PRE-CRASH SENSOR FOR PRE-CRASH SAFETY

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ABSTRACT

Improvement of vehicle safety performance is one of the targets of ITS development. A pre-crash safety system has been developed that utilizes ITS technologies. The Pre-crash Safety system reduces collision injury by estimating TTC(time-to- collision) to preemptively activate safety devices, which consist of "Pre-crash Seatbelt" system and "Pre-crash Brake Assist" system.

The key technology of these systems is a "Pre-crash Sensor" to detect obstacles and estimate TTC. In this paper, the Pre-crash Sensor is presented. The Pre-crash Sensor uses millimeter-wave radar to detect preceding vehicles, oncoming vehicles, roadside objects, etc. on the road ahead. Furthermore, by using a phased array system as a vehicle radar for the first time, a compact electronically scanned millimeter-wave radar with high recognition performance has been achieved.

With respect to the obstacle determination algorithm, a crash determination algorithm has been newly developed, taking into account estimation of the direction of advance of the vehicle, in addition to the distance, relative speed and direction of the object.

1. INTRODUCTION

Many researches and developments have been conducted to meet society's needs for safer vehicles. Particularly, occupant protection systems such as airbags, developed and introduced in order to reduce occupant injuries in crashes, are currently installed in most vehicles, making significant contributions to safety.

Meanwhile, many studies have been made into the development of active safety technologies that help to avoid crash accidents. Unfortunately, however, the current situation is that active safety technologies are not sufficiently spread. Adaptive cruise control (ACC) has been commercialized since 1995, but its primary use has been convenience, not active safety. Some audible warning systems and other systems are also being offered, but have not yet reached widespread use.

Toyota Motor Corporation has explored the possibility of producing an active safety system employing Intelligent Transport Systems (ITS) technologies, through participation in the Advanced Safety Vehicle (ASV) Project, started in 1991 and led by the Ministry of Land, Infrastructure and Transport (Ministry of Transport at that time). [1]-[5]

Critical basic ITS technologies for application to ASV include a surround monitoring sensor and an obstacle determination algorithm, which combines information from the surround monitoring sensor with other information to identify obstacles with which the vehicle is likely to actually crash.

The sensor and crash determination algorithm for an active safety system should be capable of reliably determining unavoidable crashes, that is, reliably predicting a crash before it actually occurs, as well as reliably determining that a crash will not occur in a non-crash situation. Advanced technologies are required to make these predictions and judgements correctly while also taking into account the driver's operation and behavior, and this has hampered widespread of active safety systems.

Pre-crash safety (PCS) system has been developed, which operates only when it is judged that a crash cannot be avoided by most drivers under normal driving conditions. Determining unavoidable crashes is restricted to a short time period immediately before the crash, so as to improve the reliability of the judgement. In addition, the pre-crash safety system is made with a mechanism and system that will not place the driver and the running vehicle in an unsafe condition, even if the system is operated unnecessarily (i.e., when the system operates even though a crash may not actually happen). As a result, the world's first commercial system has been achieved.

This paper describes a pre-crash sensor for determining unavoidable crashes, which is a key technology in establishing the systems described above.

2. PRE-CRASH SAFETY SYSTEM

The system configuration of the pre-crash safety system is shown in Figures 1 and 2. The developed system consists of a pre-crash sensor, a pre-crash seat belt (PSB), and a pre-crash brake assist (PBA).

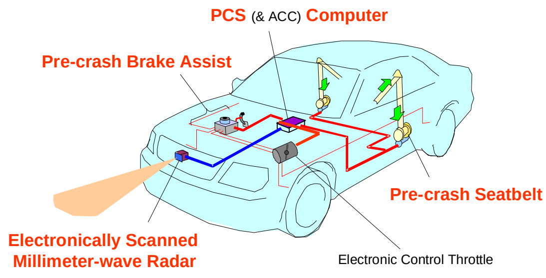

Figure1. Pre-crash safety (&ACC) **system**

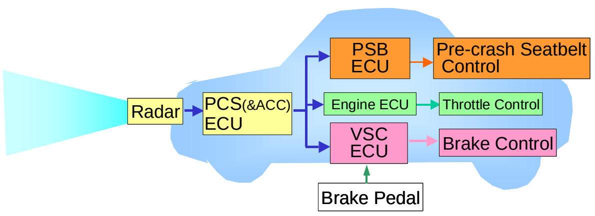

Figure 2. Block diagram of PCS (& ACC) **system**

The pre-crash sensor, which is primarily composed of a millimeter wave radar and a computer for determining unavoidable crashes, recognizes an obstacle in the course ahead and determines in advance whether a crash is unavoidable, based on location, speed, and course. The pre-crash seat belt, which employs a mechanism to retract the seat belt by a motor, reduces crash injuries through earlier restraint of an occupant. The pre-crash brake assist reduces the crash speed by quickly generating a large braking force in response to the driver's brake pedal application, even when sudden braking is not being performed.

