Predictive Maintenance for Automated and Manual Overhead Bridge Cranes

This article presents key performance indicators for cranes and illustrates how these indicators can be analyzed and automatically monitored using a variety of tools to aid in better maintenance decision making.

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Cranes are subject to mechanical wear and require regular servicing and maintenance to prevent unexpected downtimes. Preventive maintenance activities are usually performed periodically according to a predefined maintenance schedule. Predictive maintenance provides a more flexible and customized approach. Predictive maintenance schedules are created and optimized based on both general and system-specific requirements and require the ability to capture real data related to how the crane positions change over time. Based on the collected data, key performance indicators (KPIs) can be developed to establish a predictive, usage-based crane maintenance schedule that is ideal for each crane system. The result is a maintenance schedule that maximizes equipment life while minimizing maintenance costs and production downtime. This article presents key performance indicators for cranes and illustrates how these indicators can be analyzed and automatically monitored using a variety of tools, including reports, charts, and diagrams, for better maintenance decision making.

Types of Crane Systems

Cranes can be divided into three categories:

- Manual cranes are controlled manually by an operator via a joystick or control panel that controls the direction of movement and the crane velocity.
- Automated cranes receive commands from a host controller or an inventory control system, which instructs the crane to move to predefined target positions. Once a travel command is received, the crane is controlled automatically, ideally by a closed-loop positioning controller. An operator is not involved. Automated crane systems that include such a positioning controller have the added benefit that important data, such as motion-related data or travel commands, are automatically recorded by the positioning control system.
- Semi-automatic cranes can be controlled by an operator while a positioning system provides closed-loop positioning control. Semi-automated crane systems combine manual control with the benefits of both operator experience and closed-loop positioning control, which reduces system wear and compensates for motion cycle interferences such as oscillations.

Throughput increases are often achievable versus solely manual control.

Recording Different Types of Data

Important Data Types — Different types of data can be recorded during crane movements. In individual cases, a variety of data that may not seem significant at first glance can considerably simplify troubleshooting or contribute to identifying a crane's optimization potential. A data comparison and the ability to define automated notifications for different conditions enable a predictive maintenance approach. The following sections provide an overview of data types that have proven to be relevant key performance indicators in the practice of developing a truly predictive maintenance plan.

Travel Distance: Distance information is an important indicator for determining the mechanical condition of a crane over time. Travel distances are recorded using distance sensors, such as laser distance meters, encoders and other devices. To take full advantage of this data type, distance values should be read in real-time intervals, so that individual distance values can be used to create a motion profile. Synchronous serial interface (SSI) systems or real-time bus systems are examples of interfaces that are able to read distance information in real time.

By combining recorded distance values with timestamps, a motion profile can be generated which can be used as a basis for various analyses relating to storage strategies, mechanical stresses or troubleshooting. Distance information can be used to calculate crane mileage or periods of downtime. Similarly, additional values can be derived from recorded distance and time information. The most important of these values are velocity and acceleration.

Velocity: Crane velocity is derived from distance and time information based on the following formula:

$$v = \lim_{\Delta t \to 0} \frac{\Delta s}{\Delta t} = \frac{ds}{dt} = \dot{s}$$

(Eq. 1)

where

v = velocity,
lim = threshold value,
Δt = time difference,
Δs = distance difference,
ds = distance differential,
dt = time differential and
$\dot{s}$ = distance.

This formula is used to derive distance over time for a continuously operating system. Digital systems are assumed to be time-discrete. In practice, this means the smaller the analyzed time window, the more accurate the calculated velocity is going to be. A Δt value of 10 ms has proven to be useful in practice, and the calculated velocity also relates to a defined time window of 10 ms. Velocity can also be observed from the motion profile. The maximum velocity or the average velocity during regular operation, respectively, is of particular interest. The velocity graph also indicates whether the crane has a linear motion profile or whether oscillations occur while the vehicle is in motion. Similarly, the graph provides an easy means to determine if the vehicle approaches the target at creeping speed or if overshooting at the target position occurs, both of which will increase mechanical wear and predictive maintenance schedules.

Acceleration: Distance information is also used to calculate crane acceleration based on the second derivative of distance over time:

$$a(t) = \dot{v}(t) = \ddot{s}(t)$$

(Eq. 2)

where

a = acceleration,
t = time,
$\dot{v}$ = velocity and
$\ddot{s}$ = distance.

