Robotic Control System for Particles Size Distribution of industrially Produced Mineral Fertilizers

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***Abstract*— The modern mineral fertilizer industry are large-scale factories, which produce dozens of tons of product hourly. At the same time, there are practically no robotic systems of quality control of the ongoing technological processes. In present paper, main stages of mineral fertilizer production are described, and the solution to the problem of robotic online particle size control was proposed. The general scheme and algorithm of the device functioning work were given. The developed system consists of three main units: a sampling unit, a sample delivery to the analysis area unit and a control unit with optical detection of granules. Sampling is carried out by a rotary system and further, the sample is delivered to the analysis area through linear vibrations. The entire sampling and sample delivery circuit is controlled by a computer, which built into the analysis unit. The software also allows to determine the physical parameters of the granules in the analysis area (size, color, and shape). The calculation algorithm of granule parameters consists of obtaining an optoelectronic image, its pre-processing, calculation of closed contours, approximation of found contours by ellipses and calculation of ellipse parameters. The system has an algorithm for self-diagnosis and response to external conditions. Different solutions of the sampling system are given for two different forms of a fertilizer flow (on a conveyor belt and in a closed pipe) and they statistical characteristics (mean and standard deviation) were calculated. The obtained results are compared with similar laboratory granulometric composition control devices (Camsizer P4).**

***Index Terms*—robotic control system, optical analyses, mineral fertilizers, industrial automation, SCADA**

I. Introduction

In the modern industrial production, there is a clear tendency to simplify methods of technological processes control to their full automation [1, 2]. The area of mineral fertilizers production is not an exception [3]. Various systems of supervisory control and data acquisition (SCADA) are being actively integrated into technological processes, which allows to collect and visualize information from various sensors and actuators [4]. However, the major part of the information in these systems concern devices of automation level 0 and displays only a single unit of the concrete information per time. These systems are not fully allowing to supervise and to operate industrial process [4]. And although some authors [5] use this data to build supervisory models, these models do not fully reflect the real industrial process and finished product quality. After all, the main quality parameters of finished products are often complex and difficult-to-detect properties, which are sometimes, very hard to model (content of chemical elements, shape, color, etc.). For instance, one of such parameters for mineral fertilizers is particle size distribution [6]. Besides, the considerable part of SCADA uses control on the basis of programmable logic control (PLC), instead of the distributed control system (DSC) [4, 7]. Thus, the information about real parameters of product quality in the technological process ("complex parameters") is presented to a minor level. To eliminate this disadvantage, robotic control systems were proposed. They allow not only to receive specific information about the state of the device, but also to respond to changes in the technological process themselves. In other words, there are disturbed systems of the 2nd level of automation, which interact directly with the SCADA. The authors of the work [8] suggest using such systems in oil and gas industry. In the review [2], the main features and applications of such systems in the Industry 4.0 are given. However, the information about the usage of such robotic systems in industrial manufacture of mineral fertilizers is absent in the literature.

In most cases, the finished product of industrially produced mineral fertilizers is a granule with size from 1 to 4 mm [9]. Sometimes, size can vary from 1 to 5, or 2 to 6 mm (depends on the customer). The granulometric composition is one of the most important indicators of the quality of the manufactured product. This parameter is responsible for the quality of the technological process [3,9] and the agronomical effect of fertilizers [10]. It is often noted, that parameters of shape (sphericity) and color of granules are also important. They are associated with consumer properties (dustiness, hardness, solubility, etc. [11]). Thus, despite of all the importance, control of these parameters is carried out in laboratories by methods

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of sieve analysis at long time intervals [12]. The laboratory control is related to the fact, that continuous automated control requires the installation of complex equipment in aggressive production conditions (vibrations, dust, aggressive acids and gases) [5].

