A Neuromorphic Smart Camera for Real-time 360° Distortion-free Panoramas

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ABSTRACT

This paper presents a novel neuromorphic camera system rotating at high-speed (1 to 4 rotations/sec) to acquire 360° panoramas in real-time by exploiting the high temporal resolution, the high dynamic range and the sparse visual information representation using a neuromorphic vision sensor with address-event (AE) signaling mounted on a high-speed mechanical rotation device. Contrary to state-of-the-art panorama cameras (e.g. rotational cameras or catadioptric cameras), this camera system can delivers several distortion-free 360° panoramas per second at constant image resolution and efficient edge extraction of the scene under real illumination conditions without any further computation. This camera system could establish new sensing capabilities in challenging applications such as real-time environmental awareness for robotics and surveillance. After introducing panorama systems and the neuromorphic dual-line dynamic vision sensor, the new camera concept is presented. A comparative analysis of this system with state-of-the art cameras is given. The concept, the camera design and resulting images using an existing 256 pixel line sensor are presented.

1. INTRODUCTION

Panorama images cover a wide viewing angle of a scene that is typically much larger as the viewing angle of the human eye which is limited at 176°; the head rotation approximately covers 330°. Panoramas were usually used in photography and in (interactive) media to improve the visual impression of a scene [5][7][8].

Nowadays, panoramas become more and more important in robotics and surveillance [3], because panoramas improve the sensing capabilities in larger environments. Furthermore, point correspondences in images with larger viewing angle are more likely and degenerate cases (e.g., when only a single plane is observed in the image) are less likely which helps in more stable 3-D scene reconstruction and more stable ego-motion estimation of a robot [9].

There are principally two ways in generating a panorama. On one hand, single images of a moving camera are consistently aligned by image mosaicking techniques [12]; on the other hand, specialized cameras are used [2][7].

Panorama cameras have been developed for more than 164 years based on different concepts and in several forms and sizes. Most of these cameras acquire images with viewing angles of at least 110° up to a full coverage of 360°.

The first panorama camera with viewing angle 150° was developed by the Austrian Joseph Puchberger in 1843 based on the Daguerreotype. The Daguerreotype is a camera system invented in 1839 by the French artist and chemist Louis Daguerre. It was the first available photographic process that could permanently record and fix an image with acceptable exposure times for portrait photography.

Several other panorama cameras [5] have been developed since 1843 like the Cylindrographe from Moessard that covers 170°, Kodak's Cirkut (1901), the Periophote of the Lumiere brothers (1901), and the Globuscope (1981) all fully covering 360°.

Recently cameras have been developed for acquiring real-time panoramas. These cameras include catadioptric (camera/mirror) systems [10] and polydioptric (multiple camera) systems where image mosaicking is directly done in the camera system, for example, Point Grey's Ladybug camera [13] or Panoptics's panorama camera [14]. However, the performance of these cameras is limited by low spatial resolution due to mirror distortion, by the accomplishable frame-rate, by difficult illumination conditions and by available computational resources.

There exist also recent developments of 360° panorama systems using rotational cameras like the "Roundshot Livecam D2 HD" published in August 2009 by Seitz. This camera performs a very slow rotation and produce one panorama in few seconds because of the long exposure time (starting from 500µs) in challenging illuminations conditions.

In this paper, we propose a rotating neuromorphic camera that acquires real-time panoramas with high dynamic range. The biologically-inspired dynamic vision line sensor delivers edge information with high temporal resolution in a sparse data

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representation unaffected by motion blur, which is a major issue for conventional clocked imaging sensors, requiring large exposure times. The camera output are edge images of the scene that can be further processed. No mosaicking techniques or image rectification is needed, hence, no further computational resources are necessary.

The paper is structured as follows: In Section 2, a brief review of the neuromorphic dynamic dual-line vision sensor and its characteristics is given. Section 3 presents the proposed concept and shows its advantage for real- time 360° panorama vision. In Section 4, a comparative analysis of the proposed camera with respect to state-of- art systems is given. Section 5 provides the designed 360° panorama system. Section 6 shows a proof-of-concept by a first experimental result and Section 7 concludes this paper.

