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Introducing adaptive mechatronic designs in bulk handling industry

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***Abstract*—The advances of mechatronic system design and system integration have shown improvements in functionality, performance and energy efficiency in many applications across industries, from autonomous ground vehicles and drones to conveyor belts. This trend has been adopted in some industries more than others. The design of equipment to handle granular or bulk material is commonly based on traditional approaches. Therefore, introducing mechatronic concepts in the design procedure can enable new possibilities, such as sensor integration and data analyses, adaptability and control. The efficiency of bulk material handling equipment in ports, agriculture and food processing is heavily influenced by the operational conditions. Typically, a piece of equipment is designed for defined operational conditions when the maximum performance can be achieved. In this work the concept of adaptability to varying operational conditions is explored by understanding the technologies implemented in other industries and the feasibility to be implemented in the bulk handling equipment design. Sensing technology, actuation and adaptability are systematically presented in this work to support the design process of the next generation of bulk handling equipment. This will pave the way for incorporating the technological trends in the design, such as: sustainability, "smartness", Internet of Things, Industry 4.0, digital twin and machine learning. Adaptive mechatronic solutions will play a crucial role in generating and implementing innovative sustainable solutions for bulk handling equipment.**

Keywords*— *Bulk material handling equipment, mechatronics, adaptive design

I. INTRODUCTION

The global industrial landscape has changed deeply in the last few years due to successive technological developments and innovations in design and manufacturing processes. The Industry 4.0 concept has emerged and it embraces a set of industrial developments including Internet of Things (IoT), Internet of services (IoS), Robotics, Big Data, Cloud Manufacturing, Cyber-Physical Systems (CPS) and Augmented Reality [1]. A trend is visible in industries that try to incorporate the Industry 4.0 concept, such as autonomous systems, additive manufacturing and predictive maintenance.

Although there is an increasing interest in Industry 4.0, implementation is not always done due to various reasons, including absence of an urgent need for innovation and limited (research) resources. This work focuses on implementing advanced mechatronics technologies in the bulk handling industry. This industry includes transport and storage of granular or bulk materials such as iron ore, coal, grain, wood chips, sand and sugar. The transport and storage are employed by a variety of bulk handling equipment such as ship unloaders (e.g. grabs), ship loaders, stackers and reclaimers (e.g. bucket wheel reclaimers), conveyors, silos, stockpiles and mobile equipment (e.g. excavators) that form a bulk material handling system.

The bulk handling industry faces many challenges on the way to "smartness", including varying operational conditions and design restrictions that result not only in a deviation from the nominal equipment performance but also cause unnecessary extreme energy consumption and environmental pollution. The varying operational conditions include bulk material properties, human operators and interaction with other bulk handling equipment. Adaptive and sustainable solutions are required to address the complexity and the implications onto the performance of the equipment. Due to recent advances in industry 4.0 there are tools already developed to a level to be applied in industry. One example is the discrete element method (DEM), a particle based numerical method for modeling the bulk behavior of granular materials and many geomaterials such as coal, ores, soil, rocks, aggregates, pellets, tablets and powders. This way new technologies can be developed and tested in a virtual environment in a time- and cost-effective manner. *Schott et al.* [2] established a DEM-supported design framework, which was used for virtual prototyping of grab concepts in interaction with iron pellets. To develop such a DEM-supported design framework, calibration and validation steps are pivotal. Fortunately, over the past decade, reliable DEM calibration procedures have been developed to model various types of bulk material, such as iron ore fines [3], coal [4], and sand [5]. Validation experiments can be done in quantitative and qualitative ways [6–8].

However, even with accurate DEM-supported tools the technologies to be developed for the bulk handling industry is quite difficult as severe conditions of the bulk handling environment (dust, wear, moisture, heat) make it difficult to implement sensors or other types of "smart" technologies. This research seeks to identify adaptive mechatronics solutions applied in other industries that can be implemented into the bulk handling industry. The overview points out directions for achieving adaptability, its implementation and feasibility.

