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Comparison of online and offline pulp sensor metrics in an industrial setting

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Abstract: Pulp-phase dynamics strongly impact flotation performance, yet flotation control and monitoring are usually limited to surface level froth characteristics. An online pulp-phase sensor promises a better understanding of flotation process dynamics and performance. This utility needs to be demonstrated through field trials with structured experimental design and testing under representative conditions. A three-factor Box-Behnken design was implemented to test airflow, pulp level, and frother reagent addition on pulp-phase measurements. The correlation of online pulp-phase measurements to offline pulp sensor measurements is analysed and discussed.

Keywords: sensors and instrumentation; flotation; mineral processing; image processing

1. INTRODUCTION

Pulp-phase dynamics play an important role in overall flotation performance and can provide valuable flotation process information. However, pulp-phase characteristics are not easily inferred from other process conditions (Geldenhuys and McFadzean, 2019) and currently, there are few if any online pulp-phase sensors commercially available. Online pulp-phase measurements may be used for online control (e.g., by incorporating pulp-phase measurements in reagent dosing control) and real-time decision support (e.g., as an additional measurement to inform flotation state detection and its associated advisories to operators).

To address this shortcoming, Stone Three has developed an online pulp sensor (with measurement point in-situ in the flotation cell) – the Stone Three Pulp Sensor – that provides real-time measurements of a variety of pulp metrics to process operators. This work compares the online pulp sensor metrics and offline pulp sensor metrics derived from the Anglo Platinum Bubble Sizer (APBS) (Harris et al., 2013). Experiments were conducted on a mineral processing plant, with run conditions designed to provide maximum statistical coverage, given process operating constraints.

The scope of this work is the comparison and correlation of pulp sensor metrics with APBS as collected under varying concentrator operating conditions.

2. BACKGROUND

2.1 Froth Flotation

Froth flotation forms a key step in platinum recovery processes and any improvements here are likely to have a large impact on overall plant performance and economics. Flotation cells in platinum concentrators are often operated conservatively to maximise platinum recovery and obtain a sufficient grade for smelting. This is in part due to the difficulty in monitoring flotation bank performance in real-time and the large number of disturbances to which flotation cells are subjected (Bergh and Yianatos, 2011).

Flotation processes are strongly affected by several variables under the control of the process operators: pulp level, cell sparging airflow rate, and flotation reagent dosages. Of the flotation reagents, it is expected that the frother reagent dosage would have the greatest impact on pulp-phase characteristics (Zhang, 2016).

2.2 Importance of pulp bubble characteristics in froth flotation

Flotation froth layer formation is dependent on the attachment of particles onto dispersed bubbles and the stability of the emerging phases. Therefore, it can be expected that the mechanisms that dictate particle adherence dominate mineral recovery (Wills & Napier-Munn, 2005: 257). Flotation rate research has shown that bubble surface area flux is a key driver within the pulp phase of flotation cells (Wills & Napier-Munn, 2005: 285).

The bubble surface area flux (S_b) refers to the movement of bubble surface area through a cross-sectional area of the pulp in a given flotation cell and is related to bubble size (specifically, Sauter mean diameter, d_{32}), gas holdup (ε_g) and superficial gas velocity (j_g) (Wills & Napier-Munn, 2005: 285; Gorain, Franzidis & Manlapig, 1997). Gorain et al. (1997) found that bubble size, velocity and gas holdup could not independently describe observed flotation rates, however, they could be used together to model bubble surface area flux. Some of Gorain et al.'s (1997) findings were challenged by Heiskanen (2000), who highlighted bubble measurement discrepancies. Contradictions were identified, including a result that suggested larger bubbles led to improved flotation

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rates. Previous studies have highlighted the importance of pulp bubble properties. For instance, the effect of bubble size on flotation rate was empirically established by Ahmed & Jameson (1985: 209). Ahmed & Jameson (1985: 209) also showed that smaller bubbles (~75 microns) optimize flotation rate at the typical grind ranges – 300 to 20 microns (Wills & Napier-Munn, 2005: 291).

In practice, however, several factors may affect flotation rate including impeller speed, airflow rate (turbulence), particle composition, particle size and reagent addition rates. Interaction of the different factors complicates the estimation of bubble diameter effects alone (Ahmed & Jameson, 1984: 209). This can be true for the measurement of pulp bubble properties in general since many factors (pulp opacity, vibration, etc.) can bias measurements (Hernandez-Aguilar, 2004: 2).

