ULPEC Project

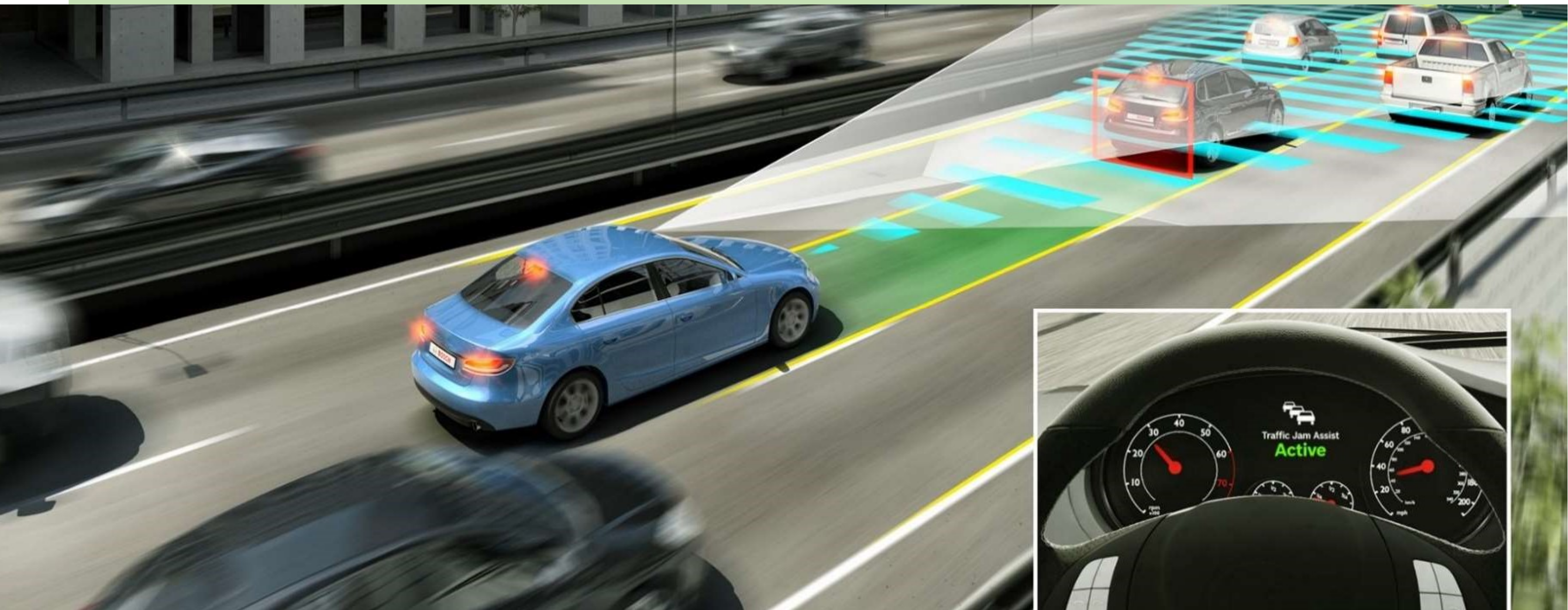
POLICYBRIEF

Event-based vision for automated driving – a promising technology for the future

Findings from the ULPEC Horizon 2020 research and innovation project (www.ulpecproject.eu)

Key Messages

1. Event-based vision sensors can respond to the multitude of challenges in the field of autonomous driving, such as reliability, safety, robustness, and accuracy under drastically changing light, weather, and traffic conditions.
2. Being modelled after biological retinas event-based vision technologies respond to the end-user need of human-like vision for autonomous cars, thus increasing public acceptance and, consequently, market success.
3. Low data rates result in low power consumption and significant energy savings in the data post-processing, contributing to EU strategies, such as the EU Green Deal and 'A Green and Digital Transformation of the EU'.
4. Further technology advances are needed in the areas of spatial resolution, algorithms, and training databases.
5. Once a higher technology maturity is reached the event-based approach will realistically reduce the overall system cost due to possible cost savings in memory, computing, transmission, resources and the overall power consumption.



Why do we need event-based vision for autonomous driving?

