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Pre-crash Sensing – Functional Evolution based on Short Range Radar Sensor Platform

Rainer Moritz
Robert Bosch Gmbh

ABSTRACT

Pre-crash functionality is defined in three functional steps: PRESET, PREFIRE and PREACT. The functional steps are in the order that they require a increasing situation analysis performance and an growing amount of application effort. Each functional step makes it necessary to define the appropriate range of view, the virtual barrier. It is subject to various constraints and the configurations possible in pre-crash sensing.

Pre-crash sensing technology uses platform radar sensors being designed for the functional integration of all possible functions that rely on sensor information from the close surrounding of the vehicle. This approach guarantees a high cost efficiency, flexibility and modularity of the sensor system still guaranteeing the full pre-crash functionality.

INTRODUCTION

Active and passive safety play a growing role in the buyer's acceptance of a new vehicle once it is released on the market. On the other hand, legal requirements prescribe a minimum standard for safety in the vehicle. Both factors drive the spread of new technologies and open up the way to innovations such as pre-crash sensing as one of the future surround sensing systems for short ranges around the vehicle.

The main focus of pre-crash sensing is helping passive safety devices in protecting the passenger in all crash situations in. Thus, passive safety devices can no longer be limited to airbags, belt tensioners and active head-rests but will include new restraint systems but also automatic brake and steering activation as well. The latter devices – traditionally being active safety devices where there is driver interaction – will more and more be partially automated compensating deficits in the human reaction.

On the way there, pre-crash functionality evolution can be divided into three steps: PRESET, PREFIRE and PREACT. The three steps are described in greater detail later on. Each of these steps require a growing capability of the sensor system to capture, evaluate and decide on complex situations as well as an increase of experience in application and field performance. As it comes to new passive safety devices such as e.g. reversible belt tensioners or automated brake activation, customer acceptance and liability issues have to be considered very carefully.

Although, the technical potential of pre-crash sensing is very high, the sensor concept has to guarantee high cost efficiency. The fact that there are other functions relying on sensor information of the vehicle's surrounding leads to a platform strategy of functional integration. A platform radar sensor featuring a carrier frequency of 24,125GHz and a wide opening angle (+/- 55° vertical, +/- 15° horizontal) is employed.

Hence, there is no special pre-crash sensor but a platform sensor fulfilling all pre-crash requirements and, at the same time, the requirements of functions like parking aid, adaptive cruise control with Stop&Go or Stop&Roll functionality, blind spot detection, backing aid, passive entry and autonomous parking. Realizing a platform sensor, the basic requirements for software and hardware have to be derived from the functional requirements at the very beginning of the sensor design phase. Such a thorough requirement analysis at the beginning of the sensor development allows great flexibility and a high reuse factor for the software side and a limited and predictable management of variants for the hardware side. Eventually the requirement analysis means higher development quality and improved process control.

Pre-crash sensing is applicable for frontal and lateral impact protection. In the following, only front pre-crash will be treated whereas the results from PRESET, PREFIRE are in quality valid for side pre-crash as well.

FUNCTIONAL EVOLUTION

The evolution in pre-crash functionality can be divided into three consecutive steps defined by the set of actuators integrated. The steps are in the following order:

1. **PRESET**
   PRE-crash **SET**ting of algorithmic thresholds
2. **PREFIRE**
   PRE-crash **FI**ring of reversible **RE**straints
3. **PREACT**
   PRe-crash **E**ngagement of **ACT**ive safety devices

The functional steps represent an evolving improvement in passive safety performance incorporating a growing set of devices whereas the each subsequent step also allows the functionality of the step before. The sensor system has to capture its information within a virtual barrier depending on the activation requirements of every single device. The virtual barrier represents the space between a maximum required detection range (range where object detection is required) and a required minimum detection range (minimum range required for data transmission time, calculation time and actuator reaction time).

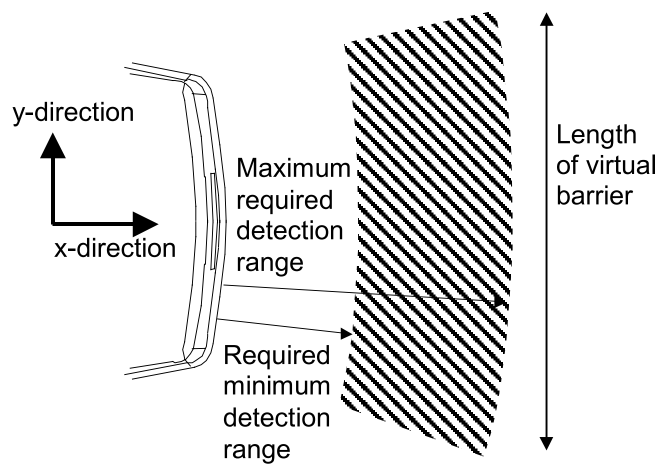

Figure 1: Virtual barrier at vehicle front and vehicle coordinates

For higher maximum ranges of the virtual barrier, the relevant pre-crash information has to be derived from a captured situation of growing complexity being more and more difficult to predict. The depth of the virtual barrier defines the amount of data available for data processing and interpretation. Finally, the length depends on the object scenarios required to be detected. Figure 2 shows the definition of a frontal crash to be detected in PRESET and PREFIRE. All three barrier parameters (maximum range, minimum range and length) may have an optimal setting once the functionality and the device incorporated are defined. The specification of range and opening angle of the sensor can eventually be derived from the virtual barrier extensions.

