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Developing Integrated Vision Applications for Active Safety Systems

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ABSTRACT

Current image-processing solutions are limited with respect to being simultaneously flexible, scalable, high-performing and efficient. As vision-based safety systems increase in functionality and become more widely adopted, system makers will require flexible and scalable solutions to accommodate the needs of an expanding market. To support the highly complex embedded automotive vision systems of the future, therefore, engineers are now turning to dedicated vision processors in place of standard off-the-shelf solutions.

This paper will describe how to develop highly integrated image processing systems for active safety applications using the unique capabilities of a highly parallel, reconfigurable SIMD-MIMD processor architecture that offers the ability to handle both single- and multi-core designs. This architecture will enable safety systems to execute multiple applications simultaneously to provide more comprehensive driver assistance information. Several sensor sources will be discussed, including radar, vision, light detection and ranging (LIDAR), in addition to common advanced safety applications such as lane tracking and obstacle detection. The paper will also describe how the reconfigurable architecture allows for more robust and efficient algorithm development, as the unique performance of the SIMD-MIMD architecture supports real-time processing of images even when using highly complex algorithms.

PAPER

According to the National Highway Traffic Safety Administration's (NHTSA) *Motor Vehicle Traffic Crash Fatality Counts And Estimates of People Injured for 2007 Motor Report*, there were over 6 million highway crashes in the U.S. alone in 2007, resulting in 2,491,000 traffic-related injuries and 41,059 fatalities.

Current technology in vehicles is focused on protecting drivers and passengers in the event that an accident occurs, and these systems have proven successful at reducing the number of injuries and fatalities. The 2008 National Transportation Statistics report also states that an estimated 18,604 lives were saved in 2006 due to passive safety systems such as safety belts, child restraints and airbags. While these numbers are notable, reaching zero traffic-related fatalities is impossible using only these mitigation technologies. More widespread implementation of crash-avoidance technologies is required to make significant progress to this goal.

There are many ways to try to avoid a vehicle. In considering the most common causes of accidents—distracted drivers, driver fatigue, drunk driving, speeding, aggressive driving and weather—all except weather are directly related to driver behavior and actions.

Creating a comprehensive crash avoidance system means having to address each of these possible causes. However, developing an electronic system that can address each one is very challenging. A great deal of technology is available; however, nearly all of the possible accident causes must be monitored and processed in a different way. For example, a system designed to reduce the possibility of driver distraction might have to process a number of variables—from eye focus, to driver posture, to driving style and even driver behavior. A camera could be used to monitor a driver's face for signs of eyelids closing or a tilted head, but the camera alone could not identify all circumstances in which a driver might become distracted nor would a camera be 100% reliable. Combining a camera with something that could monitor steering angle, speed, and other feedback would create a more robust system that could better evaluate a driver's current condition. Further combining that system with navigational information and GPS capabilities could create a system that learns, and can predict and react to driver behavior. This example illustrates how complex these systems can be, but in no way should complexity be a deterrent. Even the simplest systems can have a positive effect on driver safety.

Automakers have started adopting these crash-avoidance technologies and their penetration rate is growing rapidly. Some reports state that by 2015, more than 14 million active safety systems and driver-assistance systems will be in production. However, recent NHTSA reports state that consumers still do not understand the benefits of these systems, and therefore are not as willing to pay extra for them.

To achieve expected penetration levels, OEMs will have to find ways to introduce these systems cost-effectively while at the same educating consumers about their value, that is, their life-saving capabilities. Unfortunately, many active safety systems require a significantly larger investment than traditional automotive electronic control units (ECUs). Many advanced safety systems rely on the processing of images, and while there are a number of experts in the field of image processing, the time spent developing robust applications can result in significant costs. With volumes still relatively low, and consumers still not convinced of their value, it has been difficult for automakers to increase adoption rates for advanced image-processing systems.

However, as adoption becomes more widespread, the benefits of these systems are likely to become more apparent. Additionally, many Tier 1 automotive suppliers are beginning to promote capabilities and benefits of their systems more and more. In the future, we also expect a big push from special interest and consumer advocacy groups to make certain types of active safety systems a requirement.