2. NEUROMORPHIC DYNAMIC VISION SENSOR

Inspired by biology, the neuromorphic vision sensor [11] integrates two lines of 256 event-driven pixels and a synchronous communication interface with high precision timestamp assignment on a single vision chip. In contrast to traditional clocked line vision sensors that encode image irradiance and produce constant data volume at fixed rate irrespective of the scene activity, this sensor contains autonomous, self-signaling pixels, which individually respond with low latency to relative illumination changes. An on-chip timestamp is assigned to the pixel event to allow precise and high-temporal resolution of the sensor data [4]. This sensor offers the following advantages compared to conventional clocked imaging sensors:

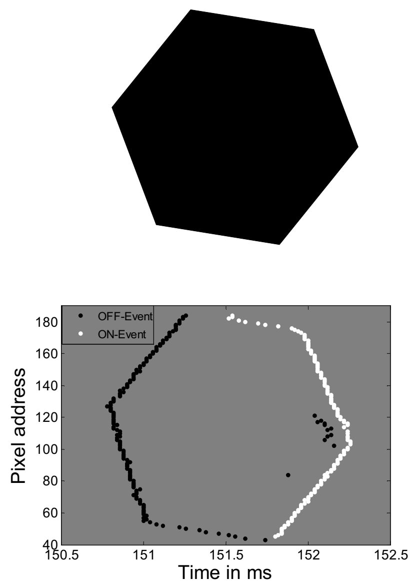

Figure 1: Original shape depicted on the top figure. The corresponding data representation using the dynamic vision line sensor is given on the bottom figure.

- High dynamic range (>120 dB) with robust operation under strongly varying illumination conditions.
- High temporal resolution with precise time stamp information of 100 ns resolution.
- High bandwidth and low latency of the pixel (<10 µs).
- Efficient and sparse asynchronous event-based data representation coding the scene edge information.

The sensor outputs a stream of events and their timestamps, the so called timed address event (TAE) representation. The events encode the address of the pixel sensing the intensity change and the “polarity” of the change (ON: for fractional intensity increase and OFF: for fractional intensity decrease).

Figure 1 (top) depicts data examples of a moving hexagon crossing the sensor’s field-of-view at a velocity of 30 m/s (at optical magnification of 5). The bottom figure shows the corresponding TAE data delivered by one line of the sensor in response to the visual stimulus. Only the edges of the shape trigger events. The vertical axis is the pixel address (0-255), the horizontal axis shows the event generation time. The time has been converted to isogonal spatial information on the basis of the known object speed. The white dots represent ON events while the black dots correspond to OFF-events.

3. REAL-TIME 360° PANORAMA CAMERA

In this paper we propose a new panorama camera approach for real-time 360° view recording, by exploiting the unique features of the neuromorphic vision sensor.
The main idea of this system is to permanently rotate the line sensor at high-speed (up to 25 rotations/sec) to scan the scene and generate 360° panoramic views in real-time. Rotating the vision sensor, allows capturing static spatial contrast in the scene that is the scene edges.

Two possible realizations of the proposed system are envisaged:

The sensor head is mounted on a rotating platform and voltage and data connections are made through commercially available slip-ring contacts. The advantage with this design is that optimized optics can be used, the disadvantages is that a relatively large mass has to be rotated at high speed. Figure 2 illustrates this system.

Alternatively, a fixed sensor and optics can be used in combination with a mirror “de-rotator“ arrangement commonly used in astronomical and military optical systems. The disadvantage of this arrangement is however small aperture and reduced light transmission due to the long optical path.

The major advantages originating from the features of the neuromorphic vision sensor for capturing real-time 360° panoramas are: (i) Possibility of realizing of several panoramas per seconds, due to the robustness to the lighting conditions and the high dynamic range, (ii) Absence of motion blur even at high rotation speeds as only intensity changes are captured. The pixel works in continuous time and scene edges are captured when the line sensor is scanning over the edge. (iii) The drastically reduced data volume due to the suppression of redundant information by the extraction of the spatial contrast supports low-cost embedded vision processing. (iv) The wide dynamic range and high pixel bandwidth even under low and indoor light conditions.

These advantages make this neuromorphic vision sensor a unique solution for real-time 360° panoramic vision.