Sensors that track flotation pulp properties have garnered attention due to ongoing questions regarding appropriate reagent dosing and air rate. Pulp observation sensors can be useful for frother reagent addition – since frothers affect bubble size (Harris et al., 2013). The measurements provided by the APBS allow estimation of flotation rate constants (Hernandez-Aguilar et al., 2005) and for estimating the carrying capacity of collection zones (Yianatos and Contreras, 2010) within the pulp phase. The APBS is an offline sampler – if an online instrument can provide real-time pulp measurements, such measurements could be used for: corroborating and calibrating air addition rate measurements, manual or automated adjustment of reagent addition and inferential recovery estimation (combined with other process measurements).

2.3 Flotation pulp sensors

Imaging, isokinetic, and acoustic techniques are methods that have been used to measure flotation pulp properties. Spencer et al. (2011) used accelerometers and hydrophones, on an industrial coal processing cell, to infer bubble sizes and solids loadings. The current acoustic monitoring tools only provide information on the expected dominant pulp bubble sizes or solids loadings (and models are required to relate the indirectly linked factors).

Isokinetic methods have mainly been used to determine pulp bubble size distributions (Hernandez-Aguilar, 2004: 11). This methodology was first described by Tucker et al. (1994) and its use is reported in industrial studies. Bubble sizing equipment, for the isokinetic method, consists of a capillary used to transport pulp samples to a reservoir that is connected to a bubble detector head (an isokinetic sampling probe). The isokinetic methods proved suitable for bubble sizing in applications where high solids fractions were present in a liquid phase. However, the significant number of components required for this method prohibits widespread industrial application (Hernandez-Aguilar, 2004: 13). The use of the capillary also limits the maximum bubble sizes that can be measured.

Visual/optical methods are relevant to the work in this paper. Existing literature on pulp bubble imaging techniques describe methods that focus on pulp sampling followed by imaging (Hernandez-Aguilar, 2004: 2). Chen, Gomez & Finch (2001) and Harris et al. (2013) describe pulp imaging (sampling followed by image acquisition case) in pilot and industrial scale flotation cells. The equipment consists of a sampling tube that guides pulp material into a viewing chamber, where a digital camera can record bubble images (Chen et al., 2001: 428; Harris et al., 2013: 291). Harris et al.'s (2013) and Chen et al. (2001) used their equipment for bubble sizing but Vinnett, Ledezma, Alvarez-Silva & Waters (2016) used similar equipment to model local gas holdup.

Direct (or in-situ) pulp sensors with online measurements have rarely been demonstrated in the literature (Hernandez-Aguilar, 2004: 14). A recent example of an in-situ pulp sensor was presented by Maas et al. (2021) - a SOPAT inline photo-optic measurement device, suitable for industrial applications, was applied to measure pulp characteristics in a 5L bench scale batch flotation cell. Previous studies, Lage & Espósito (1999) and Besagni et al. (2016) analyzed bubble properties in bubble columns (using image processing to size bubbles). However, these were laboratory-scale experiments that did not study flotation type pulps.

2.4 Anglo Platinum Bubble Sizer

The Anglo Platinum Bubble Sizer (APBS) (Harris et al., 2013) combines the measurement principles of the McGill bubble sizer and the JKMRC j_g probe to allow offline sampling of pulp bubble properties and gas flow (Malinga et al, 2018, with reference to Chen et al. 2001, and Gorain et al., 1997). During sampling, air is continuously collected from the pulp and bubbled through a water zone where bubble size and area measurements are taken by a camera. The air continues to bubble through to a reservoir system, which allows Sauter mean diameter (based on total bubble surface area estimated from image processing) and superficial gas velocity and bubble surface area flux to be estimated. Corrections are applied for differences in orifice diameters, as well as pressure and density differences between the in situ slurry sampling point and the collection point above the cell.

Fig. 1 shows the design of the APBS, as well as a sample image.