II. CATEGORIZATION OF ADAPTABILITY

In order to understand the contribution and importance of mechatronic solutions in other fields, a comprehensive literature research is carried out using three types of search methods. Studies were first identified by searching in three different databases, including Google Scholar, TU Delft's repository and Google patents, and by using a combination of keywords (i.e. Boolean operators) related to advances in adaptive mechatronics concepts. Second, backward and forward snowballing methods are applied on the found references to search for other relevant studies. Additional information regarding snowballing methods is provided by [29]. Third, a search for adaptive mechanisms or operational concepts already applied in the industry was carried out.

A list of criteria is defined to decide whether to include a study in the literature review. First, the mechatronics concepts described in the study should be able to respond to varying operational conditions during operation. Second, we include studies that are written in English or Dutch. Third, to ensure that the solution meets a certain level of feasibility, the study must be supported by experiments, simulations or acknowledged by a patent. The technologies found in the industry are evaluated based on the working principles, and adaptive characteristics. These technologies are included when they are able to respond to varying operational conditions.

Following the stated approach, our search resulted in including 31 academic studies and three adaptive mechanisms that were applied in the industry. From each of these studies we extract the adaptability concept or working principles together with the KPIs. The systems found in other references include bulk handling equipment, different type of sensors and actuators, different approaches in (big) data analyses, etc. As the main interest in the work is the adaptability to varying operational conditions, *adaptability* is defined as: *The ability of a system to sense the change in operational conditions, adjust accordingly and achieve an optimal performance*.

Operational conditions are bulk material properties (density, PSD, surface, shape, stiffness), environmental conditions (temperature, pressure, moisture), operational input of equipment (force, torque, velocity, position, human operator), and interaction properties (reaction forces on equipment, wear). The adaptability can be explored for a single operational condition or as a compilation of multiple properties. This definition of adaptability is used to categorise the various technologies found in studies and industries according to five forms of adaption as presented in Figure 1.

Adaption by geometry includes replacing the entire or part of the geometry with a new design of which the technology is described in [9,10]. An improvement of the performance may result from a change of shape or size. Adaption by fluidization includes mechanisms that can cause a granular material to behave like fluid of which the technology is described in [11] and [12]. The air cannon does not contain any reference as it is a direct application into the industry. Most theories in the field of fluidization consider an upward fluid or gas flow [11,13] and provide a more detailed description of the fluidization concept. Adaption by vibration includes mechanisms that can excite local or global vibration to a surface of which the technology is described in [14–19]. The purpose of vibration is to introduce additional forces into the system which counteracts the shear strength of the bulk material [16]. Adaption by a deformable structure includes structures that can be controlled to perform certain movements or deformations in one or more degrees of freedom of which the technology is described in [20–23]. Adaption based on control system includes sensors and actuators that can provide the necessary actions to take on the mechanism or system caused by the operational conditions of which the technology is described in [24–27].