A real-time-optimized system includes three phases: an acceleration phase, a phase of constant movement at maximum velocity and a deceleration phase.[1] The acceleration during constant movement equals 0 mm/s^2 (constant velocity). The acceleration during the other two phases should be at maximum.

As with velocity, acceleration values can be depicted as maximum or average values. In addition, acceleration can be displayed over time, so additional conclusions can be drawn from the travel profile. Acceleration offers a clearer indication of motion profile irregularities than velocity.

Moreover, further derivatives of distance can be taken into account. The third derivative of distance over time is called jerk. Derivatives, however, do not provide additional data; they merely aid in clarifying existing information and can, for instance, be used for motion analysis purposes to detect weak spots in a motion profile.

Setpoint Values for Target/Performance Comparison: In a controlled system, movement is defined by setpoint values. Setpoints can be provided by a ramp configured in a frequency converter, a programmable logic controller (PLC), a manual joystick or a positioning system. Setpoint values determine the progression of a motion sequence, the maximum velocity or the ramp at which a system accelerates or decelerates.

The recording of setpoint values enables a comparison of target performance versus actual performance. Setpoints can be transmitted as an analog voltage, as a predefined value in a bus system or as a speed reference from a frequency converter. A closed-loop positioning control system has the advantage that setpoint values can be calculated and stored right in the controller. Since closed-loop control always involves a target/performance comparison, the controller provides access to a complete set of data and greatly simplifies data recording or a data comparison.

Target/performance variances can be caused by mechanical issues, or they can be an indication of extreme wear, which makes them an important tool for predictive maintenance.

Motion Paths: In every closed-loop controlled system, motion path planning takes place either before or after a motion sequence. Ideally, motion path planning relates to the machine behavior that was "learned" by the controller during commissioning. The variance recorded for motion paths and travel profiles can be defined as a value. This value is another useful key indicator for predictive, usage-based maintenance. Warning thresholds and tolerance limits for variance values can be defined to ensure that the crane will safely ramp down to a halt when a threshold or limit is exceeded to prevent potential injury or damage.

Recording of Incidents: The recording of faults or incidents is important, as the data helps with troubleshooting and helps define corrections to eliminate these issues. A distinction between sporadically occurring and repeatable faults or incidents is critical. Analyzing and correcting repeatable incidents is significantly easier than troubleshooting those that occur sporadically. In many cases, an analysis of the most pertinent data can reveal a pattern for sporadically occurring incidents. The following list illustrates an approach for revealing such a pattern:

- A problem regularly occurs in a particular section of a crane runway.
- A problem occurs only during the acceleration phase when a certain load weight is exceeded.
- When these problems occur, the temperature is higher than usual over a prolonged period of time.
- The problems occur only after the system has been running for a certain period of time and disappear when the system is restarted.

In order to enable fast and effective troubleshooting of issues that do not have a seemingly obvious root cause, it is important to have access to as much relevant data as possible. However, being able to clearly and meaningfully compare this data is equally important.

A closed-loop positioning control system can automatically log any incidents that occur during regular operation, including an "internal" reason that led to the incident. For example, the controller may record that the crane did not start moving after having received a setpoint value. The underlying root cause, however, cannot be determined in this manner. Often, a specific pattern may have already been documented, and maintenance personnel may be able to quickly identify the root cause based on previous experience. This, of course, depends largely on staff experience. Lesser experienced and new staff may lack historical perspective, and root-cause identification takes longer. This can allow correctable incidents to persist, causing more machine stress and higher maintenance costs. Thus, having relevant real-time data allows for much faster response and minimizes the risk of inexperience and/or human error.

One way to reduce maintenance-related cost factors is to have all incidents categorized. The control system can subsequently be configured to automatically notify maintenance technicians of recurring problems, and a recommended course of troubleshooting actions can be suggested based on previously stored data.

Incidents can also be categorized and documented for manually operated or semi-automatic cranes. Incidents can either be reported automatically by a controller (semi-automated) or they can be logged and added by maintenance personnel (manually operated).

Electric Current: Measuring the electric current is another method of obtaining crane-related data. For example, the current of a crane's frequency converter can be measured and recorded. The frequency converter's maximum current provides an indication as to whether it is operating close to its current limit. During the acceleration phase, the current limit may be exceeded when heavy loads are transported, leading to a frequency converter fault. Notably, this can occur if crane systems are continuously expanded and loads successively increase over several years.

