Gated Imaging for Autonomous Driving in Adverse Weather

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Abstract

Gated imaging has become a promising technology for self-driving cars under adverse weather conditions because this technology is able to suppress backscatter very efficient. Gated images do not only provide intensity images but can also generate perfectly aligned depth information. In this work, we present a short overview of the opportunities and challenges of gated imaging when applied for autonomous driving.

1. Introduction

Nowadays, it is not unusual to encounter prototypical autonomous vehicles equipped with numerous sensors and in the foreseeable future self-driving taxis will conquer our cities. However, current systems are usually limited to good weather conditions where all sensors work reliable. Adverse weather conditions such as rain, fog, haze and snow are very challenging, because sensors typically rely on electromagnetic waves and these waves are scattered by particles in the atmosphere. For radar sensors, the propagation of electromagnetic waves is only slightly disturbed by particles due to its wavelength. At wavelengths around the visible spectrum, scattering mainly results in a decay of contrast [4]. In the particular case of lidar systems, reflected peaks disappear in the noise and the resulting point clouds get extremely cluttered [3].

Active gated imaging has been designed in order to obtain clear images even in situations with scattering media such us clouds or under water. This technique relies on a camera and a laser where illumination and exposure are time-synchronized. By gating, only photons from a predefined distance range, also denoted as slice, are integrated on the chip. As a consequence, gated imaging is able to remove or at least reduce backscatter significantly as Figure 1 shows [4]. According to the time-of-flight, gated images additionally incorporate depth information and are able to provide depth maps at image-resolution. When reducing the hardware costs for gated imaging and adapting this technology for civil applications, certain constraints of frame rate and minimum slice width arise due to eye safety regulations and hardware limitations. Nevertheless, by intelligent post-processing, it is possible to recover depth from multiple gated slices [5, 2, 8]. This extended abstract covers the main idea of gated imaging, its main advantages and fields of application, opportunities of this technique and open challenges that have to be solved in order to enable autonomous driving even in bad weather.

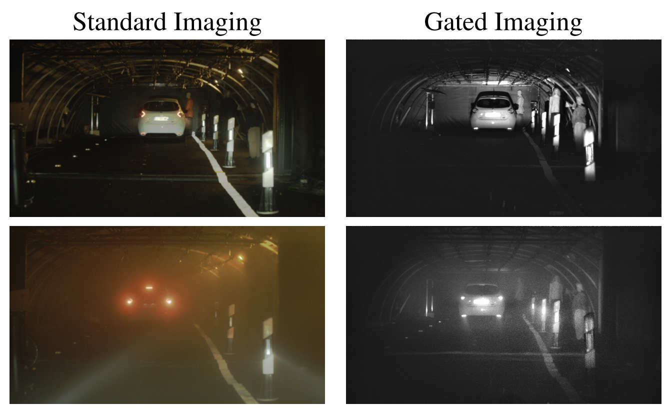

Figure 1: Comparison of standard and gated imaging in clear (top) and foggy (bottom) conditions.

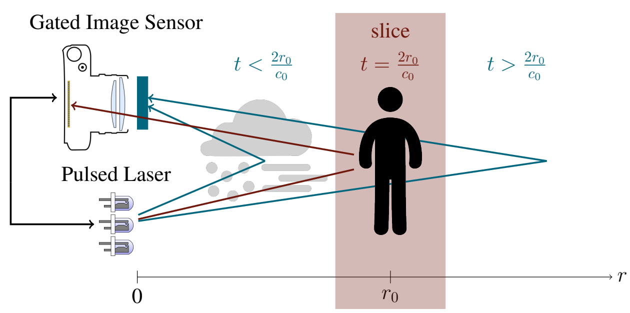

Figure 2: The principle of gated imaging: a pulsed laser illuminates the scene and the camera only exposes after a certain delay.

2. Gated Imaging

The primary goal of gated imaging was to improve the contrast of underwater photography by avoiding backscatter [10]. Using this technique, it was possible to detect sea mines [5] and to see through clouds when observing territories from a plane [15]. Military research has further driven the development of this technology for additional applications such as target identification [7], night vision [11] and three-dimensional imaging [5]. In recent years, BrightwayVision has paved the way for automotive applications by using cost-sensitive components such as laser diodes and a CMOS imager [11]. This system is already available as after-market night view solution for trucks.