According to the literature, sieve analysis [12], laser scattering [13, 14] and optical monitoring [15–18] can be used for particle size control. At the same time for robotic industrial control the optical method is the most applicable [19, 20]. There are examples where in addition to particle size distribution this method provides control of shape, color and interrelationship of particles [16,18]. However, there is no mention of the work of such equipment in mineral fertilizers industry. Moreover, the most part of such systems relate to the 0 level of automation and does not have the possibility of self-diagnostics and self-regulation.

In the present work the robotic control system of the particle size distribution, shape and color in industrial conditions was created. This system refers to the 2nd level of automation. The scheme of the optical-electronic device and algorithm of optical recognition of granules of mineral fertilizers were presented. The variants of mineral fertilizers production were considered and the places of installation of robotic system were chosen. The ways of modernization of the robotic system for sampling from the conveyor belt and closed pipe were given, and results of industrial tests and main statistical characteristics of this system were described.

II. Mineral Fertilizer Production Technology

A. General Description

In the present work, the production of phosphorus-containing mineral fertilizers is considered. The manufacturing of phosphorus-containing mineral fertilizers is a complex process that combines several production facilities. Phosphate ore (apatite, phosphorites) are consistently processed into phosphoric acid and then into fertilizers. The process starts with the mining of phosphate ore, its concentration and grinding to the required fractional composition. The resulting intermediate product (ore concentrate) is then usually dissolved in sulphuric acid and "wet processed" phosphoric acid (WPA) is obtained. The resulting phosphoric acid is mixed with ammonia and phosphorus-containing mineral fertilizers are produced (Fig. 1).

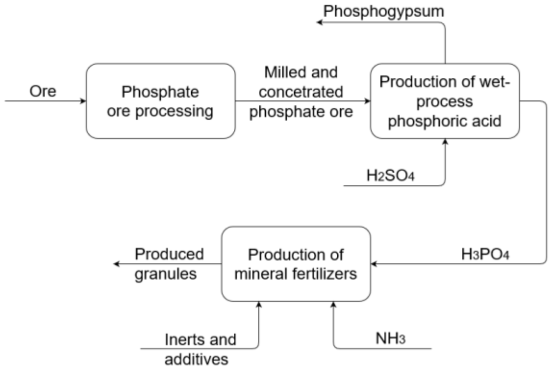


Figure 1. The principal scheme of the mineral fertilizer production process: from the extraction of raw materials to the finished product.

Each of these complexes is a self-sufficient production with they own SCADA systems. However, all the inaccuracies and failures in all of these complexes affect the quality of the final product - the mineral fertilizer, and granulometric composition in particular [6,21]. Therefore, it is important to provide robotic online control for it.

B. Selecting the Installation Place for the Robotic Control System

The present work considers the production of granular phosphorus-containing mineral fertilizers (DAP, MAP, NPK 15-15-15) at JSC “Apatite”, Cherepovets city (“PhosAgro” Corporation). Production at the plant is organized under two schemes: Drum Granulator Dryer (DGD, workshop 1) and Ammoniator-Granulator with Drum Dryer (AG, workshop 2). Each production scheme has its own features of process control and its own SCADA. However, the main production parts are the same: neutralization H_3PO_4 by NH_3, granulating and drying (together or separately for DGD and AG, respectively), screening of granules (vibrating screens), they cooling, conditioning and transportation to the storage (for the commercial fraction). After sieving, the big size granules went into the crushing process and then, together with the small size granules, is returned to the granulation process (Fig. 2). This is true and for SCADA systems: they are mostly the same. They have similar software implementation, which allows using the same connection scheme for developed robotic complex.