Comparing the measured current values to the acceleration values can reveal whether the condition of a crane has deteriorated. This can, for instance, be the case when system acceleration is low, but the measured current increases during the acceleration phase. Current and acceleration values of identical motion sequences with identical load weights can be compared at different points in time to determine whether such a change of crane condition may have occurred.

Temperature: Hardware is often rated for a specific temperature range, and machines frequently shut down after the temperature rating has been exceeded to prevent potential hardware damage and safety issues. The availability of environmental temperature data can facilitate the troubleshooting process and provide indication of when sensitive equipment is likely to fail.

For troubleshooting purposes, a temperature sensor can be attached to the hardware. The recorded temperature information can easily be transferred to a central location where all relevant data is being stored. This data can subsequently be retrieved and compared to crane-related incidents to determine whether the temperature rating was exceeded and to identify potential correlations. A thermal protection enclosure is but one means of eliminating temperature-related issues and extending equipment life.

Load Weight: Load weights can be measured using a scale, or they can be stored in a controller or an inventory control system. In either case, the load weight can be transmitted to a positioning controller and linked to the motion sequences.

The load weight can aid with troubleshooting when a particular problem occurs only at full load, at zero load or even when the rated load is exceeded.

Knowing load weight can also be very helpful for analyzing and optimizing a warehouse storage strategy, for example, with regard to wear or energy consumption. Heavy loads that are transported over unnecessarily long distances increase energy consumption, which can lead to premature wear that negatively impacts maintenance schedules and cost.

Specific Maintenance-Related Know-How — When analyzing vast amounts of data, specific maintenance-related understanding can be helpful. The following example illustrates the correlation between recorded data and what is actually happening with the crane system.

The wheels of a bridge crane are subject to high wear. Approximately one year after the installation of new wheels, high crane usage led to an increasing number of wear-related issues. The wheels were replaced during half-yearly maintenance intervals, resulting in increased production downtimes, maintenance and hardware costs. An analysis of the crane data revealed that the problems arose because the permissible target/performance variance between the ideal and the actual motion path of the crane was consistently exceeded during the year. During crane commissioning, a closed-loop positioning system controller "learns" the ideal machine behavior of the crane. This behavior is translated into a mathematical model. When the crane is in motion, the closed-loop controller uses the learned behavior (the mathematical model) to calculate an ideal motion path. The calculated values are the ideal target values for the crane. While the crane is moving, a variance between the target values and the actual motion path values occurs. This variance may be caused by mechanical issues such as uneven crane rails or when the crane passes over a rail joint. The closed-loop positioning controller compensates for this. If, however, the target/performance variance becomes too great, a failure occurs. A failure threshold and a warning threshold can be configured so that maintenance activities can take place in advance. In practice, this led to the definition of a warning threshold value for the crane based on maintenance-related expertise. Going forward, a warning will be issued before the actual threshold is reached, and the wheels can be ordered and replaced in time to prevent an outage and the resultant impact on production and profitability.

