Exploring new ray tracing methods for the Illumination Optics field

In modern illumination systems, light is sent from the light source to whatever target that is desired to be illuminated. However, this is easier said than done. Light rays behave randomly and must be precisely guided through the optical system to the point that needs illumination. This asks for a thorough design of the optical system. A process in which mathematical computations help the designers. In her dissertation, PhD graduate Carmela Filosa investigated a new calculation method that uses the phase space, which provides a full description of geometric optics. The aim was to understand how light propagates through non-imaging optical systems in order to calculate the target photometric variables, for example luminance and intensity.

A significant amount of the total electricity is consumed by residential and commercial illumination. In the US, for instance, 7% of the total electricity consumed in 2017 was for lighting. This energy consumed by illumination devices is clearly related to the efficiency of the device itself. In particular, part of the energy consumption consists of excessive, misdirected and inefficient use of light. On top of that, a tangible aspect of this misdirected use of light is light pollution, which can have adverse impacts on humans, flora, and fauna. Using efficient light sources could help to mitigate both the amount of energy consumption and light pollution.

Illumination optics
Currently, LEDs are replacing traditional sources in many applications such as street lights, automotive lighting and home illumination, because of their high energy efficacy and very long lifetime. Yet, the efficiency of the source does not reflect how much light is transferred from the source to the target. Illumination optics is the branch of optics that deals with the design of optical systems. It concerns the transfer of light from source to target. The goal in illumination optics is to obtain the desired light distribution at the receiver after its propagation through an optical system, thus avoiding to spread light everywhere.

Optical engineers who design optical systems often use the ray tracing procedure. Ray tracing is a forward method where a set of rays is traced within the system from the source to the target. The propagation of light is determined by computing the position and the direction of every ray for all the optical surfaces that it encounters. There are many ways to implement the ray tracing process, but these methods are still open to improvement.

Phase space
In order to improve the existing ray tracing methods, Carmela Filosa, PhD graduate in the Scientific Computing research group of the Department of Mathematics and Computer Science, considered the phase space (PS) of the optical system in her dissertation. The PS of an optical surface gives information about the position and the direction of every ray on that surface where the direction is expressed with respect to the normal of the surface. In PS, the rays direction is given by the sine of
the angle that the ray forms with respect to the normal of the surface multiplied by the index of refraction of the medium in which the ray is located.

**New approaches**

Two new approaches based on PS are presented in the work of Filosa. They are tested for two-dimensional systems, in which the PS is a two-dimensional space where the coordinates of every ray are specified by one position coordinate and one angular coordinate. The idea behind the two new approaches is to use the structure of PS to trace only the rays close to the discontinuities of the luminance at the target PS, and thus to determine the boundaries of the positive luminance regions to reduce the number of rays needed for obtaining the photometric variables.

The first method is called *ray tracing on PS* and it is based on the source and the target PS representation of the optical system. It takes into account the sequence of optical lines that each ray hits when it propagates inside the system, that is, the ray path. The results showed that ray tracing on PS is faster and more accurate compared to currently used ray tracing methods. In order to further improve PS ray tracing Filosa developed a second method; *backward ray mapping in PS*. This method allows tracing only the rays located exactly on the boundaries of the regions with positive luminance. The key idea of backward ray mapping is to construct an inverse map from the target to the source connecting the coordinates of the rays on the PS of each optical line encountered. Backward ray mapping in PS has two variants, concatenated backward ray mapping, and direct backward ray mapping.

**Concatenated and direct backward ray mapping**

Concatenated backward ray mapping is a method for systems formed by straight and reflective lines. The research results showed that the boundaries of the regions in every PS can be calculated analytically with this method. Concatenated backward ray mapping calculates the intensity exactly, making the method much more accurate and also faster. Direct backward ray mapping is a modification of concatenated backward ray mapping to systems formed by curved lines. In this case the boundaries of the positive luminance regions in all the phase spaces cannot be calculated analytically, therefore the exact target intensity cannot be obtained for systems formed by curved lines. Nevertheless, numerical results showed that it provides a more accurate intensity distribution in less time compared to current ray tracing methods.

**Future work**

Since the methods presented in Filosa’s dissertation are new to the field of illumination optics, her work is far from finished. The results showed that the PS ray tracing method is very promising in a two-dimensional case. However, it is not yet possible to predict how the method holds in a three-dimensional system. Filosa therefore concludes her dissertation with outlook and insight on future work to extend the methods from two to three dimensions.