3. CONCEPT OF PRE-CRASH SENSOR

Figure 3 illustrates the configuration of the pre-crash sensor system.

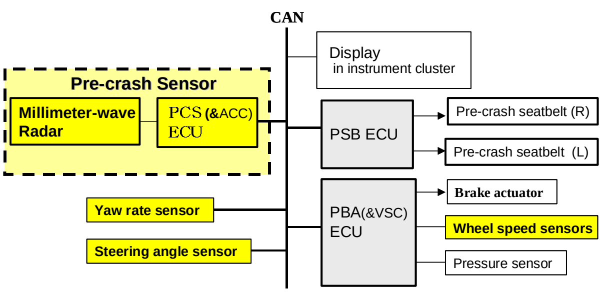

Figure3. Configuration of the pre-crash sensor system

Distances to multiple obstacles such as preceding vehicles, on-coming vehicles, and roadside objects, as well as relative speeds and directions of the obstacles are detected by the millimeter-wave radar, while the movement of the host-vehicle is estimated by vehicle speed, steering angle, and yaw rate.

The millimeter-wave radar, steering angle sensor, and yaw rate sensor are also used for adaptive cruise control (ACC) and vehicle stability control (VSC), to reduce sensor system costs.

A PCS electronic control unit (ECU) receives information from each sensor and makes judgement regarding obstacles. The judgement result is sent to a PSB ECU and a PBA ECU (also used as a VSC ECU), and the final control of each device such as the pre-crash seat belt is executed by the relevant control ECU, such as the PSB ECU.

4. MILLIMETER-WAVE RADAR

The millimeter-wave radar is robust in poor weather or dirty conditions. On the other hand, the millimeter-wave radar becomes large-sized and complicated if an attempt is made to improve its object identification performance. This project succeeded in developing the world's first electronically scanned millimeter-wave radar that uses a phased array antenna for automotive application, and it was possible to produce a compact millimeter-wave radar with excellent object identification performance.

The newly developed millimeter-wave radar consists of an antenna, a millimeter-wave circuit (T/R module), and a signal processing unit. A block diagram of the millimeter-wave radar is shown in Figure 4.

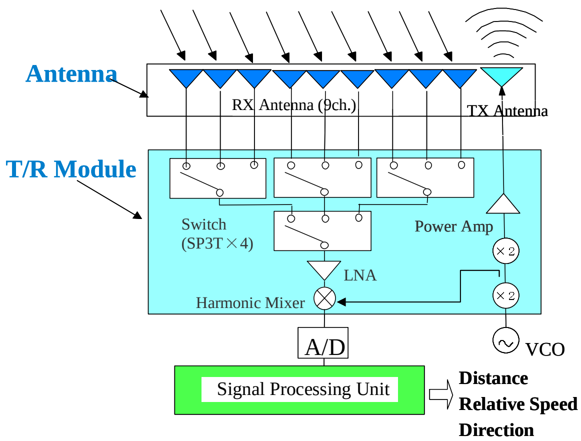

Figure4. Block diagram of millimeter-wave radar

The millimeter-wave radar systems used in this development are as follows.

