High-Speed Industrial Vision Applications Using an Embedded Smart Sensor System

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***Abstract*— A compact, low-power line-sensor vision system has been developed for use in high-speed industrial machine vision applications. The system contains a 2×256 dual-line optical transient address-event sensor with autonomous, self-signaling pixels and pixel-level precision time-stamping, and an embedded DSP platform for real-time address-event processing. Initial pre-processing of the visual information at the pixel level results in a complete suppression of image data redundancy, resulting in drastically reduced processing power requirements at the embedded system level. The sensor system features sub-microsecond time resolution, outperforming traditional, frame-based linescan sensor systems by up to two orders of magnitude. The system features are beneficial for high-speed machine vision applications in the fields of industrial automation and automotive. In this paper, the system architecture and application results examples are presented.**

I. INTRODUCTION

High-speed industrial vision applications require advanced systems with high temporal resolution sensors and fast processing engines. Standard frame-based CMOS sensors [4][6][9] with high temporal resolution produce huge output data volume, making real-time processing computationally expensive. Consequently, cost- and power-efficient processing using a frame-based sensor is only possible at a limited temporal resolution, resulting in manageable data rates. Complete image data redundancy suppression, leading to a very sparse representation of the visual information in the scene, and very high temporal resolution are key features of asynchronous, event-based vision sensors. The system presented here uses an asynchronous optical transient dual-line sensor [8] containing a dual-line of autonomous, self-signaling pixels, which individually respond in real-time to relative light intensity changes by generating address-events. Pixels that are not stimulated by a change in illumination are not triggered, hence static scenes produce no output. Time-stamps are assigned to the address-events at the pixel level with sub-microsecond temporal resolution to compose a stream of data packets and are read out via a 3-stage pipelined bus arbiter.

The sensor output is connected to a low-cost DSP for real-time data processing. An embedded processing concept has been designed [1] and implemented on the DSP platform.

The sensor system has been developed for high-speed industrial machine vision applications like shape detection, object classification, object orientation monitoring, measurement tasks, etc. as the high temporal resolution (better than 1μs) and the reduced data volume permits the efficient real-time processing of objects with high velocities (> 100 m/s).

This paper presents the sensor system architecture and results from potential high-speed industrial vision applications like objects classification and velocity estimation. The paper is structured as follows. In section II, the dual-line sensor system architecture is described. Example data from objects crossing the sensor field-of-view are shown in Section III. Section IV gives an evaluation of the dual-line sensor system for high-speed machine vision applications. Section VI concludes the paper with a brief summary.

II. OVERVIEW OF THE DUAL-LINE SENSOR SYSTEM ARCHITECTURE

The dual-line sensor system contains a sensor chip and a data processing unit for real-time analysis and interpretation of the sensor data. The layout of the dual-line sensor system is depicted in Fig.1. In the following subsections, the individual system modules are described. Furthermore, the sensor data format is summarized.

A. *Dual-line Sensor Board*

The sensor board comprises the following modules:

1. The vision sensor chip [8] that contains a dual-line arrangement of 2×256 temporal contrast pixels. The distance between the two lines is 250μm (on-chip). This distance and the event generation time are important parameters for the velocity estimation of objects crossing both lines. The chip includes two

built-in arbiters synchronous and asynchronous, which are responsible for structuring the transfer of the events generated from the pixels to the data buffer. A time-stamp generator [5] assigns time-stamps to the events at the pixel level at a time resolution of 100ns.

2. The sensor board includes auxiliary electronics for the on-the-fly configuration of the sensor chip. This allows to adapting the sensor to different scene conditions like varying illumination, object reflectance and speed.