Prior to the detailed treatment of pre-crash functionality, the dependence of pre-crash information and sensor configuration needs to be clarified. Basically, two sensor configurations can be qualified generating a specific set of pre-crash information:

Single Sensor Pre-crash:

- Crash expected decision
- Closing velocity in x-direction
- Time to expected impact
- Offset information

Dual/Multi Sensor Pre-crash:

- Crash expected decision
- Closing velocity in x-direction
- Time to expected impact
- Crash angle
- Point of expected impact
- Object overlap

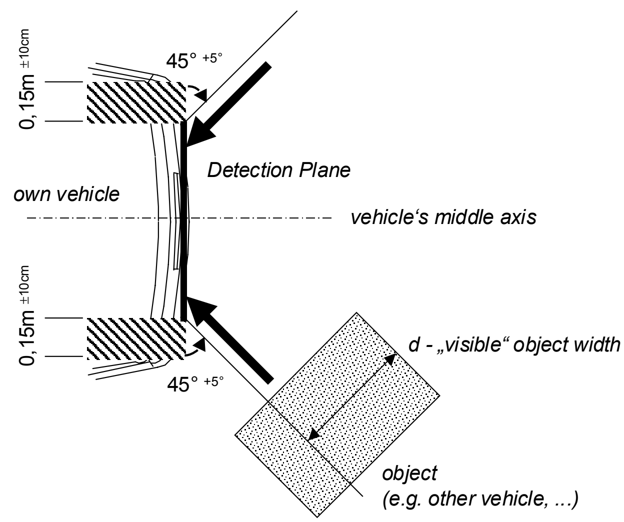

Figure 2: Definition of frontal crash for PRESET and PREFIRE by definition of a detection plane on the vehicle surface

Time to expected impact qualifies the start of the expected crash. Finally, object overlap means classifying objects in extended or punctual objects and, if they are classified to be extended objects, detecting the degree of overlap in respect to the own vehicle.

1. FUNCTIONAL STEP: PRESET

In PRESET, pre-crash information is supplementary information to the information from the central airbag control unit's immanent acceleration sensor in x-direction. Pre-crash information must be available to the airbag control algorithm prior to the start of a crash for all relative speeds up to 60 m/s so algorithmic thresholds can be adapted before entering the algorithm execution. Therefore, the virtual barrier can be defined being situated as close as possible to the own vehicle. Hence, the required minimum detection range equals 0,7 m (for single sensor pre-crash) or 0,4 m (for dual/multi sensor pre-crash). Limiting the maximum required detection range to 1,5 m, the virtual barrier guarantees both, a limited possible situation complexity being well predictable, and a sufficient amount of data even at the specified maximum closing velocity of 60 m/s.

The motivation for PRESET is a further potential of crash severity sensing. Today's airbag algorithms are exclusively based on acceleration information measured in one or more discrete locations. The algorithm has to derive all crash parameters

- closing velocity
- barrier stiffness
- mass
- stiffness of own vehicle
- mass of own vehicle

from acceleration information.

Knowing closing velocity in x-direction – one of the three main crash parameters — the calculation of barrier stiffness and mass can now be based on two physically independent quantities. If the sensor configuration allows, crash severity information can also be predicted by combining crash angle, point of expected impact and object overlap.

The PRESET functionality implies the use of common, mostly pyrotechnically driven restraints. Due to the ry risk of airbags and high repair costs of these restraints in case of a deployment, the fire/no-fire decision is based on a combination of both pre-crash information and acceleration data [1]. Figure 3 shows the necessity of such a combination.

In this diagram, crash type, labeling the y-axis, represents a combination of barrier stiffness and mass by referring to barriers used in common crash and misuse tests. Closing velocity is shown on the x-axis. Closing velocity alone does not decide about the crash severity as described above. Although, closing velocity can define the maximum set of restraints by clustering all crashes in areas of closing velocity. The lower cluster border is always defined by the minimum deployment requirement for the most severe crash test – a rigid barrier 0° test. The upper border is defined by the lower border of the next cluster. Eventually, for two firing stages, there are three clusters:

1. Non-deployment cluster (unbelted: C0, belted: C0+C1)
2. First stage cluster (unbelted: C1+C2, belted: C2+C3)
3. Second stage cluster (unbelted: C3+C4, belted: C4)

