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THREE-DIMENSIONAL IMAGE PROCESSING METHODS TO INVESTIGATE STRUCTURAL CHANGES OF GRANULAR MATERIALS DURING GRAVITATIONAL FLOW BASED ON X-RAY TOMOGRAPHY DATA

BY

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DISSERTATION SUMMARY

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Title: *Three-dimensional image processing methods to investigate structural changes of granular materials during gravitational flow based on X-ray tomography data.*

Abstract:

X-ray Computed Tomography (CT) is a powerful non-destructive technique primarily used in medical applications for generating cross-sectional images of a 3D object based on X-ray absorption. In the last two decades, CT was also widely used in different material science research fields and industrial applications like in mining, agriculture, civil engineering, food processing, and pharmaceutical manufacturing. In most of the above-mentioned industries, silos are commonly used to store, protect and load for bulk materials into process machinery. CT is the most proficient for investigating different granular flow phenomena's inside a silo as compared to other imaging techniques. However, due to the complexity of three-dimensional industrial material structures and the massive amount of data, it can be tedious and extremely time-consuming for manual analysis. Therefore, one needs to apply robust and efficient image processing algorithms that are capable of reducing noise, extracting and providing significant insights about the investigating process. This is the main aim of this dissertation.

In order to analyse such complex processes, two different kinds of X-ray tomography imaging techniques were used to acquire tomography images and various kinds of silo model structures have been designed during three major experimental campaigns. High-energy X-ray tomography and the ultrafast electron beam X-ray tomography systems are the two types of CT techniques used to generate 3D and 2D images, respectively.

The final and main part of the dissertation describes novel and modified image processing algorithms that are applied for qualitative analysis and visualization of insightful information about structural changes of granular material during gravitational flow based on the X-ray CT data. The first novel method aimed to tackle the initial thesis of this dissertation by segmenting tracer particles effectively and track their possible three-dimensional rotations while calculating their velocity during mass flow. The insight investigation demonstrates that there was no special lateral movement and rotation in the three-dimensional space. All other methods concerned with the second thesis of the dissertation, which presented gradient-and motion-based approaches. In order to extract the stagnant zone from the flowing zone of silo discharging process, two proposed algorithms were applied, namely; local signal to noise ratio and point set extraction methods for 3D edge reconstruction. In addition, in order to get three-dimensional stagnant and flow zone segmentation of granular flows and quantify their respective packing density distribution, a motion-based approach is proposed and described in details. At last, the dissertation introduces an automatic stagnant zone segmentation method that provides fast and effective outcomes by exploiting convolutional neural networks (CNN) technique with an accuracy of 97 %.

I. Introduction

The development of X-ray computed tomography (CT) system allows one to apply the image processing and analysis methods to investigate different industrial processes. Due to the complexity of three-dimensional industrial material structures, it can be tedious and extremely time-consuming for manual analysis. Therefore, to process such amount of data, one needs to use robust and efficient algorithms that are capable of reducing noise and providing significant insights.

It is generally agreed that there are two main types of silo discharging process. The first one is the so-called mass flow, it operates as the first material filled in will flow first out at the bottom as well with a uniform discharging velocity across the entire cross-section area. The second type of flow is called funnel flow, in which granulates are flowing only in the center of the silo, while in the rest is creating a stagnant zone of materials at the wall of the container.

1.1 Objectives and main thesis

The experiments of these studies were conducted at three different laboratories, namely the Henry Moseley X-ray Imaging Facility at the University of Manchester (HMXIF), the Helmholtz-Zentrum Dresden-Rossendorf (HZDR) during an Erasmus exchange program (February 2016 to June 2016), and the MATEIS laboratory at INSA-Lyon with a grant funded by the National Science Centre in Poland (author role: co-investigator, grant number: 2015/19/B/ST8/02773, Period: October 2016 to July 2018). Depending on the acquired images, types of investigated granulates and silo geometry; each experiment aimed to tackle different image processing problems as illustrated in Table 1.

Lab place	Type of granulates	Flow type	Major problem tackled
HMXIF	Fine-grain material	Funnel flow	Flow boundary detection
HZDR	Coarse-grain material	Mass and semi-mass flow	Particle tracking
MATEIS	Coarse-grain material	Concentric/eccentric funnel flow	3D segmentation of stagnant zone

Table 1. Illustration of experimental campaigns with tackled image processing problems.

Based on the different experiments presented in this dissertation allowed isolating specific image patterns and the theses of this dissertation are formulated as follows:

Thesis 1: In the context of data reduction, the study of flow dynamics during silo discharge can be reduced to the analysis of the trajectory of a small number of grains, known as tracer particles, using volumetric image processing.

