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Transform Domain Morphological Filters

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Chapter 6

Concluding remarks and future prospects

Our knowledge and understanding of the nature and the world around us has made a number of large steps forward during the past decades. We continuously try to find answers to questions growing in their complexity in various fields of science for which we have an ever growing need for large amounts of data. We have developed sophisticated and complex measurement devices to study the natural phenomena or to monitor our environment. The amount of data produced by these machines has reached the status that it is, in many cases, beyond our processing and storage capacities. A category of these devices are the ones producing data with an extremely high velocity where we need to massively filter data online to discard damaged, unwanted or redundant measurements; this reduction makes it possible to fit the data within our data transport and storage capacities. The majority of the currently available and utilised algorithms are not up to the task yet. On the other hand, reduction on power consumption for data production and processing has become a more important topic. These reasons among others such as dealing with limitations of embedded devices, heat transportation limitations, et cetera, urge us to devise highly optimised methods for analysis and processing of collected data. Methods to perform online data reduction provide a possible solution to a portion of this challenge. Algorithms to recognise damaged, redundant or unusable data while it is being produced, are examples of such methods; they reduce the amount of required space to store the data and consequently less amount of data which needs to be processed off-line.

In this thesis, we have studied the concept of mathematical morphology and morphological operators to devise new methods to recognise and reassemble paths and patterns through point-clouds. These methods have been applied to data generated by a simulator for a sub-atomic interaction detection system (PANDA). Specifically, the data from the tracking detector system (STT) have been used to reconstruct paths of charged particles passing through the magnetic field. Traditionally, the tracking task was done using various methods (Hough transform, Conformal mapping, etc.) to reconstruct particle tracks together with a number of physical properties [31, 34, 53, 84, 86, 94]. Although these methods are capable of producing high-precision results, none of them is directly suited for online data processing and reduction where the compute power is limited due to various reasons such as limited space, heat transport, limitations imposed by embedded hardware, etc. We have shown that application of morphological connected filters in transform space is a candidate solution to this challenging problem. It was shown that by exclusively using the detectors' local data and geometry, a rough estimate of the paths in 3D could be made; those estimated paths could be used to decide either to keep or discard a certain track. Because of the simplicity and intuitiveness of the introduced method, it could be utilised on rather simple hardware or maybe even on the readout system of the STT sub-system of the PANDA detector.

We have introduced a new processing hierarchy and merging scheme together with a measure to significantly reduce track reconstruction error. Due to uncertainty caused by the geometry of the detector graph, merging the tracklets and splitting the paths sharing detector nodes remained a hard problem to tackle. The geometry of the STT graph was designed to produce high-precision xy-coordinates, but is has a rather huge position uncertainty in the z direction; the latter is a consequence of the length of the tubes in combination with the small skewed angle applied to the skewed tubes layers which leads to a large overlap-volume. To solve this issue, the detector graph was extended by virtual nodes (virtual detectors) in such a way that the uncertainty in the z-direction was reduced and a rough estimate of the z-coordinates could be made for the reconstructed particle paths. Although the introduced algorithm was not optimised for memory and computation-time efficiency, its proof of concept implementation showed that it was capable of solving a part of the online tracking challenge and could produce results within acceptable error margins. Our method is of $O(Nlog(N))$ time complexity with an error of approximately 0.10. This made the introduced method a possible candidate tool to be used for path reconstruction and online data reduction. A later study inspired and built based on our work improved our results even further and showed to outperform the other methods designed for data reduction, see chapter 6 of reference [35].

The geometry of many complex detection systems and sensor networks could be modelled by generic graphs. Each sensor is represented by a node and the connections between the nodes are defined using the graph edges. The individual and local properties of each sensor are stored in the node internals; examples of these parameters are the spatial coordinates, calibration parameters and measurement structures. When an event is detected, the generated data could be considered as a pattern in n-dimensional space; the dimensions at each point depend, of course, on the type of the sensor and the values it measures. Considering this concept, it is possible to process the outcome of many multi-sensor systems using the mathematical morphology and (transform-domain) morphological connected filters. To facilitate this processing scheme, a graph based formalism was defined for time and memory efficient application of attribute-space connected filtering. This formalism facilitates processing of higher-dimensional data using more than one attribute per node without incurring huge memory costs. The properties of transform pairs acting on graphs were studied and formulated in a generic form to facilitate mapping graphs to a transform domain and inverse transforms to map the data back to the graph's original domain. Furthermore, this formalism discards the required attribute quantisation step when attribute-spaces are represented in terms of $(N + dim(A))$-dimensional discrete volumes, with N the dimension of the input and $dim(A)$ the dimension of the calculated attributes. The introduced formalism leads to opportunity to calculate various attributes for the input data simultaneously; this way, one can design multi-attribute heterogeneous transform-domain (connected) filters and operators.