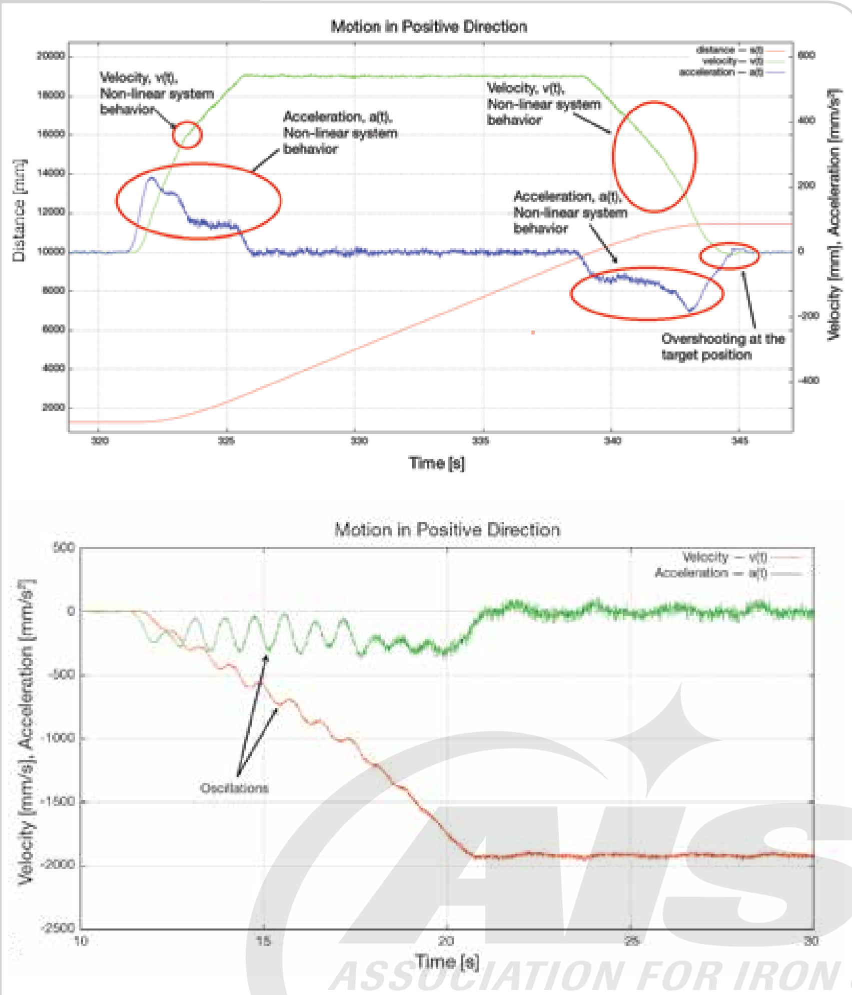
Data Comparison — In many instances, individual data points may not clearly pinpoint the reason for a crane's condition. It is only after a set of data points is collected over time (a trend), or when available data is compared to additional information or set in context, that a reliable statement regarding the crane condition can be made.

Different data comparison methods can be used:

- Progression of a particular value over time: This method is used to determine whether a particular value has changed since system commissioning and how it has changed (underlying trend) to provide an account of the changes.
- Comparison of different values over a specific period of time: This method enables an analysis of the crane's condition for the period in question.

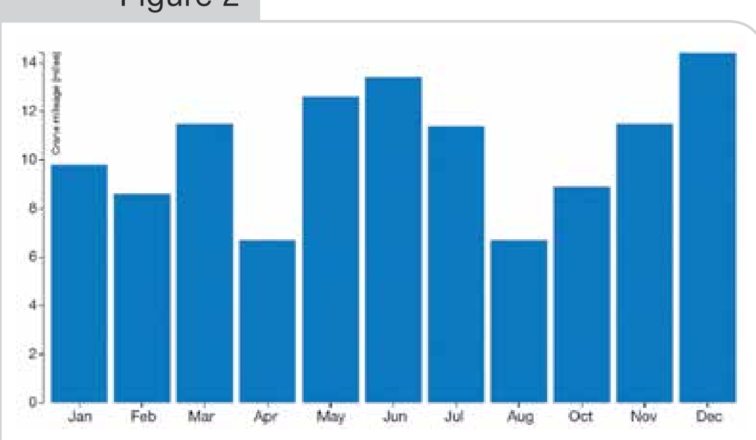
Hence, a truly predictive maintenance approach also requires the configuration of automated warnings for a variety of conditions.

Figure 1



Line charts illustrating motion-related weak spots, non-linearity, overshooting and oscillations.

Figure 2



Bar chart illustrating annual crane mileage.

Synopsis

A wide variety of data can be read and stored for both manually operated and automated cranes, and many data types can assist in identifying an underlying root cause during troubleshooting. In addition, data analyses can be used to draw important conclusions about crane behavior and to establish a concept for usage-based, predictive maintenance. It is, however, vital that data is presented in a proper format that allows for underlying root causes to be quickly identified or excluded. There are a number of proven tools that facilitate a fast and meaningful data collection and analysis. The following sections provide an overview of these tools.

Graphical Analysis Tools for Predictive Maintenance

Idea and Conceptualization — The idea of using recorded data that could be used for crane optimization and maintenance activities originated in relation to the advancement of truly closed-loop positioning control systems. The most important crane data, namely the required control parameters and data that are calculated by the controller, are readily available from the closed-loop positioning control system. The condition of a crane can be assessed by evaluating the data. This has already proven useful for troubleshooting crane operation, and the logical next step is to create an approach that system operators could use to visualize and process the data. Many data types lend themselves to graphical representation in charts or diagrams. Other types of data, including a real-time snapshot of the current crane condition, are displayed in a tabular format. This section focuses on methods of graphical representation and illustrates how these methods can be used for data analysis and evaluation and to determine appropriate predictive maintenance schedules for the crane.