On the OEM side, the focus will continue to be on creating the most cost-effective system. The current approach is to create low-cost individual systems. For mainstream lane-departure and forward-collision warning applications, among others, OEMs are hoping that volumes will increase quickly enough to enable the OEMs to recoup their initial investments. However, as technology advances are made and new systems emerge, there will be a major focus on finding ways to create integrated systems. Many of the modules in development now use the same resources—cameras, RAM, video displays— so combining systems would be a natural approach to achieving optimal cost.

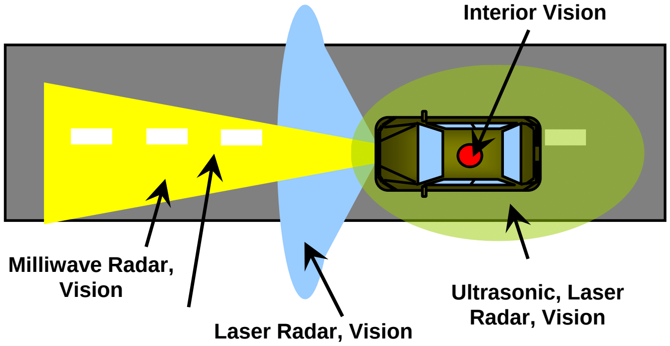
When considering how to develop integrated safety systems, it is important that we understand how the embedded automotive environment compares with the non-embedded one. Many current automotive image-processing solutions are based on consumer solutions. Vision processing has been performed in many industries on a variety of processors, for example Pentium-class machines used for monitoring assembly lines. In such cases, the algorithms and overall image-processing approach are very similar to automotive requirements: high resolution and high contrast are crucial, numerous methods are used to define edges and search for objects, and template matching and verification techniques are used for classification. Therefore, both types of image-processing systems require high-performance, real-time processing solutions. The difference, however, is that industrial and consumer requirements are much different than those for embedded automotive systems. The latter require low power consumption, a small physical area, and optimized cost. It is not acceptable, for instance, to add items such as cooling fans or heat sinks to dissipate heat in an embedded automotive system. Likewise, real estate in a vehicle is limited, and it is usually not possible to allocate large amounts of space to processing functions.

In addition, the quality levels required by automotive systems are much greater. Because these systems are used to determine potential danger so as to alert drivers, product failure is unacceptable. Stringent reliability levels, combined with the high-volume shipments associated with automotive electronics—totaling millions of units per year—have very difficult requirements that only the highest-quality semiconductor companies can meet.

Requirements for hardware in the automotive industry are vastly different than in other industries, as are requirements for software. Many software companies see active safety applications such as vision processing as good business, but they don't consider the resources available to the integrator. For example, developing an image-processing algorithm on a computer with Matlab® functions has no value if the algorithm cannot be implemented in an embedded controller that can be used in an automotive module. Many companies have very robust image-processing applications, and do not consider performance and memory size requirements as limiting factors.

As we consider how to develop active safety systems, it is important to understand how these systems will interact so as to create a comprehensive safety system. Active safety systems can consist of many different inputs. There are generally two groups of sensors or inputs: ranging systems and camera systems. Ranging systems—or distance-based inputs such as radio detection and ranging (radar), light detection and ranging (lidar), and ultrasonic systems—can be used to detect objects and to calculate their distance and velocity. Images from cameras can be used to confirm the ranging data, to identify items not detected by the ranging data, and to perform recognition or classification of data. With these inputs, automakers can create systems that use ranging sensors to detect obstacles and vehicles; vision sensors to detect lane makers, signs and signals; and a combination of the two to detect and recognize pedestrians and other objects. A truly integrated active safety system would employ all of these input technologies so as to acquire the most reliable data about driving conditions.

