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2D RADAR TECHNOLOGY INCREASING PRODUCTIVITY BY VOLUMETRIC CONTROL AND HOPPER CAR POSITIONING IN BROWN COAL MINING

1. Introduction

This paper is characterized by the innovative development and application of electronically scanning microwave radar sensors for mining operations. Based on fundamental laboratory experiments, comprehensive field-tests in open-pit and underground mines, the development of the 2D radar technology has been steadily supported by customers like OEMs and mining operations as well as academia like the IMR of RWTH Aachen.

In 2010 a coal shearer loader with the indurad Dual Range Radar iDRR based radar collision avoidance solution has been awarded with the bauma innovation award, after receiving the RAG research award in 2009. Besides the main working field in continuous mining operations which are dominating in Europe, the authors are presently developing solutions as well for the large segment of discontinuous mining.

For inventory control reasons and stock market publishing obligations however mines need at least periodically a high accuracy and reliable volumetric information of the ore they handle in all stages of the process and they have in stock. Both has been e.g. achieved manually by laser measurements surveying the stockpile. Besides the high personnel requirements, special measurement windows were required for the fragile and sensitive laser measurement devices to operate. For complete volumetric information measurements from several different positions with limited or risky access were required.

The radar technology is a new way of solving a current industry need, currently lacking an online and real-time solution approach. Based on a unique 2D radar sensor and further radar components the authors have been developing a robust microwave based automated solution that can calculate the volume of stockpiles. Furthermore a 3D model is generated and stored on a thin-client web server, being accessible for any authorized user in the mines intranet.

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2. Technology

Thanks to different wavelengths of laser light (approx. 1 µm) and radar (4 mm), the impact of environmental conditions on the quality of the radar measurements are minimal. While the radar "over looks" smallest particles, laser light reflects on dust and fog, leading to a dispersion of the laserlight. Laser, other than radar, cannot detect objects lying "behind" the dust or fog curtain.

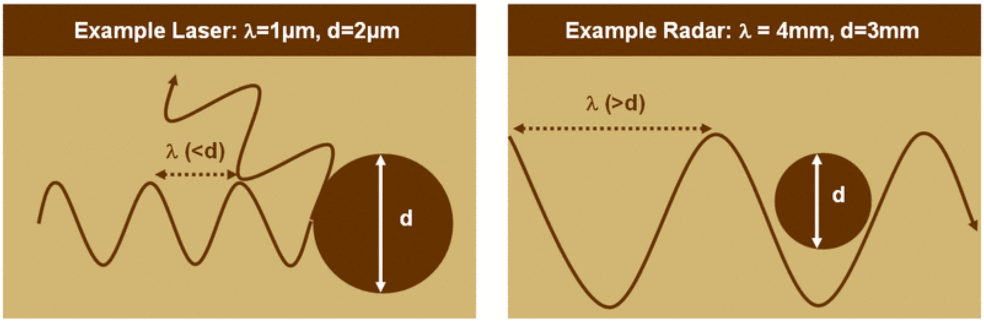


Fig. 1. Influence of Dust with Laser and Radar

Laser scanners deliver accurate measurements. Despite an availability of > 99% these sensors do not supply usable data in tough environments which are quite common for mining environments such as fog, dust, rain or sensor pollution. But assistance and safety is first and foremost needed under these conditions. Radar sensors in tough environments leads to a higher plant availability and can also be a useful safety backup to laser based solutions.

Within indurad's brochure (available in Polish on www.indurad.com a more detailed comparison matrix as well as some more background on the iDRR radar technology can be found.

3. Results and discussion

Indurad has been addressing the need of the industry with developing both sensors and complete integrated solutions. Within this chapter four solutions along the brown coal production chain are described:

- excavators working bench (cutting depth control),
- transfer units / hopper car (positioning),
- conveyor belt transport (volumetric flow)
- stockpile volume scan (stockpile inventory control).

