Investigating the lateral resolution in a plenoptic capturing system using the SPC model

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ABSTRACT

Complex multidimensional capturing setups such as plenoptic cameras (PC) introduce a trade-off between various system properties. Consequently, established capturing properties, like image resolution, need to be described thoroughly for these systems. Therefore models and metrics that assist exploring and formulating this trade-off are highly beneficial for studying as well as designing of complex capturing systems. This work demonstrates the capability of our previously proposed sampling pattern cube (SPC) model to extract the lateral resolution for plenoptic capturing systems. The SPC carries both ray information as well as focal properties of the capturing system it models. The proposed operator extracts the lateral resolution from the SPC model throughout an arbitrary number of depth planes giving a depth-resolution profile. This operator utilizes focal properties of the capturing system as well as the geometrical distribution of the light containers which are the elements in the SPC model. We have validated the lateral resolution operator for different capturing setups by comparing the results with those from Monte Carlo numerical simulations based on the wave optics model. The lateral resolution predicted by the SPC model agrees with the results from the more complex wave optics model better than both the ray based model and our previously proposed lateral resolution operator. This agreement strengthens the conclusion that the SPC fills the gap between ray-based models and the real system performance, by including the focal information of the system as a model parameter. The SPC is proven a simple yet efficient model for extracting the lateral resolution as a high-level property of complex plenoptic capturing systems.

Keywords: Camera modeling, plenoptic camera, lateral resolution, sampling pattern cube

1. INTRODUCTION

Established capturing properties like image resolution need to be described thoroughly in complex multidimensional capturing setups such as plenoptic cameras. This investigation is required both to understand trade-offs among various quantities such as spatial, angular or depth resolution between unconventional capturing systems as well as exploring each systems behavior individually.

Capturing systems sample the light field in various ways which result in different capturing properties and trade-offs between those properties. Models have been proposed that describe the light field and how it is sampled by different image capturing systems.[1,2] The light field model which is a simplified representation of the plenoptic function (with one less dimension) has proven useful for applications spanning computer graphics, digital photography, and 3D reconstruction. The scope of the light field has also been broaden by employing wave optics to model diffraction and interference[3] where the resulting augmented light field gain higher descriptive level at the expense of increased model complexity. Our previously proposed sampling pattern cube (SPC) model is utilized in this work and contrary to the previously proposed ray-based models, it includes focus information at a more simple way than the wave optics model.[4] Focus information is a vital feature for inferring high-level properties such as lateral resolution in different depth planes. Being able to easily quantify such properties is of practical use for conventional image capturing systems in general but of specific interest when working with more complex systems such as camera arrays[5] and light field or plenoptic cameras.[6]

Light field sampling behavior of an optical system, and hence its associated features such as the captured resolution, can vary for different depth planes or different distances from the main optical axis. Adjustments

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in the system, or unintended variations in the capturing system properties, are other sources for variations in the sampling behavior and therefore in the high-level properties of the system. Accordingly, it is beneficial to have a model that provides straightforward extraction of features with a desired level of details, when analyzing, designing and using complex capturing systems. This knowledge can also be used for developing, rendering and post processing approaches or adjusting prior computational methods for new device setups. Resolution in plenoptic cameras is an example that asks for more detailed investigations, which considers the properties of the capturing system. Such investigations of complex capturing system has been the subject of prior and recent works.[7–9]

Models previously proposed to describe how the light field is sampled by different image capturing systems range from simple ray-based geometrical models to complete wave optics simulations, each with a different level of complexity and a varying level of explanation of the systems capturing properties. Our formerly proposed Sampling Pattern Cube (SPC) model is a geometrical optics model that contrary to the previously proposed ray-based models, includes focus information and this is done in a much simpler way than the wave optics model. Focus information is a vital feature for inferring high-level properties such as lateral resolution in different depth planes. In our prior work we have demonstrated the capability of the SPC model in extracting the lateral resolution in different depth plains as a high level property in plenoptic cameras.[10] The task was done with low complexity and high level of details compared to the common models. Here the aim is to investigate more thoroughly the characteristic of the SPC model in extracting the lateral resolution.