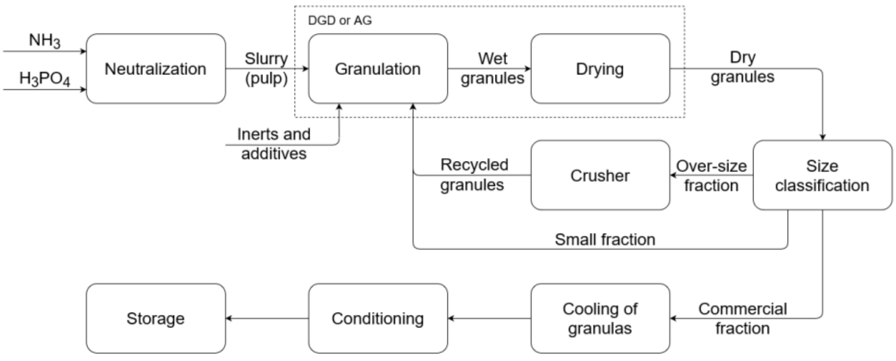


Figure 2. The general scheme of mineral fertilizers production.

Two developed robotic system for optical analysis of the granule-size composition (AGS) were deployed at the considered factory. These systems control the products, which are delivered to the storage. One robotic system takes a sample from a conveyor belt, another - from a closed pipe with the product. This scheme provides control of the overall production process and the quality of finished products.

III. Methods

The developed system of robotic control consists of 6 main components.

1) Sampler is based on a Single-turn Electrical Actuator (SEA). It's designed for gathering the fertilizer samples from production line and to deliver them at the vibrating table of AGS.
2) Vibrating table is based on special vibro-magnets. It's used for even separation and distribution of fertilizer sample granules under the camera, and their removal after the analysis is done.
3) LED lighting assembly is used for even lightening of granules, which is one of the crucial parameters affecting the analysis quality.
4) High-speed digital camera is used for gathering digital pictures of granules for the analysis (at least 320 frames per second with resolution of at least 640x480 pixels, focal length 2.8 - 12 mm and a sensor of ½ 7`` CMOS).
5) Controllino - is an Arduino-compatible PLC, used to control SEA, lighting and vibrating table by signals from computer. It also sends ready signal from SEA to PC, to tell the system when the analysis process can be started.
6) PC runs a Linux operating system (Ubuntu) with an analysis software. It processes digital pictures from camera to calculate particle size, then creates a data file and sends it to the factory SCADA system.

In terms of industrial processes automation, AGS covers three lower automation levels – from zero level to second level and sends granulometric composition (vector with numbers) to industrial SCADA system (named PI System in JSC "Apatite") (Fig. 3).

To represent the flow of data and signals in AGS, the structural diagram was created (Fig. 4). This structural diagram represents the functional algorithm of a system and may be described as follows. SEA of a sampler cyclically rotates a bucket, which crosses the fertilizer stream, thereby capturing a sample. When it reaches the highest rotation point, SEO hits the endstop, signalizing the PLC that the probe distribution can be started, and turns the bucket to the starting position. PLC turns on the vibrating table relay for a set time period, after that, it shuts table off, turns on the lighting module relay and sends ready signal to computer (PC). After the set time delay, PLC shuts down the lighting module and turns on the vibrating table to remove the probe. Removal duration is also configured by a time delay, after which PLC shuts down the table and goes to standby mode for the next cycle. A sample of approximately 80 grams is taken for analysis. The use of linear vibrations provides an even distribution of the granules in the analysis area as a single layer. Analysis software receives ready signal from PLC and sends a command to the camera, which makes a set of digital pictures and sends them back to program. The software processes this data and calculates the fertilizer particle size. After that, data file is generated and being sent to the Pi System, where it will be processed and represented in graphs.