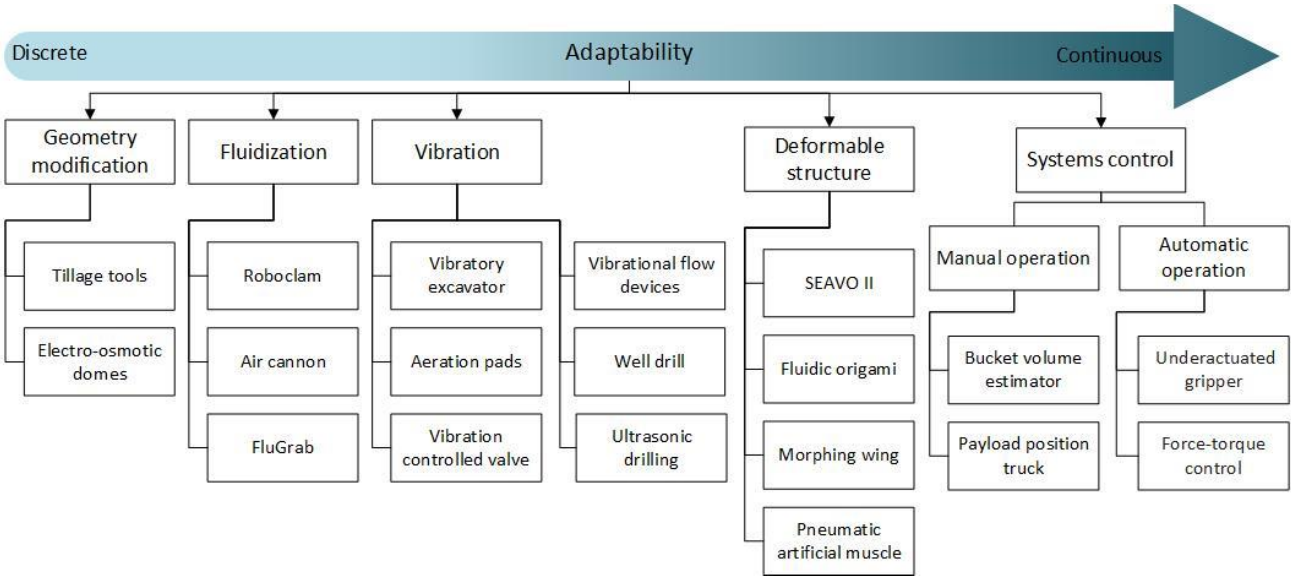

Figure 1. Overview of adaptability categories and adaptive design operation technologies, from discrete to continuous technologies.

Table 1. Criteria for evaluating feasibility and continuousness

Criteria	Description
Feasibility	
1. Industrial application	The solution with or without variation is used at the industry scale successfully
2. Small scale experiments	KPI's are measured in laboratory scale experiments under one or more operational conditions
3. Full scale experiments	KPI's are measured in industry scale experiments under one or more operational conditions
4. Prototype testing	Prototype is built and tested
5. Simulation	Numerical methods (e.g. DEM, FEM, CFD) are used to predict the solution's efficiency
6. Continuous developments	Multiple research studies are conducted on the solution, which shows its potential and applicability
7. Implementation	The implementation strategy for the intended application and working principles are described adequately
Continuousness	
1. Adaption	The solution is able to adapt continuously before and\or during the operation which makes it suitable for operational conditions that vary frequently
2. Material	The solution can be applied to different types of (bulk) material, and this is supported by evidence

Control and operation of the systems adaptation can be manual or automatic. Manual operation incorporates the human as controller, receiving information from sensors and acting accordingly. Automatic operations are established without human intervention.

A further possibility for categorization relates to the distinction between discrete or continuous adaptability. Discrete mechatronics can only adapt at certain predefined moments in time to the varying operation conditions by having a finite number of changes in the geometry or input parameters prior, during or after the operation. In contrary, continuous mechatronics can adapt at every desired moment in time by changing the input parameters to the varying operational conditions. For example, the geometry can typically only be modified or replaced prior to commencing the operation, while vibration or deformable structures can be activated or deactivated even during the operation. Therefore, mechatronic solutions such as deformable structure and vibration have a higher level of continuousness compared to the geometry modification.

III. ADAPTIBILITY EVALUATION

In general, the mechatronic solutions that were described in the literature and industrial examples are able to respond to varying operational conditions, which creates a certain degree of adaptability. Operational conditions always vary in the bulk handling industry. For example, a silo or bucket wheel may be used for different types of bulk material with varying material properties (e.g. particle size, moisture content), which can be transported and stored in different compaction states (e.g. pressure levels). Therefore, the mechatronic solutions that were found from literature (and industrial examples) are evaluated in terms of the level of continuousness and feasibility for implementation in the bulk handling industry.

Table 1 presents a comprehensive list of criteria for this evaluation. In Table 2, the analysis of the adaptability evaluation matrix for all mechatronic solutions are presented. A quantitative scoring system is used to enable evaluation of feasibility and continuousness in a systematic way. The scores are quantified based on the literature review and thus analyzing the main findings, operational conditions, strengths and limitations of the mechatronic solutions. If an adaptive solution shows a good agreement with the described feasibility criterion (e.g. prototype testing), or a high level of continuousness, it receives a "+" score. In contrary, if an adaptive solution shows a poor agreement with the described feasibility criterion, or a low level of continuousness, it receives a "-" score. Next, score values in a column are summed to determine the total score of each adaptive solution, in terms of feasibility and continuousness. According this quantitative systematic analysis, it can be concluded that the categories of deformable structure and control have the highest overall score on both the feasibility and continuousness. In contrary, the lowest overall scores are observed for the categories of geometry modification and fluidization. The technologies under the category of geometry modification score low on continuousness, because a different design is needed in every specific situation for reaching an optimal performance. For example, when the type of material (e.g. type of soil or ore) is changed, a part of equipment needs to be replaced manually for reaching an optimal performance, which is not beneficial if the bulk handling process must be interrupted.