For this purpose, first we have modified the previous lateral resolution extractor and come to a new extractor with improved functionality. We have evaluated the newly defined extractor by comparing the obtained lateral resolution results with those from the Monte Carlo numerical simulation based on the more elaborate wave optics model. Then we have investigated how the lateral resolution profile in depth varies with variations in some of the capturing system parameters such as the number of pixels behind each lenslet. Afterwards we have shown how the SPC model predicts the lateral resolution profile when capture parameters like pixel size changes. Finally those predictions are supported by qualitative reasoning.

In the following parts, we first give a general overview of the SPC model in Section 2 and then in Section 3 we define the lateral resolution operator in this model. Section 4 gives the details of the plenoptic camera system setups that we model as an SPC and apply the proposed resolution operator to. Section 5 illustrates the obtained results from the SPC model for the capturing system setups followed by a discussion and comparison with results from other models. Finally, Section 6 concludes the work with a hint on possible future interests.

2. THE SPC MODEL

The SPC is a geometry-based model for the optical capturing systems. Light samples in this model are in the form of light containers (LCs) defined by a tip position (x_C, y_C, z_C) and an angular span $(\phi_s, \phi_f, \theta_s, \theta_f)$:

$$LC := \begin{cases} (x_C, y_C, z_C) \\ (\phi_s, \phi_f, \theta_s, \theta_f) \end{cases} \tag{1}$$

and

$$SPC := \{LC_i\}, i = 1, \ldots, k. \tag{2}$$

Figure 1 shows an LC in 3D space and we stick to a rectangular base shape for simple illustration purposes. LCs represent the form of in-focus light and so the SPC model preserves the focal properties of the capturing system in a compact but at the same time comprehensive way. To generate the SPC model of a capturing system, we start from the initial set of LCs with their tip position at the center of each pixel on the sensor plane and an angular span equal to the light acceptance angle of each sensor pixel. Then we backtrack each LC through the optical system passing elements such as apertures and lenses, which will transform the initial set of LCs into new sets using geometrical optics. The transformations continue until we reach a final set of LCs with new tip positions and angular span that carry the sampling properties of the capturing system. This final set of LCs and their correspondence to the initial sensor pixels build the SPC model of the system and preserve the focal information and the information about where each recorded light sample on the sensor cell is originating from.

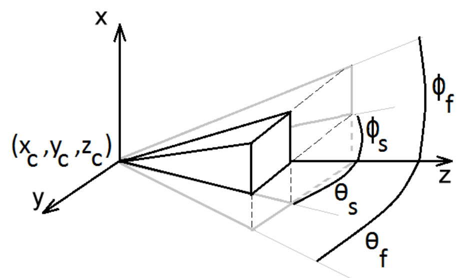

Figure 1. Illustration of an LC in 3D space

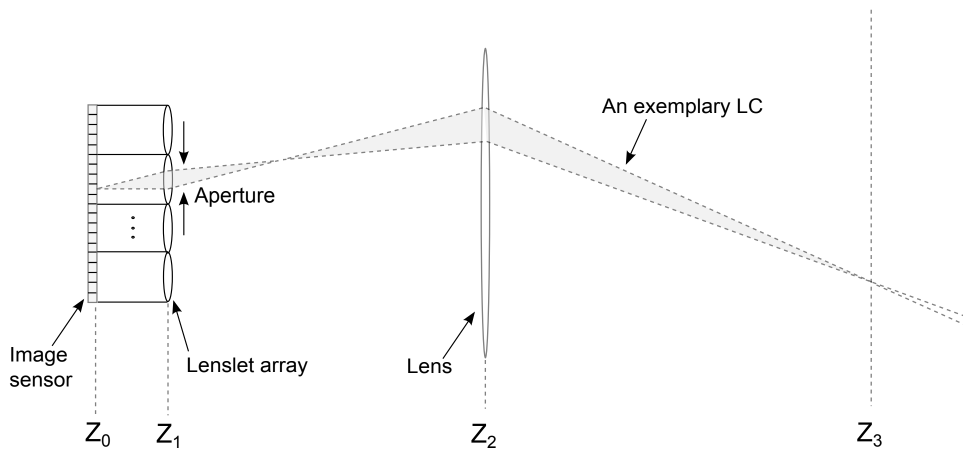

Figure 2. Illustrating the process of backtracking an exemplary LC into the space in front of a camera

Figure 2 demonstrates how the LCs are backtracked from the sensor plane, Z_0, passing optical elements at Z_1 and Z_2 and reaching into the space in front of the camera (back in-focus on the plane Z_3).

