Powder Technology 301 (2016) 805–814

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Numerical modeling of an automated optical belt sorter using the Discrete Element Method

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ARTICLE INFO

Article history:
Received 4 March 2016
Received in revised form 8 July 2016
Accepted 9 July 2016
Available online 12 July 2016

Keywords:
Discrete Element Method
Optical sorting
Non-spherical particles
Multiple object tracking

ABSTRACT

Optical sorters are important devices in the processing and handling of the globally growing material streams. The precise optical sorting of many bulk solids is still difficult due to the great technical effort necessary for transport and flow control. In this study, particle separation with an automated optical belt sorter is modeled numerically. The Discrete Element Method (DEM) is used to model the sorter and calculate the particle movement as well as particle – particle and particle – wall interactions. The particle ejection stage with air valves is described with the help of a MATLAB script utilizing particle movement information obtained with the DEM. Two models for predicting the particle movement between the detection and separation phase are implemented and compared. In the first model, it is assumed that the particles are moving with belt velocity and without any cross movements and a conventional line scan camera is used for particle detection. In the second model, a more sophisticated approach is employed where the particle motion is predicted with an area scan camera combined with a tracking algorithm. In addition, the influence of different operating parameters like particle shape or conveyor belt length on the separation quality of the system is investigated. Results show that numerical simulations can offer detailed insight into the operation performance of optical sorters and help to optimize operating parameters. The area scan camera approach was found to be superior to the standard line scan camera model in almost all investigated categories.

1. Introduction

The amount of bulk material processed on a global scale continues to grow. In 2012, more than 8687 MT of coal [1] and 2520 MT of grain [2] were produced. The maritime trade of iron ore, grain, coal, bauxite and phosphate increased from 448 MT in 1970 to 3112 MT in 2014 [3]. It is estimated that 10% of the worldwide energy supply is required for the handling and transport of bulk solids [4]. The annual production of bulk materials and powders has a value of over $10 billion and around 25% to 30% of the products produced by the pharmaceutical and chemical industries are particulate solids [5].

With continuously growing material streams, the handling and sorting of bulk solids is of great importance. In addition to conventional separating processes like screens [6], which separate the material depending on physical properties, automated optical sorters can be used. Minerals, agricultural products, granules of recycling processes, or particulate chemical/pharmaceutical substances can be separated based on optical criteria [7–9]. For this purpose, the particulate matter is transported and isolated by chutes, slides or vibrating conveyors and passed by an optical sensor. The bulk solids are then separated into two fractions by pneumatic air valves, which are triggered based on optical properties of the material like size, shape, color, brightness or texture.

Scientific studies conducted in the field of optical sorting can be separated into different core areas. Investigations regarding the sorting of nanoparticles discuss the necessary experimental structures for particle separation and are presented in [10–12]. The main focus regarding the optical sorting of bulk solids is the testing of sorting processes for specific applications. Examples include the separation of magnesite from waste streams [13], the selection of quartz pebbles [14] and the sorting of wheat grains infested with plant disease [15,16]. Other studies investigate the potential of new or modified machine components [8,17–19]. An additional category of research focuses on the applicability of automated optical sorters in new industrial fields or in sub-processes like metal recovery [20], glass recovery [21] or lithium minerals processing [22].

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http://dx.doi.org/10.1016/j.powtec.2016.07.018

Due to the high technical effort necessary for the material transport and flow control, the optical sorting of many bulk solids is still difficult. The gap between particle detection and separation makes it crucial to reduce the proper motion of the bulk solids during transport to be able to reliably predict the particles' position for the material separation. De Jong and Harbeck [23] investigated the maximum throughput of an optical sorter based on different particle sizes. They concluded that the separation efficiency decreases significantly if a minimum distance between adjacent particles is below a certain threshold. Pascoe et al. [24] developed a simple model for predicting the efficiency of their automated sorting system depending on the belt loading and the number of particles to be ejected. In a further study [25], the authors investigated the influence of particle distribution on sorting efficiency with the help of a Monte Carlo simulation.

Due to the heterogeneous nature of bulk solids, the design and calibration of optical sorters is mostly product-specific and highly empirical. The number of air valves required for the material separation and their distance to the optical sensor are currently determined experimentally. Furthermore, the calibration of the valve activation time and the air blast duration is based on simple assumptions (linear particle movement and constant velocity). Hence, adjustments of the system, especially regarding components involved in particle transport and flow control, are based on numerous experiments.

In order to reduce the duration and number of extensive experiments required for the initial calibration of optical sorters, improve sorter accuracy, decrease error probability and enable the optical detection of new particle properties, a new multi-disciplinary approach is employed in this study. It combines digital imaging, algorithmic image processing and numerical simulations. An area scan camera is mounted on an optical belt sorter and enables the real time tracking of the recorded particle stream, giving detailed information of the particles' positions and velocities at the end of the belt. A detailed description of the process can be found in [26,27].