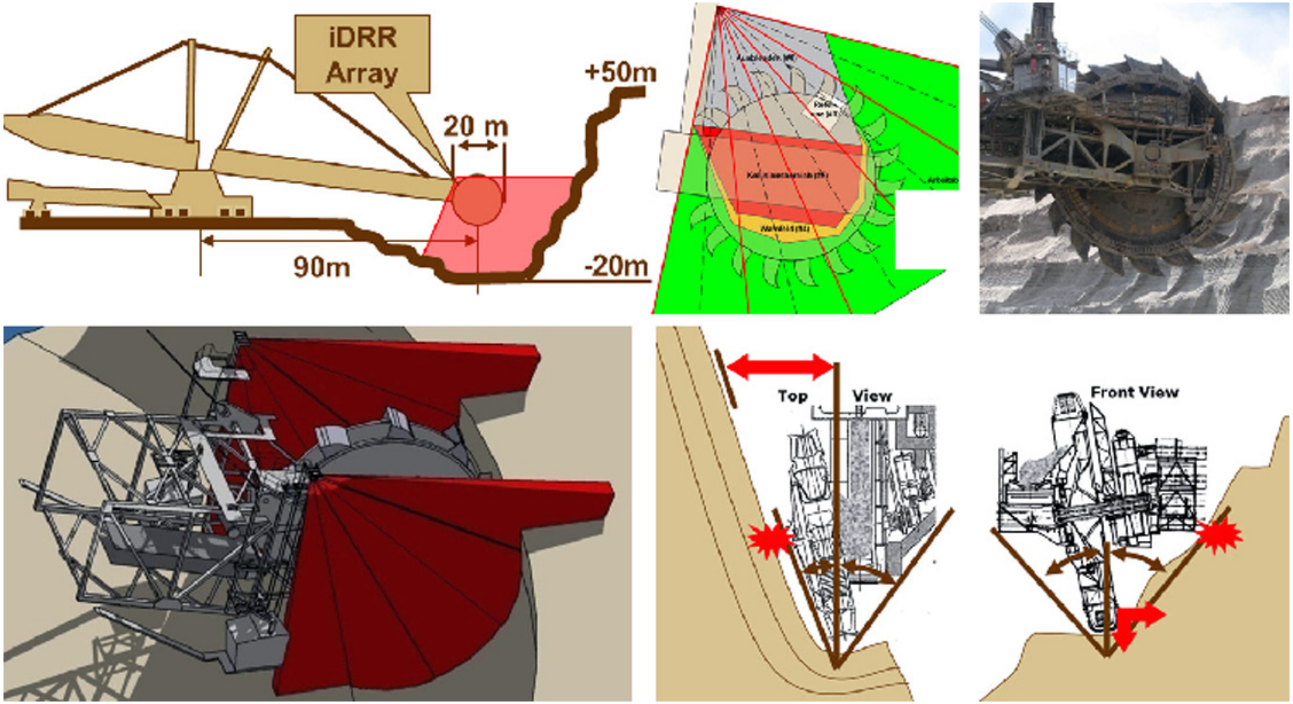


Fig. 2. Radar Array installation on a bucket wheel excavator providing data for collision avoidance and predictive volume control

Solution 1: Bucket Wheel Excavator — Cutting Depth Control

The large dimensions and resulting blind spots of large bucket wheel excavators make it difficult for operators to observe the environment for collisions and estimate ranges for excavation control. Figure 2 shows the dimensions of such a machine (top left) including the position of the iDRR radar array, a 3D illustration of the position of the iDRR array on both sides (bottom left), a picture of the bucket wheel in front of the slope (top right) and the slope collision scenario (bottom right) with gear box, bucket wheel bearing and operator cabin, the flexibly adaptable collision zones (top center) in green, yellow and red.

Indurad has been commissioning the 2D radar which addresses on one hand monitoring the collision zone besides a large bucket wheel and on the other hand providing accurate surface data for a predictive volume control. To deliver a maximum accuracy, on both sides of the bucket wheel an array of five radar sensors is applied. To demonstrate the reliability of the solution, the client covered the iDRR sensors have with a mixture of mud, clay and coal, like shown in Figure 3. The signal intensity of the radar has been attenuated by the coverage, but still accurate and reliable for performing the objectives.

Fig. 3. Radar blockage test with mixture of clay, sand and coal

The radar data are captured from both radar arrays and transferred to the radar processing unit iRPU. Furthermore GPS positioning information from multiple antennas on the boom are fed to the iRPU, giving the position of both arrays as well as the orientation in roll, pitch and yaw. On the iRPU the radar raw data is processed and then spitted to two algorithms — surface profiling and collision avoidance. For surface profiling the raw data is filtered, smoothed with sophisticated statistical functions and then merged with GPS data to 3D Gauss-Krüger-Coordinates. The iRPU then delivers continuous, accurate and real time data of the surface in 3D for the mine model and for the predictive volume control (i.e. cutting depth and swing speed).

Within a performance test the iDRR Array has been audited to an expensive and surveyor grade Riegl Q120i Laser Scanner. The laser data has been processed on a different

PC using the same GPS data, however both were not ideally time synchronized resulting in slightly different sensor data and GPS matching. Further both laser and radar have been installed a couple of meters apart from each other, but the 3D offset have been compensated as far as measurable by a total station. The comparison has been performed during full operation at a swing movement with all common vibrations. The results were highly impressing even without these negative circumstances: Calculating the distance of both planes at randomly chosen 40 000 points in 3D a standard deviation of 0.159 m and a gauss peak offset of 0.031 m could be determined. In the following Figure 4 the distance of the planes is colour coded and supplemented by the histogram. In the figure a red colour indicates that the laser was above the radar plane, the blue indicates that the radar was above the laser plane. Within the top-right corner a common slope profile is illustrated.

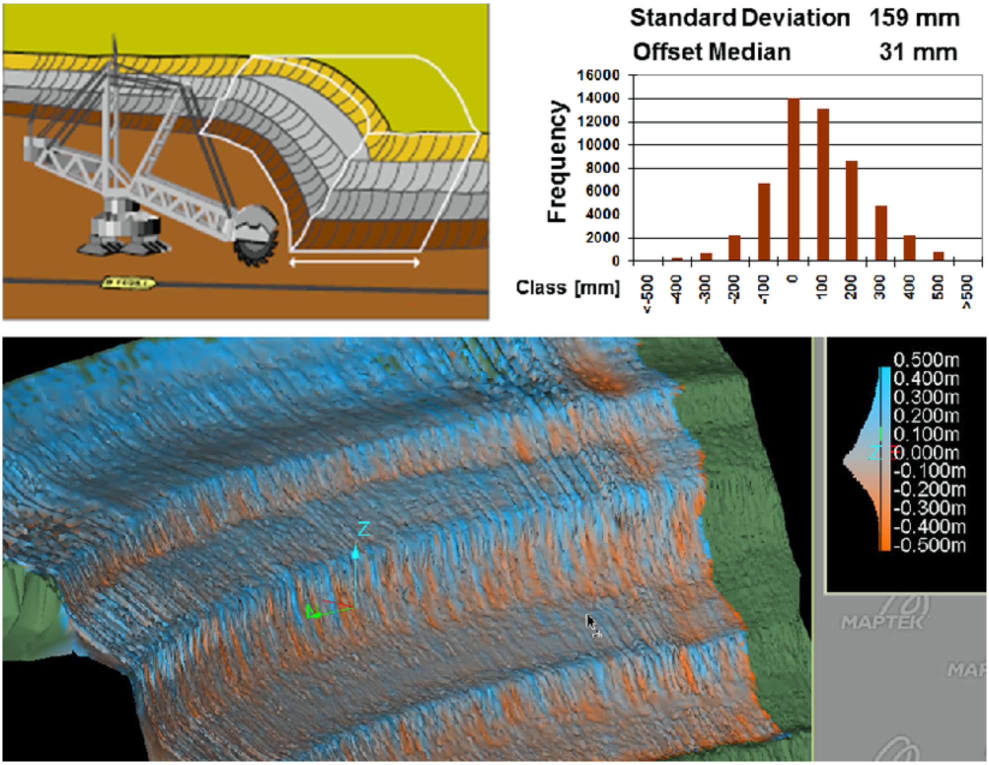


Fig. 4. ± 0,5m Color Coded Distance of the Radar Surface Measurement and the Laser Surface Measurement at good conditions (needed for the usage of the laser)