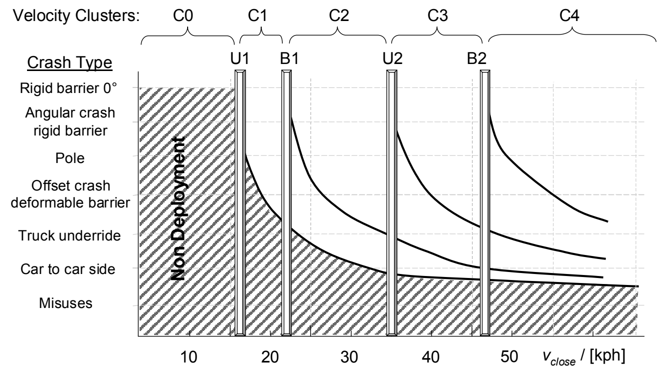

Figure 3: Clustered crash set with thresholds separating the required set of restraints

The non-deployment cluster defines a zone where all crashes within that cluster are not relevant to firing any sort of restraints. Defining a clear no-fire zone the risk of inadvertent deployments is reduced in more than 40% of all crashes (see figure 4). At the same time, sophisticated acceleration based algorithm modules for the separation of fire and no-fire crashes can be simplified.

The first stage cluster helps avoiding an airbag inflation being too aggressive in the mid-speed range reducing the injury risk especially for softer crashes. Furthermore, the performance and robustness of triggering staged inflation airbags can be improved using simplified algorithm modules, too. The structure of the pre-crash algorithm is shown in figure 5.

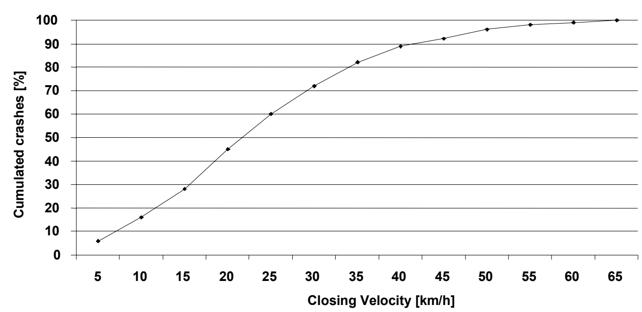

Figure 4: Crash distribution over closing velocity [2]

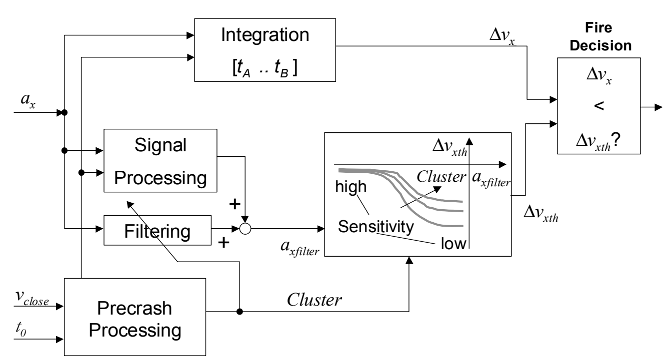

Figure 5: Algorithm block diagram for a single sensor configuration (v_{close} = closing velocity, t_0 = time to expected impact)

Time to expected impact serves as plausibility for the “start of crash” based in the integrated acceleration information preventing misuses (e.g. side walk, pot hole, etc.) from starting the algorithm. It also serves as plausibility information for the crash expected decision itself as well as a parameter for all time dependant functions within the algorithm which improves the firing performance in case of consecutive crash events.

The key to earlier triggering times lies within the calculation of the parameter compound barrier stiffness and mass (“signal processing” block in figure 5) at a very early time within the crash. Having stiffness and mass information, crash severity can reliably be determined very early allowing some significant triggering times improvements especially for belt tensioners. For this calculation all information available in the airbag control unit can be used. For the single sensor configuration, the barrier stiffness / mass calculation is based on the first peak of acceleration within a crash and closing velocity. For dual / multi sensor configurations, the parameters crash angle, point of expected impact and object overlap can be used additionally to the ones above for an improved barrier stiffness / mass calculation.

With earlier triggering times, airbags in the future can be modified such that they inflate slower and therefore aggressive or eventually even adapt their airflow in accordance to the crash severity expected.

Pre-crash information does not only allow earlier triggering times but will also limit the possible deployment time by defining a deployment window for each cluster with minimum and maximum firing times. This brings further robustness to the airbag performance.

2. FUNCTIONAL STEP: PREFIRE

The next functional step is called PREFIRE targeting at a further improvement of the restraint system performance through the use of cost efficient reusable restraints fired prior to the crash. For example, firing a reversible belt tensioner, before the collision starts, represents an improved ride down benefit showing significantly better protection in high-speed crashes against stiff barriers. On the other hand, reversible restraints do not need to be replaced after the crash which might lower vehicle insurance ratings.