IV. IMPLEMENTATION IN INDUSTRY

A. Required sensor-based measurement systems

Key performance indicators (KPI's) are measurable values that quantify to what extent the system is achieving its targets. In bulk handling systems different KPI's can be defined to measure or indicate the performance of a piece of bulk handling equipment, such as handling capacity or throughput, payload, energy consumption, dust and noise. In order to apply the adaptability to a bulk handling system, the KPI's need to be well defined, and there should be a potential to measure KPI's directly or estimate based on available data. Data can be obtained from a variety of sensors, which need to be installed to measure the desired KPI's. Nowadays different types of sensors are available that are applied in a wide range of industries at adequate or high levels of maturity. The bulk handling industry can learn from available sensor-based technologies by adopting certain measuring methods for the benefit of monitoring its own KPI's.

Table 2. *Adaptability evaluation matrix: determining feasibility and continuousness of available adaptive solutions*

Legend
+: good agreement, continuous adaption
0: mediocre agreement, multiple discrete adaptions (> 2) over time
-: poor agreement, ≤ 2 discrete adaptions over time

	Geometry modification		**Fluidization**			**Vibration**						**Deformable structure**				**Systems control**			
Feasibility	Tillage tool	Electro-osmotic domes	Roboclam	Air cannon	FluGrab	Vibratory excavator	Aeration pads	Vibration controlled valve	Vibrational flow devices	Well drill	Ovipositor drilling	SEAVO II	Fluidic origami	Morphing wing	Pneumatic artificial muscle	Bucket volume estimator	Payload position truck	Underactuated gripper	Force-torque control
Industrial application	+	-	-	+	-	-	+	-	+	-	-	-	0	-	+	+	-	-	+
Small scale experiments	+	+	+	N/A	+	-	+	+	+	+	-	+	+	+	+	+	+	+	+
Full scale experiments	-	-	0	N/A	-	-	+	-	+	-	-	0	-	-	+	+	-	-	+
Prototype testing	+	-	+	N/A	-	-	+	+	+	+	-	+	+	+	+	+	-	+	+
Simulation	+	+	-	-	-	-	-	+	-	-	-	+	-	-	+	+	+	+	+
Continuous developments	+	-	0	+	-	-	+	0	+	0	-	+	+	+	+	+	0	+	+
Implementation	0	-	0	+	0	0	+	0	+	0	-	0	0	0	+	+	0	+	+
Total	**4**	**-3**	**0**	**2**	**-4**	**-6**	**5**	**1**	**5**	**-1**	**-7**	**3**	**1**	**0**	**7**	**7**	**-1**	**3**	**7**
Continuousness																			
Adaption	-	-	-	0	0	0	0	0	0	0	0	+	+	+	+	+	+	+	+
Material	+	0	0	0	0	+	0	0	0	0	-	0	N/A	N/A	N/A	+	+	+	0
Total	**0**	**-1**	**-1**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**-1**	**1**	**1**	**1**	**1**	**1**	**2**	**2**	**1**