Solution 2: Loading Unit / Hopper Car Positioning

Presently the loading/hopper cars are manually positioned by an operator. As the operator has limited visibility and process information, misalignment, collisions and lost availability are the consequence of manual transferring without assisting systems. Indurad has been jointly with its automation partner Cegelec fully automating a loading car in the rhenish brown coal mine Inden. A detailed description about the Solution can be found in literature reference [1].

One of the main tasks to be fulfilled in the execution of the project is the integration of the various sensors into the overall control system. There was no known, tried and tested solution available for determining the relative positions between the feeding table and the conveyor frames. Within the scope of extensive field trials different ultrasonic sensors, RFID systems and radar sensors were tested for use on the feeding table. Besides their superiority precision and availability within rough environmental conditions (dirt, dust and fog) radar sensors have already proven their robustness in the case of heavy vibratory and shock loads by the installation on shearers employed in underground coal mining.

The job of the radar sensors is to determine the height (x) and lateral offset (y) of the feeding table relative to the conveyor frames and the angle between the loading car and the belt conveyor. This data is used as a basis for controlling the feeding table and steering the loading car.

Three iDRR sensors, spaced approx. 2.50 m apart, were installed on the loading car. The conveyor structure frames were defined as a reference for determining the position of the loading car. To allow gaps between the 7.50 m long conveyor frames to be bridged and ensure that valid data is available as a positioning basis, three sensors needed to be installed per loading car. The alignment of the iDRR sensors was optimized so that they are a) perpendicular to the external plate of the conveyor frame edges in order to provide a maximum radar reflection and b) to arrange them at a sufficient distance so that the frame edges are registered even with maximum car movements. To prevent interference with the travel path, they were installed at a maximum distance of 1.20 m to the conveyor frame (cf. Fig. 5).

All radar sensors capture their surroundings 15 times per second and transmit the raw data to the indurad RadarProcessingUnit (iRPU) via CAN bus. The iRPU is based on an industrial PC (IPC) platform with a Linux operating system and the indurad software framework. The iRPU determines the position of the reflection centers in terms of distance, angle plus intensity and classifies / filters these on the basis of geometric criteria (by conveyor frame edge, water tube, ground and garlands, etc.). The data is processed in 500 ms intervals to permit the noise caused by vibrations and other disturbances to be eliminated by averaging. With the aid of tracking filters, the distance to the conveyor frame edge is individually determined by all sensors and converted to Cartesian coordinates (x, y). Subsequently, the three pairs are compared. In addition the iRPU, using a computational model, calculates a virtual regression line that represents the angle between the loading car and the belt conveyor as travel direction offset with an accuracy of about 0.1°. This angle, determined over several conveyor frames, is used as an input variable for the steering control system of the loading car.

Figure 6, top left, shows the positions of the three iDRR sensors and a frame gap by way of example.

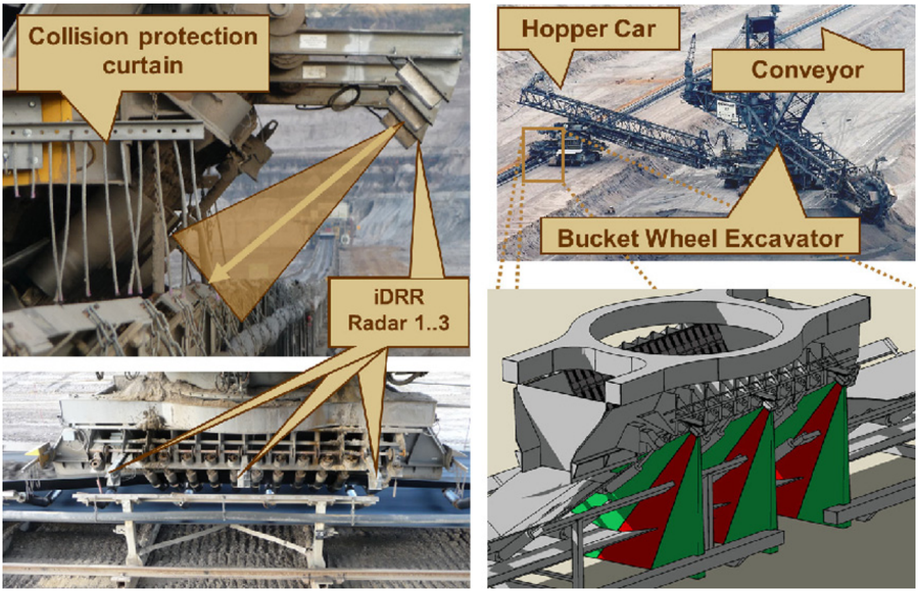


Fig. 5. Mounting position and alignment of the iDRR sensors and the collision protection curtains

