Spectral imaging and tomographic reconstruction methods for industrial applications

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Summary in English

With globalization, growing world population, and other increases in scale taking place, humanity is becoming increasingly dependent on efficient industrial production. An essential component of industrial production is the execution of quality controls. These controls ensure that the product does what it is intended for and that no harm can occur when a product is used or consumed.

An important part of the industrial sector is food production. Various processes during food processing in and around factories can lead to contamination of the food product. This can include the presence of organisms (such as unwanted bacteria like E. coli in cheese) or the presence of chemicals (such as pesticides and cleaning agents on fruit) in or on the product. An important category is physical contamination, where small objects remain in the product. This can manifest as small pieces of glass, metal, or plastic that are left behind in food products. These small objects are referred to as *foreign objects* in this context and can be harmful when accidentally consumed. This is one of the reasons why supermarkets often have to organize large-scale recalls. It goes without saying that physical contamination leads to potential health risks, loss of time, financial damage, and loss of trust in the manufacturer. Because of the possibility of food contamination at various stages, quality control methods are constantly in development.

There are many methods for food contamination detection. Many methods are based on the interaction with *X-rays*, which can (partially) penetrate objects. For example, a foreign object can absorb more X-rays than the product it is hidden in. If the product is exposed to X-rays, an image can be formed by using an X-ray detector, on which the foreign object becomes visible. Although the developed methods are often applicable in a broader sense, their use for detection of foreign objects with X-rays is the common thread in this dissertation.

Although X-ray images reveal many properties, it can happen that projections of certain materials look similar to each other and are difficult to impossible to distinguish. X-ray *computed tomography* (CT) can offer a solution to this. In this method, multiple X-ray images of an object are taken at different angles. Afterwards, the object can be visualized in a three-dimensional volume using a reconstruction algorithm. Because CT generates a 3D volume instead of a 2D projection, the object can be analyzed more accurately and, for example, more thoroughly checked for the presence of a foreign object.

Even if X-ray imaging and computed tomography can provide a lot of insight into the composition of objects, there are many challenges to applying these methods for industrial purposes. In industry, it is important to make a decision based on the obtained information that is both *fast* an *accurate*. These goals are in conflict: X-ray images can be analyzed relatively quickly but do not always provide a definitive answer, while analysis of CT volumes is more time-consuming.

Additionally, in CT volumes, different materials may still appear as too similar and difficult to distinguish.

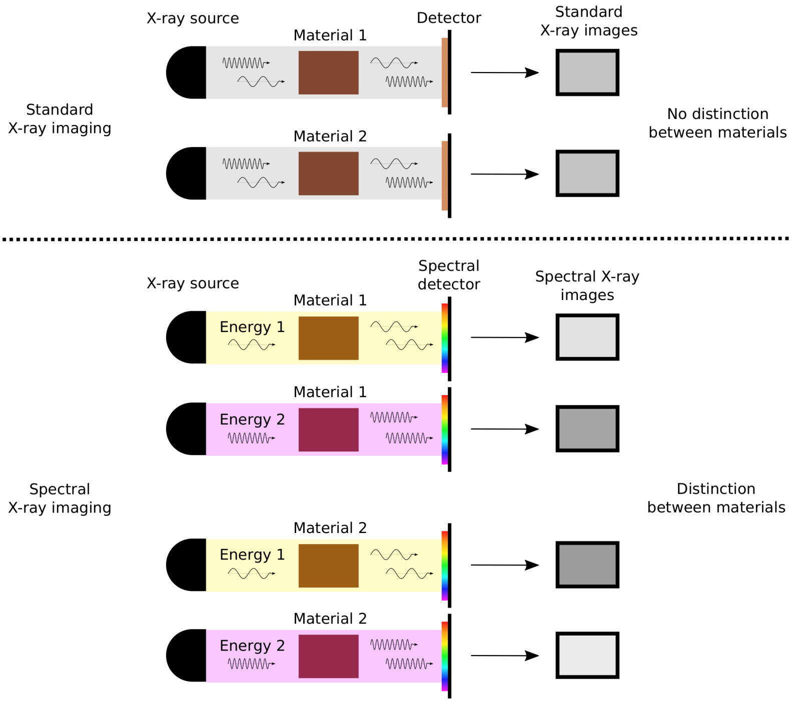
Two relatively new techniques offer possibilities to make object inspection both faster and more accurate. The field of artificial intelligence has recently experienced significant growth, in part due to the development of *deep learning* methods. In these approaches, a deep neural network (which is based on the networks of neurons in the human brain) can be trained with examples and their corresponding solutions to continuously improve its performance on a specific class of problems. A special category of neural networks is that of convolutional neural networks, which are capable of quickly detecting objects in X-ray images without requiring human intervention once they are trained.