PREFIRE represents a direct deployment of restraints solely based on pre-crash information. Considering this fact, four premises have to be set up:

1. The actuators can only be of low injury risk
2. The actuators can only be reversible
3. The actuators must not confuse the driver in case of an inadvertent deployment

Pre-crash information are deduced from radar sensor signals. The singular radar sensor signals always bears the risk of temporary and sporadic measurement errors which demands robust signal processing routines generating the pre-crash information. Still, it is appropriate to add a further functional safety margin by limiting the employed actuators to reversible restraints and low risk deployment (see items 1 and 2). Examples for such restraints are

- Belt tensioner
- Knee padding

There is no broad field experience neither of such sensor systems in the automotive environment nor of the customer acceptance regarding reversible restraints. Additionally, due to liability reasons, the whole restraint system has to guarantee that there will be no further risk to the restraint system (see item 3). Hence, actuators such as active seats or foot padding are seen to be critical in this respect due to the risk of producing an accident by confusing the driver.

For the definition of the virtual barrier for PREFIRE, it is important to know the activation specification of the envisioned restraints. For all reversible restraints a certain time is necessary to have them enfold their protection potential (50 ms - 200 ms). The maximum closing at the point of impact is specified to 65 km/h covering almost 100% of all field crashes (see figure 4). The required minimum detection range is therefore no fixed parameter but depends on

- closing velocity
- acceleration / deceleration derived from closing velocity
- restraint activation time.

Having no pre-conception about the on-coming object, the following worst case example is important for the definition of the maximum required detection range of the virtual barrier: Considering a maximum acceleration effect of a = -20 m/s² (both vehicles heading onto each other with maximum braking force) and therefore expecting a closing velocity of 65 km/h at the point of impact, the required minimum detection range is 4 m for a restraint activation time of 200 ms.

Giving the sensor system enough time to detect the object and gain plausibility for the detection, the resulting maximum required detection range is 7m. At the distance of 7m, the derivation of the crash expected decision is not trivial to signal processing facing rather complex situations.

3. FUNCTIONAL STEP: PREACT

The goal of PREACT is to mitigate the average crash severity or to possibly even lower crash severity beyond the severity of an insurance crash. Statistical data shows the potential of automated crash avoidance maneuvers prior to a crash. In 40 % of all frontal and angular car-to-car crashes with fatalities, there has been no avoidance maneuver reported [3]. The avoidance of crash situations taking over control of the whole vehicle and calculating escape strategies will not be treated here. PREACT based on short range radar sensor technology will only employ the automatic activation of brakes. Still, PREACT is the most demanding functional step in terms of system application effort and functional safety within pre-crash functional development. The brake shall override the driver in situations where a crash has become securely unavoidable. Herein, the liability aspect of possible false alarm situations is prominent in PREACT and the functional safety needs to be validated under all circumstances.

The definition of the virtual barrier for PREACT is based on

- the vehicle's own dynamics
- the estimated driver reaction
- the estimated dynamics of the detected object(s)

and will be defined dynamically by the sensor system. Although, the maximum sensor range of 7m limits the closing velocity specified for PREACT to 30 km/h maximum. The minimum required detection range will dynamically be defined by the sensor system considering the time to expected impact of 0,6 s – 0,8 s where the expected crash can no longer be avoided by any driver activity.

Further parameters such as e.g. environmental conditions influencing vehicle dynamics or the personalized estimation of the driver's reaction are possible parameters might support the function in the future.

FURTHER FUNCTIONAL DEVELOPMENTS

Along with the functional evolution described above, there are other new perspectives of passive safety. The main three tendencies shall be describes in the following. All of them have in common that they also can use or even must rely on pre-crash information.

The first new tendency is pedestrian protection. Traditionally, the focus of passive safety has been protecting the passenger situated in the own vehicle. Now, pedestrian protection wants to make passive safety features available to the outside world, too. Pedestrian protection became an issue especially in Europe expecting a European legislation in 2002-2004 that would force the OEM's to provide a certain level of pedestrian protection. So, pedestrian protection itself does not necessarily need pre-crash information, but the platform sensor technology can also serve this functionality.

The second tendency is the automatic establishment of crash compatibility. The focus lies on avoiding any underride or override crash situations. The motivation for working on this issue is the fact that in crashes between the wide spread sports utility vehicles and regular size vehicles, the fatalities in the regular size vehicle are five times higher that in the sports utility vehicle [4]. Since regular vehicles are very difficult to protect from underride crashes, active bumpers or lowering the suspension level can help once these features become more and more common to sports utility vehicles.

The third tendency is the active reinforcement of vehicle structure affected by the crash. Where structural entities join, like a door structure in the frame of the passenger compartment, the overall stiffness can be optimized such that the intrusion is reduced and, therefore, the survival space of the passenger improved.

In the order of the pre-crash evolution, all these new functions are close to PREFIRE and all its requirements in respect to the definition of the virtual barrier and the premises 1 – 3 stated above.

SENSOR TECHNOLOGY FOR PRE-CRASH

SENSOR HARDWARE

Early in the development process it became very clear the automotive world would not accept the cost of a pre-crash stand-alone radar sensor. Even low-cost radar design bears too little cost efficiency if there is no multi-functional use envisioned. Whereas other sensor systems are first introduced into the vehicle and eventually combined later on for cost reasons, here the combination has to take place at the very beginning. This was the birth of the radar platform sensor.