Figure 1. Autonomous Sensing



To ensure that an integrated system receives the most reliable data possible, it is important to understand the advantages and disadvantages of each input type. Camera systems yield the most data about driving conditions and offer superior sensing of vision-focused targets for lane tracking, traffic sign recognition and traffic light detection. Any instance in which image recognition is necessary, such as for recognizing a red light or a stop sign, requires visual data to be captured and processed by the system. In a single frame, an image processor could search for lane markers, identify objects in the roadway, and look for signs on the sides of the road. The challenge of working with cameras is that the processing required to search an image is very complex and requires algorithms that are bandwidth-intensive. For example, the processing of one video frame involves tens of thousands or even hundreds of thousands of pixels, each of which is treated as a piece of data. Each frame is typically preprocessed to correct distortion or perform scaling. A system might then binarize an image to create a black-and-white representation that can be used to look for edges or shapes, or alternatively, to produce a color histogram that can be used to search for specific colors. After that, systems often go through a correlation step to determine if objects match requirements or templates. Ideally, each of these and other steps are performed on every image frame, at rates up to 33 frames per second. Tracking algorithms can even combine data from multiple frames, further increasing a system's complexity.

Finally, while images can provide superior data about driving conditions, they are limited in their ability to provide distance information and suffer in situations with limited or poor visibility. This is where ranging sensors can help compensate for the limitations of cameras. Ranging technologies such as radar, lidar, and ultrasonic systems do not yield as much information but are easier to implement and can be an excellent complement to vision-based systems in non-ideal driving conditions.

Perhaps the most common ranging sensor is radar. Available in short- and long-range versions, radar is based on the reflection of radio signals at objects. The reflected signal is processed to detect objects and their distance. Radar is fairly immune to weather conditions and can provide range as well as relative velocity information. Additional benefits of using radar include the wide availability of radar sensors and an abundance of knowledge on radar processing.

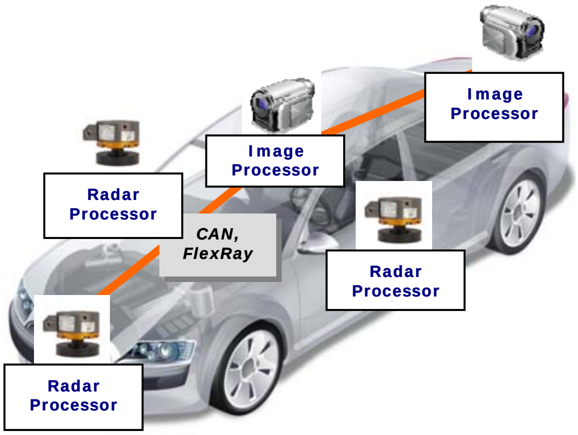
Lidar is similar to radar but is based on the reflection of laser pulses from objects rather than radio signals. While algorithms used for lidar systems are simpler than those used for radar processing, lidar is based on light and therefore is more affected by environmental conditions. A small buildup of dust or dirt on a lidar sensor can keep the system from functioning. Additionally, lidar is newer in the market, so cost is still somewhat higher and there is not as much expertise available compared to radar.

Ultrasonic systems are based on sound waves being reflected by objects. The reflected sound waves can be used to detect distance and/or relative speed of objects. Like radar, ultrasonic systems are widely used in many industries and there is a lot of expertise on the subject.

With any of the ranging technologies, correct positioning and tuning of the system is critical to get successful data. A well-tuned ranging system offers a simpler and easier way to get distance and velocity information, and can be used to develop systems that detect objects and measure distance. In an integrated system, the ranging technology can be used as the first step to identify objects, and then the image processor can be used to confirm and classify them.

A robust and accurate active safety system would take advantage of multiple different sensor types and combine them, resulting in a so-called "sensor fusion" system. While a low-end sensor fusion system could rely on local processing of the sensor signals, sharing only the analysis results, a high-end integrated system would benefit from having all processing data available within one processing unit. However, this can only be achieved if the processing unit is capable of handling multiple different sensor interfaces. Flexible, yet efficient sensor interfaces are required to process the incoming data streams without loss of data, a challenge that requires thorough analysis and planning during the early phase of any device development. Devices such as the NEC Electronics IMAPCAR2® processor combine multiple capture interfaces with a high-performance, flexible parallel-processing architecture that provides an ideal solution to this problem.