Thesis 2: Gradient- or motion-based image processing method allows to distinguish stagnant zone from flowing ones during silo discharge and the choice of the method is strongly linked to the relationship between the grain size and the spatial resolution of the X-ray tomography system in use.

II. Image processing algorithms summary

The main contribution of this dissertation can be summarized as follows. In this dissertation, two different X-ray CT imaging techniques and various kinds of granular materials (such as sand, glass beads, sorghum, and rice) with different silo geometries are used to investigate the interior flow dynamic granular materials. In the context of the 1st thesis, a novel method was proposed to improve segmentation accuracy of tracer particles by applying a robust method named irregular grid local Otsu segmentation (IGLOS). The insight investigation was able to track the movements of tracking particles and it demonstrates that there was no special lateral movement and three-dimensional rotational motions.

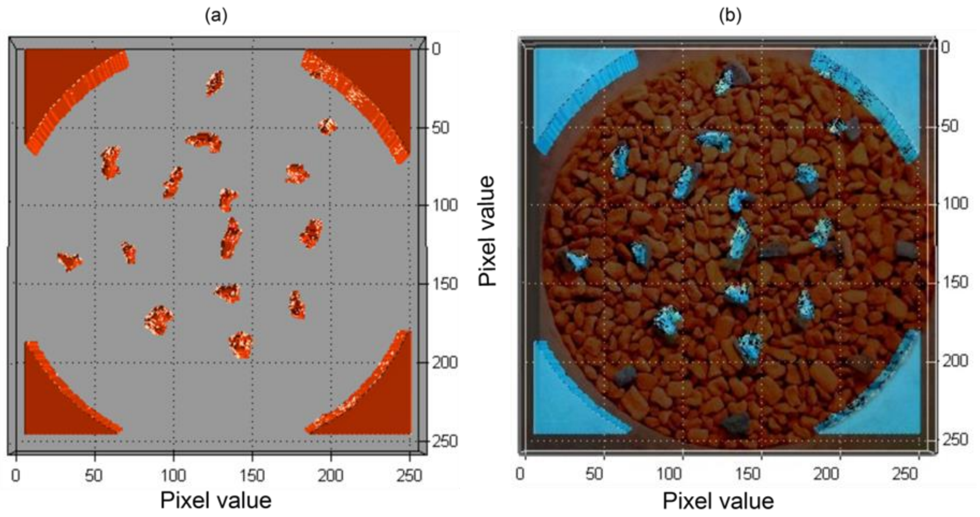

Figure 1. 3D view of segmented tracer particles at scanning height of 800 mm. (b) Top view photo was taken before discharging during the experiment at silo height of 900 mm superimposed with figure-a.

All remaining image processing works concern the second thesis on this PhD dissertation. The second method is proposed to segment the boundary between the stagnant and flowing zone of fine-grain granulates. Signal-to-Noise Ratio (SNR) is one of the signal processing and image quality methods which are used to improve the contrast of the original CT images and facilitate the detection of the boundary between funnel area and stagnant zone. The third approach introduced an automatic point set extraction method for reconstructing 3D tomography images of funnel flow boundary. After applying a rectangular kernel size filter on the original CT image, the method uses intensity profile for extracting and connecting those jump points gave a boundary line of the funnel flow from the stagnant zone. The final step of this algorithm applied a special method based on digital topology for filling the holes of the grid cells and generate 3D volumetric funnel flow boundary as shown in Figure 2.