Line Charts: Line charts are the diagrams of choice for depicting processes over time. Generally, time is displayed on the x-axis, while the y-axis represents the data type value for a particular point in time. Motion profiles are a typical example of data types that can be displayed as line charts. A single chart can include distance, velocity and acceleration graphs. Figure 1 illustrates the motion profile of a crane. Motion-related weak spots, such as non-linearity, overshooting and oscillations, are clearly visible in the charts.

Additional information, like setpoint values, motion paths or frequency converter currents, can be included for a more comprehensive comparison. Recorded events can be included in a line chart to provide an overview and to enable a quick visual allocation of events.

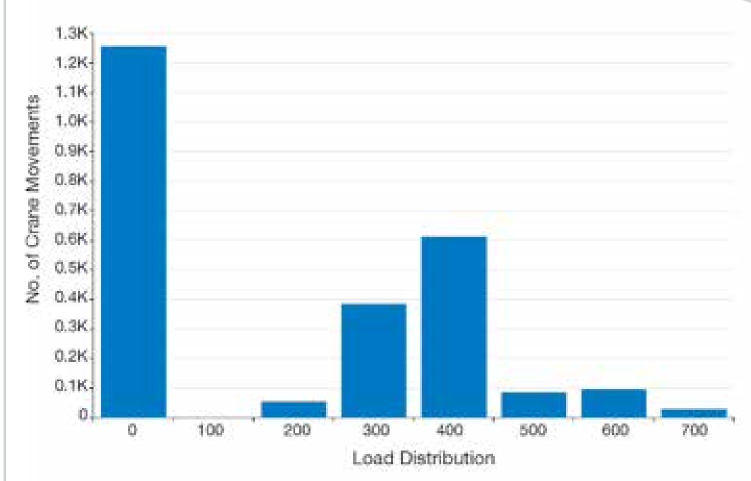
Bar Charts: While line charts are particularly well-suited for visualizing a large number of measuring points, bar charts are a helpful tool for presenting a small amount of points or combined values. Bar charts can, among others, be used for comparing aggregated values on a per-month basis. Figure 2 contains an annual mileage overview of a crane system displayed in monthly intervals. Ideally, the crane operator or maintenance staff should have access to gather data in real time or have it reported regularly to help confirm the crane is behaving as intended and no modifications need to be made.

Bar charts can also include the number of incidents per months and can be used as a tool for validating previous maintenance activities or for future maintenance planning. Histograms can also be presented as bar charts.

Figure 3 contains an example of a load weight distribution per number of crane movements during the month of December 2013. This type of chart can, for instance, be used to support a storage strategy optimization that aims at reducing the number of movements with zero load.

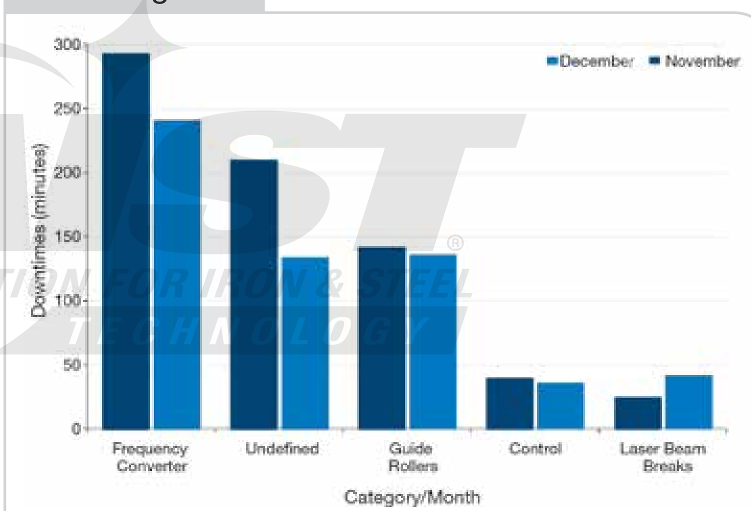
Pareto Diagrams: A Pareto diagram is a special type of bar chart that represents bars organized in a descending order. This type of diagram is based on the Pareto principle, also known as the 80/20 rule. According to the Pareto principle, the majority of results originate from a minority of inputs: approximately 80% of results stem from 20% of causes, or, in other words, 20% of causes produce an effort of 80%.[2] A Pareto diagram is especially suitable for troubleshooting categorized incidents because it provides an at-a-glance overview of the causes that led to the highest number of incidents. For a particularly effective analysis, data that was previously collected by maintenance personnel can be included — for example, data relating to defects that were descriptively categorized after the

