array and wavefront reconstruction, a resolution of 3 degrees is achieved within the horizontal field of view. The range resolution is approximately 1 meter. Fig. IV illustrates the installed transmitter/receiver.

Measurements show that this arrangement provides a significant enhancement in signal and signal-to-noise ratio between normal incidence and about 22 degrees, but not at larger angles of incidence. The ineffectiveness at smaller-than-expected angles appears to be due at least in part to the recessed mounting geometry of the license plates, which is not taken into account in the modeling. The issue will be resolved by future measurements. It is nevertheless already clear from these preliminary tests that PLP will be a valuable ”sensor-friendly” technology.

B. Radar-Reflecting Corner Cubes

The roadside obstacle-mounted radar-reflecting corner cube (RRCC) model is that a small array (˜6) of macroscopic (˜10-20 cm diameter) corner cubes can be arranged in simple distinctive patterns that are geometrically coded to identify obstacles such as bridge abutments, overpasses, etc., thus labelling them as clutter to be distinguished from moving and stopped vehicles. As in PLP technology, we assume a 77 GHz FCW/FCA radar infrastructure is in place. Considering the angular and range resolution characteristics of this infrastructure, the most promising arrangement exploits range resolution. The basic pattern, six corner cubes spaced at 1 meter range intervals, is designated {111111}. Specific obstacle classes are coded by specific missing ”bits”, e.g., {101011} might signify an overpass. In our preliminary experiments we placed the arrays at the side of the road, but other possibilities can certainly be considered. Fig. IV illustrates the experimental arrangement.

The results are definitely encouraging. Future work will address alternative geometries, the possibility of alternatives to corner cubes, e.g., technologies like PLP that might be embedded, e.g., within lane markings, as well as optimal signal processing techniques.

C. Fluorescent Paint for Lane and Obstacle Marking

Here we consider an optical marking technique, wherein fluorescent pigments (transition metal oxides) are added to lane marking paint, or to the retro-reflecting glass beads that are typically sprinkled on top of the damp paint as it is applied. Since inexpensive high brightness light sources (lasers) are easiest to obtain in the red region of the visible spectrum (laser diodes), and fluorescent pigments can easily be tailored to emit in the near infrared region, where inexpensive detectors (Si PIN diodes) are available, we chose these alternatives for initial experiments. To detect the relatively small fluorescence signal amid the potentially enormous background signal from direct sunlight, we employ a narrow-band interference filter over the detector. We square-wave modulate the transmitted laser light and employ synchronous detection at the receiver. Fig. IV schematically depicts the experimental arrangement.

In the simplest case a particular fluorescent material would simply indicate the presence of lane markings. We can easily imagine that, with little additional technology, we could create and exploit a small code space, in which we encode information such as which lane separator is in view, the existence and direction of upcoming curves, etc.

Our experiments considered four issues: detectability of the fluorescence signal, its dependence on viewing angle, its dependence on relative velocity between the vehicle-mounted transmitter/receiver package and the roadway, and its robustness against direct sunlight. Easily adequate signal-to-noise ratios, i.e., at least 1000:1 at useful working distances, were obtained with a low-cost visible red laser excitation source, low cost infrared fluorescence sensor, and low cost coupling optics. The angular distribution of the fluorescence was found to be Lambertian, i.e., the signal falls off as the cosine of the angle between the normal to the roadway surface and the interrogation direction. [5] The fluorescence signal appears not to be substantially affected by relative motion of the sensor and the roadway; although advantageous, it is somewhat counter-intuitive, so further modeling and confirming experiments are being contemplated. The sensitivity of the specific fluorescent material (provided by Sunstones, Inc.) for these experiments was substantially suppressed by ambient infrared illumination. Thus this particular pigment is not suitable for daylight operation. However Sunstones is confident they can design alternative fluorescent pigments that couple inexpensive excitation light sources to inexpensive fluorescent light sensors robustly in sunlight. Based on the signal-to-noise ratio obtained in the high signal-to-noise geometries, we conclude that adequate code space is available to contemplate embedding simple informative messages in the lane markings. Additional details on fluorescent paint technology and its experimental evaluation are presented in a separate paper, ‘Fluorescent Paint for Roadway Lane Markers’. [6]

Fluorescent paint for lane marking – and perhaps for other roadside object marking applications – is a promising technology. However the details of its practical implementation are in early stages of formation. Like RRCC, fluorescent paint is a vehicle-to-roadway technology; this is, of course, in contrast to PLP and LEDBM (next section) technologies, which are vehicle-to-vehicle approaches. Whereas radar-reflecting corner cubes are probably most applicable to a relatively low density of high importance features, e.g., overpasses and bridges, fluorescent paint would probably be applied continuously, i.e., in contrast it is applicable to marking a higher density of relatively lower importance features. As the only apparently practical vehicle-to-roadway technology in this class that we have identified, it thus merits ongoing investigation despite its immaturity relative to the other three technologies investigated.