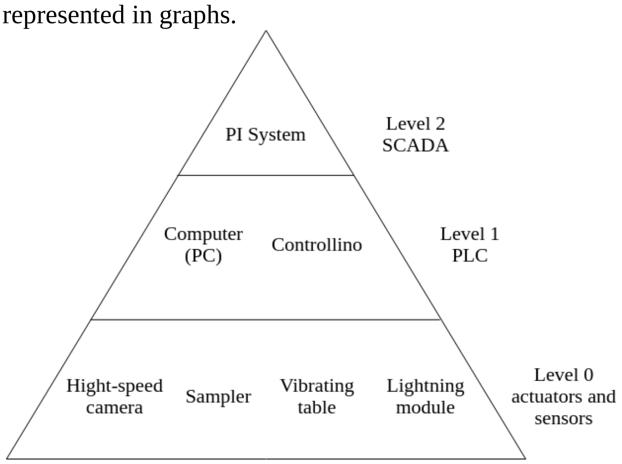


Figure 3. Level of automatization for AGS

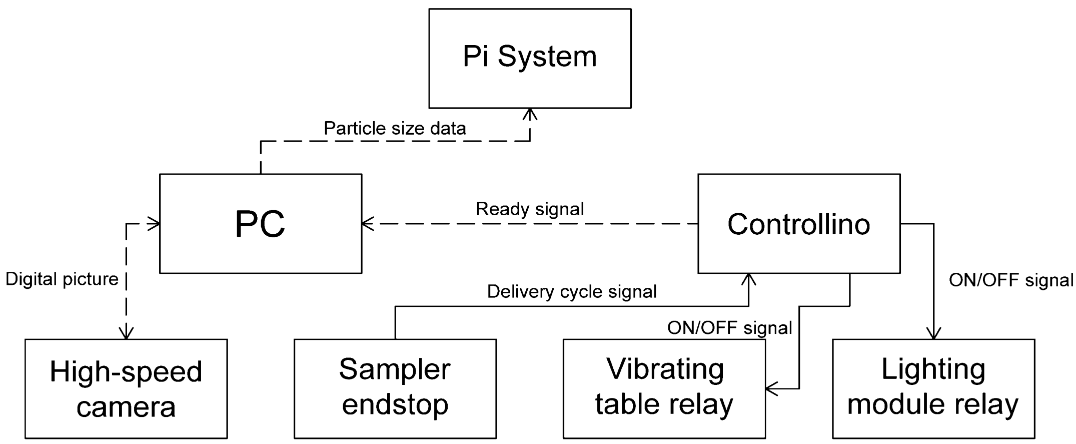
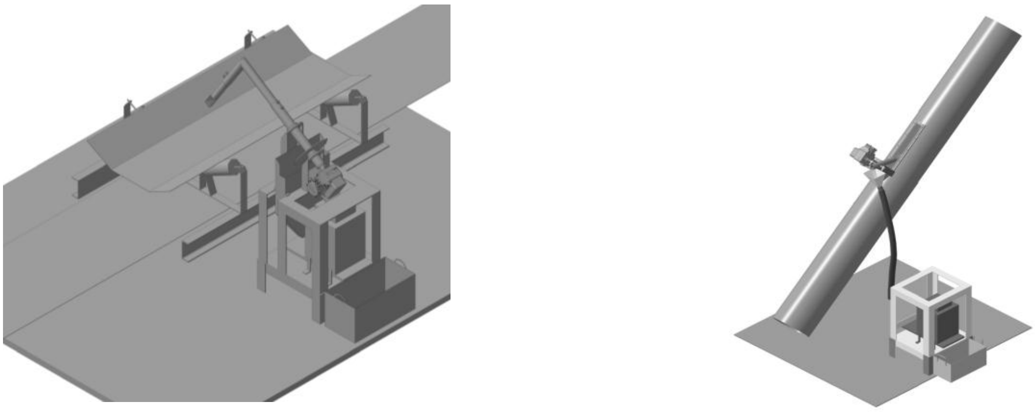


Figure 4. Flow of data and signals for AGS. Dashed lines represent digital signals, solid lines – analog signals.



(a) (b)

Figure 5. Rotary sampling systems from conveyor belt (a) and closed tube with product (b).

It is known that the point sampling system is not representative enough. However, granules are delivered to the sampling point after several transfer units. This is how the homogeneous granulometric composition of the entire product flow is achieved. In addition, the analysis every 7 minutes provides the necessary set of statistics. In this way, it is possible to conclude that the sample taken for analysis is representative. The sampling system is designed for a conveyor belt and a closed pipe with the product are show on Fig. 5.