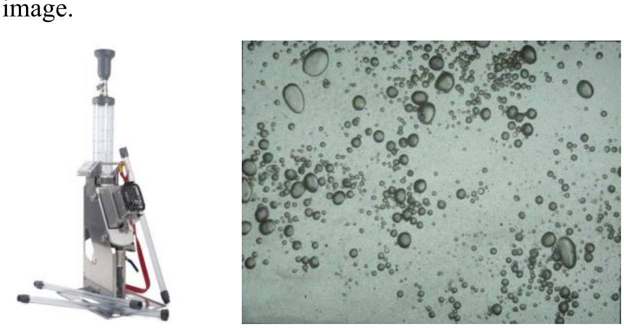

Fig. 1: Anglo Platinum Bubble Sizer (left) and an example image of collected bubbles flowing past viewing box (right).

2.5 Online Pulp Sensor

The Stone Three Pulp Sensor, or online pulp sensor (OPS), illustrated in Fig. 2, performs in-situ machine vision analysis of the flotation cell pulp using a high-speed camera (300 frames per second) – see Fig. 3 for an example image. The pulp sensor is intended to remain in situ for continuous real-time measurements that can be incorporated in automated control. Slurry abrasiveness keeps the lens clean, while LED lighting provides illumination.

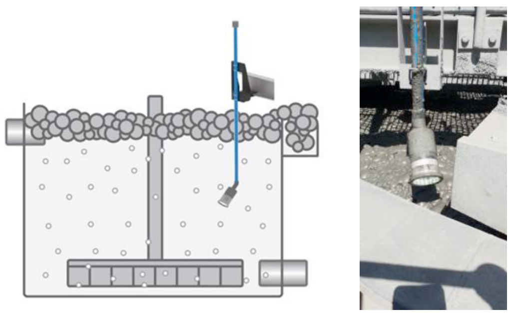

Fig. 2: Schematic of online pulp sensor as position in a flotation cell (left); online pulp sensor before emersion (right).

Image processing techniques are applied to single images to determine bubble properties in the pulp, including average (d_m) size. Equivalent circle diameters are estimated based on the actual bubble areas – this leads to the assumption that d_m is also the d_{32}. Gas holdup can be estimated based on visible total bubble area over the total visible area in the region of interest. Analysis of sequential images allows the estimation of average bubble rise velocity (u_g), and combining this with the gas holdup estimate, the superficial gas velocity can be estimated ($u_g\varepsilon_g$). Bubble surface area flux is calculated from j_g and d_{32}.

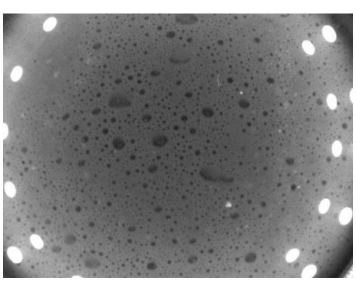

Fig. 3: Example image captured by the online pulp sensor (white spots are LED light reflections).

3. METHODOLOGY

3.1 Data Gathering and Experimental Design

The data used in this work came from three sources focussing on a single flotation cell: online historian data from the platinum concentrator, online metrics from the pulp sensor, and offline measurements of pulp characteristics from the APBS. A Box-Behnken randomized design was implemented for step testing with two repeats of the centre measurement to evaluate process drift. This was considered the minimal design, with additional repeats to be performed as time permitted. For each step, the flotation cell would be left to stabilize for a set period depending on the factor changed. This was determined in consultation with the site and bearing in mind the time constraints for testing. During the step testing, these times would be evaluated in the process response and modified as required.

Data was gathered over two days of testing and APBS samples were taken just before the end of each step change in the experimental design. Pulp level setpoints and process values, cell sparging airflow setpoints and process values, as well as frother reagent addition were collected from the process historian. Fig. 4 shows the time series trends of the manipulated process conditions and a selection of the OPS measurements.

The logged times for each APBS sample were used as a reference after confirming that this timestamp was before the next step-change. Data for APBS/OPS correlation was sampled as recorded from the historian and pulp sensor database and averaged for the 10 minutes preceding the APBS sample. As it was expected that the process would be at a steady-state before the APBS sampling, averaging the data before the APBS sample time removes some noise and disturbances from the online sensor measurements.

The experimental data used in this study is summarised in Table 1.