D. Light Emitting Diode Brake-light Messaging

The light emitting diode brake-light messaging (LEDBM) system is comprised of modulated LED brake-lights that communicate information about a vehicle's state to any following vehicle that is equipped with an LEDBM receiver. The LEDBM system is conceived as a supplement to radar in a FCW or FCA system; it identifies only cooperating vehicles, not clutter [2]. A key to its implementation, of course, is large-scale market penetration of modulated brake-light transmitters and the corresponding receivers. LED taillight assemblies are increasingly common, and the electronics needed to modulate them is simple and inexpensive. More expensive considerations are the sensors for observing forward vehicle state, and the required add-on receivers.

We built a prototype sensing, modulation, and detection system to determine the practical range and field-of-view of an LEDBM system, determine the system reliability of system, e.g., acquiring and retaining signal lock, test system performance during cut-in maneuvers, test system performance through curves, and test system performance through hills. Fig. IV shows the vehicle-mounted experimental arrangement.

The "lead vehicle" was equipped with a modulator, an LED transmitter, a longitudinal accelerometer, a wheel speed sensor, and modules to encode the signals and modulate the LED brake-lights. The "following vehicle" was equipped with two LED receivers mounted on the front bumper, and signal decoding and annunciation modules. A two-way radio channel and other auxiliary equipment, not envisioned for a deployed system, were used to transmit confirming experimental data and otherwise support the experiments.

The following vehicle was usually able to receive reliably when the transmitting vehicle was within the 25 degree receiver field-of-view (FOV) and its 60 meter range. However reliability results are mixed; better signal locking electronics are needed improve the LEDBM systems performance everywhere within the nominal FOV and range boundaries. Nevertheless, the LEDBM was shown to be a potentially effective supplement to radar; it outperforms the EVT-300 radar used in the parallel comparison experiment in terms of acquiring and holding the signal of the forward vehicle during complicated driving maneuvers such as sharp curves, tight cut-in maneuvers and quick transitions to hills.

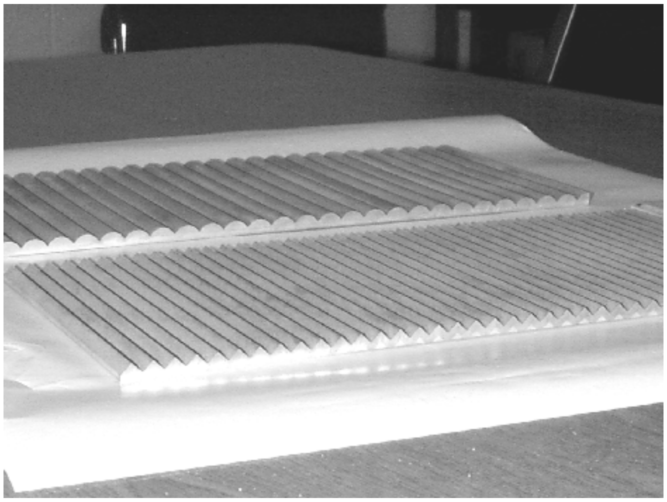

Fig. 1. Two designs of passive license plates substructure with enhanced radar reflectance

IV. CONCLUSION

Passive License Plates (PLP), Roadside-Mounted Radar Corner Cubes (RRCC), Fluorescent Paint, and LED Brake-light Messaging (LEDBM) are all shown in laboratory and/or early field tests to be viable sensor-friendly aids to enhancing the detectability of vehicles and/or obstacles and/or marking objects that would otherwise be mistaken for these objects, i.e., clutter. The four technologies are at different stages of maturity, require different investments in infrastructure, address different aspects of the overall problem, and have somewhat different anticipated payoffs with respect to saving lives and decreasing costs. Thus ongoing research on these and possibly other sensor-friendly concepts seems strongly warranted.

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Fig. 2. Roadside-deployed basic {111111} array of radar-reflecting corner cubes

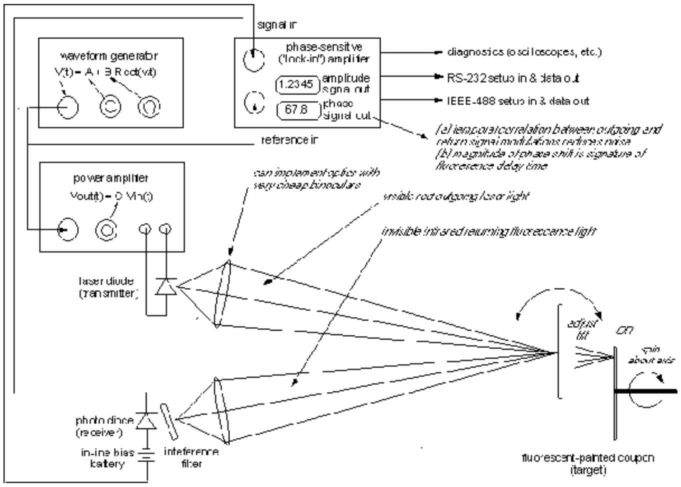

Fig. 3. Schematic arrangement of components for testing fluorescent paint

Fig. 4. Bumper-mounted LED brake-light receiver and auxiliary test components

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