VIRTUAL COMMISSIONING OF A MOBILE ORE CHUTE

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Abstract

This paper describes the virtual commissioning of a mobile ore chute for sequential loading of trucks from a conveyor system with a continuous material flow. The design and control were tested in simulation environment and improved prior to its installation in an underground mine in full production. The altered design met the performance goal and the amount of rock spill and wear on surrounding equipment could be reduced significantly. The simulations were based on a novel combination of discrete element and multibody simulation using a nonsmooth dynamics formulation, integrated in a 3D modeling software. This enable both fast simulation, based on original CAD drawings, and high flexibility in modifying the design and control.

1. INTRODUCTION

Development and installation of a new material handling system in a mine or mineral processing plant that is in full production is a challenging task. These systems are business critical and therefore not accessible for experiments. Full production capacity must be reached in short time after installation with minimal production downtime before that. At the same time, it is important that the solution is free from faults that may cause excessive wear and maintenance or poses risk for catastrophic events. It is however difficult to predict the behavior of a particulate material handling systems *á priori*. The performance depends intricately on the geometry and material of system components, kinematics design, selection and placement of sensors and actuators, control algorithms, and, of course, the inflow of particulate media and its physical behavior.

The option of validating a design and automatic control of a system in simulated environment before installation is therefore very attractive [1]. Besides identifying and addressing design flaws and operational faults, this can be used for optimization and for practicing the installation procedure and production ramp-up. The simulation must be a highly realistic representation of the real system, based on the authentic 3D CAD models and control program PLC (programmable logic controller) code, as well as on rich and faithful physics of the particulate material, drive system and other moving parts. In the manufacturing industry this is known as virtual commissioning [2]. The tool-chain and workflow must to support multidisciplinary engineering and give possibility for rapid experimentation and design iterations. Supporting cross-organizational collaboration and possibility to involve the suppliers is also a success factor. This calls for flexible and easy-to-use tools, sufficiently powerful and accurate, accessible for simulation non-specialists but interoperable with tools and models developed by and for the specialists. Interactivity and visualization are key features.

2. MATERIALS AND METHODS

In this section we describe a recommended workflow and simulation tool for virtual commissioning of particulate material handling systems. The workflow, illustrated in Fig.1, has three main steps: modeling, control and simulation, before the final commissioning.

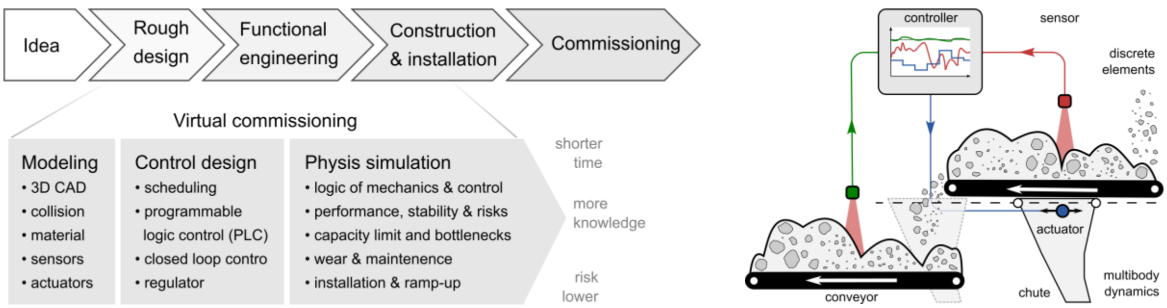

Figure 1. In virtual commissioning the actual 3D models and controllers are tested with virtual material to ensure that the real commissioning will be fast, safe and reach the performance goals.

Algoryx Momentum Granular [3] is a modeling and simulation tool that meet the needs described in Section 1. The software combines 3D CAD modeling, import/export, discrete element and rigid multibody simulation, Python scripting for event handling, virtual sensors, actuators and simple controllers. Other simulation and control software can be included through co-simulation using the Functional Mockup Interface (FMI) standard [4,5]. Momentum Granular come with dedicated tools for visualization and analysis, but any other tool with Python bindings can be used. Simulations scenes can be exported to Unity 3D and explored using VR and AR.