The general algorithm of software operation is shown in Fig. 6. An example of displaying data of the particle size distribution in the SCADA is shown in Fig. 7.

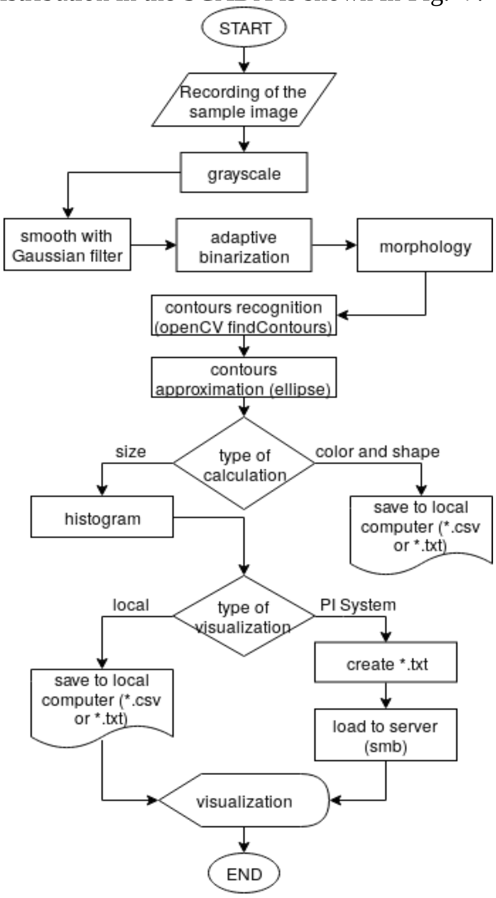


Figure 6. Algorithm of work of software on optical analysis of granulometric composition.

The developed system allows carrying out the automated analysis of granulometric composition. At the same time, there is a unified control of the system of sampling, delivered system, lighting, particle size distribution analysis and information transfer to the control system. In addition, the system has the self-diagnostics and response to possible failures and errors options. If an error occurs, the information is output to the SCADA, and the computer tries to fix the problem or goes into standby mode (when production stops or sampling system is broken). In this way, it can be concluded, that the designed system is a complete robotic control system.

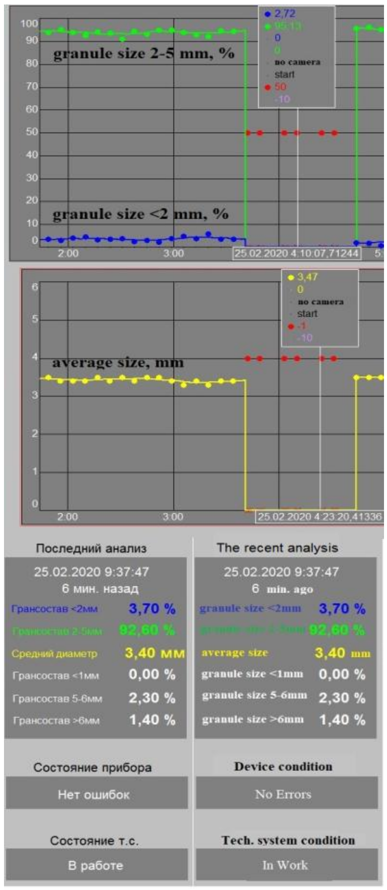


Figure 7. Part of displaying data in SCADA system.

IV. Result and Discussions

Industrial testing of the described system was carried out from 12.2018 to 03.2020; because of it, both systems were accepted by JSC "Apatite" for further operation. Diagnostic data and particle size distribution displays in SCADA online every 7 minutes. Data of the color and shape (sphericity) of the granules are stored locally on the AGS. Considering the design of the equipment, easy repair and high fail-safe operation in aggressive industrial environment (dustiness and vibrations) is provided. The system has not stopped for more than 3 hours in the last 5 months,

At stable running of the technological process the evaluation of statistical parameters of AGS, based on 1200 measurements, was made (table 1).