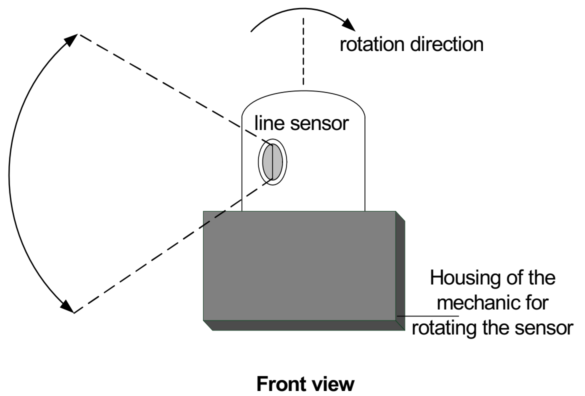

Figure 2: Neuromorphic panorama camera illustration

4. COMPARISON OF THE PROPOSED PANORAMA CAMERA WITH STATE-OF-THE-ART SYSTEMS

In this section, current technologies are presented and compared with the proposed panorama camera. The key parameters assumed for the application of the system are an illumination of 1 kLux for low light outdoor scenery and a 25 fps temporal resolution for real-time panoramic scene information. We further assume that a minimum angular resolution of 0.3° is sufficient for most of the above mentioned applications.

The fastest clocked optical line sensors currently available on the market are able to achieve 140 kHz line rate, but only at a strong illumination (>100 kLux). In an average illumination of 1 kLux a much smaller line rate, typically below 1 kHz can be reached. For achieving a 0.3° resolution at a panorama frame rate of 25 pan/s, a line rate of 30 kHz is needed. For this reason such sensors are not adequate for 360° panoramic scanning of a natural scene at real-time. In contrast to this, the neuromorphic vision sensor is able to achieve high bandwidth even at a low indoor illumination level of 1 kLux.

The recent rotational camera “roundshot-livecam” (Figure 3) is able to acquire one panorama in several seconds such that a maximum number of 2000 frames/s can be acquired. While rotating, the camera can make up to 72 stops per rotations to acquire the different views and concatenate them to realize the 360° view. Thus, this camera is not able to acquire real-time panoramas (10 pan/s and more).

Catadioptric systems [7] are realizations of omni-directional vision through mirror-lens combinations. They consist of a coaxially aligned conic mirror and a camera. Figure 4 shows a typical panorama image resulting from a catadioptric system. Existing systems allow panoramic recordings with one shot and in real-time (25 fps equals 25 pan/s) of color images. However, these

Figure 3: image of the roundshot camera

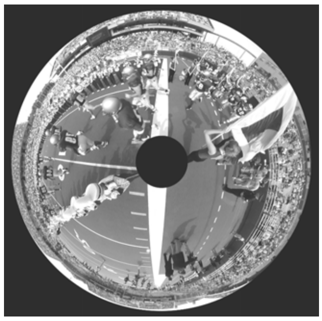

Figure 4: Example of a captured panorama view with the catadioptric camera

systems suffer from a severe image distortion due to the non homogeneous optical & digital resolution at the upper and lower rims of the circular projection. Therefore, additional processing power and memory has to be foreseen for a real-time image rectification. There is also a possibility of motion blur in case of simultaneous object and camera motion. The proposed panoramic vision system exhibits undistorted panoramic scene data due to a 360° scanning of the line sensor. Furthermore to extract the panoramic information large parts of the image sensor remain unused (see black regions in Figure 3). High resolution (typ. 4 megapixel) imagers have to be used to achieve acceptable angular resolution resulting in relatively high data rates. Real time processing of these image data is therefore computationally expensive.

Polydioptric vision systems combine the images of many cameras (e.g. 5 x 80° using Ladybug2 [13]) pointing in different directions to cover a 360° panorama. Figure 5 shows the Ladybug2 system and the resulting panorama image. These systems allow panoramic scene color information with one shot and acceptable frame rate. However, additional processing and memory have to be foreseen for image rectification of the large data volumes. Furthermore, there is a possibility of motion blur in case of simultaneous object and camera motion. The neuromorphic sensor exhibits low data rates due to scene redundancy suppression by edge extraction and by using sparse TAE data representation. Simulation and estimations (see following sections) based on the available 256 pixel resolution neuromorphic vision sensor yield a data rate of approx. 20 Mbyte/s at 25 panoramas/s for typical sceneries (extrapolated to a

1024 pixel vision sensor). A comparable spherical camera system with 6 x 1 megapixels produces a fixed data rate of 153 Mbyte/s at 25 fps regardless of scene complexity.

Figure 5: “Ladybug 2” panorama camera from PointGrey (top), and reconstructed panorama (bottom)

Table I summarizes the comparative analysis between the proposed panorama camera and the existing technologies. The analysis outcome confirms our expectations from the proposed system (Section 3).