Autonomous driving is a particularly challenging field for vision systems. It has strong requirements on the reliability, safety, robustness, and accuracy of perception systems, which must operate under drastically changing light, weather, and traffic conditions. Decisions such as the activation of an emergency brake assist are taken in fractions of seconds with the computational resources available on board of the vehicle since cloud-based solutions have too high latency.

An additional, social challenge that autonomous driving faces is that of low user acceptance. *Automotive World* recently stated that 'human-like vision' was pivotal to unlocking autonomous driving[1]: *"The average consumer doesn't trust self-driving vehicles. And in the development of any kind of technology, it is pivotal to keep the end-user in mind. What will ensure that their car is driving safely? What will ensure they feel safe in their vehicle? Vehicles that see the way they do, in a way they can understand. The human body is built with two eyes that report to one neural network. With this 'system' they navigate traffic, slow down to a stop, and park their car. So what's stopping autonomous vehicles from driving the same way?"*

The importance of event-based vision systems for autonomous driving is highlighted by Tesla's recent move towards 'Tesla Vision'[2], their camera-based Autopilot system. Beginning in May 2021, Tesla's Model 3 and Model Y vehicles built for the North American market will no longer be equipped with radar. Instead, these will be the first Tesla vehicles to rely on camera vision and neural net processing to deliver Autopilot, Full-Self Driving and certain active safety features.

Event-based vision sensors respond to the multitude of challenges and the end-user need for human-like vision. They are in fact modelled after biological retinas, which respond mostly to relative changes in light intensity in the field of view of individual cells[3]. Compared to conventional vision sensors, which record frames that read out the intensity at all pixels at the same sampling time, this creates a much sparser response, and therefore reduces the amount of information that needs to be transferred and processed later.

Pixels in event-based vision sensors operate asynchronously and independently, which allows them to generate output with extremely high temporal resolution, indicating changes precisely when they happen in the scene, instead of waiting until the next frame is recorded at an artificially introduced time step. By detecting relative rather than absolute intensity changes event-based vision sensors can operate under a much greater variety of lighting conditions than conventional cameras. In combination with the pixel-independent results this even produces useful input in the challenging case where the visual field contains both very bright and dark areas. This is for example the case in the presence of shadows and bright sunlight.

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[1] https://www.automotiveworld.com/articles/human-like-vision-pivotal-to-unlocking-autonomous-driving/
[2] https://www.tesla.com/support/transitioning-tesla-vision
[3] Posch et al. 2014, Lichtsteiner et al. 2008

The greatest advantages of the event-based measurement technique lie in areas where conventional CMOS sensors are fundamentally limited by design. The combination of both sensor technologies could therefore provide the best of both worlds and help to overcome safety-critical limitations of conventional vision for autonomous driving.

ULPEC Key Findings

Advantages of event-based vision

✓ **High temporal resolution.** Event-based vision sensors can detect changes almost immediately, with latencies in the range of few µs. This is substantially faster than conventional cameras, which typically operate at frame-rates below 100 frames-per-second (fps). Conventional high-speed cameras can reach similar temporal precision only at the cost of vastly higher data rates, and a high degree of redundancy in the recorded frames.

> ➢ High temporal resolution is essential for Autonomous Driving (AD) and emergency Driver Assistance (DA) systems because cars driving at high speed on highways can cover substantial distances in the time between the processing of two frames. Furthermore, pedestrians or other road users and objects unexpectedly entering the field of view from the side require immediate reactions. In addition, light intensities often change rapidly, e.g. when entering a tunnel, and thus require immediate adaptations.

✓ **Absence of motion artefacts.** One consequence of the high temporal resolution in event-based sensors is the absence of motion blur. Blurred regions result from the relative motion between an observed object or the ego vehicle itself during a camera's exposure period. This results in lower quality images, which are highly challenging for most computer vision algorithms. Event-based sensors' high temporal resolution and the independent operating of event-based pixels prevent motion blur.

> ➢ Motion artefacts are a big problem for highly relevant applications in autonomous driving, such as classification, detection, motion estimation, and scene reconstruction algorithms, so their absence in event-based vision systems is a major advantage.