The difference in granulometric composition of workshop 1 and 2 is caused by production methods and brands properties. In case of workshop No. 1, Diammonium Phosphate (DAP) is produced according to the BGS scheme. It has a better-established production mode and the fertilizer is obtained with a lower proportion of small fraction. In case of workshop No. 2 complex triple fertilizers (NPK 15-15-15) are produced according to AG-SB scheme. These fertilizers are characterized by a greater presence of small fraction and large variations of granules size in the production process.

In addition, 30 samples were taken after the AGS analysis and the data were compared with the laboratory control results (obtained with Camsizer P4 optical device, Table II).

The increased difference for the small fraction (-2 mm) for 2nd workshop compared to 1st is due to the large amount of dust and the -1 mm fraction in the granules. This fraction is determined by the robotic system poorer than the Camsizer P4 because the resolution of the installed camera is not sufficient under production conditions (strong vibrations and large amounts of dust in the air). In our opinion, the deviation with the Camsizer P4 can be reduced by further optimizing the mass of the injected sample and by damping vibrations in the analysis area. Although the obtained absolute deviations are quite large, the proposed analysis system provides visual control of the trend in mineral fertilizer production, which allows to rapidly monitoring the quality of products. Thus, the system can be used as an indicator of the technological process, allowing employees to respond rapidly to changes in technology.

TABLE I. Statistical Parameters of AGS Operation

	Workshop No. 1 (selection from the conveyor)			Workshop No. 2 (selection from the pipe)		
	fraction < 2 mm, %	fraction 2-5 mm, %	average granule size, mm	fraction < 2 mm, %	fraction 2-5 mm, %	average granule size, mm
Average	4.85	95.14	2.96	13.75	86.02	2.86
Average square deviation	1.53	1.54	0.09	6.83	6.62	0.19
Number of self-diagnostic messages [a]	111			49		

[a] Includes: no granules in the analysis area, production stop, absence of light, optical camera failure, no signal from the sampler.

TABLE II. Absolute Deviation of AGS from Laboratory Methods of Analysis (Camsizer P4)

	Workshop No. 1 (sampling from the conveyor)	Workshop No. 2 (sampling from the pipe)
fraction < 2 mm, %	1.93	3.29
fraction 2-5 m, %	2.22	2.90
average pellet size, mm	0.26	0.18

V. Conclusion

As the result of the work, the robotic method of optoelectronic control of complex mineral fertilizers in industrial conditions was carried out. General schemes of mineral fertilizers production were described and the necessity of robotic quality control was justified. Online control of granulometric composition, color and granule shape factor was provided. The general schemes of equipment and software of the developed system were given. Interrelation between the robotic system and the SCADA was shown. Features of the developed system include online analysis of granule size distribution, possibility of granule shape and color analysis, operation in production conditions and data transfer to the factory SCADA system every 7 minutes. The system has algorithms for self-diagnosis and response to external conditions. The statistical characteristics of the proposed robotic system (mean and standard deviation) for two types of production were studied. The obtained results were compared with similar laboratory devices for particle size distribution control (Camsizer P4). The received results show the possibility of using the proposed system for determining the trend of industrial production and control of technological processes. The provided information on granulometric composition allows staff to quick response, which reduces the output of defective products.

Conflict of Interest

The submitted work was carried out without any conflict of interest.

Author Contributions

Each author makes great contribution to this work. D. Yunovidov conducted the research, developed the idea and wrote the software; K. Menshikov modernized the device and constructed the robotic system, E. Sidorova analyzed the data and described technological schemes. All authors had approved the final version of this paper.

References

[1] H. Meissner, R. Ilsen, and J. Aurich, "Analysis of control architectures in the context of industry 4.0," *Procedia CIRP*, vol. 62, pp. 165–169, 2017.

[2] M. Aiman, K. Bahrin, F. Othman, N. Hayati, N. Azli, and F. Talib, "Industry 4.0: a review on industrial automation and robotic," *Journal Technology*, vol. 78, pp. 2180–3722, 2016.

