Integrated Automotive Sensors

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Invited Paper

***Abstract*—This paper focuses on automotive applications and discusses the development of a suite of integrated radar and IR sensors that can be used to surround a vehicle (car, truck, boat, etc.). The primary function is to provide information to the vehicle systems and operator as enhancements to passenger and vehicle safety. It may also provide vehicle information (speed, location, destination, etc.) and integrate information (weather, road/traffic conditions, service/rest-area location, route details, etc.) from an intelligent vehicle highway system.**

***Index Terms*—Airplane, automotive, boat, car, GPS, highway, intelligent vehicle highway system, IR, radar, sensors, truck, vehicle.**

I. Introduction

THE spinoff of Department of Defense products in the 1980s and 1990s has brought military technologies into the daily life of the average consumer in many ways. Examples include previously classified Desert Storm electrooptical sensors that are now available on high-end model Cadillacs, handheld global positioning systems (GPSs) for the weekend hiker or sailor, satellite communications systems that bring hundreds of television channels into the home, and multiwavelength and graded index optical fibers for high-speed Internet connections. Military radar technology has been available to the commercial market for many years in air traffic control, high seas, weather, wind shear detection, small boat, and police applications. We are currently on the verge of an era in which radar use, technology, and terminology will become part of the everyday world, just as the personal computer has permeated our world today.

Commercial radars extract from their military origins the essential building blocks, algorithms, hardware, and software needed to provide the consumer with a radar that may have less performance, but will still provide useful and desired functionality at an affordable price. Improvements in these units due to the large volume and marketplace pressures can then, in turn, provide cost savings at the component/subassembly level to both military and commercial markets.

II. Automotive Radar Sensors

Automotive radar sensors have been in development since the early 1970s as aids in detecting objects ahead of, adjacent to, and behind a vehicle [1]–[11]. Simple backup sensors and side-looking blind-spot detection sensors are commercially available today. With the recent addition of a forward-looking radar system (FLRS) sensor to this suite, it is now possible to provide a full 360° envelope of coverage around the vehicle.

The automotive FLRS is by far the most complex, but promises to be the most revolutionary of these developments. Automotive forward-looking radar provides a driver with a precise all-weather representation of the roadway environment ahead to beyond 100 m (and to the side), allowing cruise control to take on another dimension, automatically regulating itself with the relative motion of traffic. It can also provide detection and warning, and perhaps some degree of vehicle control.

The near object detection system (NODS) is a shorter-range radar sensor that is positioned in multiple locations around the vehicle to detect cars, motorcycles, bicycles, and people in the vicinity of the vehicle, for blind-spot detection, and as an aid in parking and backing up.

These automotive radar sensors are exposed to extreme temperatures, salt spray, shock, vibration, and abuse that in many ways are similar to the military conditions that the radar industry is accustomed to. They must tolerate these conditions while demonstrating high precision and unquestioned reliability. To be marketable, they must be priced for the consumer, have an outward physical appearance that does not violate the sensibilities of the automobile stylists, and must be easy for the consumer to use and understand. With the rapid development of monolithic microwave integrated circuits (MMICs), application-specific integrated circuits (ASIC), and data-processing technology over the last decade, however, the realization of inexpensive, yet sophisticated and reliable systems of this nature, in quantities of 1000s, are upon us.

III. FLRS

Raytheon's FLRS is a bistatic, frequency-modulated continuous wave (FM/CW) radar operating at 77 GHz with electronic scanning capability of nine beams and detection range of beyond 100 m. The functions of the nine beams include two for self-alignment, diagnostic tests, and overpass detection, and seven for vehicle tracking. Embedded within the unit is software capable of path prediction, discrimination between moving and stopped objects, overhead object discrimination (overpasses, signs, etc.), and multipath mitigation. The unit is housed in a single box that accommodates the transmit and receive antenna as well as the RF circuitry and digital-processing devices. A

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TABLE I
COMPARISON OF FLRS AND NODS RADAR PARAMETERS

Parameter	FLRS	NODS
Frequency	76.5 ± 0.15 GHz	24.125 ± 0.09 GHz
Number of Beams	9	programmable
Range	1 to > 100 meters	0 to > 30 meters
Range Accuracy	< ± 0.5 meters	< ± 0.1 meters
Range Precision	0.1 meters	0.5 meters
Range-Rate	± 44 meters/second	N/A
Range-Rate Accuracy	± 0.31 meters/second	N/A
Range-Rate Precision	0.1 meters/second	N/A
Azimuth Field of View	± 7.0 degrees	± 60 degrees
Elevation Field of View	4 degrees	± 15 degrees
Update Rate	10 Hz	20 Hz of complete field of view

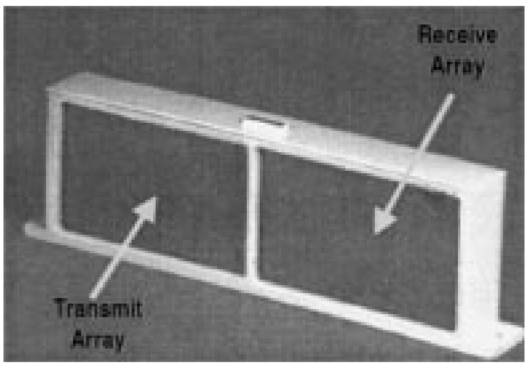

Fig. 1. Bistatic FLRS sensor.

summary of FLRS performance is presented in Table I and Fig. 1 shows a photograph of the prototype hardware.