The base B of an LC on plane z is defined as its projection on the plane (or the intersection area of that LC with the depth plane z):

$$B\left[LC, z\right] := (x_1, x_2, y_1, y_2, z, \phi_s, \phi_f, \theta_s, \theta_f) \tag{3}$$

where

$$\begin{aligned} x_1 &= x_C + (z_C - z)\tan\phi_s \\ y_1 &= y_C + (z_C - z)\tan\theta_s \\ x_2 &= x_C + (z_C - z)\tan\phi_f \\ y_2 &= y_C + (z_C - z)\tan\theta_f \end{aligned} \tag{4}$$

2.1 Feature Extraction

Some of the high-level properties of the optical capturing system and how they are reflected in the SPC model are investigated in,[4,10] however, the concept of the feature extractors in the SPC model and more specifically an operator to extract the lateral resolution in a complex capturing system is initially introduced in.[10] In the work presented here, we go deeper and try to modify the lateral resolution operator to include the projected pixel size in order to avoid sampling issues. We later apply the defined operator to a set of exemplary plenoptic capturing system setups and evaluate the operator by comparing the results to those from ray based model and wave optics based Monte Carlo simulations for the same capturing systems. Later we investigate how the variation in the image sensor pixel size influences the final lateral resolution profile.

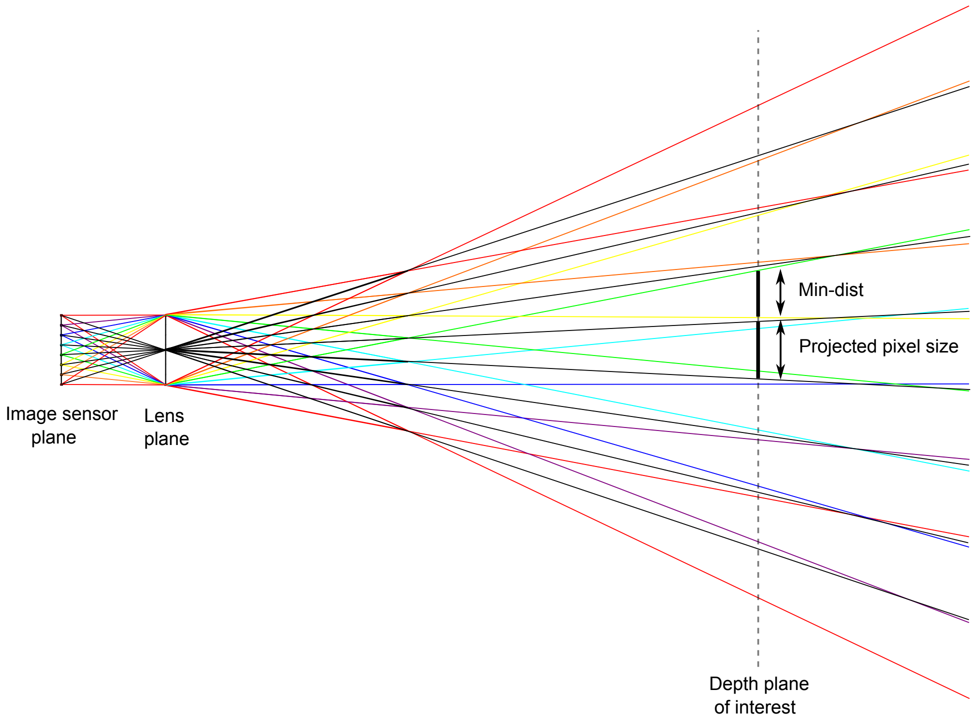

Figure 3. Illustrating the contributors in the lateral resolution limit on the depth plane of interest

3. THE LATERAL RESOLUTION FEATURE EXTRACTOR

The SPC model incorporates the focus information of the capturing system in the form of the span of the light containers. The idea that the lateral resolution in the SPC model could be defined as a function of the light container distribution and span in each depth plane was initially introduced in.[10] In that work, a lateral resolution feature extractor was proposed using the distribution of the light containers in each depth plane and their width. The introduced feature extractor was also evaluated for the case of a plenoptic capturing system there. In this work a more in-depth investigation of the lateral resolution feature extractor is performed in order to cover a wider range of the capturing systems. Pixel size projected in each depth plane is an attribute which is included in the new definition for the lateral resolution feature extractor in order to bring the model based results closer to the results from other more complex models like the wave optics model or the empirical data. Noting that the projected pixel size at a certain depth plane is also a part of the system properties embedded in the SPC model in the form of the distance between two initially neighboring LCs at the depth plane of interest.