1) Detection of the distance and relative speed: FM-CW system
2) Detection of direction: Beam scanning by digital beam forming (DBF) (See Figure5)

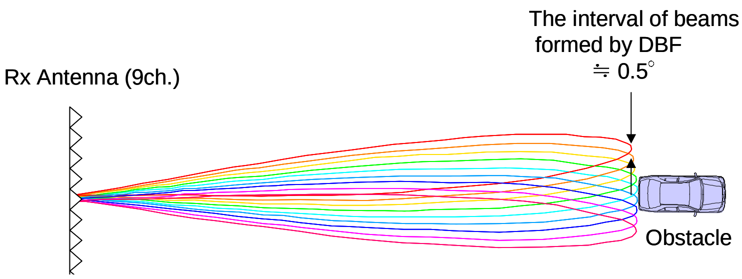

Figure5. Electronically scanned beams using DBF(Digital Beam Forming) technology

The characteristics of the millimeter-wave radar are as described below.

a) Antenna:

A triplate type phased array antenna was adopted from the standpoints of reducing sensor size and securing gain on transmission and reception of signals. One transmission channel and nine receiving channels were integrally constituted as one unit. However, as will be explained later in this paper, since reduction of wrap-around noise from the transmission side to the receiving side is important, an optimized design was adopted so as to minimize the wrap-around noise particularly from the transmission antenna to the receiving antenna.

b) Millimeter-wave circuit (T/R module):

In a phased array antenna for DBF, it is in principle necessary to sample received signals (9 channels) almost simultaneously, in order to secure phase difference synchronicity between channels. Nevertheless, a system that carries out signal sampling while carrying out nine reception channel switching was employed in order to simplify the circuit. Possible adverse effects involved by the use of such sampling system are SNR(Signal Noise Ratio) deterioration due to switching, and large influence from wrap-around noise between the transmission side and the receiving side. To deal with these issues, low-loss millimeter-wave switches (SP3T x 4), a high power amplifier, and a harmonic mixer that has less wrap-around noise from the transmission circuit to the receiving circuit were developed.

c) Signal processing unit:

Since DBF requires an enormous quantity of signal processing operations, a system that predicts in advance a point at which an object is likely to exist and forms beams around that point using DBF was developed. This system enables the processing of at least 50 objects with a 0.5° lateral beam scan interval resolution in a ±10° 150 m range within 100 milliseconds, by a single RISC microcomputer.

The specifications of the millimeter-wave radar with the aforementioned characteristics are shown in Table 1, and the structure of millimeter-wave radar is shown in Figure 6. Furthermore, photographs of the sensor assembly are shown in Figures 7 and 8, and a photograph of the T/R module is shown in Figure 8.

Table 1.
Specification of electronically scanned millimeter-wave radar

Item	Specification
Range	2－150m
Relative Speed	±200km/h
FOV(Interval of beams)	±10° (0.5°)
Calculation frequency	10Hz
Size	W107×H77×D53mm