The choice of radar technology was based on the evaluation of several sensing technologies. The technical requirements have to fulfill the main functional requirements of the different functions envisioned: adaptive cruise control Stop&Go, parking aid, backing aid, blind sport detection, autonomous parking and pre-crash sensing for frontal and side impact. For the complete technology evaluation, the criteria were the following:

- Meeting the main functional requirements for the set of functions mentioned above
- Meeting automotive requirements (meeting legal constraints, electrical and mechanical robustness against environmental influences, robustness against aging, packaging size, ease of installation, etc.)
- Technical availability / development effort necessary
- Cost (Initial costs for OEM, repair costs)

After having weighed these criteria, one of the most favorable sensing technologies was pulsed radar. After a period of sensor trials, the pulsed radar technology turned out to be the most versatile technology for the goal of a low cost platform sensor for short range object detection.

The choice of 24,125GHz as the carrier frequency was driven by the constraints of

- resolution and sensitivity required
- packaging size as a derivative of RF structure size
- positive evaluation of possibility for legal admission for ultra-wide-band appliances at 24,125GHz

The patch antennae were designed to detect objects at a very large opening angle in order to minimize the amount of sensors necessary for a complete coverage of the vehicle's surrounding. There is no angle sensitivity nor angle selectivity realized due to cost reasons. On the other hand patch antennae allow a flat housing of the sensor which is one major benefit for any invisible mounting location below the vehicle's outer skin.

In the following a detailed specification is listed in table 1.

Operating frequency	24.125 GHz
Distance range	0.3 m - 7 m (measuring) 0.1 m – 0.3 m (detecting)
Velocity range	0 m/s – ±60 m/s
Beam angle	horizontally ±50° vertically ±10°
Selectivity of staggered targets	0.3 m
Resolution	0.03 m (distance) 0.1 m/s (closing velocity)
Accuracy	1% +/- 0.05 m (distance) 5% +/- 0.5 m/s (closing vel.)
Length of measurement cycle	Typically 10 ms for 0.3 - 7 m (distance) Min. 1,5 ms for 60 m/s (closing velocity)
Smallest object	Metal bar 10 mm Ø, vertically placed at 1.5 m
Operating temperature	- 40 °C to +85 °C
Power supply	7 V – 16 V / 0.08 A
Dimensions (without connector and flanges)	85 mm x 42 mm x 15 mm

Table 1: Radar sensor specification

SENSOR PLATFORM SOFTWARE

The design of a platform sensor is not done by having a hardware fulfilling the main functional requirements in tests. As a safety critical function, the sensor has to fulfill all commonly known safety requirements from airbag development in respect to hardware, software, diagnosis and the function itself. The sensor becomes a platform sensor as soon as its software is part of a commonly design sensor platform software that guarantees modularity and clear-cut interfaces resulting in a defined design processes and a maximum reuse of code.

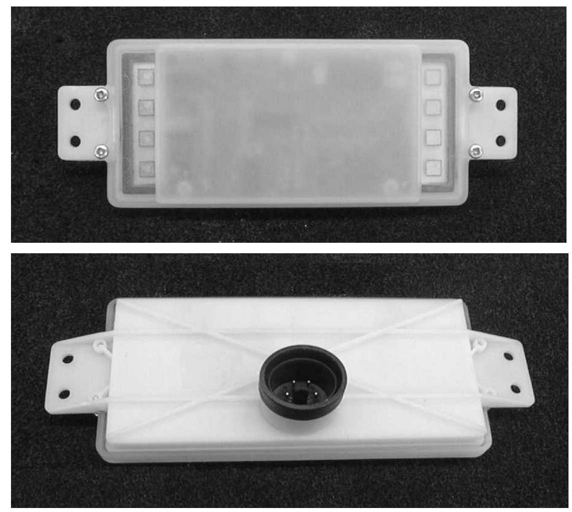

Figure 6: Radar sensor

The software design steps from a platform sensor to a sensor platform consist of

1. domain analysis
2. definition of logical interfaces
3. customized requirement analysis
4. definition of objects and classes

The platform sensor design started out with two parallel process strings. The first string begins with a domain analysis naming all possible tasks and grouping them together in respect to core tasks at different hierarchy levels. Then, the definition of logical interfaces defines a structure of functional and informational dependencies. The definition follows the systematic rules of CARTRONIC® [5].

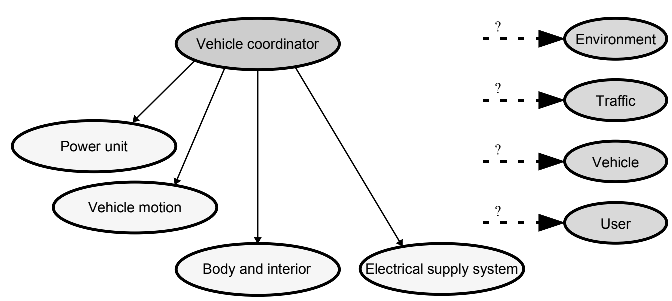

Figure 7: CARTRONIC® structure for the complete vehicle systems (first level)

The CATRONIC® rules prescribe the structuring of functions and data flow on hierarchical levels. On each level, a coordinator controls sub-functions and serves as an arbitrator in conflict situations relying on a specific set of sensor data (see example in figure 7). Each sub-function can represent a new hierarchical level being structured in the same way. The CARTRONIC® structuring process guarantees the full compatibility between the different vehicle functions and supports the software quality process by graphically defining the functional and informational dependencies. Finally, the results of the domain analysis is transferred to CARTRONIC® structure giving the defined logical functions a software background ready to be put into code.