In order to improve the tracking modeling and to get a more detailed understanding of the bulk solid's behavior as well as to improve the design of optical sorters, particle-based simulation approaches like the Discrete Element Method (DEM) can be employed. The DEM has already been successfully applied to describe other material separators like screens [28–31] and cyclones [32–34]. In this study, an optical belt sorter is modeled with the DEM and the influence of different operating parameters like particle shape, applied particle mass and belt length on sorting quality are investigated. The method used to model the complex shaped particles in this study has already been successfully employed and validated against experiments [35,36]. In addition, the results of employing a model of a line scan camera (thereby assuming that the particle is moving in belt direction with belt velocity at the detection point) are compared with using the model of an area scan camera in combination with particle tracking (the actual particle velocity and direction of movement at the detection point are considered). This is a novel approach to optimize sorter performance where the DEM can provide the required insight into particle behavior and sorter parameters.

The particle ejection by air valves is modeled and analyzed with a MATLAB script in a processing step after the simulation. Here, the effects of the number of air valves, air blast duration time and distance between the detection point and the valve bar on the sorting quality are examined. It is planned to model the particle ejection by coupling the DEM with Computational Fluid Dynamics (CFD) in future research, similar to the recently published paper by Fitzpatrick et al. [37]. This study constitutes a first step to numerically model an entire optical sorter, which can be used as a design tool and for further process optimization.

2. Methodology

In this section, the employed DEM approach, the numerical setup and operating parameters as well as the operational procedure are presented.

2.1. DEM approach

The bulk solids and the walls of the optical belt sorter investigated in this study are described with the Discrete Element Method (DEM), first introduced by Cundall and Strack in 1979 [38]. It allows the detailed analysis of particle-particle and particle-wall interactions. The translational and rotational motion of every particle is calculated with Newton's and Euler's equations of motion and can be written as

$$m_i \frac{d^2\vec{x}_i}{dt^2} = \vec{F}_i^c + \vec{F}_i^g, \tag{1}$$

$$I_i \frac{d\vec{W}_i}{dt} + \vec{W}_i \times \left(I_i \vec{W}_i\right) = \Lambda_i^{-1}\vec{M}_i, \tag{2}$$

where m_i is the particle mass, $d^2\vec{x}_i/dt^2$ the particle acceleration, $\vec{F}_i^c$ the contact force and $\vec{F}_i^g$ is the gravitational force. The second equation gives the angular acceleration $d\vec{W}_i/dt$ as a function of the angular velocity $\vec{W}_i$, the external moment resulting out of contact forces $\vec{M}_i$, the inertia tensor along the principal axis I_i and the rotation matrix converting a vector from the inertial into the body fixed frame Λ_i^{-1}.

The contact forces originating from particle-particle or particle-wall collisions are separated into a normal and tangential component. A linear spring damper model is used to obtain the normal component of the contact force

$$\vec{F}^n = k^n \delta \vec{n} + \gamma^n \vec{v}^n_{rel}, \tag{3}$$

with the spring stiffness k^n, the virtual overlap δ, the normal vector $\vec{n}$, the damping coefficient γ^n and the normal velocity in the contact point $\vec{v}^n_{rel}$ [39]. The coefficients of normal restitution between particles e^n_{pp} and particles and walls e^n_{pw} combined with the employed time step directly determine the spring stiffness k^n and the damping coefficient γ^n. A linear spring limited by the Coulomb condition is employed to calculate the tangential component of the contact force

$$\vec{F}^t = \min\left(k^t\left|\vec{\xi}^t\right|, \mu_C\left|\vec{F}^n\right|\right)\vec{t}, \tag{4}$$

where k^t is the stiffness of a linear spring, μ_C is the friction coefficient, $\vec{\xi}^t$ is the relative tangential displacement and $\vec{t}$ is the tangential unit vector [40].

In addition to the tangential contact force, the moments resulting from the rolling friction between particles and particles as well as particles and walls are considered and included in the external moment resulting out of contact forces $\vec{M}_i$ described in Eq. (2). A rolling friction model devised by Zhou et al. [41] is used in this study

$$\vec{M}_i^r = -\mu_r\left|\vec{F}^n\right|\frac{\vec{W}_i}{\left|\vec{W}_i\right|}. \tag{5}$$

Here, μ_r is the coefficient of rolling friction, $\vec{F}^n$ the normal component of the contact force and $\vec{W}_i$ the angular velocity.

The non-spherical particles employed in this study are modeled with polyhedrons. With the help of a triangular surface mesh, different particle shapes can be realized. The contact detection between the polyhedrons is based on a fast common plane algorithm [42]. The contact force laws are equal to those of the spherical particles [39,43].