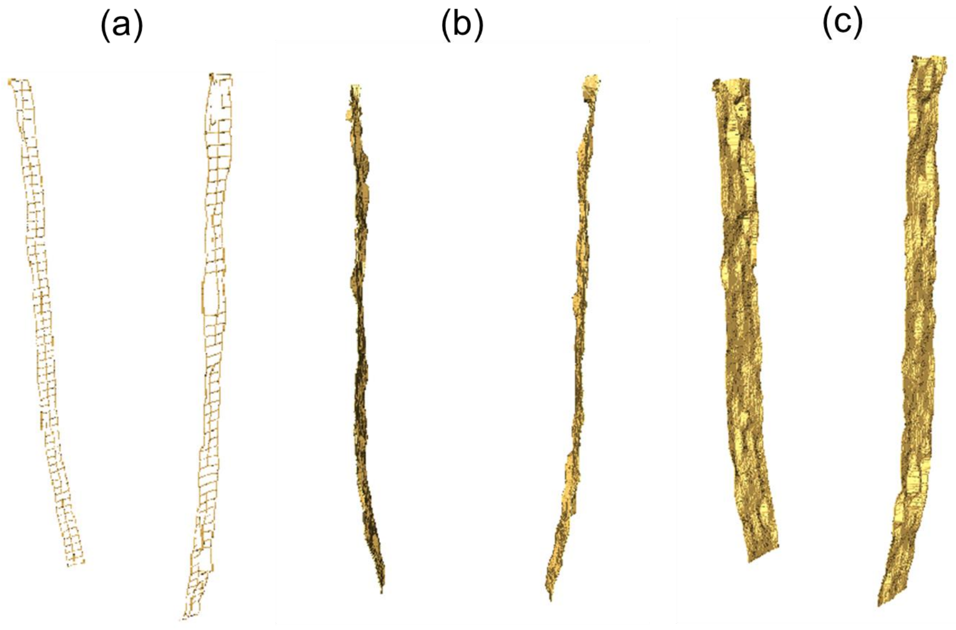

Figure 3. Three-dimensional edge reconstruction of funnel flow boundary: (a) creating 3D grid (b) front view after hole closed (b) side view after hole closed.

The last two approaches deal with coarse-grain materials (rice), unlike the previous two methods which concerned fine-grains (dry sand grains) as a granular material. The fourth approach uses the motion of the particles for applying 3D segmentation of the stagnant zone and it calculates the packing density between flowing and stagnant zone. The last approach exploits the latest CNN technique for automatic segmentation of the stagnant zone. Once after having trained u-net modified model, the end-to-end 3D automatic segmentation offers an effective and fast segmentation of stagnant zone as presented in Figure 4.

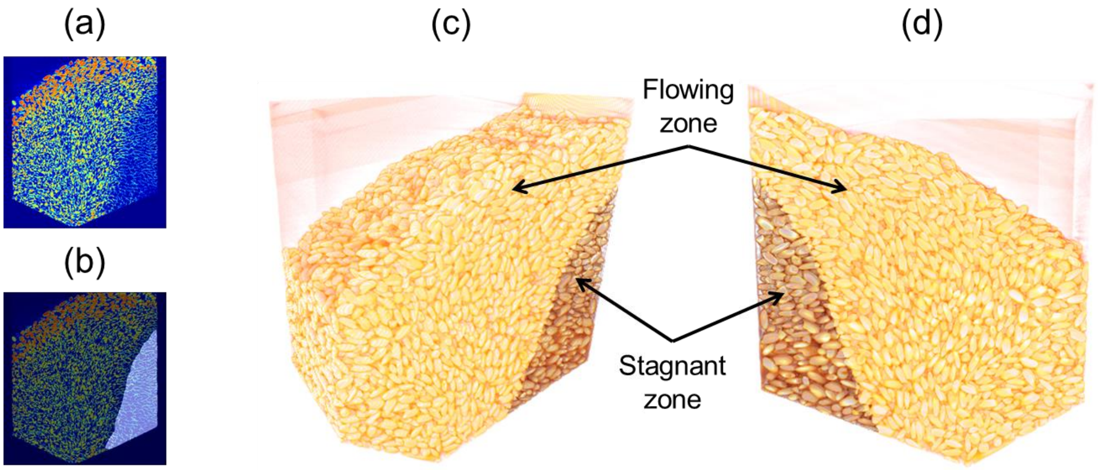

Figure 5. Volumetric segmentation with the modified u-net model. (a) The absolute difference between two successive original scans of rice grains flow (b) predicted segmentation. The network predicted dense segmentation (c) left side (d) front side view.

Conclusions

In order to analyse the CT data that has been acquired from different experimental campaigns and complex structure of granular material flows, it can be tedious and extremely time-consuming for manual analysis. In this dissertation, there are five major methods introduced as a sole-author. The first novel approach is named as IGLOS, which demonstrates that there was no special lateral movement and three-dimensional motions during the mass flow. The second and third approaches used the gradient changes of the flow by applying the local signal-to-noise-ratio and point set extraction techniques to extract and reconstruct the funnel flow boundaries of fine-grain materials in 2D and 3D respectively. The motion-based approach was the fourth method which was applied to segment and then calculates the packing density between stagnant and flowing zones of coarse-grain materials. Finally, the dissertation presents a new approach for automatic segmentation of the stagnant zone in an effective way by exploiting the CNN technique with an accuracy of 97%.

The accuracy of the approaches has also been compared with different algorithms and made breakthrough results in most cases. However, some of the methods still have some drawbacks. Particularly, a problem associated with segmenting stagnant zone in the flow where packing density is the same in both zones. The accuracy of the CNN approach could also probably be further improved if the delineations of the ground truth were acquired from different experts and more number of the dataset was used for training the model.