The lateral resolution limit in a certain depth plane is defined as the inverse of the minimum distance between two resolvable points located at a specific depth plane within the system's common field of view (CFV). Depending on the purpose of lateral resolution analysis, the number and locations of depth planes may be arbitrarily chosen. The concept of resolvability is defined in the SPC terms where there exists at least one LC (pixel) which contains one of the point light sources but not the other. This means that there should be a light container which is not contributing to the content of the first pixel but the second.

Following the above definition, the lateral resolution operator in the SPC model which extracts the lateral resolution limit, Res_lim in a certain depth plane is described as:

$$Res\_lim := pps + min\_dist \tag{5}$$

where pps is the projected pixel size in the plane of interest and min_dist is the maximum line piece created by the overlapping span of the LCs in that depth plane (see a single lens example in Figure 3).

Evaluation of the above feature extractor is intended in the following sections.

Table 1. Camera system specifications

	Setup 1	Setup 2
Lenslet array size	11×11	11×11
Lenslet focal length, f	$12mm$	$12mm$
Lenslet pitch	$4.2mm$	$4.2mm$
Lenslet f-number, f/D	22	22
Spacing between lenslet array and image sensor, g	$12.507mm$	$12.507mm$
Image sensor pixel number behind one lenslet	251×251	301×301

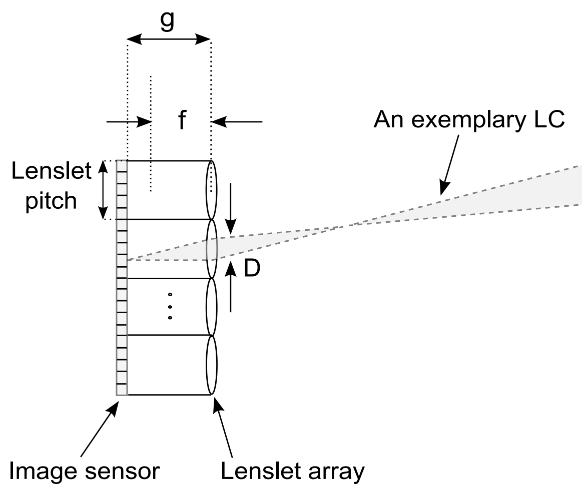

Figure 4. Illustration of the test setup

4. TEST SETUP

We have considered two plenoptic capturing systems with specifications given in Figure 4 and Table 1 when applying the proposed lateral resolution operator. In addition, we consider pixels behind each lenslet to be optically decoupled from any neighboring lenslets.

We first generate the SPC model of the capturing systems with details in Table 1, as described in.[4] The lateral resolution operator, stated in Section 3 is then applied to the achieved SPC model of each setup. Symmetry in the defined capturing system makes analysis of the resolution values identical in both x and y dimensions. Moreover, the resolution analysis only considers the space directly in front of the lenslet system and discards the effect of the main lens, as that part of the capturing system merely acts as a relay to bring far objects closer to the lenslets by a magnification factor.

As the reference for our proposed lateral resolution operator we use wave optics based Monte Carlo simulations results. This data whose validity is also confirmed by physical experiments is considered the ground-truth of the evaluated system in terms of lateral resolution.

5. RESULTS AND DISCUSSION

The proposed feature extractor gives the lateral resolution as a function of the projected pixel size, the span of the LCs and their distribution at each depth plane. All contributors to the proposed lateral resolution operator are obtained from the geometry and focal properties of the capturing system which are embedded in the SPC model of the system. Results from the proposed lateral resolution extractor are well in line with the Monte Carlo simulation results for the examined range of the system parameters.