In parallel the second process string begins with a thorough requirement analysis of all functions envisioned to use the platform sensor. Starting out from the results of the requirement analysis (see table 2), the interdependencies of configuration variations are defined in respect to functions and the number of sensors.

	Parking Aid Backing Aid	Blind Spot Side Obstacle	ACC Stop & Go	PreCrash	Passive Entry
parameter to measure	distance to first target	distance to first target	distance to first 4 targets, v(rel)	v(rel), time to collision	data communication
monitoring range	0,2...1,5 m 0,2...5 m (US)	0,5...7 m	0,2...7 m	0,5..2 m (front) 0,3..1 m (side)	0...1,5 m
distance accuracy	0,1 m	0,2 m	0,03 m	0,2 m	-
multi target selectivity	0,3 m	0,3 m	0,3 m	-	-
velocity measurement range	-	-	20 m/s	5..200 km/h 5..100 km/h	-
velocity accuracy	-	-	0,5 m/s	±10%	-
horizontal field of view	±60°	±60°	±60°	±60°	±60°
vertical field of view	±20°	±20°	±10°	±10°	±20°
measurement cycle	≤ 50 ms	≤ 10 ms	≤ 10 ms	≤ 10 ms	≤ 50 ms
smallest object	rod ∅ 1 cm at 1 m	bicycle	bicycle	rod ∅ 5 cm at 1,5 m	-

Table 2: List of functional requirements for sensor platform

At the end, the results of both process strings serve as basis for modeling the software. From hereon, the regular software code can be generated.

Considering the example of a sensor platform configuration of 4 sensors, the sensor data from all 4 sensors has to be processed together in central sensor control unit. A distributed system requires, that the status or mode of each sensor must be known to the data processing unit. Even more, in order to guarantee the functionality of the whole sensor platform avoiding an undefined over-all system status, the working modes of each sensor must be controlled from the central sensor control unit. The described software development process guarantees full testability of the product, software quality, modular and clearly defined structure and interfaces.

PRE-CRASH SPECIFIC SIGNAL PROCESSING

The sensor is pulse modulated which traditionally serves as a modulation for pure distance measurement. But pre-crash sensing cannot rely solely on distance information. Both, distance and closing velocity, are of importance.

Therefore, the received pulse can deliberately be correlated in the sensor so that the sensor can also measure Doppler frequencies. Due to the proper pulse correlation, the Doppler measurement is located at a defined distance – the so-called range-gate. So, every Doppler information comes together with a distance information.

The complete pre-crash measurement eventually represents a combination of pure distance measurement where several objects can be detected and tracked as well as Doppler measurement where only the closest and most dominant target is measured. In general, pre-crash signal processing has to draw its information out of the detection of complex object situations in the field of view coping with several radar effects in short ranges of the vehicle surrounding.

The three most important radar effects and possible sources for errors are:

1. Jumping centers of radar reflection as the perspective of the detected object changes
2. Doppler information represents the relative speed of the center of reflection in an radial direction to the sensor not the direction of its trajectory
3. The center of radar reflection is unknown in its location and number (There can be several centers of reflection at one and the same object which are at the same radial distance to the sensor.)

Radar reflection being a very complex issue, there are more effects to radar reflection such as e.g. multi-path effects. From our application experience of the pre-crash sensor, it is known that these effects do not interfere with the function.

In the sensor's default measurement mode, the sensor system works in a 7 m scan mode at a cycle time of 10 ms. The scan mode generates object lists of the objects being within the sensor's range. Objects with relative speeds up to 60 m/s can be captured and placed in an object list. Transition 1 represents a threat assessment based on the object list generated in the 7 m scan mode. As soon as there is at least one object that approaches the own vehicle at a speed, at which a severe collision relevant to the restraint system cannot be excluded, the sensor will be switched in the Doppler mode. Being in the Doppler mode, the sensor tracks down the closest object and measures the object's relative velocity at several defined distances as shown in figure 8. Distance information is necessary to acquire the time to expected impact and to create plausibility information to the measured Doppler information. Using this plausibility information, the measurement strategy of the Doppler mode detects a jump of the center of reflection. The Doppler mode eventually creates the primary information, the closing velocity in x-direction and the time to expected impact based on the said closing velocity.