Transform-domain (connected) filters on binary images have been introduced in [107, 108] and studied as a theoretical concept by researchers. The main idea was to transform the input image in to a different domain where morphological (connected) filters could be applied; the results were transformed back to the original image domain using the corresponding inverse transform. In case of attribute-space as an example, the idea is to transform the image to a higher dimensional space, the so called attribute-space, by assigning one or more attributes to each pixel, where the morphological attribute-space (connected) filters could be applied to, for example, segment the input image. The results of those theoretical studies have not been explored afterwards and also not been applied to solve real-life challenges. Hierarchical structures such as Max-Tree were introduced and studied to process grey-scale images. The basic idea is to create connected regions of the same intensity, the so called flat regions, by application of a series of thresholds on the input image and to structure these regions in a hierarchy one on top of the other. Various attributes could be calculated while the tree is being built or afterwards for the tree nodes which could be used by morphological (connected) filters to perform tasks such as denoising, segmentation or data compression. The same strategy could be applied to data obtained from multi-sensor systems. The detection system itself is represented as a graph and the readouts of a recorded event as a pattern. By application of transform function pairs (transform F and its inverse F^{-1}) the input data can be transformed in to a different domain where attributes could be determined from the data in its new domain; morphological (connected) filters could be applied afterwards on the data and the results are transformed by F^{-1} to the original domain of input. It is important to mention that the transforms F might modify the neighbourhood relations of the input. As a demonstration of this concept, it was applied to images transformed to the wavelet domain. To compute the transforms and their inverses, traditional wavelet transform-functions were used. A number of morphological attributes have been calculated on data in the wavelet domain and used to filter the input to achieve image compression.

Graph-based representation and processing input data gives us access to a broader set of mathematical tools and also makes it possible to process a wider range of data sets. In addition, it removes some limitations such as the need for discretisation of calculated attribute values and facilitates memory-efficient transform-domain representations. The methods introduced in this thesis are generally applicable to data sets where a neighbourhood relation is defined for each data points independent of their dimensions.

6.1 Perspective

This thesis presents the results of our study on application of mathematical morphology to recognise and reconstruct paths and patterns in point clouds. The concept of attribute-space and attribute-space connected filters was extended to graphs and formalised to a framework for construction of time and memory efficient filters. This method is applied, as a proof of concept, to reconstruct charged particle paths through the magnetic field. The data for this experiment was produced by a simulator of a detector designed for subatomic particle experiments; specifically the tracking subsystem (STT) which is designed to track particle paths through a magnetic field. It is shown that by exclusively using the geometry of the STT subsystem, it is possible to reconstruct the particle tracks in 3D. The results imply that using the same method, the data produced by similar detection systems could be processed. This gives the opportunity to apply and possibly extend the introduced method to process data obtained by currently running similar experiments that produce "real" data. This extension could entail exploring the usage of other advanced data structures or vector attribute filters to reduce execution time and memory footprint. Another interesting area to consider is to expand the theoretical framework to cover hyper-graphs. This allows structural conversion of the data by representing it as a hyper-graph. The latter might lead, in some cases, to a more efficient processing of data with higher structural complexity. In the presented methods, the attributes are assigned only to the graph nodes; exploring the possibility and effect of assigning attributes to endpoints of edges to construct non-binary or weighted attribute-filters is another interesting concept to consider. The concepts and methods discussed in this thesis rely on the spatial arrangement of the data points with respect to their neighbours (neighbourhood function). This makes adaptation and application of the introduced methods to analyse other data sets a rather straight-forward task, given the data points have a proper neighbourhood definition. Processing other data types such as remote sensing or medical imaging data using the methods discussed in this work is another interesting application area to explore.

The concept of transform-domain morphological connected filters was studied where transforms and their inverses were discussed. Thus far, we have only considered the traditional wavelet domain and its properties in a single decomposition level. It could be an interesting exercise to study this concept using the nonlinear morphological wavelet transforms for mapping the input. These transforms use the input's structural properties and could be computed efficiently, for example by, using the lifting scheme. Another interesting area to discover is extending this concept to cover second-generation and hyper-connectivity. The latter may be of interest to process images with a fair portion of missing data when, for example, denoising or segmentation are the objectives. Building a hierarchical structure, such as a Max-Tree, of an image could be considered as a domain transformation. The input image is transformed from its original domain into a hierarchical representation; one can build a component tree of the data in its new domain for filtering purposes, the so-called shapings [115]. These methods turned out not to be practical when one uses vector attributes; a solution to this issue was presented in [104] by combining component trees and machine learning methods to find the optimal filtering parameters. The concept of application of connected filters in transform-domain based on hierarchical transformations using machine-learning techniques to find optimal filter parameters, is another interesting path to explore; this will open the doors to a more practical usage of advanced and sophisticated vector-attribute filters. In addition, it may facilitate the design of new training schemes for machine learning algorithms which do not require vast amounts of data during the training phase. So far, we have studied the hierarchical structuring of the transform-domain data using the Max-Tree algorithm. Another interesting hierarchy is that of an α-tree structure [62, 83] where the components are defined using the concept of α-valued paths between the pixels. One of the advantages of this concept is that the connected components may be of a heterogeneous intensity across their pixels. A possible future work may be to explore the effects of using such a hierarchy.

Thus far, various concepts of morphological image analysis have been discussed through this thesis and applied on single channel data sets and images (binary and grey-scale). It would be an important step and a future challenge to extend the introduced theory and methods to cover, for example, processing of hyper-spectral and tensor data or cases where the input-data contains a larger number of channels per node; this will facilitate processing data produced by multi-sensor systems in which the output of various local sub-detectors could not be processed independently. Other studies [14] have explored the application of mathematical morphology on tensor data, but none has considered transform-domain morphological data analysis yet; this extension might lead to a more generic and universal theory when it comes to processing high-dimensional data sets. In case of colour images, a possible greedy solution might be processing each colour band separately; this may lead to the problem of recombining the results afterwards in case that some pixels are removed in one channel and remain untouched in another. Another problem that needs to be faced, when processing multi-channel data (for example colour images) using morphological operators, is imposing an order on vector-data. Previous studies have introduced partial solution for this issue [39, 98]; further research on this topic is another important path to explore.