Table 1: Information of experimental data used

Variable	Description
Pulp level process variable	Experimental factor: manipulated variable (through set point of related controller)
Air rate addition process variable	Experimental factor: manipulated variable (through set point of related controller)
Frother flow rate process variable	Experimental factor: manipulated variable (through set point of related controller)
OPS j_g	Experimental response: Online superficial velocity measurement
OPS d_{32}	Experimental response: Online bubble size measurement
OPS S_b	Experimental response: Online bubble surface area flux measurement
APBS j_g	Experimental response: Offline superficial velocity measurement
APBS d_{32}	Experimental response: Offline bubble size measurement
APBS S_b	Experimental response: Offline bubble surface area flux measurement

3.2 Error Estimate

Error (precision) estimates for the two devices are required if a meaningful comparison is to be done. For the APBS, Geldenhuys and McFadzean (2019) give error bars for the Sauter mean diameter, calculated as the standard deviation of approximately 75 photographs. Their reported errors are in the range of 0.1 to 0.5 mm for bubbles in the size range of 1.5 to 3 mm. No literature data was found for errors in the superficial velocity or the bubble surface area flux.

The standard deviation of the APBS_d32 and APBS_jg were calculated for each of the twenty runs performed (see Table 2). The average for all the standard deviations for APBS_d32 was 12% of the average. The average for all the standard deviations for APBS_jg was 7% of the average. The APBS_Sb is a ratio and the error is calculated from

$$Var\left[\frac{X}{Y}\right] = \frac{1}{\mu_Y^2}Var[X] + \frac{\mu_X^2}{\mu_Y^4}Var[Y] - 2\frac{\mu_X}{\mu_Y^3}Cov[X,Y]$$

It is assumed that the covariance is zero, and the results of the calculation is a standard deviation of APBS_Sb is 20% of the average.