N/A: Not Applicable

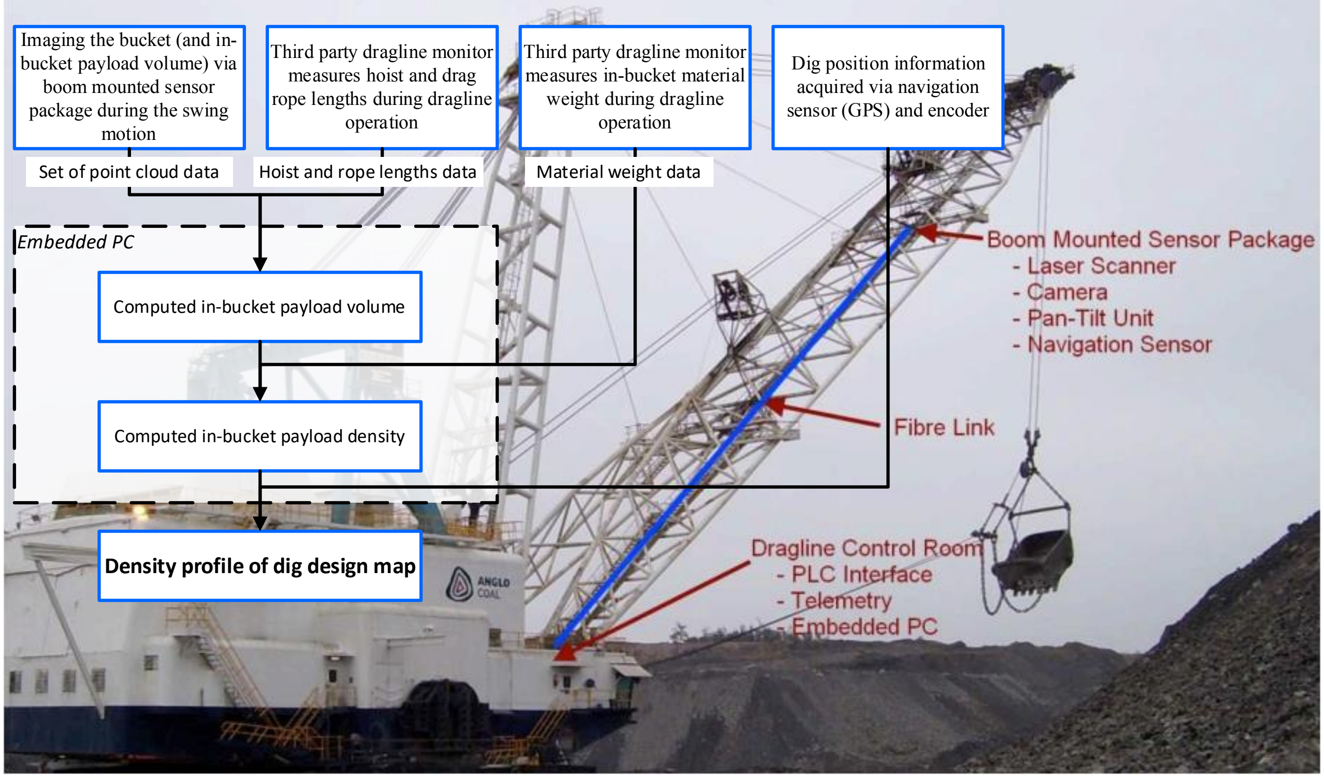

Figure 2. Setup of an integrated sensor-control system mounted on a dragline excavator [30]

Table 3. Overview of KPIs and the corresponding sensors

	Technology	KPI
Geometry modification	Tillage tools	Stress on cutting disc
		Cutting force
	Electro-osmotic-domes	Sample displacement (digital gauge)
		Sliding wear
		Pressure
Fluidization	Roboclam	Void fraction (video camera)
		Displacement on burrowing (potentiometer)
		Pressure of compressed air
	Air cannon	Mass flow rate
		Flow profile
	FluGrab	Penetration depth (ultrasound distance sensor)
Vibration	Vibratory excavator	Excavation resistance
	Aeration-pads	Mass flow rate (load cell)
		Flow profile
		Aeration rate (rotameter)
	Vibration controlled valve	Mass flow rate (video camera)
		Occurrence of bridging (video camera)
	Vibrational flow devices	Shear force (shear force sensor)
		Unconfined yield strength (accelerometer)
		Wall friction angle
	Well drill	Drilling force (force meter & laser scanner vibro-meter)
		Drill holes
		Feed speed
	Ovipositor drilling	Safety
		Drilling force
Deformable structure	SEAVO II	Excavation depth (pressure gauge, flow gauge & water level sensor)
	Fluidic origami	Longitudinal stiffness of the structure
		Normalized volume
	Morphing wing	Lift/drag ratio (pitot tube)
		Load capacity
	Pneumatic artificial muscle	Contraction ratio (phototransistor & pressure sensor)
		Force exerted by the mechanism
		Pressure inner actuator
Systems control	Bucket volume estimator	Payload volume
		Bulk density (sick LD-MRS laser, video camera, pan-tilt unit & navigation sensor)
	Payload position truck	Rack, roll, pitch (photo-modeller scanner & photo-modeller scanner)
		Whole Body Vibration (photo-modeller scanner & video camera)
		Tonne Kilometer Per Hour (load cell)
	Underactuated gripper	Input displacement of the gripper (embedded sensor)
	Force-torque ctrl.	Torque in joints (strain gauge)