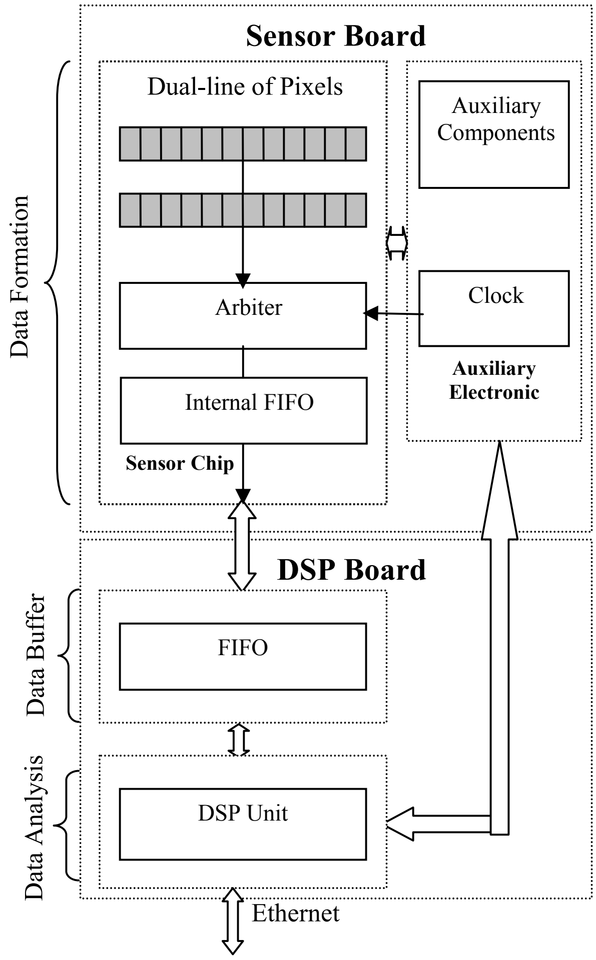

Fig. 1. A diagram of the dual-line sensor system

B. DSP Board

The DSP board includes the following modules:

1. A FIFO to handle peak data rates.
2. A data processing unit (DSP) that is responsible for the analysis and the interpretation of the data. The processing concept for real-time object classification [1] and velocity estimation [2] is depicted in Fig.2. It consists of four steps, which include the data acquisition, pre-processing, analysis and interpretation. In the pre-processing step, the data are prepared such that the outliers are removed from the detected object. Afterward, data for the detected objects in both lines are used for the velocity estimation in the analysis step. This velocity information is used to scale the data from x,t (space-time) coordinates to x,y (2D space) coordinates. Then, dedicated features are extracted from the detected object using the scaled data from one sensor line sensor after applying the circle fit. The features include the circle radius, the fit error (the deviation between the fit circle and the original object shape), the object length and orientation [1]. Finally, the extracted features and the velocity information are used for recognition and classification in the interpretation step. This concept is beneficial for high-speed vision in industrial applications for its ease implementation and computationally efficiency.

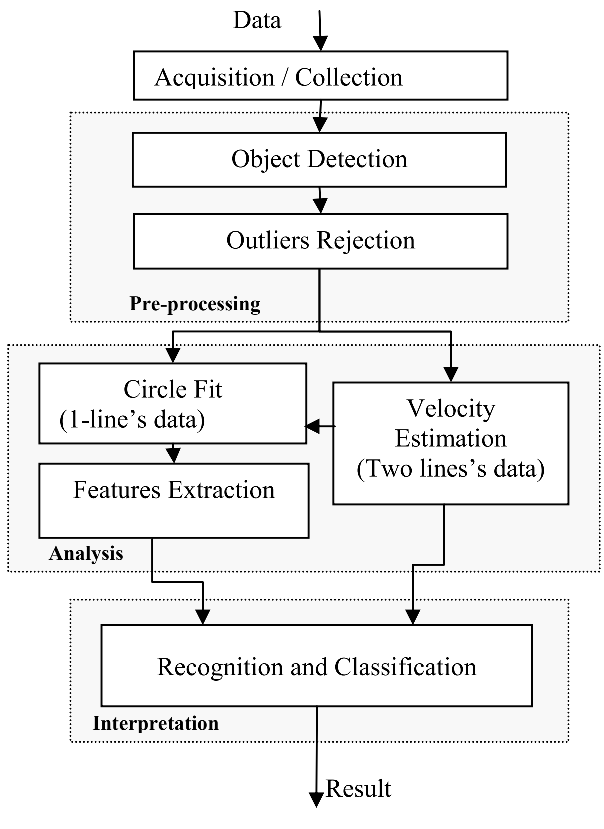

Fig. 2. Data processing concept

C. Data Format

The dual-line sensor encodes the information in the form of a TAE (***T****imed* ***A****ddress* ***E****vent*) representation. The TAE stream consists of the event generation time (timestamp) concatenated to the AE (***A****ddress* ***E****vent*), which encodes the coordinates of the pixel in the 2×256 matrix. The sensor chip generates timestamps at a minimum temporal resolution of 100ns. Such a temporal resolution would lead to a huge computational complexity when using classical (synchronous) CMOS sensors.