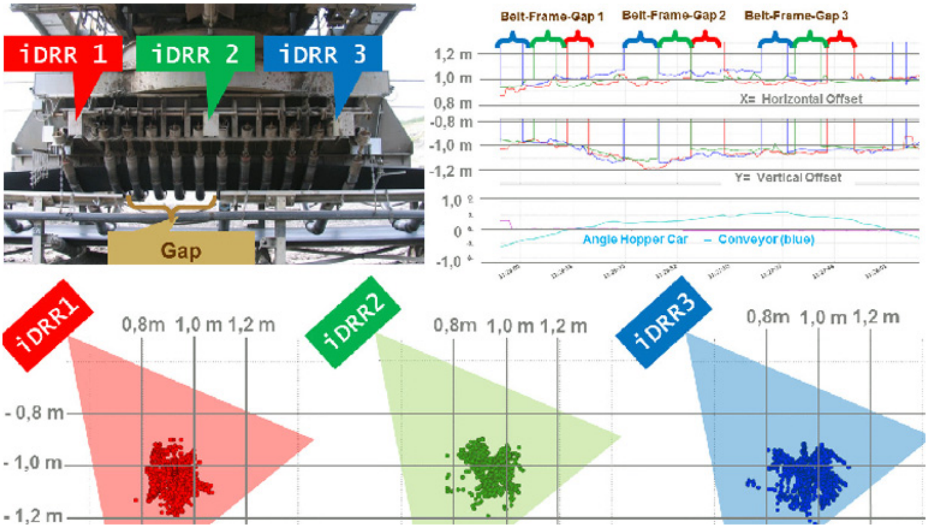


Fig. 6. Arrangement of the iDRR sensors (top left), position-time diagram of the measured values over three conveyor frames (top right) and *x*, *y* scatter diagrams over approx. 15 conveyor frames (bottom)

The top right diagram shows the progression of the *x* and *y* values over about three conveyor frames in automatic mode. As can be seen, the independent recordings of the three sensors are precise and consistent in a narrow corridor of ± 0.05 m, although the point being travelled over in each case is measured with a time lag. The bottom diagram in Figure 6 shows the range in which the feeding table is moved relative to the conveyor frame edges in automatic mode. In the three *x* and *y* scatter diagrams, the positions are plotted over a travel distance of approximate 100 m or 15 conveyor frames in an accumulated manner.

The movement range is in a narrow corridor of approx. ± 0.15 m, reducing even the usual movement range in manual mode. On the basis of the 2D iDRR radar sensors and an efficient fault-tolerant evaluation algorithm, the radar solution provide a reliable foundation for the following control systems that is unaffected by weather conditions.

The trial run was performed over a period of one month with an unmanned operator's cabin of the loading car and successfully completed in November 2010. During this time, the fully automatic system was active for approximate 700 hours and the loading car covered a distance of some 15 km in automatic mode. At over 99%, availability — the central evaluation criterion for the quality of the overall system — was in the range of the contractual requirements. The positioning of the feeding table in vertical and horizontal direction and the setting of its lateral inclination was always sufficiently precise. This created the basic conditions needed to implement belt position and steering control. The belt position control system succeeded in significantly reducing the number of stoppages of the conveyor belt caused by off-track running compared with the uncontrolled operation of other, semi-automated loading cars. In particular when covering long distances the loading car was positioned very precisely.

Solution 3: Belt Volume Flow Control

The following Figure 7 illustrates the measurement principle of the 2D Radar belt volume scanner solution.

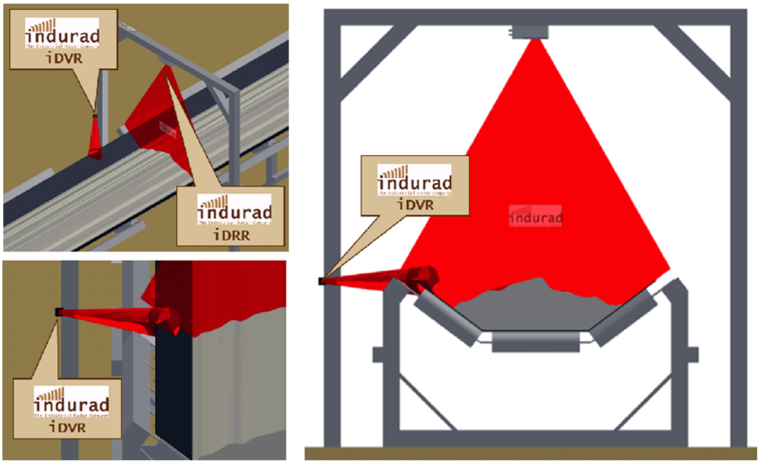


Fig. 7. Measurement Principle of Volume Flow Solution
with 2D Cross Section Radar (iDRR) and Belt Velocity Radar (iDVR)

The indurad Dual Range Radar (iDRR) Sensor module detects a 2D Surface of the conveyor belt. The detection of the beltspeed is needed in order to calculate mass flow over time. This information is either provided by customer or can be detected with an additional sensor: the indurad Doppler Velocity Radar (iDVR).

The iDVR measures the velocity of steel cord belts continuously. If textile belts are used the iDVR need to measure the conveyed material as textile belt is nearly „transparent" for the radar waves. Thus a velocity is only measured when there is production, which is however sufficient as otherwise the volume flow is anyhow zero.

Indurad has performed several tests within saxonian brown coal mines as well as rhenish brown coal mines. The picture in Figure 8 illustrates the scenery.