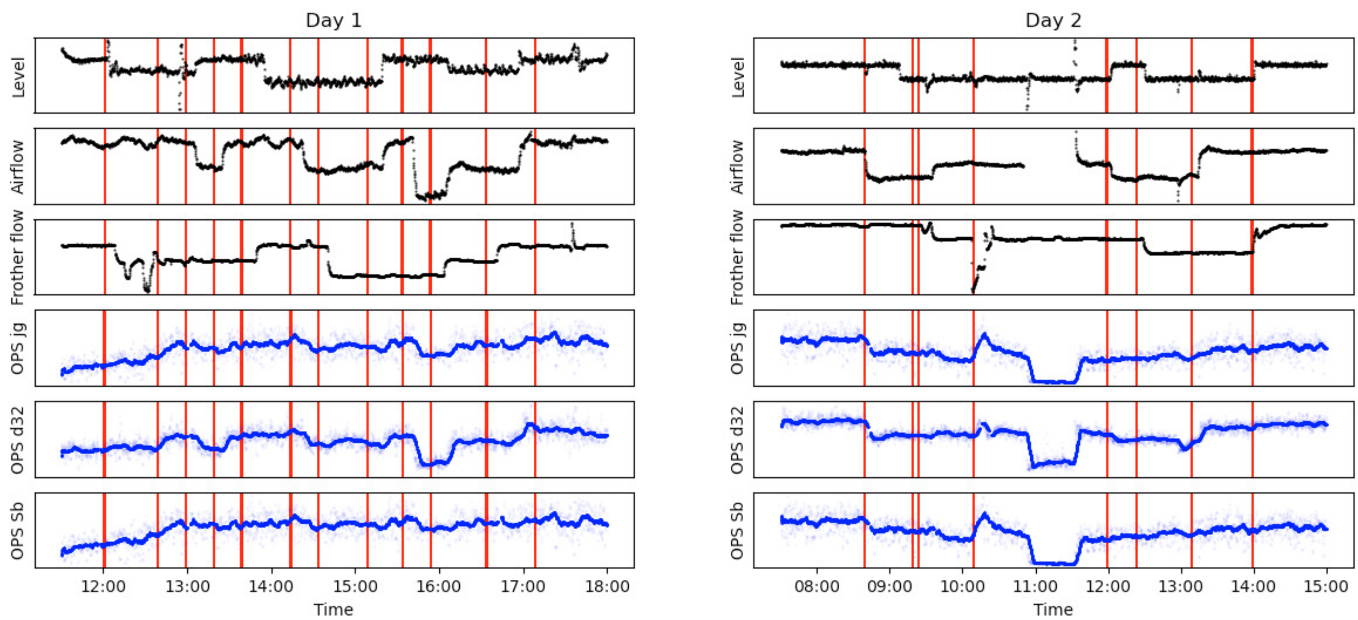

Fig. 4: Time series plots showing the experimental conditions which were manipulated (pulp level, airflow, frother flow) as well as the online pulp sensor (OPS) trends: the filtered trends indicate rolling means (based on a 5-minute window size). Actual values are omitted for confidentiality reasons. Red vertical lines indicate sampling times for APBS. Note the airflow abnormality between 11:00 and 12:00 on day 2 – airflow was switched off, but interpolated in the historian. Another abnormality is in frother flow around 12:30 on day 1 and 10:00 on day 2.

For the OPS, a similar approach was used to calculate the precision (repeated values from steady-state conditions used to represent replicates). The standard deviations of OPS_d32, OPS_jg and OPS_eg are 3.7%, 22.2% and 21.1% respectively.

From the error estimates, the OPS error ranges correspond at worst with the worst of the APBS error ranges.

Table 2: Error (precision) estimates for APBS and OPS

Quantity	**APBS** **Standard deviation/ Average**	**OPS** **Standard deviation/ Average**
Sauter Mean Diameter	12%	3.7%
Superficial velocity	7%	22.2%
Bubble surface area flux	20.0%	21.1%

3.3 OPS Validation

To validate the outputs of the online pulp sensor, two approaches are considered: 1) evaluation of the directional response of OPS metrics to changing process conditions (level, air and frother addition); 2) comparison of APBS and OPS metrics. For the latter approach, an exact one-to-one match is not expected, since the APBS has its own biases and limitations. While the APBS still provides valuable information, it does not serve as definitive ground truth for pulp characteristics.

4. RESULTS AND DISCUSSION

4.1 OPS metrics response to design factors

From Fig. 4, a few observations can be made in terms of the response of OPS metrics to level, airflow and frother flow changes. Where airflow is stepped with no changes in other factors OPS j_g tends to increase with airflow increase and decrease for airflow decrease. This agrees with expected behaviour. Where frother flow and level are stepped with no changes in other factors, the effect on OPS metrics is less clear.

Three multiple linear regression models were fitted as an initial exploratory assessment: each model had an output of either OPS j_g, d_{32} and S_b while level, airflow and frother flow served as the three inputs for each model. Models were fit on data from the process historian and OPS database, excluding the anomalous frother flow periods on days 1 and 2. For each experimental step, the average values of the last 5 minutes before the indicated APBS sampling times were used to represent the process and OPS values for that experimental run. The regression results are shown in Table 3. Of interest in these results is the significant and strongly correlated response OPS j_g and OPS d_{32} with airflow (significant coefficients with large values). This indicates that the OPS metrics are responsive to relevant process changes.

4.2 Comparison of APBS and OPS metrics

A comparison of APBS and OPS metrics is provided in Fig 5. Given the potential biases of the different sensor principles, as well as the reality of challenging industrial testing conditions, the correspondence between APBS and OPS metrics is promising.

Table 3: OLS model results for design factors as inputs (scaled to range -1,+1 for design levels) and OPS metrics as outputs

	OPS j_g	**OPS d_{32}**	**OPS S_b**
Regression model fit	**Significant fit (p = 0.051) R^2_{adj} = 0.291**	**Significant fit (p < 0.05) R^2_{adj} = 0.744**	Insignificant fit (p = 0.644)
Design factor: Level	Coefficient: -1.25 (p = 0.41)	Coefficient: -0.0767 (p = 0.476)	Not applicable
Design factor: Airflow	**Coefficient: 3.91 (p = 0.008)**	**Coefficient: 0.631 (p<0.001)**	Not applicable
Design factor: Frother flow	Coefficient: -0.0044 (p = 0.997)	Coefficient: 0.109 (p = 0.254)	Not applicable