[3] D. W. Swisher, S. C. Borgelt, and K. A. Sudduth, "Optical sensor for granular fertilizer flow rate measurement," *Trans. ASAE*, vol. 45, pp. 881–888, 2002.

[4] M. Ehlali and S. El Asri, "Potential development of DCS in phosphoric acid and fertilizers units: OCP Jorf Lasfar experience," *Procedia Eng.*, vol. 83, pp. 195–207, 2014.

[5] Y. Fu, H. Su and J. Chu, "MIMO Soft-sensor model of nutrient content for compound fertilizer based on hybrid modeling technique," *Chinese J. Chem. Eng.*, vol. 15, pp. 554–559, 2007.

[6] M. Al-Dahhan, S. Aradhya, F. Zaid, N. Ali, and T. Aljuwaya, "Scale-up and on-line monitoring of gas-solid systems using advanced and non-invasive measurement techniques," *Procedia Eng.*, vol. 83, pp. 469–476, 2014.

[7] L. Balasevicius, D. Ezerskis, A. Straksas, and R. Stulpinas, "Appreciation of process control automation in the fertilizers production," *IFAC Proc.*, vol. 33, pp. 41–43, 2000.

[8] A. Shukla and H. Karki, "Application of robotics in onshore oil and gas industry-A review Part 1," *Rob. Auton. Syst.*, vol. 75, pp. 490–507, 2016.

[9] D. M. Ivell and V. T. Nguyen, "The evolution of screening systems for optimum granular fertilizer product quality," *Procedia Eng.*, vol. 83, pp. 328–335, 2014.

[10] E. Tarragó, S. Puig, M. Ruscalleda, M.D. Balaguer, and J. Colprim, "Controlling struvite particles' size using the up-flow velocity," *Chem. Eng. J.*, vol. 302, pp. 819–827, 2016.

[11] P. H. Travis, *Fertilizer Manual*, Alabama: Kluwer Academic Publishers, 1998.

[12] M. Kimura, *Testing Methods for Fertilizers*, Tokio: Incorporated Administrative Agency, 2013.

[13] V. Lilkov, E. Dimitrova, and S. Gaidardzhiev, "Microscopic and laser granulometric analyses of hydrating cement suspensions," *Cem. Concr. Res.*, vol. 29, pp. 3–8, 1999.

[14] Particle size analysis – Laser diffraction methods, ISO13320-2009.

[15] T. E. Bjørk, K. Mair, and H. Austrheim, "Quantifying granular material and deformation: Advantages of combining grain size, shape, and mineral phase recognition analysis," *J. Struct. Geol.*, vol. 31, pp. 637–653, 2009.

[16] G. M. Chávez, D. Sarocchi, E. A. Santana, and L. Borselli, "Optical granulometric analysis of sedimentary deposits by color segmentation-based software: OPTGRAN-CS," *Comput. Geosci.*, vol. 85, pp. 248–257, 2015.

[17] Particle size analysis - Image analysis methods - Part 1: Static image analysis methods, ISO 13322-1-2014.

[18] Particle size analysis - Image analysis methods - Part 2: Dynamic image analysis methods, ISO 13322-2-2006.

[19] R. P. Panckow, L. Reinecke, M. C. Cuellar, and S. Maa, "Photo-optical In-Situ measurement of drop size distributions: Applications in research and industry," *Oil Gas Sci. Technol.*, vol. 72, pp. 14-31, 2017.

[20] B. Zhang, B. Gu, G. Tian, J. Zhou, J. Huang, and Y. Xiong, "Challenges and solutions of optical-based nondestructive quality inspection for robotic fruit and vegetable grading systems: A technical review," *Trends Food Sci. Technol.*, vol. 81, pp. 213–231, 2018.

[21] N. P. Cheremisinoff and P. Rosenfeld, *Handbook of Pollution Prevention and Cleaner Production*, Elsevier, 2010, ch. 3.

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