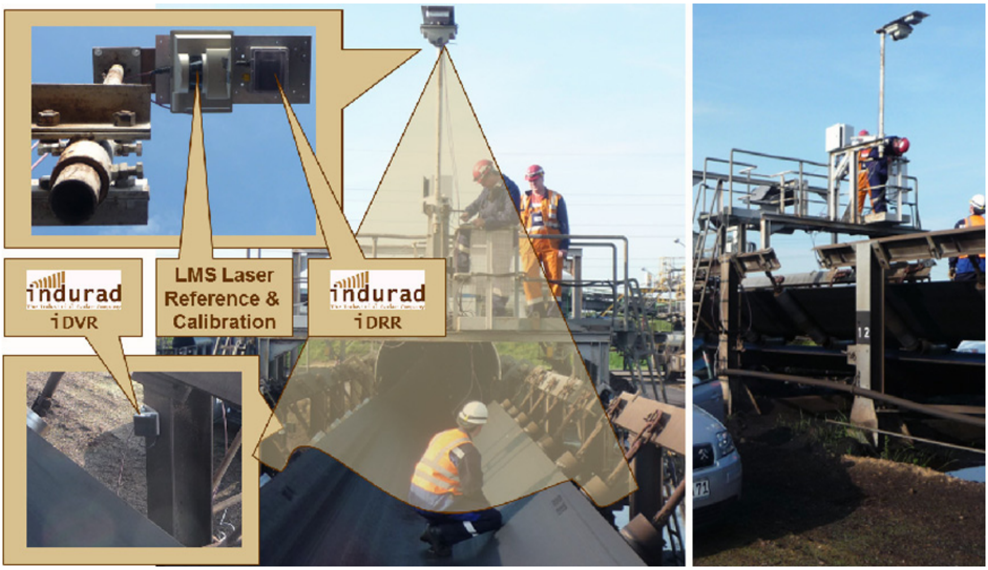


Fig. 8. Field testing scenery with iDRR and Sick outdoor laser for comparison

In the industry the volume flow measurement on conveyors is mainly done with load cells using fixed density parameter. In some applications laser scanners are used, as they do not require a complex mechanical integration and frequent calibration. However laser based systems are prone to downtime caused by fog and dust; furthermore they can send false information which is more critical than no information.

Figure 9 depicts the sensor set up for mass flow measurement. The large picture shows, how dust affects a Sick LMS outdoor laser scanner (red), while the iDRR radar (blue) is not affected.

The other two pictures highlight that radar detects the mass flow within the same boundaries, representing a comparable accuracy at higher robustness.

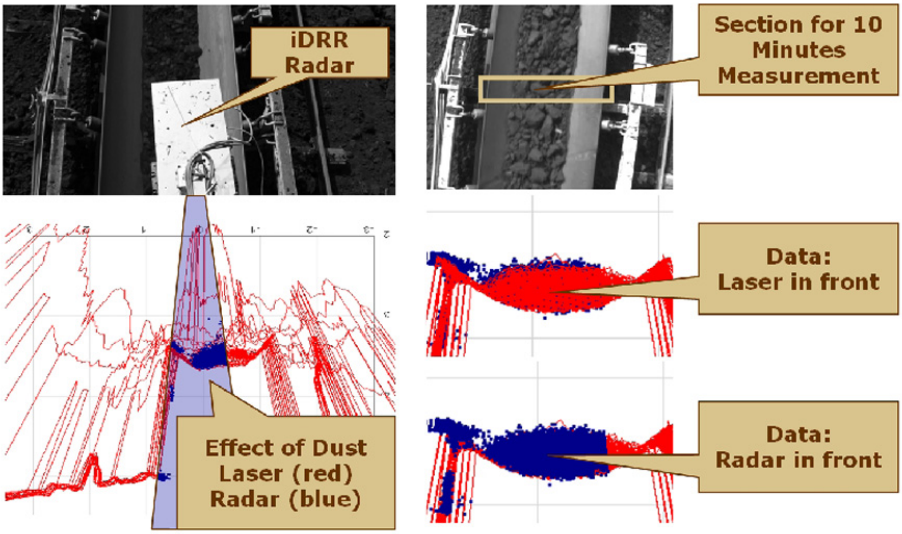


Fig. 9. Results of 2D Radar and Laser for Mass Flow Measurement

Within the following diagram (cf. Fig. 10) the 2D Radar Solution has been compared on a large 2.8 m wide brown coal belt with a belt scale and a laser system. For this a time span of 5 minutes has be selected, when there was no adverse weather impact on the laser, like shown in the picture before. It illustrated, that all three sensor solutions deliver similar results in good conditions. In bad conditions the iDRR performs much better than the laser. In comparison with the belt scale it has to be considered, that converting its mass flow to a volume flow has to be done by the density factor of bulk coal, which is changing. Using a belt scale at rain will consider the water as coal and using a later at fog produces virtual volume as well. As well stockpiles, silos and rail cars are limited by volume and not by tonnage, thus indurad recommends directly measuring the volume.

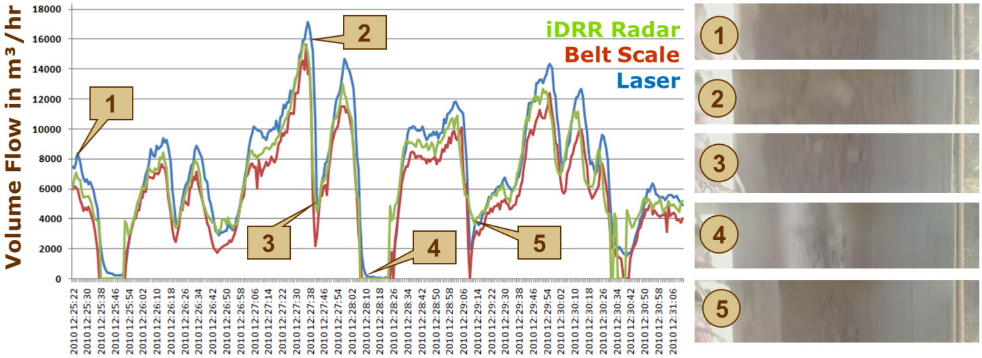


Fig. 10. Data Comparison of three different physical measurement principles

Solution 4: Iron Ore Stockpile with Stacker

The Australian iron ore stockpile is fed by a Tripper with approximate 1500 t dumping capability per hour, building a stack with a length of 500 m of magnetite & hematite iron ore in a windrow or a cone format (cf. Fig. 11). The operator had a tough job with keeping the dumping height as low as possible to minimize dust, preventing of over and under filling as well as avoiding collisions. As the problems in daily operations were substantial, the plant asked indurad to develop an operator assistance solution and delivering additional value with process transparency for the management and engineers.