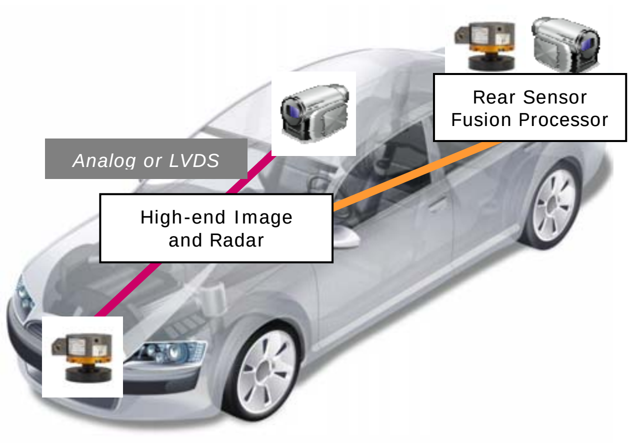
Figure 2. Low-End Systems



Decentralized systems execute local processing and exchange results through the automotive network

There are several challenges to realizing a combined or integrated solution. First, automakers must consider the layout of the system. A system with multiple ECUs located in proximity to the sensors can use the standard automotive networks such as CAN or FlexRay® to transmit the sensor results. With an integrated solution, it is necessary to transmit data from the radar sensors and cameras over a long distance, requiring the use of more expensive wiring such as analog cables or low-voltage differential signaling (LVDS) wiring. LVDS is currently one of the only options that can offer the required speed with low power consumption. In addition, an ideal combined system would require the processor to have multiple sensor interfaces and the bandwidth to process multiple inputs at one time.

Figure 3. Integrated System



Processing radar and image sensor information in a single module provides cost advantages on system level

Benefits of the combined system would include a reduction in the number of ECUs required, in addition to a system that does not have the latency of waiting for sensor data from other modules. With all data in one ECU, decisions about obstacle information and driving conditions could be made even faster, an important factor for systems where real-time functionality is critical. If you consider that a study by Daimler-Benz showed that an extra half second of early warning can prevent 60 percent of rear-end accidents, and 1.5 seconds will prevent 90 percent of them. Therefore, removing any latency from the system should be the target.

Creating a single module capable of processing these multiple inputs requires dedicated processing solutions that have the required sensor interfaces. For example, consider an integrated forward system that employs two cameras and a radar antenna array. A typical system such as this would require a minimum of two 8-bit video interfaces and another 8- to 16-bit capture interface for a radar chipset. To capture the multiple, simultaneous inputs, the processor would have to have built-in hardware for transferring the camera and sensor data to memory. Devices such as the NEC Electronics IMAPCAR2 processor have multiple capture interfaces, up to four channels on some devices, each with its own buffer to capture the image or radar frame. An on-chip direct memory access (DMA) controller then transfers the captured data to external memory, which can then be worked on by the individual processors. Also, with a flexible and fast memory controller, the IMAPCAR2 processor has the ability to read and write to external memory in 32- or even 64-bit increments, further increasing a system's ability to efficiently transfer data from the capture interfaces to the memory workspace.

Once the data is captured by the system, the challenge becomes processing it in real-time. While a radar frame and image frame are very similar with regard to spatial orientation of data relative to the receiver, the processing of the data is very different. The main use of the radar system is to measure Doppler Effect, or subsequent Doppler shift of the returned echoes from any objects in order to determine their distance and velocity. Processing of this data requires traditional signal processing, mostly using fast Fourier transforms (FFTs) to find shifts in the transmitted and received frequencies.