Once the Doppler mode has gathered all possible information, two things will decide on transition 2:

- a crash is expected
- the target left the field of view

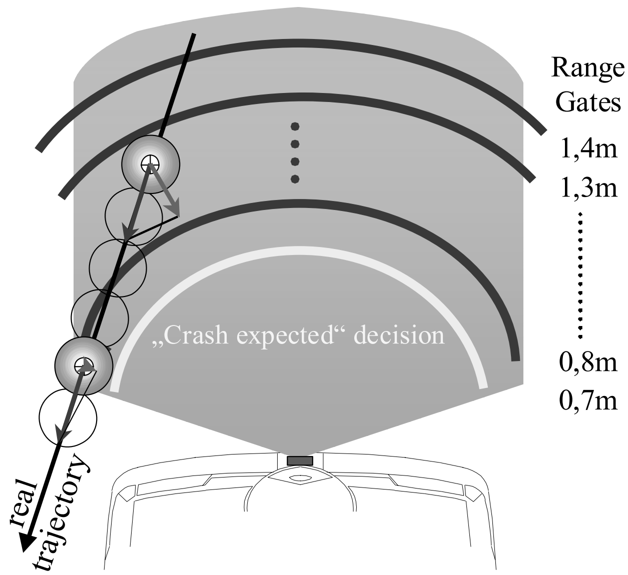

Figure 8: Closing velocity measurements during Doppler mode for single sensor configuration

In both situations, the pre-crash system continues to work as if there will not be a crash. The system assumes, that there possibly is a second target approaching the own vehicle at a closing velocity (much) greater after Doppler mode has finished. If transition 2 would lead directly back to the 7 m scan mode, fast following targets might not be detected due to the 10 ms data rate. The 2 m scan mode is fast enough to safely detect possible fast objects in very close ranges. Due to its short cycle time, the 2 m scan mode is used as intermediate mode before going back to the 7 m scan mode.

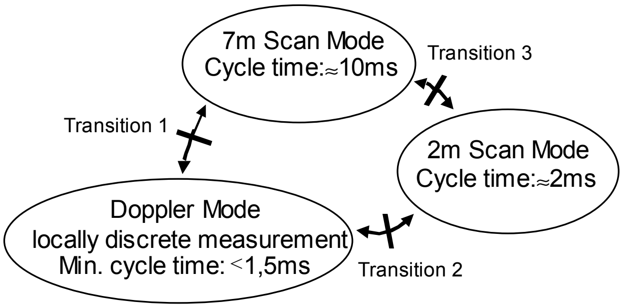

Figure 9: State diagram with sensor measurement modes and transitions

If the 2 m scan mode detects no object that might lead to a pre-crash situation, finally transition 3 sets back the process to the 7 m scan. This happens after target plausibility reaches a certain plausibility after several 2 m scans. If the 2 m scan mode detects fast objects with a trajectory towards the own vehicle, transition 2 takes place again resuming the Doppler mode. The sensor system tries to acquire more precise pre-crash information of the object.

For the single sensor pre-crash system, closing velocity and the time to expected impact are generated by interpreting the data from the Doppler mode using a mathematical model. The model uses the Doppler information, distance information and time information to calculate an estimated closing velocity at the expected impact in x-direction. Once the closing velocity is estimated, the time to expected impact will be derived. The mathematical model for the estimation has three assumptions about the object being tracked:

- Object is a singular target
- Object moves in a straight line
- Object’s acceleration is constant

The reason for such a model based approach was the fact, that raw Doppler data would not satisfy the tolerance requirements of pre-crash functionality. The model was designed such that it reduces the tolerances under all circumstances and estimates the relevant closing velocity.

For the dual/multi sensor pre-crash system, each sensor contains the performance of the single sensor pre-crash system. The algorithms for a dual/multi sensor configuration will extend, not replace, algorithms of the single sensor configuration for safety reasons. That way, a sensor failure within a dual/multi sensor configuration can partially be compensated. So, the dual/multi sensor configuration is a combination of several single sensor configurations with additional signal processing performing a lateral resolution of objects and eventually generating the information about the crash angle and the point of the expected impact. The overlap of an object colliding with the own vehicle, can be detected with an decreasing tolerance as the number of pre-crash sensors increases.

PRE-CRASH APPLICATION AND TESTS

Pre-crash application is dependant on the functional step envisioned and on the choice of implemented functions realized on the sensor platform. All pre-crash application is split into three fractions: One fraction is in respect to the sensor system, the second fraction is application work within the airbag algorithm processing the pre-crash information and the third fraction is the actuator application. Here, the sensor application for pre-crash shall be discussed in greater detail giving one test example.

The sensor application for pre-crash has two major aspects:

1. Mounting with stability and height over ground as the two most prominent factors
2. Functional sensor application

Mounting

The sensor itself is robust against vibrations in the vehicle (<50Hz). But taking legal requirements into consideration (e.g. Canadian bumper test CMVSS 215) the housing, mounting and bracketing of the sensor has to withstand the shocks keeping the directional stability of the radar beam. Concerning the mounting height, the bumper represents a minimum mounting height for pre-crash sensing if side walks or other low objects used in airbag misuse tests (objects with a height lower than 20cm) are not to be tracked as relevant objects. At last, it has to be guaranteed that the used plastic cover won't distort the radar beam characteristic such that any function within the sensor platform is able to guarantee its full functionality.