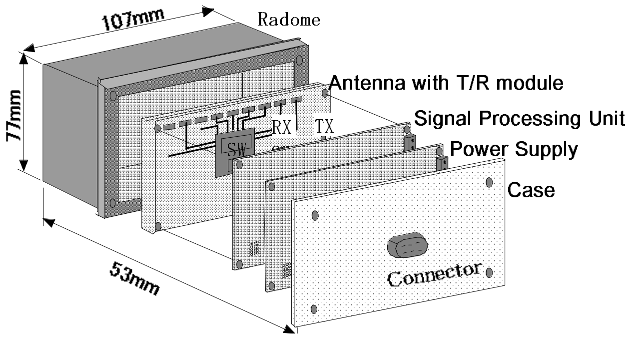

Figure6. Structure of millimeter-wave radar

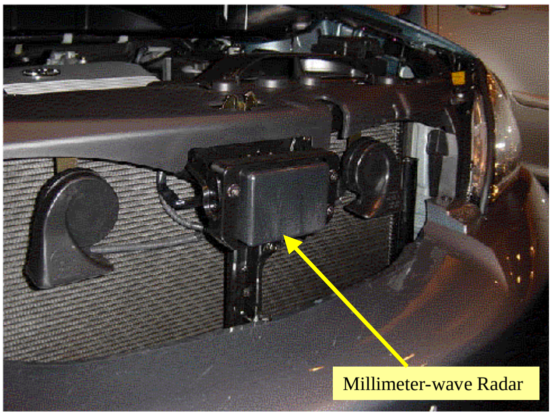

Figure7. Millimeter-wave radar installed in a vehicle

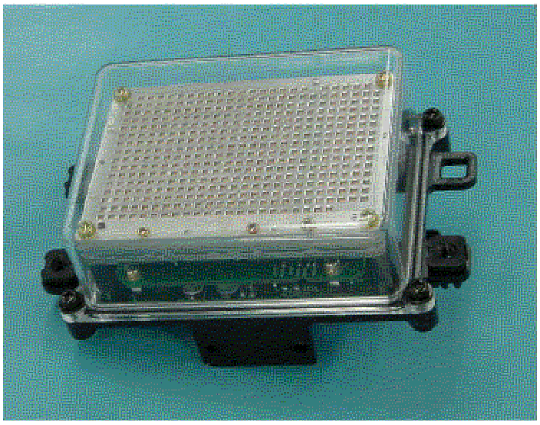

Figure8. Skeleton model of millimeter-wave radar

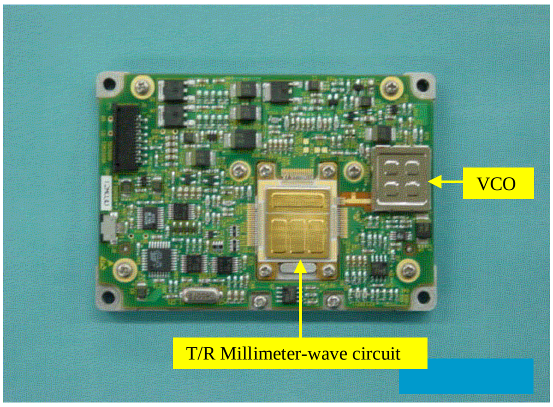

Figure9. T/R module

5. OBSTACLE DETECTION

The algorithm for obstacle detection is mainly composed of the three blocks shown below.

1) Determining whether an object exists either in the same lane or ahead of the host-vehicle. (See Figure10)

Since the developed millimeter-wave radar is also used for ACC, the ACC algorithms for lane width and the probability that the preceding vehicle is in the same lane as the host-vehicle were applied. However, the algorithms and constants for ACC, whose use is designed for use on highways and freeways, are not completely suitable for use with PCS, and therefore some algorithms have been added and adapted for PCS. For example, in a case where a vehicle passes by an obstacle immediately before a crash (such as an on-coming vehicle at the entrance of a curve), simply making a judgement based only on information of the host-vehicle's lane will result in an unavoidable crash being determined. Therefore, to prevent such erroneous judgement, the side position of the obstacle at the point when the crash is predicted to occur, obtained from the path of the obstacle, is added to the crash prediction algorithm, as shown in Figure 11. Furthermore, as with the case of ACC, a curve R, estimated by the steering angle sensor and yaw rate sensor, is used on estimation of the direction of advance of the vehicle. However, because the required response and the like differ from ACC, a correction method based on a curve R different from that of ACC has been added.

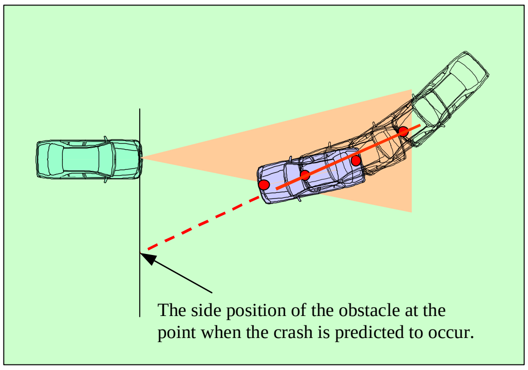

Figure11. Path estimation of the obstacle

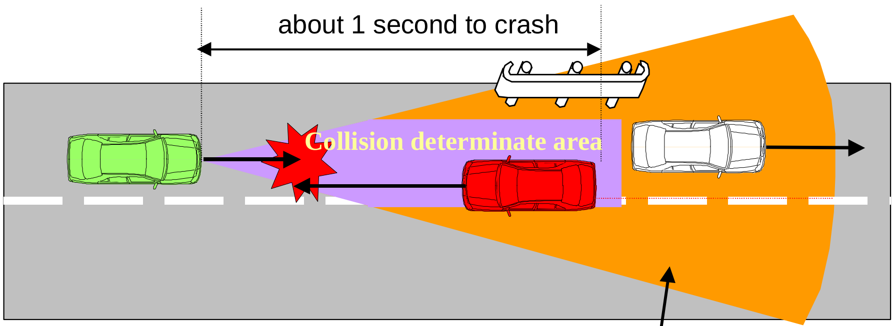

Figure10. Pre-crash sensing area

2) Determining whether the obstacle can be avoided by driver operation (braking and steering wheel operation)　(See Figure12)