Figure 5 shows the minimum resolvable distances, or the inverse of the lateral resolution for a range of depth planes, for the Setup 1. The data from the ray-based model as well as the wave optics based Monte Carlo

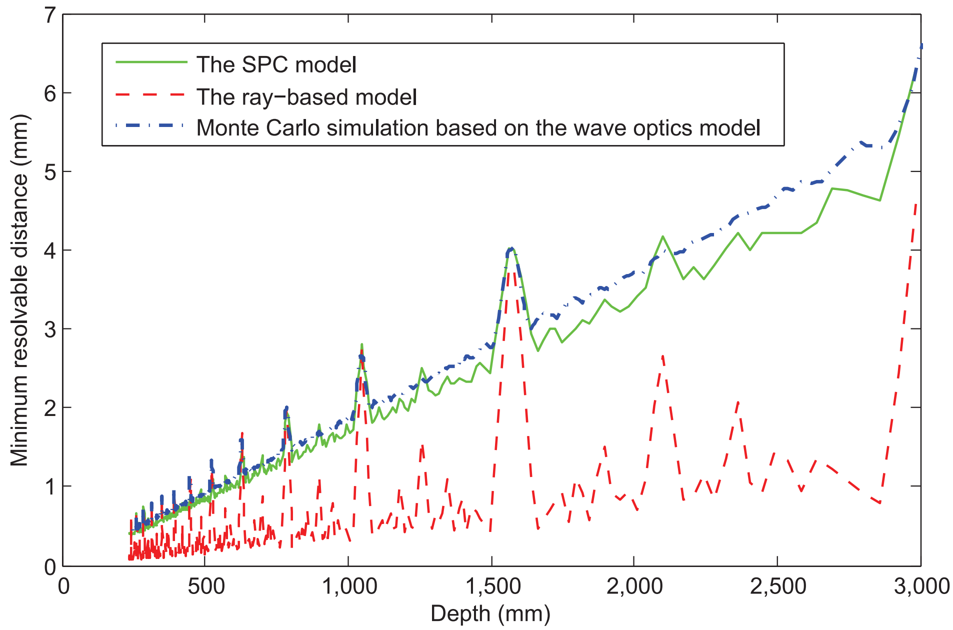

Figure 5. The minimum resolvable lateral distance at different depth planes achieved from the ray-based model, the proposed SPC lateral resolution operator using focal properties, and the reference data from wave optics based Monte Carlo simulations.

simulation results are also provided as reference data for comparison purposes. The focal plane of the system under the test is about 300 mm and the data at depth planes around and further away than this is presented.

Similar to the results in,[10] a general trend is observed in the graph shown in Figure 5 which indicates there are depth planes where the lateral resolution drops (location of the peaks) compared to depth planes slightly closer or further. In these depth planes, LCs overlap and form clusters and the lateral resolution decreases as a result of the poorer distribution of the LCs. As shown in Figure 5, results from the ray-based model are aligned with the wave optics based Monte Carlo simulations results in terms of the location, value and periodicity of the peaks. However, the general slant of the results from the ray-based model and values at the depth planes between the peaks are not matching with the results from the wave optics based Monte Carlo simulations. We would like to point out that the SPC model allows for producing results equal to a ray-based model by considering the case that all the information is carried by the center of the LC (or the single ray) as explained and implemented in.[10] Figure 5 also shows the results from the proposed lateral resolution operator which is based on the complete LC properties. Compared to the results from the ray-based model, the resolution values from the proposed lateral resolution operator are much better in line with the wave optics based Monte Carlo simulation results. Graphs well agree in location of peaks, maximum amplitudes and the general slant at the intermediate depth planes. The proposed lateral resolution operator also reduces the gap between the previous SPC extractor results obtained in[10] and the ground-truth reference data by taking into account the projected pixel size as a contributor to the lateral resolution limit at the depth plane of interest.

Figure 6 gives the lateral resolution limit results from the SPC model for both Setups 1 and 2. The graph showing the proposed lateral resolution operator results for the Setup 2 is also closely in line with the Monte Carlo simulation results (not shown in this graph) for the respective capturing setup. The effect of the varying pixel number per lenslet on the lateral resolution limit of the system can be observed in Figure 6 mainly as a stretching effect in the z direction. We explain this effect qualitatively by recalling the projected pixel size, pps, and the maximum line piece, min_dist as the two parameters directly contributing to the lateral resolution limit at the depth plane of interest and investigating their contributions. The increased pixel number per lenslet results in a smaller pixel size and so a smaller pps for the Setup 2 compared to the Setup 1 at the same depth plane