Nevertheless, even the best X-ray images may not reveal a foreign object. To solve this, the technique of *spectral X-ray imaging* can be used. Spectral X-ray detectors can not only detect the photons that make up the X-rays, but can also determine the energy carried by each photon. The absorption of photons depending on energy is called an *absorption spectrum.* Because the absorption of photons depends not only on the material but also on the energy, this yields a unique absorption spectrum for each material. With spectral X-ray imaging, improved discrimination of materials present in an object is possible, where this is often difficult to measure with standard X-ray imaging (see Figure S1 for an example).

Similarly, for spectral X-ray imaging, the composition of an object can be better analyzed by using *spectral CT.* This can be done, for example, by reconstructing the measured CT images separately for each energy. By comparing multiple CT volumes - each corresponding to a certain energy - materials that are present in the object can be determined even better. However, as with standard CT, the reconstruction process takes extra time. Therefore, spectral CT reconstruction algorithms are constantly being developed to improve both accuracy and speed.

Machine learning and spectral X-ray imaging are two important ingredients for the methods developed in this thesis. **Chapter 1** explains how these techniques work and gives an overview of the most important existing methods. The chapters that follow cover various aspects of possible application of these techniques.

In **Chapter 2** we focus on a fundamental problem of deep learning: a large number of *training examples* is required to make a trained network function properly. However, for inspection with X-ray imaging, these examples are usually not easily available and require a lot of manual work to create. Therefore, we develop a *workflow* in which only a limited number of objects need to be CT scanned and reconstructed, from which a large number of training examples can be efficiently extracted. Through the use of a dataset collected in the FleX-ray laboratory at CWI, we demonstrate that this method can be used for foreign object detection and other deep learning based industrial applications.



Figuur S1: Schematic representation of the advantage of spectral X-ray imaging over standard X-ray imaging. With standard X-ray imaging, two different materials can result in the same intensity on the X-ray image. With spectral X-ray imaging, the energies in the X-ray beam can be separated from each other (by adjusting the source, or by measuring both energies in a spectral detector, or both). This gives multiple X-ray images per material. Based on the differences in these spectral X-ray images between materials, we can distinguish them.

The workflow is designed such that it can be expanded in many ways to obtain even better training data. An important extension is to use spectral X-ray imaging. In **Chapter 3**, we look at hyperspectral images, where many energies can be captured simultaneously. Because these hyperspectral images can contain a lot of data and can therefore be very large, it processing these with a deep learning trained network is relatively time-consuming. Therefore, it is necessary to *compress* these images. To preserve the important properties in these images for the tasks that need to be performed (such as detection of foreign objects), compression can be carried out in a *task-driven manner*. We achieve this by linking two neural networks and training these *simultaneously*: the first component is responsible for compression and the second part is responsible for performing the imaging task. We demonstrate with several examples that training of this composite network leads to stronger and more robust compression than conventional compression methods. This compression method not only has advantages in industrial tasks, but also in other applications where efficient data transmission is required (such as sending data from a satellite to Earth).

In the following chapters are dedicated to improving CT reconstructions with spectral X-ray imaging. In **Chapter 4**, we condsider objects that contain *few different materials*. An existing algorithm specialized for these cases uses this property to achieve significantly better reconstructions than other methods that do not (fully) use this property. We develop an extension of this algorithm to multiple energy levels and demonstrate that with the use of spectral data objects consisting of more materials can be reconstructed accurately.

In **Chapter 5** we explore an alternative approach to spectral CT. We assume access to a spectral detector that can measure how much X-ray radiation is absorbed per energy by each material. If these spectra are known for a range of materials that may occur in the object (resulting in a *dictionary*), it can be used to steer a spectral CT algorithm to certain solutions. We develop such an algorithm and in a series of experiments, we not only demonstrate its robustness but also show that it can yield better results than current leading spectral CT algorithms.

Taken together, this dissertation proposes methods for improving industrial processes, with a specific motivation from food inspection. The methods use deep learning and spectral X-ray imaging. The proposed workflow for detecting foreign objects can be applied in factories, and can be expanded with the other methods proposed and analyzed in this thesis. Nevertheless, we expect that the individual methods are also applicable in a broader sense for medical purposes (such as CT scans in hospitals), security purposes (such as scanning luggage at airports), and a wide spectrum of other areas.