The TAEs are classified into two types; ON-events that represent a fractional increase in intensity and OFF-events that reflect a fractional decrease. The TAE data word is 16 bit wide where the most significant bit (bit 15) is used to distinguish between the timestamp and the AE. Examples of the TAE data streams are depicted in Fig. 3. One timestamp can be assigned to one or several AEs, which occur in the next timestamp interval (see the upper part of Fig. 3). A timestamp can also be generated without following AEs if the Timestamp counter wraps around (see the lower part of Fig. 3).

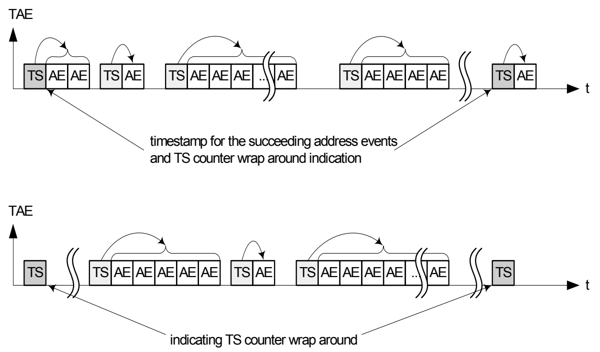

Fig. 3. Two examples of TAE data stream

III. Data Examples from the Dual-Line Sensor

Fig. 4 (right figure) depicts data examples from different object shapes passing across the sensor's field-of-view with a velocity of 10 m/s at a distance of about 15 cm. Only the edges of the moving objects, generating temporal contrast, trigger events. The left side figure shows the corresponding TAEs delivered by one of the pixel lines of the sensor in response to the visual stimulus. The x-axis (horizontal axis) is the pixel address (0-255), the vertical axis corresponds to the event generation time in units of the timestamp period. The vertical axis has been scaled for adequate illustration of the object shape.

The time-stamps has been converted to isogonal spatial information on the basis of the estimated object velocity by correlating the data from the two pixel lines.

The white dots consist of OFF events while the black dots correspond to the ON-events.

The total data amount required representing those objects, using one line of pixels, ranges between 300 – 1200 events per object. Unlike for standard CMOS sensors where the object's data volume depends on the time needed by the object to cross the sensor field-of-view, the event-based sensor's data amount only depends on the object length, independently from its velocity. For instance, a classical linescan sensor with 1000 frames/sec readout rate would require 100 frames to represent an object with 0.1 sec scanning time while 1000 frames are needed for the same object crossing the sensor line in 1 sec such that the object's data volume depends on its velocity. Thus, the advantage of the dual-line sensor's data sparseness independently from the object velocity and its regularity can be exploited for efficient data processing.