Fig. 11. Tripper with Stacker (top right), Transfer Point Tripper to Stacker for Volume Flow Measurement (top left), Boom with Windrow Cones in background (bottom left), Stacker boom head idler pulley (bottom right)

Within the customer specification the following requirements were defined before the project started:

1) Collision Detection: One of the problems is stacker collision with the stockpile, if operations misjudge stacking requirements or in case of component failures. Presently collision protection is provided by lanyards down each side of the boom, and a tripper switch at the boom head. This is aggravated by operational personnel being unable to see the stacker due to dust & other stacks etc. in their line of sight.

2) Dust Mitigation: A further problem is dust creation due to inappropriate height control while stacking, this being made difficult due to the geometry of the stack and stacking angle of the boom. For this a radar based dump height control needed to be established.
3) Long Travel Control — Belt Volume Scan: Presently the windrow height is controlled by the long travel speed via a belt weight cell, with no method of adjustment for material density. Thus the volume of the iron ore travelling on the belt should be measured, to replace weight for this purpose.
4) Long Travel Control — Positioning: The stacker long travel position is presently supplied via encoders on the stacker wheels, so this should be replace by robust distance measurement which can penetrate dust.
5) Process Visualization: All information gathered should be collected in a database for further analysis. The surface profiles scanned by the radar sensors should be used to create a 3D Volume model using the existing luff and slew absolute encoders. The visualization should be available for engineers as well as quality and sales people in the management.

All objectives could be reached using four iDRR sensors, two iATR distance measurement devices and one iRPU. Within the specification phase it has been decided, that one iDRR will be installed on both sides of the idler pulley at the stacker head, one iDRR below the boom for collision avoidance and one iDRR over the belt on the tripper car for volume flow measurement. All devices can be seen in the following Figure 12.

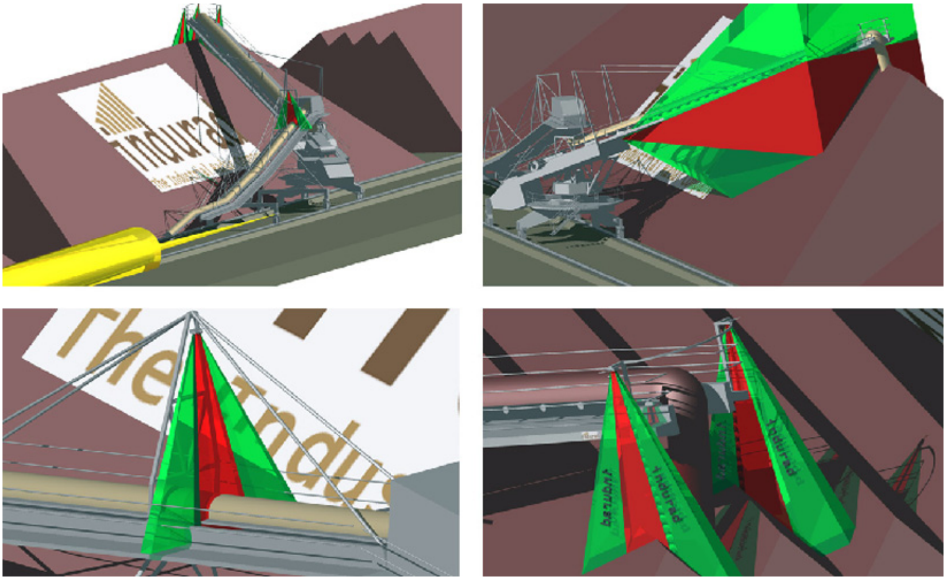
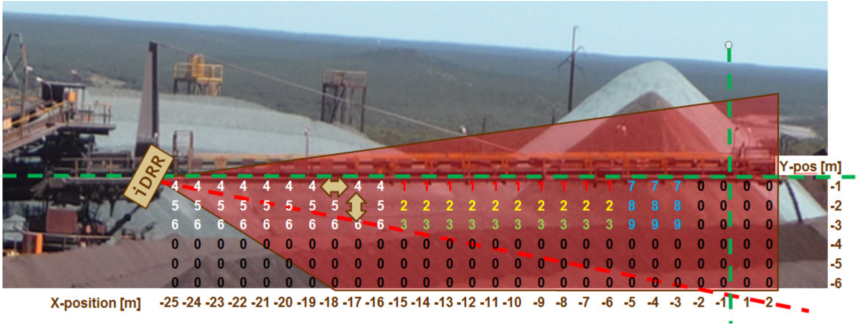


Fig. 12. Tripper/Stacker Positioning with yellow iATR (top left), Collision Detection for Boom (top right), Belt Volume Scan (bottom left) and Dump Height control (bottom right)

For collision Avoidance one iDRR has been mounted below the boom, working as a „electronic radar fence" (cf. Fig. 13). Within indurad web based iPROXIMITY Software the collision zones can be flexibly set by allocating collision Zone IDs.



X-position [m]	-25	-24	-23	-22	-21	-20	-19	-18	-17	-16	-15	-14	-13	-12	-11	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	1	2	Y-pos [m]
	4	4	4	4	4	4	4	↔	4	4	1	1	1	1	1	1	1	1	1	1	7	7	7	0	0	0	0	-1
	5	5	5	5	5	5	5	5	↕	5	2	2	2	2	2	2	2	2	2	2	8	8	8	0	0	0	0	-2
	6	6	6	6	6	6	6	6	6	6	3	3	3	3	3	3	3	3	3	3	9	9	9	0	0	0	0	-3
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-4
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-5
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-6

Fig. 13. Collision Avoidance Sensor for Stacker boom

Using the iDRR close to the boom's pivot point as well as the two sensors at its head, the 3D coordinates of the heap surface are determined from the positions of the installed components using the luff angle encoder, the slew angle encoder, and the tripper's position that was determined by the indurad Active Transponder Radar iATR. This data is then being processed and shadowed areas are inter- or extrapolated using boundary conditions (like the repose angle). Another process is the determination of the heap's volume (Fig. 14).