The software Algoryx Momentum Granular is an add-in to the solid modeling CAD software ANSYS SpaceClaim. The add-in is based on AGX Dynamics [3], which is a multi-purpose physics engine for realtime simulators as well as for engineering and scientific simulation of mechatronics, materials and industrial processes. AGX is oriented around rigid multibody systems with nonsmooth dynamics, use variational numerical time integration and high-performance parallel equation solvers that for robust and valid simulations even for systems with extreme loads and mass ratios, kinematic loops, redundant constraints, frictional contacts and impulsive dynamics [6,7]. AGX has both direct and iterative equation solvers, tailored for sparse linear algebra operations of contacting multibody systems. A hybrid direct-iterative solver and smart splitting scheme supports the simultaneous use of both direct and iterative solver kernels for solving different parts of the system with different precision. This enables simulations that combine high performance, accuracy and scalability. This is essential for efficient and reliable simulation of systems where the reaction force from the particulate material on the machinery doing transport and processing affect the dynamics of the machine such that it cannot be represented by a kinematic model [8,9].

Algoryx Momentum Granular support coupled discrete element and multibody simulation integrated with a single time-stepper and solver framework, avoiding the hurdles and numerical difficulties with co-simulation. This is accomplished by a time-implicit version of the discrete element method (DEM), that is referred to as the nonsmooth discrete element method (NDEM). It enables large time-step integration, often up to 10 ms, by modeling contacts in terms of constraints and impulse propagations obeying the contact laws of Hertz, Signorini-Coulomb and Newton impact law. The underlying theory, implementation details and techniques for computational acceleration are found in [10,11]. The technique has been validated and used extensively for simulation of iron ore pelletization systems [12,13].

3. MOBILE ORE CHUTE

LKAB is a producer of refined iron ore products for steel manufacturing with mines, refineries and ore harbor in northern Sweden and Norway. In 2016, LKAB installed a mobile ore transfer chute in one of the underground mines in Malmberget. The mobile transfer chute makes it possible to divert a continuous flow of material to sequential loading of trucks via a chute, see Fig. 2. Before the installation, the material was conveyed directly to a hoisting skip system. The conveyor was divided into one incoming belt conveyor loading onto one outgoing, with a mobile diverter at the discharge point. The diverter has two V-shaped sections, one pointing downwards and one upwards, dressed with deflector plates. Depending on which section is positioned in the flow, the material is lead either down a twin chute for loading a truck or to the outgoing conveyor, leading to the skips.

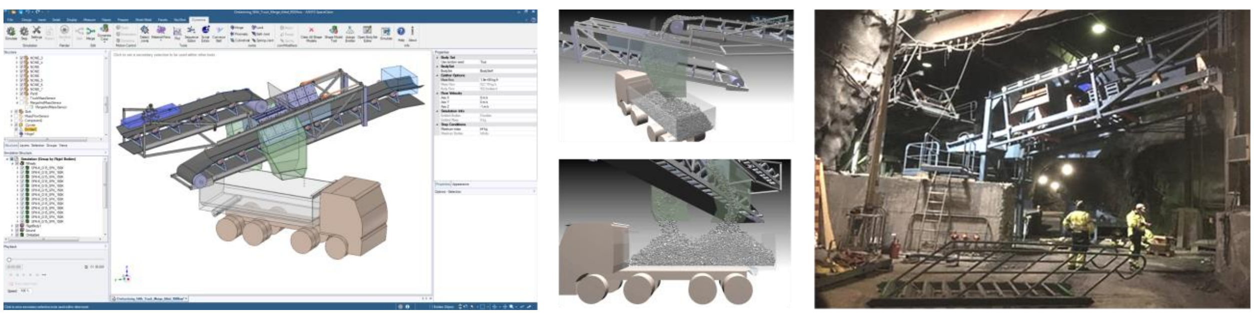

Figure 2. The mobile ore chute in the 3D modeling and simulation tool Algoryx Momentum (left), snapshots from simulation (middle) and photo from the installation in the mine (right).

The challenges were to find a design for filling the ore trucks to the target capacity of 37 tons in short time without any rock spill around it, with minimal wear and tear on the equipment, and minimal risk of flow obstruction and catastrophic failures. Flow variations between 1900 and 3000 tons/h should be handled. The transfer station is a production critical point since all material from the mine passes through it. LKAB engaged the subcontractors Mecon and Algoryx Simulation to perform a simulation study to evaluate the intended design in order to minimize the risk of production disturbances during and after installation.