As illustrated in Figure 2, a gated imaging system consists of a pulsed laser source and a gated image sensor. By time-synchronizing the image sensor and its illumination, the image sensor can be exposed only after a predefined delay. Hence, only photons from a certain range r_0 can be captured and objects can be cut out from foreground and background. Therefore, backscatter from fog can be strongly suppressed because only backscatter within the slice is integrated on the chip. The brightness of the gated images, and thus the signal-to-noise-ratio (SNR), is controlled by integrating multiple laser pulses on the chip. Moreover, the number of pulses can be adjusted to the distance for uniform illumination of the scene. By integrating slices with increasing delay directly on the chip, a *full image* is obtained. As the illumination unit works in the near infrared (NIR) regime, the scene can be illuminated much better than with standard high beams, but also color information gets lost.

Nevertheless, all the manifold advantages of gated imaging come at the cost of active illumination that produces other problems such as interference with other systems and limitations due to eye safety regulations. Moreover, in order to benefit from the slicing, a sequence of images with different delays is required, which creates motion artifacts at higher speed.

3. Range-Intensity Profile

The range intensity profile (RIP) characterizes the pixel intensity for a fixed slice with respect to the distance r. Following [2], the pixel value $I(r)$ is given by

$$I(r) = \kappa\,(r) \int_{-\infty}^{\infty} g\,(t - t_0)\,p\left(t - \frac{2r}{c_0}\right), \qquad (1)$$

where g models the gating function, p is the laser pulse shape and t_0 the delay between laser illumination and start of the exposure. $\kappa\,(r)$ incorporates laser irradiance, reflectance of the target and atmospheric attenuation. If the gating function and laser pulse are assumed to be rectangular, the shape of the RIP is basically a trapezoid, but multiplied by $\kappa(r)$.

4. Gated Depth Estimation

Gated images inherently contain depth information that can be extracted by multiple approaches such as time-slicing [5, 9, 2, 6], range-intensity correlation [14, 13, 16] and gain modulation [17, 12]. Range-intensity correlation requires only a small number of very broad and overlapping slices. Then, depth can be estimated pixel-wise based on the varying intensity value in each slice. This inverse problem can be solved by either training a regression tree [1], a small neural network [8] or solving a least-squares problem. However, either a large amount of real data or perfect knowledge of the RIP is required.

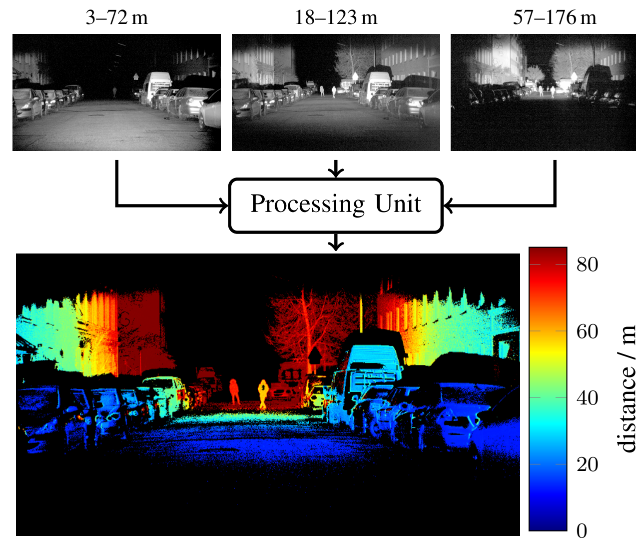

Figure 3: A very small neural network (NN) as processing unit genereates a super-resolved depth map from three slices of an active gated imaging system [8].

5. Challenges and Conclusion

Since gated imaging relies on active illumination, good performance at very bright days is very challenging because the illumination cannot get over the sunlight due to eye-safety regulations. Switching to other wavelengths such as short wave infrared (SWIR) will enable much higher illumination power, but also at much higher costs. It is still an open question how this passive component from the sun can be handled best, because only the photons from illumination are important. For example, the sunlight can be subtracted by an additionally captured passive component.

The design of the RIP profile is crucial for depth estimation and offers an enormous potential of variation and improvement. Varying laser duration, gate duration, delay and number of pulses will definitely affect the performance of depth estimation. Increasing the number of slices will probably improve depth estimation but yields at the same time stronger motion artifacts.

If all these challenges are addressed and finally solved, we believe that gated imaging will be a sensor that is inevitable for safe autonomous driving in bad weather.

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