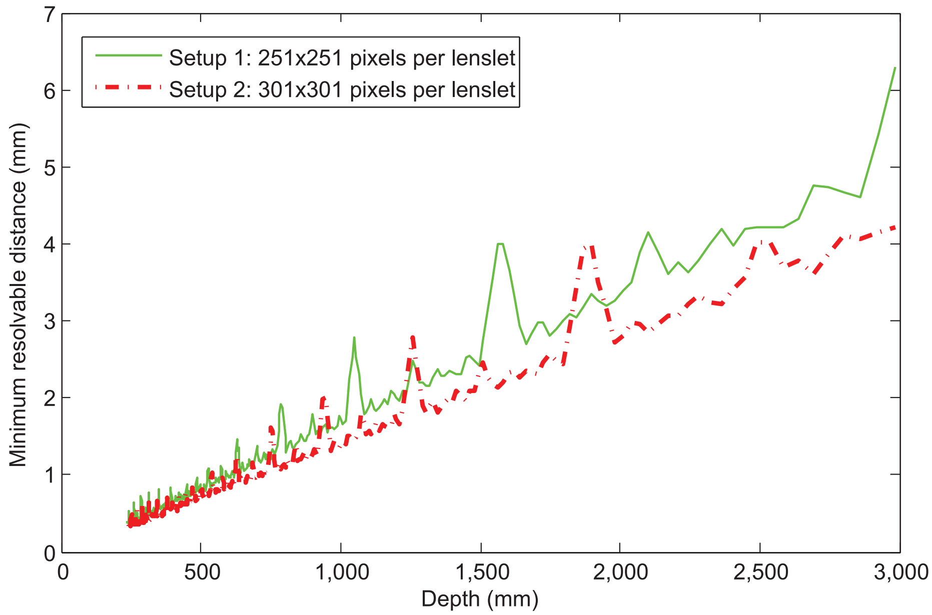

Figure 6. The effect of varying pixel density (varying the pixel number over a fixed area) behind each lenslet on the lateral resolution limit

is expected. Since the *pps* is the major contributor to the slant of the minimum resolvable distance graph, the results corresponding to the Setup 2 then have a smaller general slant compared to the results corresponding to the Setup 1. Additionally, the width and the distribution of the LCs in the depth plane of interest, illustrated in the parameter *min_dist*, are major contributors to the location and amplitude of the peaks in the results obtained from the proposed lateral resolution operator. The poor distribution of the LCs, previously mentioned as the clustering effect and which is causing large values for *min_dist*, generates the peaks in the minimum resolvable distance graphs. Increasing the pixel number per lenslet while keeping constant the other parameters will cause the clustering of the LCs happen in proportionally further depth distances and so resulting a proportional shift in the position of the peaks in the z direction. Results from the proposed lateral resolution operators for Setups 1 and 2 demonstrates the SPC lateral resolution operator as a straight forward predicting tool for investigating the effect of system variations on the lateral resolution limit of the system.

However, the current work is not considering the effect of overlapping LCs as a contributor to the lateral resolution extractor yet. This contributor has shown to have a small effect in the tested ranges of the system setups but can be expected to become more influential in setups with smaller f-numbers or at much larger distances from the camera objective where the span of the LCs are wide with possible large overlaps among them. Detailed investigations of the above contributors to the lateral resolution extracted by the SPC model could be a subject of the future works.

6. CONCLUSIONS

We have made an in-depth investigation of the lateral resolution as a high level property of the capturing system using the SPC model. We introduced a lateral resolution operator that leverages on the SPC features including the LCs' span, distribution and the projected pixel size, to extract the lateral resolution in each depth plane. We applied the proposed lateral resolution operator to the SPC model of a plenoptic camera setup and observed that the SPC model can achieve results comparable to those from the more elaborate wave optics model for the lateral resolution. Moreover, the proposed lateral resolution operator predicted the maximum resolvable distance values in line with the wave optics based Monte Carlo simulation results in case of varying the capturing system parameters. Therefore, the SPC is proven a simple yet efficient model for extracting the lateral resolution profile in complex capturing systems. Next step is to develop the lateral resolution extractor by taking into account more features of the SPC model like the LCs' overlap in order to express and expand the descriptive level of the model. Other possible tracks are introducing additional feature extractors in the SPC model for other properties of interest such as angular and depth resolution, and validate and evaluate the introduced operators by applying them to complex capturing setups.

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