A 3D model of the transfer point was created, including incoming and outgoing belt conveyors, chute pair, a mobile diverter with deflector plates, hoist truck and ground plane. CAD models of the conveyors and the chute, produced in a pre-study, was imported in the software Algoryx Momentum. The various geometric components were assigned collision properties and contact materials. The conveyor belt surfaces were assigned a variable transport speed. The coupling between the mobile diverter and the immobile conveyor is modeled as a prismatic joint with joint position limits, and a pair of linear motors for controlling the motion of the diverter in the direction of the conveyor. The motor is assigned a target velocity and its controller aims to deliver the required force to reach and maintain that velocity. The most important model and simulation parameters are given in Table 1.

Table 1. The key parameters for the mobile chute system, ore material and simulation settings.

System parameters	Value
Mass flow	1.9–3.0×10^3 ton/h
Conveyor speed	2.1 m/s
Conveyor width	1.6 m
Actuator max speed	0.36 m/s
Truck body volume	17.7 m^3

Ore parameters	Value
Particle size	[60,110] mm fraction 77/23 %
Specific density	4300 kg/m^3
Friction coefficient (ore, belt, chute)	0.55, 0.6, 0.4
Restitution coeff. (ore, belt, chute)	0.2, 0.3, 0.2
Elasticity modulus	2.0 GPa

Sim. parameters	Value
Time-step	8 ms
Impact velocity threshold	0.1 m/s
Solver iterations	50
Time duration	86 s
Number of particles	80×10^3

The material flow was controlled by an emitter at the beginning of the incoming conveyor. The emitter produces material with a specified mass rate and material parameters. A material sink was placed at the end of the outgoing conveyor. Virtual sensors are introduced for measuring the mass flow rate on the conveyor belts, the weight of material in the truck and the actuation forces for moving the diverter. The sensor measurements are recorded as a function of time. The size of the ore particles was limited to the range of 60 and 110 mm, while the real material has substantial fractions down to 1 mm. The particle shape was represented with solid convex polygons. The specific mass density was calibrated to 4300 kg/m^3 in order to correspond to a bulk density of 2500 kg/m^3 that is measured in reality. The friction and restitution coefficients are based on experimental data from LKAB. As a validation test, the simulated angle of repose, $38^\circ \pm 1^\circ$, was compared to the experimentally value of 36°.

The simulations were performed as follows. First, an even flow of material was established with the mobile diverter positioned to deflect the material to the outgoing conveyor. The diverter is moved at a target speed of 0.36 m/s, for a time duration of 5 s, until the material flow is deflected into the chutes. The time for filling the truck to the target load of 37 tons varied between 66 and 76 s. After that, the diverter was driven back to its original position, again with duration of 5 s, where the material is deflected onto the outgoing conveyor. The total simulation time thus amounts to about 86 s. The computational time was about 20 CPU hours, involving up to 80×10^3 rocks and nearly 10^6 contact variables to solve for at each timestep. Simulation videos can be found at: http://umit.cs.umu.se/chute.

4. RESULTS AND DISCUSSION

From the simulations it was found that the main goal of filling the truck with up to 37 tons of ore without any severe problems could be reached with the proposed design. See Fig. 3 for example images from simulations. The robustness was tested by using different mass flow rates between 1.9–3.0×10³ ton/h, see Fig. 4. A certain amount of rock debris was found to spill outside the truck body when the diverter was moved in and out of position, however. Also, it was observed also that material may accumulate on the diverter, with the risk of falling straight down to the ground when no truck is there. The design was modified based on these observations.