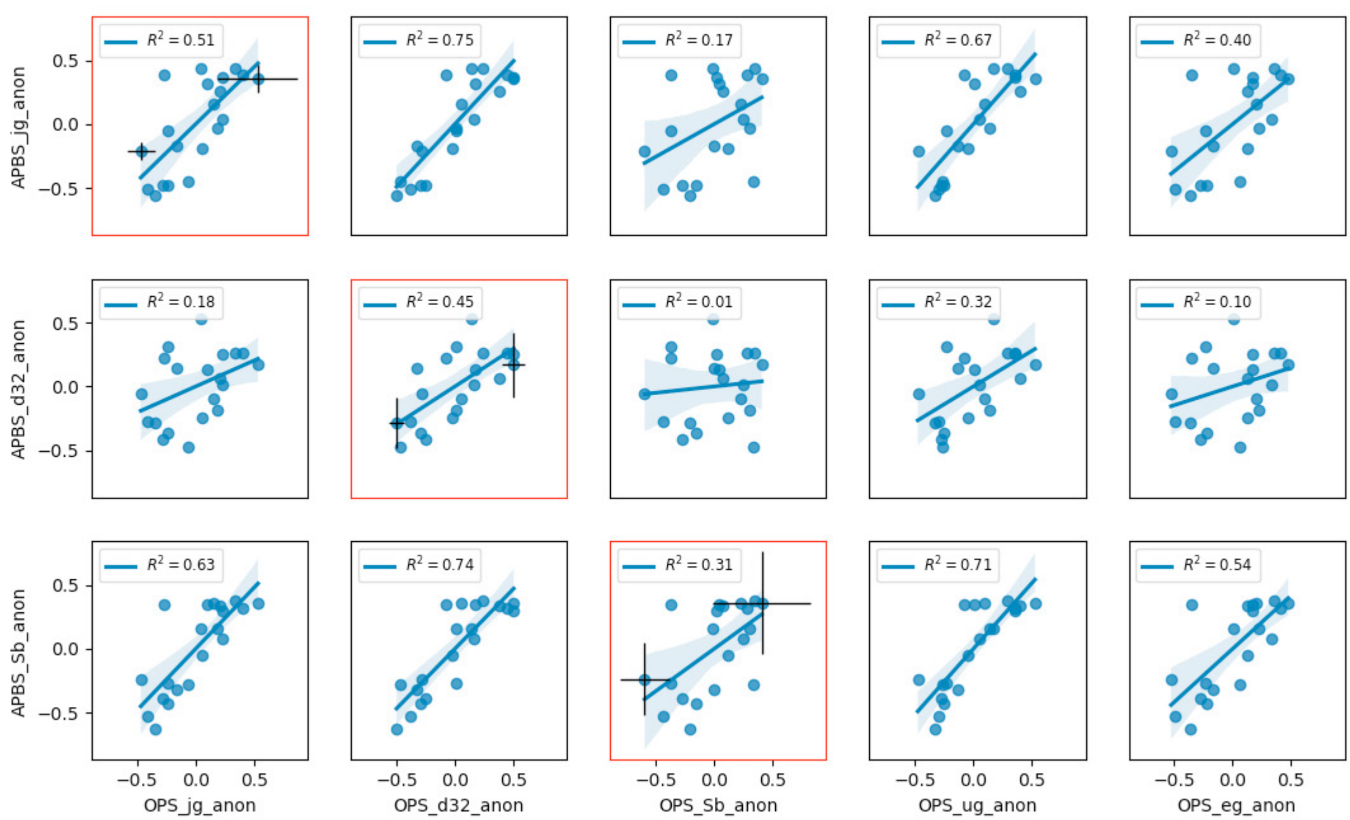

Fig. 5: Relationship between APBS and OPS pulp measurements for sampling campaign – note that anonymization was applied for confidentiality reasons. 95% confidence intervals shown are calculated by bootstrapping methods – refitting regression models on 1000 resampled manifestations of the original data. Error bars are indicated for a selection of minimum and maximum values.

5. CONCLUSIONS AND RECOMMENDATIONS

This work has shown that the online pulp sensor produces measurements that are responsive to relevant process changes. Results have highlighted that the exact calibration of the OPS requires more work.

Future work will include dynamic system identification of OPS metrics in the context of flotation operation variables such as pulp level, airflow and reagents flow, but also in the context of flotation performance measures, such as grade and recovery, to validate the potential of incorporating such metrics in advanced process control solutions. Online pulp-phase measurements may be used for online control and real-time decision support.

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