✓ **Low data rate.** Despite the high temporal resolution, the data rate for event-based vision sensors is orders of magnitude lower than for conventional vision sensors. This is because only pixels with local changes will generate events, not all pixels need to be recorded at every time step. This is most obvious in the case where the sensor does not move, but even if there is ego motion, for an event-based sensor continuous regions with similar pixel colour and little texture, such as the sky, the road or buildings will produce few events and, as a result, few data. As a consequence, post-processing and communication has to deal with less data.

> ➢ Post-processing and communication have to deal with less data, which allows faster and more efficient interpretation of the recorded sensory signals.

✓ **High dynamic range.** One of the biggest challenges for computer vision (CV) in autonomous driving is to deal with the vastly changing lighting conditions encountered during different day times or seasons. Most CV algorithms are severely impacted in dark conditions, or if there are strong contrasts. This is the case when a vehicle enters or leaves a tunnel, or when artificial lights or lightning bolts make certain image regions much brighter than the rest. Since pixels in event-based sensors operate independently and indicate relative changes, they can locally adapt to the light intensity. This allows pixels that observe objects in the shadow to still see objects, even though other pixels are strongly illuminated. Modern conventional cameras can adapt to changing overall illumination conditions via (global) exposure control, but their adaptation rate is not nearly as fast as it is possible with event-based sensors.

> ➢ The ability to adapt to highly changeable lighting conditions at very high rates make event-based vision a highly promising solution for autonomous driving, where strong contrast or fast changes in lighting are abundant.

✓ **Low power consumption.** Event-based cameras are power efficient because pixel activity is sparse, and almost no energy is needed for silent pixels. The resulting low data rates also lead to significant savings in the post-processing, making them attractive for embedded solutions. Power consumption for sensor systems is becoming increasingly important for autonomous vehicles, especially with the shift from combustion to electrical engines, which requires reduction of power consumption for all systems.

> ➢ Low data rates of event-based vision results in low power consumption and significant energy savings in the data post-processing. This directly contributes to European strategies and policies, such as the EU Green Deal[4] and the declaration on 'A Green and Digital Transformation of the EU'[5].

Challenges and limitations for event-based vision

Despite the impressive potential of event-based vision there are challenges that either must be overcome on the way to everyday applications or that lead to certain limitations in the use of technologies. Naturally, event-based vision has a much shorter history than conventional computer vision, and significantly less development has gone into the optimization of event-based pixels and sensors. In addition, the algorithms to interpret recordings from event-based vision sensors are at an early stage, and many of the algorithms that have proven useful for conventional computer vision cannot be directly transferred to the event-based domain, or do not take advantage of the efficiency of the event-based representation.

✗ **Spatial resolution.** Low spatial resolution was one of the most important limiting factors for event-based vision. In the past years, however, there has been great progress in

[4] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en
[5] https://digital-strategy.ec.europa.eu/en/news/eu-countries-commit-leading-green-digital-transformation

increasing the resolution of event-based cameras. Both, Prophesee, who is partner in the ULPEC project, and Samsung have shown sensors that now reach megapixel resolution (Prophesee Gen4 CD: 1280 x 720, Samsung DVS-Gen4: 1280 x 960)[6]. This will make event-cameras much more attractive for many applications than they have been in the past, e.g. for object classification and object detection especially at larger distances.

> ➢ Recent advances in high-resolution event-based sensors make them more attractive for automotive applications and are expected to create more market pull.

✖ **Variable data rate.** Although the data rate of an event-based sensor is lower than that of a conventional sensor, it can vary drastically over time, depending on the movement of the ego vehicle, other traffic participants, and the overall texture in the scene. This does not occur in conventional cameras, where the data rate only depends on the frame rate and available number of pixels. A variable data rate can also be an advantage, because it adapts to the scene, but post processing needs to take this into account.

> ➢ More research and development efforts are needed for efficient event-based computer vision algorithms and vision system architectures that can deal with variable data rates.