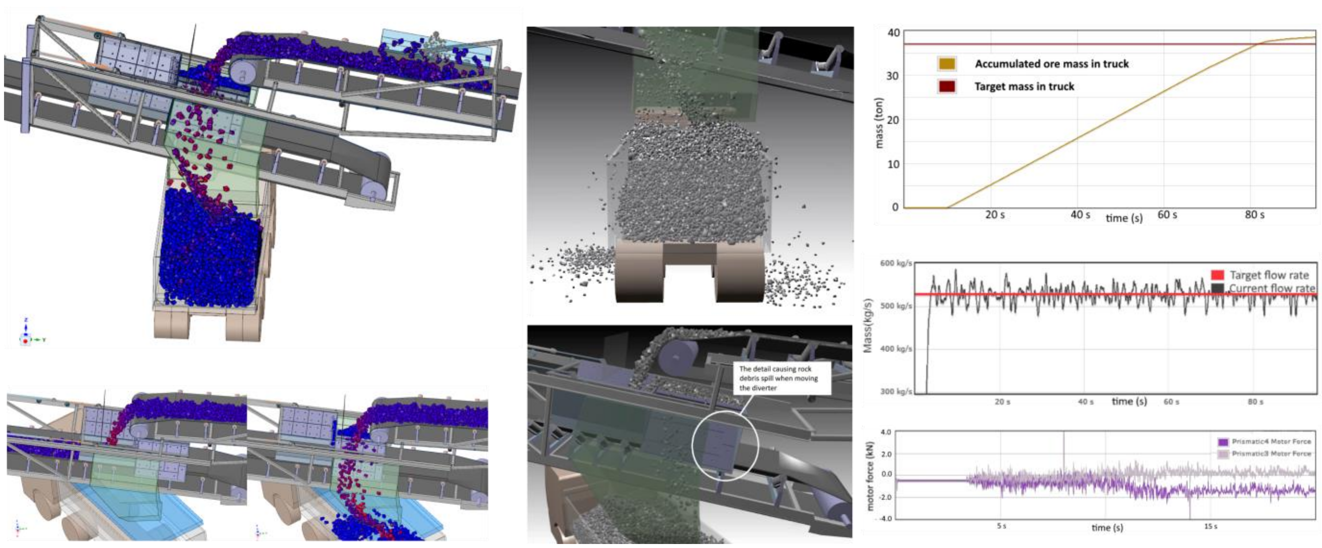

Figure 3. Analysis of the mobile ore switching from conveying to truck loading (left). The original design caused some rock spill around the truck (middle). With the final and installed design, the ore truck can be filled to the target capacity of 37 tons at 70 s without problems. The material flow rate, truck filling and actuation force to move the ore chute is shown to the right.

The mobile chute was built and installed according to the modified design. It was tested with gradually increasing flow rate and truck loading frequency until the target capacity of 600 tons/h by truck was achieved. Vibrations in the structure of the transfer station were discovered and eliminated with additional anchoring points. With a certain amount of structural flexibility in the simulation model, this could have been discovered during the simulation phase. After two years of operation, it can be concluded that the system is functioning as planned, with normal maintenance in the form of replacing the deflector plates. The only incident has been one of the hydraulic cylinders being damaged once by an impacting rock.

5. CONCLUSIONS

Doing virtual commissioning - with a novel combination of discrete element, multibody and control simulation integrated in a 3D modeling software - prior to the actual commissioning of ore material handling systems can create large values by shortened time before reaching full production capacity and avoiding faults and excessive wear and maintenance. The interactivity and visualization aid the multidisciplinary and cross-organizational communication around design flaws and experimentation with solutions.

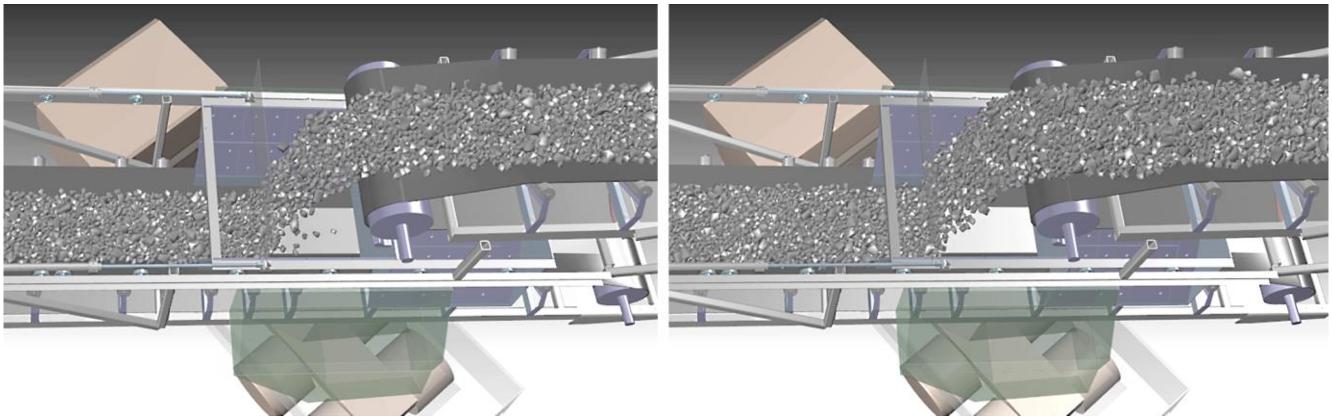

Figure 4. Robustness testing with flow rate 1900 ton/h (lefty) and 3000 ton/h (right).

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