Table I: Comparative analysis for real-time 360° panorama

	line sensor	Roundshot camera	Catadioptric camera	Polydioptric camera	Neuromorphic panorama sensor
360° horizontal FOV	Yes	Yes	Yes	Yes	Yes
Undistorted scene	Yes	Yes	No	No	Yes
Scan frequency @ 0.1° angular resolution (1klx scene)	0.1 pan/s	0.1 pan/s	15 pan/s	30 pan/s	25 pan/s
Temporal resolution @ 1klx scene	10s	10s	67ms	33ms	40ms
Data volume @ 10pan/s, 0.1° horiz. resolution	290 MB/s	~66 MB/s	120 MB/s	190 MB/s	<10 MB/s
Dynamic range dB	60-80	60-80	60-80	60-80	120
Motion blur on moving platform	Yes	Yes	Yes	Yes	No

5. PANORAMA SYSTEM DESIGN

A 360° panorama demonstrator system has been designed, including the neuromorphic dual-line vision sensor and a rotating platform. This latter contains a stepper motor driven via gear belt and two different sized timing pulleys and a slip ring for routing the power to the sensor and transferring the data out of the sensor. The number of rotation per second (rps) revolutions per second can be adjusted from 0 to 10 rps in 1rps steps via a rotary switch on the front panel. A microcontroller is used to generate 10 different rectangular signals for the stepper motor controller. The rotation direction can be switched clockwise or anti-clockwise via a front panel switch. Another switch resets the sensor and the microcontroller. A green status LED indicates whether the switch is on or off. The back panel includes a 5VDC connector for the sensor and the µC, a 24VDC connector for the stepper motor controller and a 1Gbit Ethernet connector for the communication with a PC/Host computer through the slip ring. The used slip ring is commercial and can only achieve a maximum of 4 rps in a continuous mode. For higher rps a more sophisticated different slip ring model is required.

Figure 6 depicts the detailed view of the demonstrator without the vision sensor and the numerated items can be described as follows:

1. An aluminum mounting plate to hold the vision sensor;
2. A turning lathe made polyamide 6 nylon shaft for mounting the aluminum plate;
3. CNC machined plates to secure the ball bearings and the stepper motor, screwed together with the aluminum housing (9);
4. A two deep groove ball bearings;
5. A spacer ring;
6. A turning lathe made polyamide 6 nylon main shaft;
7. A slip ring with 12 leads for max. 4rps;
8. A stepper motor;
9. 4mm aluminum square tube housing for stepper motor end phase, microcontroller and wiring;
10. A gear belt;
11. An aluminum timing pulley for motor shaft.

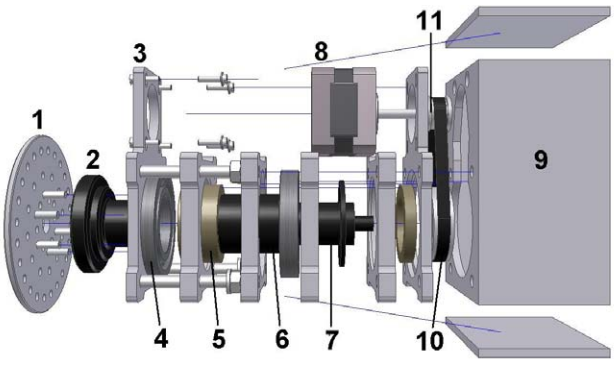

Figure 6: Detailed view of the demonstrator

6. EXPERIMENTAL EVALUATION

A preliminary test setup has been made as a proof-of-concept for the panorama camera. Figure 7 depicts the realized 360° panorama vision system with dimensions of 23 × 8 × 11.5 mm³. This setup consists of a 2 × 256 dual-line dynamic vision sensor rotating at up to 4 rps to acquire the 360° panoramic views. The limitation of 4 rps emanate from the used commercial slip ring that only operates at this speed for long lifecycle. The data are transferred from the sensor to a PC through Ethernet connection for the visualization of the 360° panorama views.
The system was evaluated for an indoor scene (Figure 8) with an average illumination of 200 lux, with the sensor rotating at 4rps. We took two different images, with persons standing or sitting around the system. Example 360° panorama views from the system is shown in Figure 9 (top) for sitting persons and Figure 9 (bottom) for standing persons where the sensor was installed in a middle of table with seven persons around.