✖ **Dependence on ego motion.** The output of an event-based sensor is strongly dependent on the motion of the sensor itself. When a car is stopped only objects which move themselves will be visible. This means that event-based sensors will not see static obstacles when the ego car is not moving. Instead, the algorithm "knows" that the object is still there, as it cannot have moved without triggering new data. When the car moves, the data rate will be higher at high speed, which means that classification algorithms must either pre-process the data depending on the overall event rate or learn the appearance of the same object at different speeds. In addition, the sensor output depends on the movement direction. The same field of view looks different if the car drives straight toward it, or whether it is driving a curve. In objects that move horizontally in the field of view, for example because they enter from the side or are seen while driving a curve, the vertical edges are much more pronounced than horizontal edges. This is because the object does not move vertically. All these points make it more challenging to train a classifier that is invariant to movement direction.

> ➢ Much more data and openly accessible databases are needed to train event-based vision systems and suitable algorithms in object detection, so the dependence on ego motion can be overcome. ULPEC made a successful start by providing the largest open training databases that are currently available.

[6] Gallego et al., 2019 https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9138762

What are the potential market barriers for event-based vision for autonomous driving?

➲ Technology maturity and cost

Event-based vision has a much shorter history than conventional computer vision, and much less development has gone into the optimization of the entire system, including event-based pixels and sensors. Event-based cameras are currently not mass produced, which makes them expensive compared to conventional sensors. This is a common disadvantage of new disruptive technology at lower maturity levels and may be reduced once event-based vision sensors become more widely used.

Start-ups like ULPEC partner Prophesee, iniVation, and CelePixel, as well as Samsung and Sony as large industry players, have continuously improved the design of the sensor and the available software framework. This facilitates technology transfer from the research labs to industry applications. This progress in technology maturity has led and will further lead to a more wide-spread use in various application fields, including the automotive sector.

Costs of event-based sensors have also gone down with higher levels of maturity but costs of system design, adaptation and integration are still to be invested.

Since cost is a highly important factor for Original Equipment Manufacturers (OEM) in the automotive sector, the market will only begin to utilize a new type of sensor when significant added value has been proven.

The initial proofs-of-concept and the progress achieved in the ULPEC project, by individual consortium partners and the wider project network will help to raise user interest in novel sensor technologies. A strong market pull will bring more industrial players to the stages of technology upscaling, which will result in higher technology maturity levels and decreasing costs.

➲ Standardisation

Conventional digital cameras can be easily integrated into advanced driving assistants because their data formats follow international standards, and the knowledge about how to use conventional computer vision is widespread. Event-based cameras in comparison are in their infancy, and there is no industry standard or common standard for event-based processing formats between different vendors yet. In addition, few developers of higher-level functionality know how to interpret event data.

With increasing technology maturity levels, industry standards must be agreed upon. This will increase the compatibility of technologies, act as quality labels and create end user trust in novel solutions, which in the user-sensitive field of autonomous driving and car safety represents a serious potential market barrier.

ULPEC breakthroughs on the way to event-based vision systems for the automotive sector

In a nutshell:

- ULPEC developed a high speed, ultra-low power microsystem – as ‘System-on-a-Chip’ – for visual data processing that is natively brain inspired and that will pave the way to a new generation of miniaturised smart systems with significant improvements in power consumption and latency.
- ULPEC designed a neural network to support the implementation of a recognition algorithm for object detection and tracking in the automotive domain.
- ULPEC co-developed the design, technology and algorithm as an industrial roadmap that can provide an alternative to traditional solutions.
- ULPEC created the first publicly available event-based automotive databases for training neural network architectures and developing suitable algorithms for object detection.