FLRS sensors have been conceived as components currently used in intelligent cruise control. In this application, the sensor must be capable of accurately and reliably detecting objects (vehicles, pedestrians, and obstacles) in the forward path of the host vehicle. A fundamental requirement is that they have to detect objects in the path of the host vehicle as either the object or host changes direction and moves out of the host's direct line of travel. As the host vehicle approaches a curve in the roadway, prior to actually turning itself, the sensor must maintain track on all the forward-located objects in its field of view (FOV) and understand that if they are all moving in the same angular direction, it is the roadway that is curving, and not a particular object changing lanes. With the host vehicle and the objects both in the curve, the FLRS must maintain track on the lead vehicle in the same lane, even if it is not in the direct line of the host vehicle. This is called path prediction.

The path prediction approach that has been developed by Raytheon Electronic Systems, Sudbury, MA, includes an FLRS for collecting range, angle, and velocity data information on objects within a FOV in front of the vehicle, measuring systems for providing vehicle speed and yaw rate data, and a processing system responsive to the forward-looking sensor and measuring systems. The methodology consists of: 1) calculating an estimated path of the vehicle based on its speed and yaw rate; 2) calculating estimated paths for each of the objects; 3) determining the lateral distance of each object from the predicted path of the vehicle; and 4) classifying each object as either in or out of the highway lane of the vehicle.

Characteristic of the FM/CW waveform used is the generation of highly linear up and down frequency ramps. Tracking objects in frequency, not space, minimizes calculation load and memory requirements. The input to the signal processor is the frequency difference between the transmitted ramp (either up or down) and the delayed Doppler-shifted object return. Based on the return from a single ramp, a frequency track file is generated. Subsequent radar actions repeat these measurements and refine the track file of each object. As required, the frequency track files from separate up and down ramps are compared, and range, range rate, and acceleration information extracted.

Objects are also tracked in angle. The angular information is derived from the presence of the object in different azimuth antenna beams. An object could appear in one or more adjacent beam locations. Should objects appear in two adjacent beams, each with the same track history, it is assumed to be one object located in the area between the beam centers, and the actual angular position is calculated from the relative power levels of the radar echoes in the two beams. This, with the information from the processor about the object's range, allows all objects to be located in polar coordinates, with the radar at the origin.

IV. NODS

Raytheon's NODS is a 24-GHz FM/CW radar that uses a linear 180-MHz 1-ms chirp. FM/CW radar has the advantages of high sensitivity, relatively low transmitter power, and good range resolution. An upchirp is used to induce a forward prediction time of $\sim$0.1 s. Baseband video is filtered, digitized, fast Fourier transformed (FFTed), and thresholded for object detection. Range gates are reprogrammable in software to alter the detection zone for different vehicle sizes and configurations. Seven sequential beams arrayed in azimuth cover the FOV for the sensor. The selection of seven was accomplished by a tradeoff between alert zone sharpness, sidelobe levels, and antenna cost. The seven beams are formed by combining adjacent pairs from eight switched beams generated by a Butler matrix feeding a 6×8 array of waveguide slot apertures. The bistatic antenna assemblies (transmit and receive) provide feedthrough isolation and are fabricated in multilayer low-temperature co-fired ceramic (LTCC). A summary of NODS performance is also presented in Table I and a photograph is shown in Fig. 2. The NODS physical configuration consists of a two-piece housing with a base and a cover (radome), a top substrate containing the antenna and RF transmit and receive circuits, a second substrate

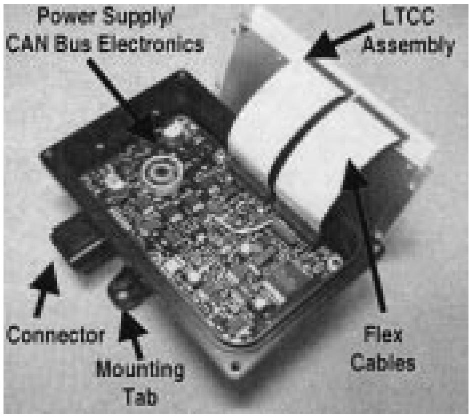

Fig. 2. NODS sensor.

in the base containing the IF circuits, flex circuits to connect the RF transmit and receive circuits to the IF circuits, and an electromagnetic interference (EMI) shield to reduce the amount of stray energy radiated from the sensor.