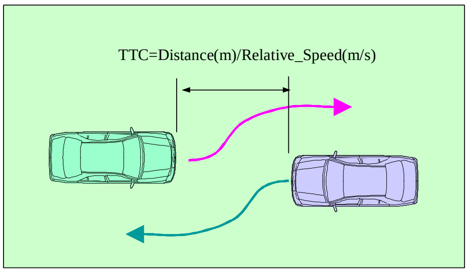

Figure12. TTC (time to collision) in which most drivers would not be able to avoid a crash even with a sudden avoiding operation

To determine whether a crash is unavoidable, the future crash-avoiding operations by the driver must also be anticipated. In this development, however, unavoidable crashes are determined based on a "time to collision (TTC)" in which most drivers would not be able to avoid a crash even with a sudden avoiding operation. When several potential obstacles exist, the obstacle with shortest TTC is judged as the top-priority obstacle for crash avoidance.

3) Other: object existence probability and system operation conditions

Since the reflection power of the millimeter-wave radar generally fluctuates significantly (particularly in the case of vehicle movement in longitudinal, lateral, and oblique directions), the normal procedure is to gradually decrease the object existence probability in a time-series manner while continuing to estimate the physical quantity of the object for a period of time, instead of erasing the existence of the object immediately after temporarily losing sight of it. This is particularly the case in ACC, where the tendency is to maintain the existence probability of the object for a period of time even if the system has temporarily lost sight of it, because importance is attached to the function of tracking the vehicle ahead. In PCS, however, this has a negative effect whereby the system continues to track the object even after the vehicle has avoided it as an obstacle. Therefore, the existence probability is calculated in a different manner to ACC, thereby reducing unnecessary obstacle detection.

In order to minimize unnecessary detection of an obstacle, a restriction has been placed on judgements of obstacles based on relative speed or in a host-vehicle speed area where the effectiveness of the system is reduced.

The millimeter-wave radar described in Section 4 above and the obstacle determination algorithms were developed and evaluated based on the results of driving tests conducted with a total driving distance of more than 100,000 km in Japan, the United States, and Europe. As a result, optimal adaptation of the system was achieved.

6. CONCLUSIONS

Developments aimed at reducing traffic accident injuries through application of active safety technologies in addition to passive safety technologies such as airbags have long been attempted, and such development was also a dream for engineers in this field. Nevertheless, until now, sensor system performance (including size and cost, as well as recognition performance) has not reached a sufficient level, which has prevented commercialization of a system that detects actual obstacles in advance and activates devices for occupant protection **prior to the crash**.

In this development, in addition to the highly-functional, compact millimeter-wave radar that can be applied to the safety systems, crash determination algorithms that can determine an unavoidable crash more reliably has been developed. As a result, the production of a system that activates safety devices prior to an actual crash has been accomplished. Not many systems have these technologies yet, and this technological development may be just one small step, but it is probable that this is a step forward in the field of active safety.

In the future, the crash injury reduction effect is expected to be further enhanced by constructing more advanced sensor systems through further research and work on millimeter-wave radar performance and combined usage with an image sensor, as well as by increasing and upgrading application systems

ACKNOWLEDGMENTS

In closing, we would like to express our sincere gratitude to Denso Corporation and Mitsubishi Electric Corporation for their cooperation in developing the pre-crash sensor.

REFERENCES

[1]S.Tokoro 1996. "Automotive Application Systems of a Millimeter-wave Radar." TOYOTA Technical Review Vol.46 No.1 Sep., 51-56

[2]T.Matsumoto, N.Yoshitsugu and Y.Hori. 1996. "TOYOTA Advanced Safety Vehicle(TOYOTA

ASV).” TOYOTA Technical Review Vol.46 No.1 May, 56-63

[3]Y.Yamada, S.Tokoro and Y.Fujita. 1994. “Development of a 60 GHz Radar for Rear-end Collision Avoidance.” Proceedings of the Intelligent Vehicles Symposium, 207-212

[4]H.Satonaka, Y.Hashimoto, Y.Yamada and T.Kakinami.1995. “A Study of Sensor Fusion Technology for Collision Avoidance System.” ITS World Congress ’95 Vol.III, 1108-1115

[5]M.Kawai. 1994 “Collision Avoidance Technologies.” Proceedings of the International Congress on Transportation Electronics, SAE P-283,94C038, 305-316