Functional sensor application

The generation of the test matrix needs to consider all situations, effects and conditions that might arise in the field. Figure 10 shows the influences coming from different parameter fields.

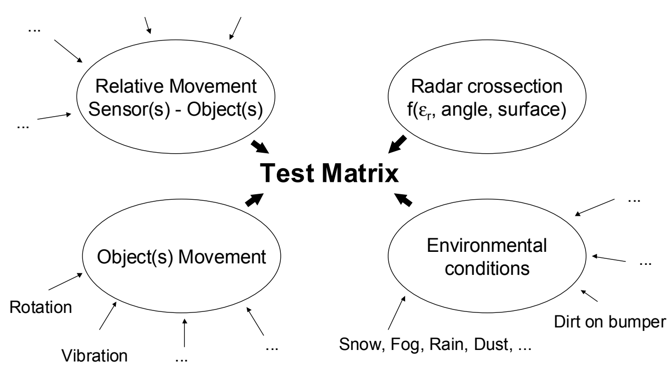

Figure 10: Generation of a test matrix and influences

In the following, one test result is presented. The test situation is shown in figure 11. The vehicle is equipped with a single sensor pre-crash test system. The output data is the corrected closing velocity and the corrected time to expected impact. The sensor is connected to a PC via an RS232 interface. The Doppler measurements and timing for these measurements runs on the sensor. The mathematical model for the correction of closing velocity and time to expected impact runs on PC as well as a visualization surface for the data-taking. The reference data for closing velocity was taken from the vehicle's speedometer. The reference data for time to expected impact has been calculated in reference to a virtual border at 0,75 m (see figure 11). The main focus of the test was to prove the performance of the model-based data correction.

In figure 12, the Doppler measurements at discrete distances are shown. The reference closing velocity is approximately 23 km/h and the subsequent time to expected impact 117 ms. Using the mathematical model, the corrected data results were:

- Corrected closing velocity: 23 km/h
- Corrected time to impact: 118 ms

at an estimated offset of 0,49 m. As a comparison, the mean of all measured values is 27 km/h (error of 17%) and the time to the expected impact based on this figure is 164 ms (error of 40%).

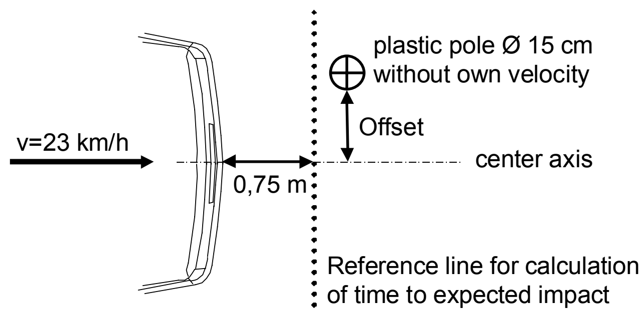

Figure 11: Pre-crash test situation with vehicle

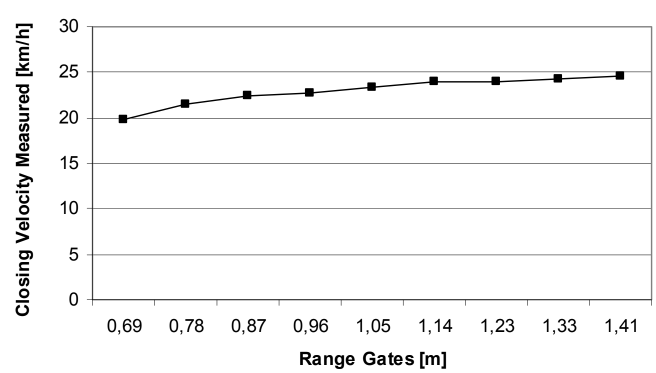

Figure 12: Doppler measurements at discrete distances

CONCLUSION

The described functional steps of pre-crash are expected to be a scenario of introducing pre-crash into the market. Each step is independent and does not interfere with the prior step. So, PREFIRE allows PRESET and PREACT also allows both, PREFIRE and PRESET. The introduction in functional steps opens up the possibility to qualify the important issues of market acceptance and liability.

In the long run, pre-crash functionality bears a great potential. Although, for a fast market introduction of pre-crash, activities for cost reduction are necessary. In order to achieve this, the sensor platform approach has been chosen realizing the cost reduction through cost splitting on several different functions.

The results from front pre-crash investigations and application can easily be applied to side pre-crash, also. It merely needs to be considered, that side impact situations and dynamics vary from those of front collisions which has an impact on the definition of the virtual barrier and the mathematical model of pre-crash data correction.

Pre-crash functionality opens up the was to a new understanding of passive safety as the different systems in the vehicle are more and more networked together. Passive and active safety will meet in the future. But passive safety also starts to reach out to the outside giving a great contribution to the over-all safety on the road.

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CONTACT

Dipl.-Ing. Rainer Moritz, Department K8/EES Development Electronic Restraint Systems, e-mail address: Rainer.Moritz@de.bosch.com