V. Night Vision

Night Vision is a thermal imaging system developed by the Raytheon Company that made its debut as an option on Cadillac's 2000 DeVille model. The Night Vision system uses an uncooled thermal camera mounted behind a car's front grill. Images from the camera are viewed with a heads up display on the bottom of the driver's windshield. Night Vision is unaffected by ambient light and provides an image that allows drivers to see beyond the glare of oncoming headlamps. During nighttime driving, when more than one-half of all traffic fatalities occur, the Night Vision system uses the heads up display to project real-time thermal images onto the lower part of the driver's windshield. The projected image resembles a black-and-white photographic negative—hotter objects (such as humans or animals) appear white and cooler objects appear black. Night Vision evolved from a militarized driver's vision enhancer that is standard equipment on the Bradley fighting vehicle with over 1000 systems in service.

VI. Tracking and Fusion

The use of both millimeter-wave radar and IR-based sensors in an integrated automotive application takes advantage of the best properties of each. IR sensing of the region directly in front of the vehicle provides the driver with a long-range visual image. The 77-GHz FLRS system accurately provides high-resolution all-weather object information to the intelligent cruise control. The 24-GHz NODS units provide programmable detection zones for side-object detection, backup aids, and parking assistance. Fig. 3 highlights how these functions are incorporated in different regions around the vehicle. By placing sensors around the vehicle, as shown in Fig. 4, full 360° coverage is achieved.

The development of small low-cost vehicular sensors, as described above, is critical to the success of intelligent highway systems. However, the signal processing, tracking algorithms, and reliability of the integrated system will go a long way toward

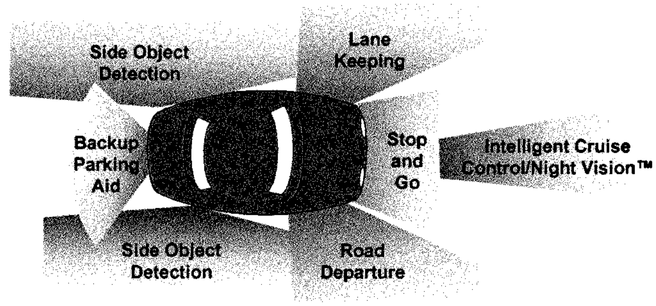

Fig. 3. Integrated sensor functions.

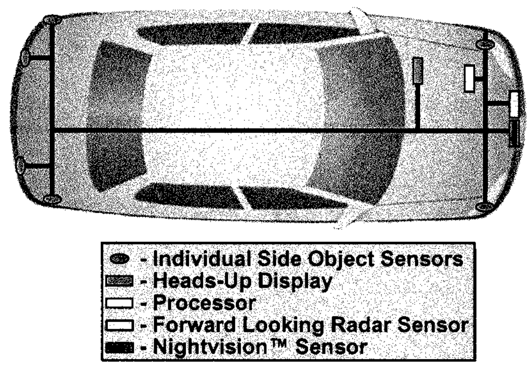

Fig. 4. 360° coverage component locations.

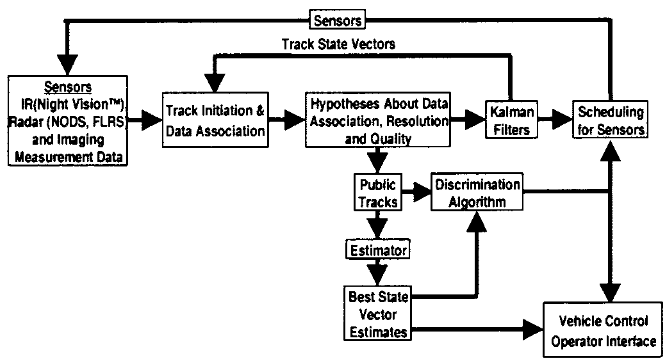

Fig. 5. Sensor data fusion.

satisfying the consumer and ultimately determining whether this multiple sensor system is readily accepted. Complex tracking, detection, and low false-alarm-rate algorithms must seamlessly fuse data from each of the sensors.

Usable data needs to be extracted from the sensors based on specific detection criteria, with reduced interference and high probability of detection. Tracking algorithms must initiate individual object tracks, continuously maintain track on multiple objects, update the track file data, and intelligently drop and reacquire tracks.

Scenario assessment algorithms need to include identification of the most important road hazard(s), reconfiguring the operating mode of sensors with respect to the specific hazard type and upcoming hazard predictions. This is done with a mixture of deterministic behavior and probabilistic behavior algorithm designs, while maintaining maximum detection and minimum false alarms. The different types of road hazards need different approaches. Fig. 5 highlights Raytheon's system flow diagram controlling the data processing and directing of the different sensors.

VII. Conclusion

As highway congestion and distractions continue to increase, automotive manufacturers and consumers look toward technology to improve and enhance safety. The sensors described here, individually or together, provide a new driver awareness of the environment surrounding the vehicle and may lead to a safer highway. The less mature automotive forward-looking radar application requires the development of industry standards for functionality, performance, and interfaces with other intelligent vehicle highway system (IVHS) components before it can realize its full market potential. The future of automotive radar may remain solely as a component of an enhanced cruise control or blind-spot detection without continued collaboration between industry and NTHSA to develop vehicular collision avoidance as a component of an overall IVHS. It is envisioned that, in the IVHS application, the radar suite will be integrated with GPS, automated steering control and braking, other on-board sensors, and numerous embedded roadway sensors to assist in the total control of the vehicle.

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