Encoding hidden information for robotic and autonomous vehicle guidance using selective retroreflectors

Yong Geng, Rijeesh Kizhakidathazhath and Jan P.F. Lagerwall*
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Widespread automation is a key component in the on-going fourth industrial revolution (Industry 4.0). Although automation was central also to the third industrial revolution (the digital revolution), humans encountered it only in very rare cases (like the Automated Teller Machine, or ATM) whereas most automation in that era was restricted to heavy-duty industrial production in restricted areas where humans were generally not present. The current interest in automation envisages an enormous expansion of the concept, often involving machines that are not only automatic but also autonomous and mobile, such as self-driving cars or drones. In contrast to what the term "Industry 4.0" might suggest, these machines (effectively robots, broadly defined) are also likely to engage in direct interaction with humans, even in places outside industrial production, like our homes or non-industrial work places. As well illustrated by visionary architect Vishaan Chakrabarti in his 2018 TED talk, this is not a development that we need to see as scary and inhumane, but on the contrary, it can actually free us of many restrictions we have been living with since today's cityscapes started appearing in the early 20th century: small autonomous vehicles for personal mobility and flying drones transporting items and people in the vertical dimension can allow architects to make cities that are truly humane. The ubiquitous deployment of robots tailor-made for specific purposes, sometimes operating in swarms, may also support the transition to more energy-efficient and green technical solutions.

However, as beneficial as this transition to ubiquitous automation could be, it also comes with significant challenges of many types. Among the most important threshold is caused by safety concerns: as demonstrated by recurring tragic fatalities involving autonomous vehicles, they currently have an insufficient understanding of their environment despite state-of-the-art on-board sensor and computation technology. It is simply not easy to make sense of the

*University of Luxembourg, Department of Physics and Materials Science, 1511 Luxembourg. Email Address: Jan.Lagerwall@lcsoftmatter.com

busy, complex and messy world that we humans create and live in, full of signals, some important, some only distracting, and others yet being pure noise. While most attempts to allow robots access to human-populated environments focus on providing the robots a combination of multiple sensory inputs and massive computational power, in order to allow them to analyze our world as it is, accurately enough to guarantee safe operation, a different approach is proposed in an article published in the leading materials science journal *Advanced Functional Materials* by researchers of the University of Luxembourg.

The idea developed by the article authors, Yong Geng, Rijeesh Kizhakidathazhath and Jan Lagerwall, in collaboration with Prof. Mathew Schwartz at the New Jersey Institute of Technology, is to help the robots by introducing tailor-made graphical information in the environment, greatly reducing the difficulty in analyzing the surroundings. The information would be passively encoded as optical codes similar to the QR-codes that we are now all used to, meaning that the solution is very energy effective and does not add to the radio frequency bandwidth crowding that the trend of internet of things (IoT) is leading us into. Importantly, the encoding is invisible to humans, as it is designed for read-out in the infrared (IR) or ultraviolet (UV) ranges of light, both outside the window of light that the human eye can see. However, the UV light range used is adjacent to the visible spectrum, meaning that it is limited to a range that is totally harmless to humans, in contrast to high-energy UV light.

The key breakthrough presented in the article is the realization of retroreflective spheres made from cholesteric liquid crystals, which are then turned into solid state by a process called polymerization. In one way, these spheres are similar to the retroreflectors we have in the safety vests in our cars, in road signs and in certain clothing, because they send light back to the source regardless of the direction along which they are illuminated. But there are two very important differences that make these Cholesteric Spherical Reflectors (CSRs) so useful. First, the reflection is limited to a narrow wavelength range, explaining why the human eye does not see them. Second, the reflection is circularly polarized, in the same way as each of the two movies simultaneously shown in a 3D cinema are circularly polarized, in orthogonal ways.

If you ever took off your goggles while at a 3D cinema you will have noticed that the human eye cannot distinguish different polarizations, as both our eyes then see both movies, and we simply experience a strange ”shadow” effect. The goggles contain circular polarizers, the right one orthogonal to the left one, ensuring that our right eye sees only the movie for the right eye, the left only the movie for the left eye. Outside a movie theater, the world is very rarely circularly polarized and this means that the circular polarization of CSRs is quite unique. A robot designed to read out CSR-encoded information will have two cameras, both operating in the UV and/or IR regions where the information is localized, and each will have a circular polarizer orthogonal to the other, just like 3D cinema glasses. The robot subtracts one image from the other, meaning that all visual information that is not circularly polarized, thus all content except the CSRs, is cancelled out, because this information appears identical to the two cameras. But the CSRs remain, as they are visible only to one camera but not

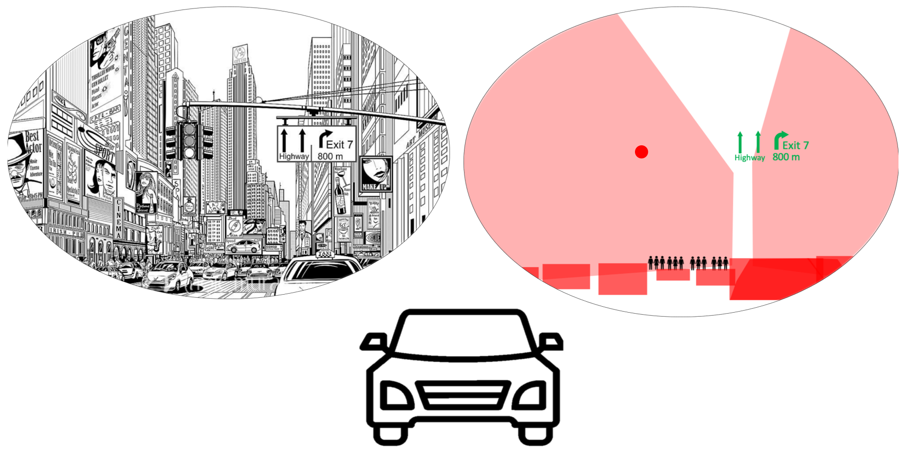

Figure 1: By subtracting images taken simultaneously with different circular polarizers, traffic signs and other crucial information can quickly be identified even in a visually noisy environment, if the scene has been labeled with CSR-encoded information on selected objects.

to the other. This allows the robot to identify the CSR-encoded information extremely rapidly, with minimum computing power, and without risk of false positives.

In addition to the practical breakthrough of making the CSRs with the right optical properties for the envisaged application, Geng et al. also carried out a numerical analysis of the optical properties of the CSRs when they are embedded in a transparent coating. This coating acts as a glue that locks the CSRs into their particular locations, in order that they spell out the codes for the robots to read. The analysis confirms that the CSR encoding can be made fully or very nearly invisible to the human eye, and CSRs designed for IR operation can even be seen by today's standard night vision cameras, allowing very low-cost technology to be used.

While CSRs and the concept of encoding robot-detectable information in a way that is invisible to humans are new, the idea to support robotic navigation with graphical codes is not. In fact, in restricted environments like research labs, military facilities or nuclear power plants, this is a very well established technology already today. Robots look for so-called "fiducial markers" placed on walls, doors, other robots and items that they will manipulate, in order to ensure reliable localization and object identification. However, today's fiducial markers are large and highly visible, typically being realized as black squares on a white background. By realizing the fiducial markers with CSRs, this well-established solution for supporting robotic navigation could be taken out of the restricted environments where it is used today, to our everyday environments. This would provide an enormous aid for robots deployed in human-populated spaces, without any negative impact for us, since we cannot see the markers. In order for this to work, the optical performance of the CSRs must be fine-tuned with great care, following the guidelines laid out in the paper by Geng et al.