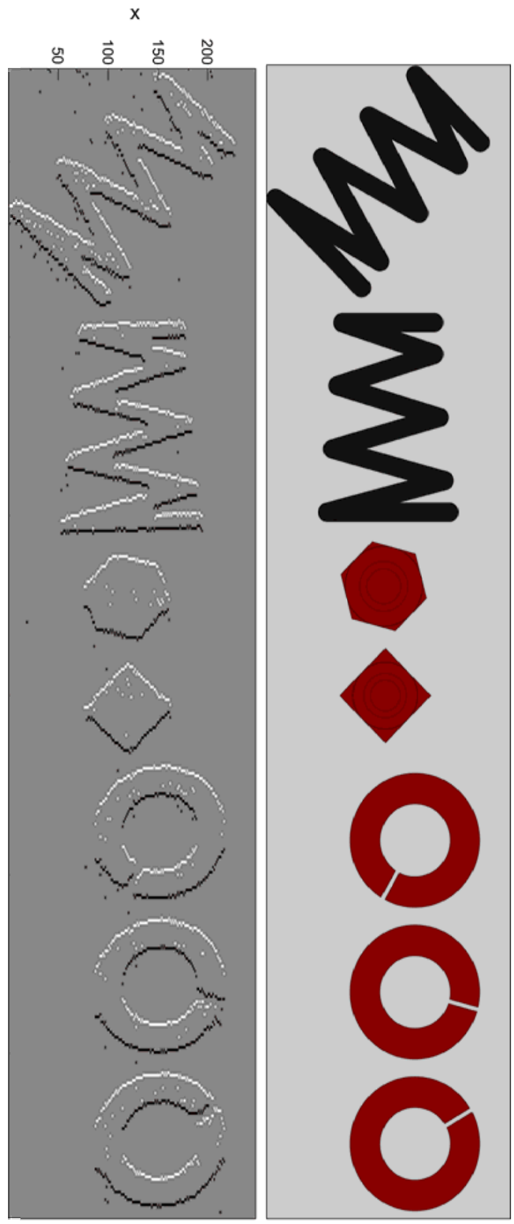

Fig. 4 Original shapes depicted on the right figure. Their correspondent data representation using the dual-line sensor are given on the left figure

It can be observed in Fig. 4 that events are present only on the object`s contours facilitating the shape recognition. Some isolated events can be also noticed that are due to the sensor high sensitivity to the illumination variation. Although this noise does not affect the quality of the data, it can be reduced by decreasing the sensor sensitivity or using a salt-and-pepper filter in the processing step.

IV. Evaluation of the Dual-Line Sensor System for High-Speed Industrial Applications

The sensor system has been evaluated for two industrial vision applications: velocity estimation [2] and object recognition [1]. The evaluation results from both applications are reported in the following subsections.

A. Velocity Estimation

Accurate velocity estimation is an important requirement to the sensor systems targeting industrial vision applications as it facilitates the manipulation of the objects and supports the recognition tasks. Therefore, the sensors capable of estimating objects velocity have the advantage to provide better vision performances in industrial applications.

Data have been recorded from several objects passing the field-of-view of the dual-line system at a distance of 15 cm and with different velocities ranging from 1 – 22 m/s. A data processing concept has been applied using four velocity estimation algorithms [2]. Using the Median and the RANSAC [3] algorithms, the resulting velocity estimation error was less than 1%, which demonstrates the excellent estimation accuracy of this vision sensor.

B. Object Recognition

The object recognition is a major concern in many high-speed industrial vision applications such that robust recognition methods saturate the processing power due to the large data volumes. Therefore, the efficiency of the recognition strongly depends on the sparseness and temporal resolution of the sensor's data.

The dual-line sensor system has been tested for the recognition of many shapes and a processing method has been developed and implemented on the DSP for performance evaluation. The recognition results using four regular shapes (a ball, a screw nut, a cube and a cuboid) have been published in [1]. Dedicated features have been extracted in real-time from the objects using the circle fit method in order to allow the separation of the object properties in a feature space. The recognition rate was 100% using the four regular shapes, tested 1000 times at different velocities. For an average of 500 TAE per shape, the processing time is less than 1ms per object. Therefore, the system is able to process data for up to 1000 objects per seconds.

Many applications can exploit the advantage of the dual-line sensor system in monitoring high-speed objects for surface vision (defect recognition, remote diagnosis…), quality vision (presence inspection, contour inspection, position inspection…) and for automated fabrication processes (sorting, classification…).

V. Conclusions

This paper presents a dual-line vision sensor system architecture producing asynchronous data only upon activity on the scene that are processed in real-time on an embedded DSP platform. By combining the data sparseness and the high temporal resolution, this sensor system provides adequate features for high-speed vision in industrial applications. The sensor's data consists of time-stamped events typically located on the object contours, which facilitates the recognition with low power and low processing cost for more than 100 objects per second. Furthermore, using the distance between both lines, the system can be exploited for accurate velocity estimation of objects with an estimation error less than 1%.

This recognition concept can be adapted to the shapes of the industrial application at hand in recognizing the main shape properties in the features extraction step

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