The image data is processed much differently than the radar. An image frame consists of thousands of pixels, which can represent a great deal of information to the system. Depending on what information the processor is looking for in a frame, different processing techniques are chosen. Generally the first step is to scale the image and isolate areas of the image that are considered regions of interest. For lane tracking and obstacle detection, this is obviously the area of the road directly in front and to the near sides of the vehicle. Traffic signs would be different areas, to the sides of the road. After scaling the image and making corrections, the system can take a number of approaches to perform detection and recognition. Many of the tasks for these systems involve searching for obstacles. A first approach to distinguishing objects is to search for their boundaries or edges, which can be done using algorithms such as those used in the Canny edge detector. From there, additional functions can search for and identify obstacles in the frame. Using various methods, such as symmetrical scanning and other verification techniques, the system can further classify the objects into vehicles, obstacles, and even pedestrians.

In functions that rely on color, producing histograms in the frequency domain can provide data that shows where certain colors appear in a frame. From there, additional processing can determine if areas of color have any additional characteristics that would help to identify them as a known object, such as a stop sign. Functions for lane detection could employ either a color approach or an edge detection approach. Using both can create an even more robust solution, such as the IMAPCAR2 processor.

The processor employs NEC Electronics' new IMAPCAR-XC® core, a reconfigurable core capable of single instruction/multiple data (SIMD) operation, multiple instructions/multiple data (MIMD) operation, or a combination of the two. In SIMD operation, the device behaves like a single processor that can handle multiple data points simultaneously. This is the solution of choice for applying filers to entire frames, for processing large amounts of data very efficiently, or for performing parallel operations such as FFTs. In MIMD operation, the device operates like a multiprocessor architecture with a shared memory base. This would be an idea processing solution once areas of interest have been identified. Depending on the original analysis, each MIMD element could process for a specific target using a unique function or operation. With up to 128 parallel cores available, and the ability to reconfigure operating mode on the fly, the IMAPCAR2 processor has the flexibility and performance to take on the processing challenge of an integrated system.

For radar systems, a pure SIMD configuration is most ideal. By running FFTs on each of the 128 SIMD cores, the system can process an entire radar frame efficiently. Image data processing can take advantage of both SIMD and MIMD capabilities. As stated, the first step is focused on preprocessing, such as filtering or scaling. SIMD operation is advantageous here, since it can process multiple data points in parallel. Once initial processing is complete, configuration of the cores depends on the particular application or subsequent algorithm being processed. Some algorithms can be designed with a highly parallel structure, while others might have a dependency on other data in the image and therefore require a sequential structure, which can be supported by configuring the cores for MIMD operation.

IMAPCAR2 devices make an excellent platform for developing an integrated solution for both hardware and software reuse. Based on the previous-generation IMAPCAR processor, the IMAPCAR2 lineup will consist of four derivatives starting with the highest-performing device capable of executing over 270 giga, or billion, operations per second (GOPS) and supporting three additional derivatives with a scaled number of processors to support varying customer requirements. Three of the devices will be available with the same packaging and pinouts, allowing customers to create a single hardware platform and then choose the IMAPCAR2 derivative for a given application's needs. This means that an automaker could develop a forward safety system based on IMAPCAR2, and add and remove features with only software modifications.

Active safety systems are becoming more popular and automakers worldwide are continuing to invest and develop even more advanced and innovative ways to protect drivers, passengers, and even pedestrians. In addition, many of these systems are used by automakers as ways to differentiate their vehicles from the rest of the market. As these systems increase in quantity, automakers will have to look at ways to reduce the overall system costs. One approach will certainly involve the creation of integrated modules. While the physical challenges required to combine these systems (along with high-bandwidth processing requirements) have been considered roadblocks in the past, advancements such as the IMAPCAR2 processor are providing automakers with real, scalable platforms on which to base designs that can be flexible, yet cost-effective.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

1. Canny edge detector: uses a multi-stage algorithm to detect a range of edges in images
2. DMA: direct memory access
3. ECU: electronic control unit
4. FFT: fast Fourier transform
5. GOPS: giga-operations per second
6. GPS: global positioning system
7. IMAPCAR: integrated memory array processor for the car
8. LIDAR: light detection and ranging
9. LVDS: low-voltage differential signaling
10. NHTSA: National Highway Traffic Safety Administration
11. MIMD: multiple instructions/multiple data
12. RADAR: radio detection and ranging
13. SIMD: single instruction/multiple data