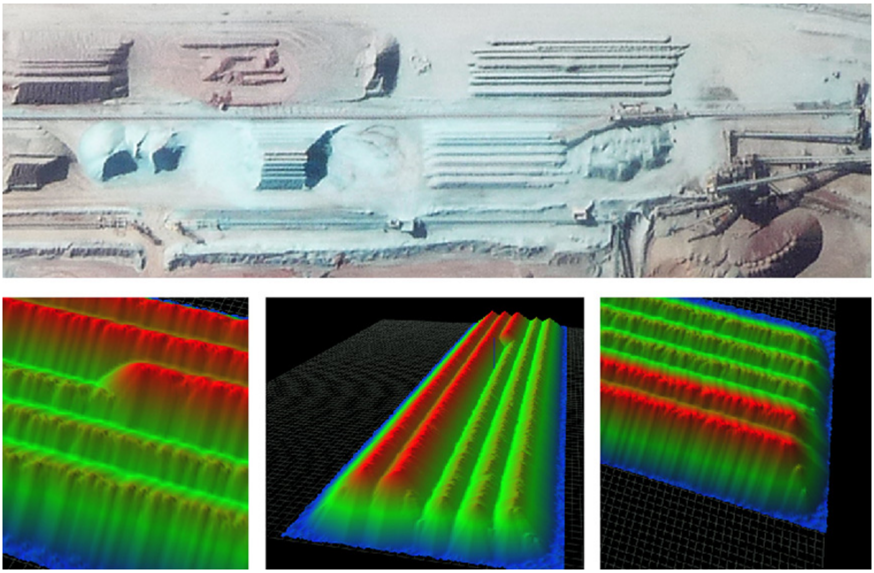
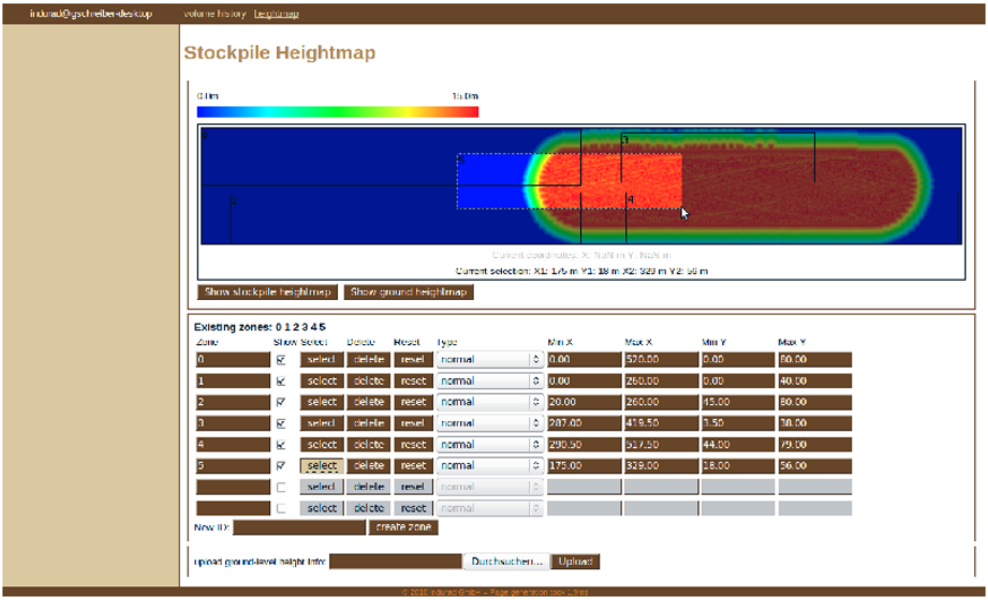


Fig. 14. 3D Stockpile Model calculated from radar data used for volume calculation

The heap can be captured with a profile accuracy of < 0.1 m. The inaccuracies of the rotary encoder as well as the distance measurement simply lead to a model shift and do not result in a volume error.

The iStacker, as indurad calls its customizable off-the-shelf solution package, allows to differentiate between different areas of the stockpile, for example if different qualities of raw material are stocked side by side. The iWEB based software allows definition of different areas by mouse drag and drop or by input parameters (Fig. 15). The Volume can be calculated and visualized for each of the zones individually as well as trend charts can be visualized on a separate iWEB page.



Current coordinates: X: NaN m Y: NaN m

Current selection: X1: 175 m Y1: 18 m X2: 329 m Y2: 56 m

Existing zones: 0 1 2 3 4 5

Zone	Show	Select	Delete	Reset	Type	Min X	Max X	Min Y	Max Y
0	☑	select	delete	reset	normal	0.00	520.00	0.00	80.00
1	☑	select	delete	reset	normal	0.00	260.00	0.00	40.00
2	☑	select	delete	reset	normal	20.00	260.00	15.00	60.00
3	☑	select	delete	reset	normal	287.00	419.50	3.50	38.00
4	☑	select	delete	reset	normal	290.50	517.50	44.00	79.00
5	☑	select	delete	reset	normal	175.00	329.00	18.00	56.00
	☐	select	delete	reset	normal				
	☐	select	delete	reset	normal				

New ID:

upload ground-level height info:

Fig. 15. 3D Stockpile Volumetric Calculation in Zones

The same technology is applied as well for large indoor stockpiles like round coal bunkers or large bunkers with tripper cars.