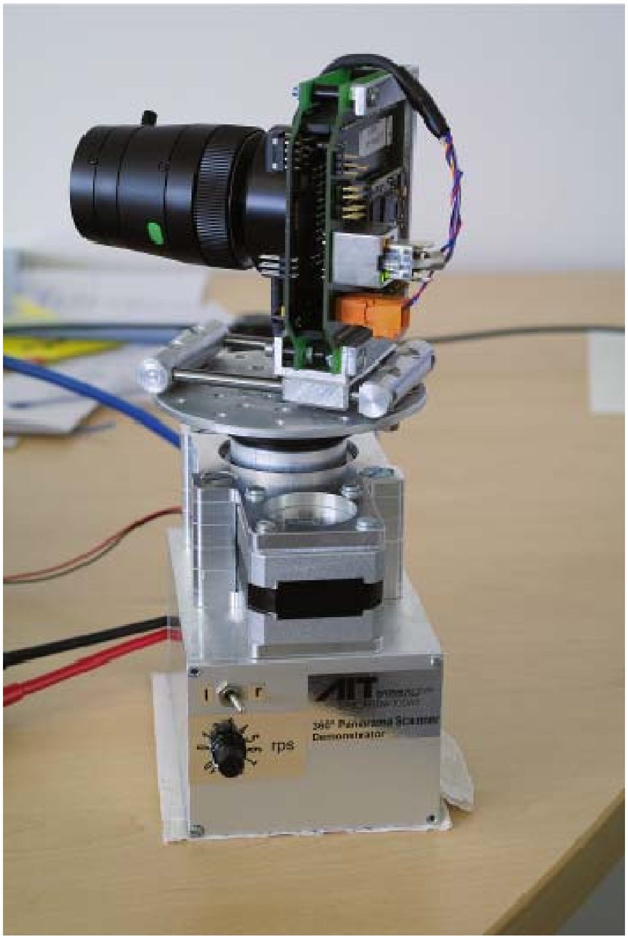

Figure 7: Realized panorama demonstrator

Figure 8 Test environment (about 130 lux)

The resulting panorama reconstructions show the shapes (contours) of the seven persons. This test is preliminary as the sensor was rotated at 4 rps. This scene generated up to 10,000 events per pixel per second using a 256 pixel line sensor. This extrapolates to a data rate of 0.27 MByte/s (an event has 16 bit resolution). This experiment is very preliminary showing the proof-of-concept of the proposed neuromorphic panorama camera.

7. CONCLUSIONS AND OUTLOOK

This paper presents a novel camera system for real-time 360° panorama scene recording. By rotating the neuromorphic dynamic line vision sensor, it is possible to capture real-time, undistorted panoramas containing edges of the surrounding scene. The fundamental advantages of the neuromorphic dynamic vision sensor are the high temporal resolution, the high dynamic range and the sparse visual data representation of the scene, such that this sensor is unique for this novel concept of panorama cameras. This system will establish new sensing capabilities, which can be exploited by many computer vision applications in areas like robotics and surveillance. A demonstrator has been designed and a test panorama system has been build, constrained by rotations up to 4 rps due to the used commercial slip ring. There are still open questions concerning, the pixel performance for challenging lighting conditions and the usability of this kind of imaging data for computer vision applications.
The current perspective is to build the software for real-time 360° panorama views and analyze the camera capabilities for selected computer vision applications (surveillance and robotic).

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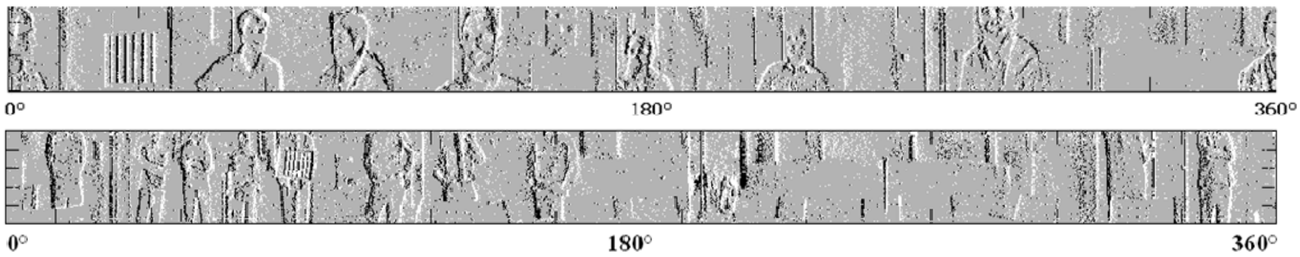

Figure 9: Resulting panorama for sitting persons (top) and for standing persons (bottom).

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