  ULPEC partner Prophesee has made the two datasets openly available at

  https://www.prophesee.ai/dataset-n-cars/

  and

  https://www.prophesee.ai/2020/01/24/prophesee-gen1-automotive-detection-dataset/

POLICY RECOMMENDATIONS

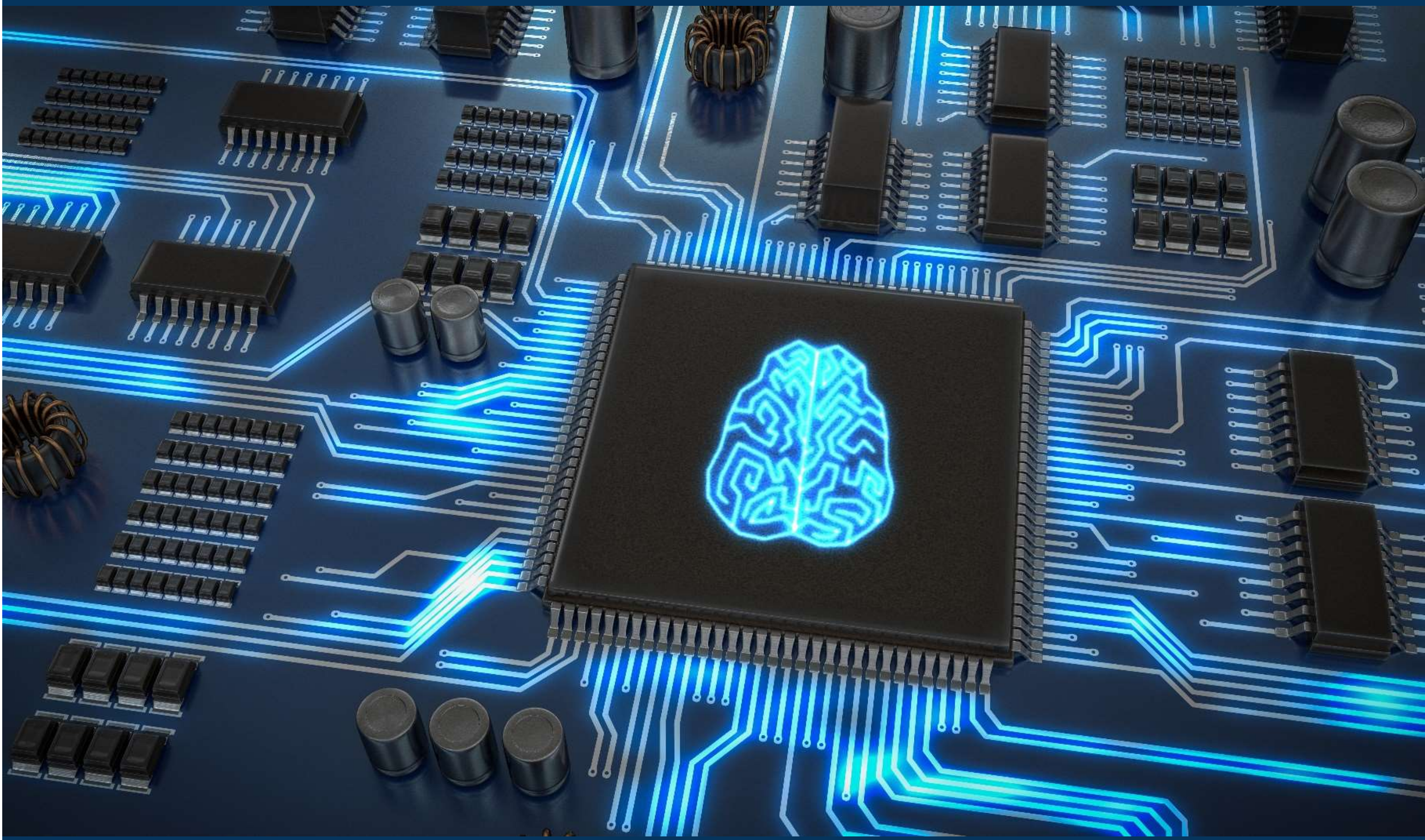
1. Invest further in European frontier research on event-based vision and neural networks.

2. Support public-private research and innovation networks and international cooperation in the fields of event-based vision and neural networks

3. Promote a future European workforce through training programmes in algorithms for event-based vision.

4. Develop sensible data protection regulations for traffic data collection by event-based vision systems that allow public data sharing for suitable training databases.

5. Reinforce dialogues with end users, including OEMs, consumer protection organisations and citizens, to create trust in novel computer vision technologies and autonomous cars.



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Website	All ULPEC Policy Briefs, Fact Sheets and other publications are available at: https://ulpecproject.eu/

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