4. General system configuration

The raw data of up to twelve iDRR sensors is sent via an extremely robust CAN Bus to the indurad Radar Processing Unit ™ (iRPU) where it is processed depending on the individual application. The processing includes signal processing, sensor fusion, volume calculation and 3D modelling on the basis of the individual installation positions and stockpile/ silo geometry. For the 3D modelling of large stockpiles with a moving iDRR further external sensor information like inclination sensors, slew sensors or GPS information or the indurad Active Transponder Radar™ iATR for absolute positioning need to be integrated. Depending on the choice of the customers the data can be send on different interfaces depending on the information depth, like shown in the following Figure 16.

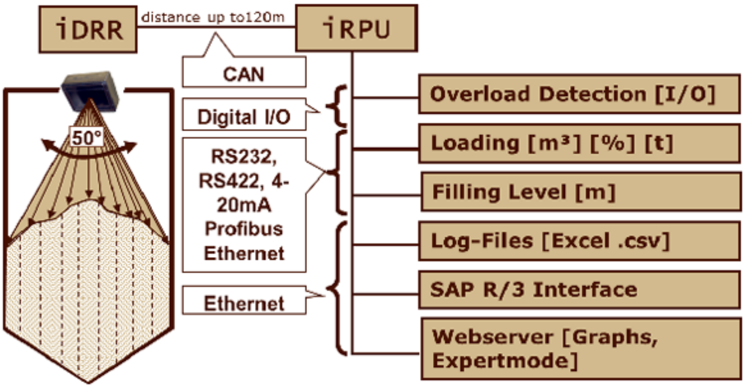
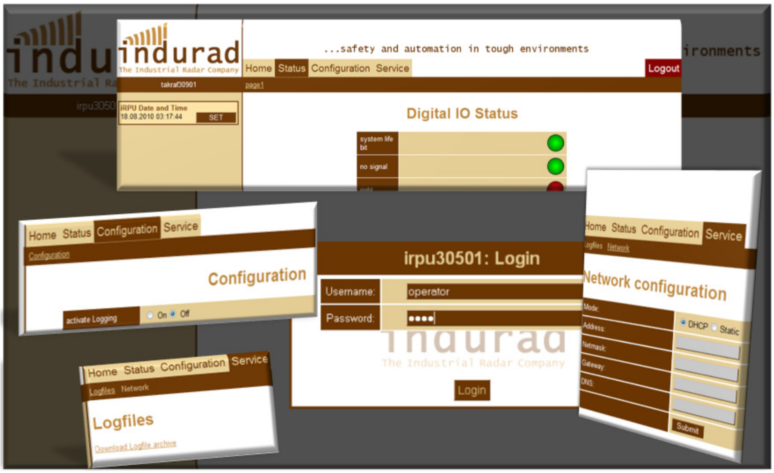


Fig. 16. Integration of the Radar in the Process Control System

The configuration of allindurad solutions can be done flexible via a web interface, like shown in Figure 17.



iRPU Date and Time 18.08.2010 03:17:44 SET

Configuration

activate Logging ○ On ● Off

Username: operator

Password: ••••

Mode: ● DHCP ○ Static

Fig. 17. Thin Client Webserver for system configuration, data analysis and diagnostics

Besides data analysis and configuration it allows remote firmware updates and upgrades in case of a future change in the process. Logfiles (for example .csv for analysis with Excel) containing volume changes or even radar raw data for indurad expert analysis can be downloaded as well via a mouse click. The data can also be accessed via the indurad iWEB Webserver thorough the mine network easily from a standard computer, including all information like 3D Visualisation, filling level and data for historic one click analysis.

5. Conclusions

Developments in the field of 2D radar technology that were achieved by indurad allow implementation of process optimizations in harsh environments that would not be possible using conventional manufacturing technology. Radar based measurement solutions are capable of producing a significant increase in process optimization. It appears, though, that the complex raw data requires a high level of expertise and know-how in the field of wave propagation and signal processing, a good understanding of applications and processes as well as a flexible software architecture. In cooperation with the IMR of the RWTH-Aachen University, indurad developed a software framework to minimize development costs for customized software, thus being able to offer its customers specific and cost effective individual solutions.

The radar hardware and software solutions developed by the authors enable significant process optimization in rough environments, in which traditional sensing technology from the manufacturing industry reaches their limits. With the indurad Solutions, potential can be unlocked in every mining, processing and stockpile operation across the resources industry. The 2D iDRR technology has a high impact on safety, process control and inventory control.

In the field, the iDRR technology has proven to be highly applicable. The measuring process allows, depending on the effort put into calibrating the equipment, a profile accuracy of up to 0.03 m. The measuring frequency of 15 Hz proved to be of great advantage. The equipment is insensitive to environmental stresses like dust, rain, fog or snow and the sensor technology even provides adequate measurements when in motion, with high dynamics in the silo or while loading and unloading of trains.

The unique solutions will create substantial benefits and advantages, therefore yielding maximum customer value:

- Technically:
  - 2D profile scanning 15 times per second for high accuracy;
  - Insensitive to high environmental stress (dust, vibrations, wind, etc.);
- Engineers:
  - Management process transparency over inventory and mass flow;
  - 3D visualization for material distribution and improved dispatching;
- Management/Economical:
  - Permanent online status of heap / stockpile information and history;
  - Planning tool for improved production and sales;

— Maintenance & Instrumentation:
  - Zero Maintenance as merely one initial parameterization is required;
  - Collision Avoidance by Detection of Stockpile and Machinery.

The innovation of the work is directed in the three dimensions technology, application and solution development. The global trend in the mining industry towards increased demand for assistance and automation solutions facilitates the developed technology in a way that it is anticipated to become an integral part in most future mining equipment concepts.

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