Although the industrial examples are rare or non-existing, laboratory experiments under controlled environments show possibilities for sensor integration in the bulk handling industry. This study shows the existing technology and the potential for industrial implementation by stating the KPI's and their measurable parameters in Table 3. In case measuring KPI's using sensors was not possible in the reviewed literature, alternative approaches such as visual observation or analytical solutions were employed. In many cases, no specific details of the applied sensor technology were described in the literature. The majority of the sensors from Table 3 were only used in laboratory scale experiments. Therefore, the technology readiness of these sensors in industrial scale applications is not yet demonstrated. Therefore, sensor-based measurement systems should be further investigated to reach a sufficient level of maturity for implementation in industrial applications.

B. Example of implementation strategy

We explain through an example how an adaptive mechatronic solution by including a sensor-based measurement system could be implemented in bulk handling industry. In this example, illustrated in Figure 2 a dragline excavator is equipped with an integrated sensor-control system with optical sensors to enhance the process efficiency as well as obtaining value information about the performance, such as the payload volume and density. In general, a laser or camera device can be used to generate a surface profile of the material inside an open shell bucket. In this example, Bewley et al. [24,28] used a Sick LD-MRS laser mounted on a pan tilt unit (PTU) to sample the environment constantly. During the swing motion of the bucket, the laser scans the in-bucket material surface that results in a set of point cloud data to be used for computing the in-bucket payload volume. The bucket position is approximated using the hoist and drag rope lengths as shown in Figure 2. The combination of the data obtained from the laser scanning with the information of the rope lengths enables determination of the bucket movements with six degrees of freedom and eventually used for computing the in-bucket payload volume. Then, the computed in-bucket payload volume combined with the measured weight of the material is used to compute the in-bucket payload density. The bulk densities were mapped back to their original dig positions using a combination of GPS and encoder information from the dragline monitor. Having an accurate estimation of the bulk density at different locations of the digging area provided 1) a reliable assessment of dig and blast performance, 2) an improved bucket size selection, and 3) decreased production downtime [24,28]. However, if the configuration of the operating ropes/cables are unknown or the related sensor system has high uncertainties or faults, determining the bucket's movement would be challenging. Probably it would require additional sensors to quantify additional parameters for accurate bucket movement representation.

The sensor-based measurement system shows that there are much potential for other types of bulk handling equipment to be transformed into adaptive design. Developing these kind of technologies for other bulk handling equipment as well can contribute in improving performance, creating a safer working environment and reduce the energy consumption.

V. CONCLUSION

This work showed an overview of mechatronic concepts that could be adopted in the bulk material handling industry. The focus is on adaptability to varying operational conditions and ways to adapt the piece of equipment in a discrete or continuous manner for improving the performance or ideally ensuring a maximal performance regardless the operational conditions. To achieve adaptability, sensing technology is necessary to detect the variations of certain operational parameters. The choice of sensors, their placement, data acquisitions and data analyses can bring information offline and in real-time to better understand the process of material handling. Different actuators can support the adaptability concepts by providing additional energy or by adjusting to the process need, ensuring energy efficiency. Real-time controllers are maturing for industrial applications and could be implemented in this industry even if multiple operational conditions need to be monitored and used in control algorithms.

Recognizing adaptive mechatronic solutions from different industry can inspire to integrate them in bulk handling equipment which can result in a more efficient and sustainable industry. Bringing adaptability as a concept to bulk handling industry can contribute in overcoming the complexity and the implications onto the performance of the equipment.

By integrating all the additional mechatronic elements in the equipment, these systems become once step closer to the benefits of technologies like digital twin, Industry 4.0, IoT and AI. The new generation of adaptive bulk handling equipment will be integrated, "smart", connected and sustainable.

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