Figure 3



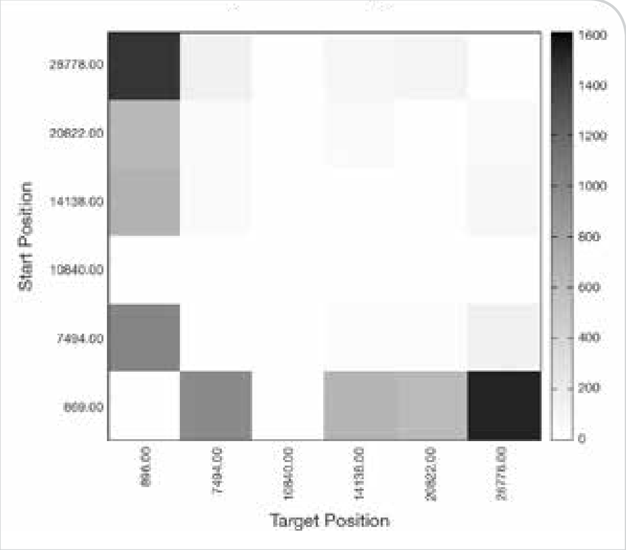
Load weight distribution in kilograms per number of crane movements performed (1 month).

Figure 4



Pareto diagram with crane downtimes categorized according to root cause (comparison November/December 2013).

Figure 5



Rainflow matrix showing the frequency of crane movements.

issue had been resolved. It also indicates the order in which root causes may need to be identified and resolved during troubleshooting.

Apart from the number or frequency of incidents, a Pareto diagram can be based on a variety of evaluation criteria and can contain information such as the duration of maintenance-related downtimes after a particular incident. The sample Pareto diagram in Figure 4 illustrates the duration of downtimes over a one-year period, categorized according to root cause.

Rainflow Matrices: The so-called rainflow matrix is a particularly useful tool for evaluating and optimizing warehouse storage strategies. It can, among others, be used to visualize the frequency of crane movements within a matrix. Figure 5 contains a rainflow matrix for an automated crane system. The start positions are shown on the y-axis; the target positions to which the crane was instructed to move are displayed on the x-axis. In this example, the frequency of movements is shown in varying shades of gray but can be displayed in color.

Figure 5 illustrates that the longest distances (darkest boxes) were also the most frequently traveled. In a real-life application scenario, the efficiency of the crane system could be considerably improved after a warehouse strategy was revised using a rainflow matrix.

Additional Tools

Apart from graphical representations, a variety of additional tools can be used for maintenance optimization. The crane condition can serve as a tool for optimizing maintenance activities. An overview over the machine condition, the traveling profile and the total mileage are important key indicators for dynamically planning usage-based maintenance activities. Additional tools are listed as follows.

Timeline — A timeline provides a means of recording and graphically displaying events. It can include events like maintenance activities, incidents, planned downtimes or the introduction of merchandise with a higher load weight. A timeline can contribute to improving both troubleshooting efficiency and maintenance planning efficiency.

Dynamic Alerts — Planning is in integral part of an effective maintenance strategy. A usage-based predictive maintenance strategy that goes beyond corrective or calendar-based maintenance can include dynamic alerts. Dynamic alerts for different key performance indicators, such as crane mileage or target/performance variance, can be defined. Individual threshold values for dynamic alerts are crane-specific, and a threshold value for a crane with a span of 5 m can considerably differ from a threshold value for a crane with a span of 60 m. Therefore, the definition of thresholds will largely be based on empirical data and previous experience.

Specific alert trigger events can be established and linked by operators such as “OR” or “AND.” If crane mileage is used as a key performance indicator, mileage alerts can be combined with alerts relating to maintenance deadlines, among others. For example, a maintenance task may be triggered only when the last task was at least six months ago AND the crane has traveled at least 600 miles total in the past six months.

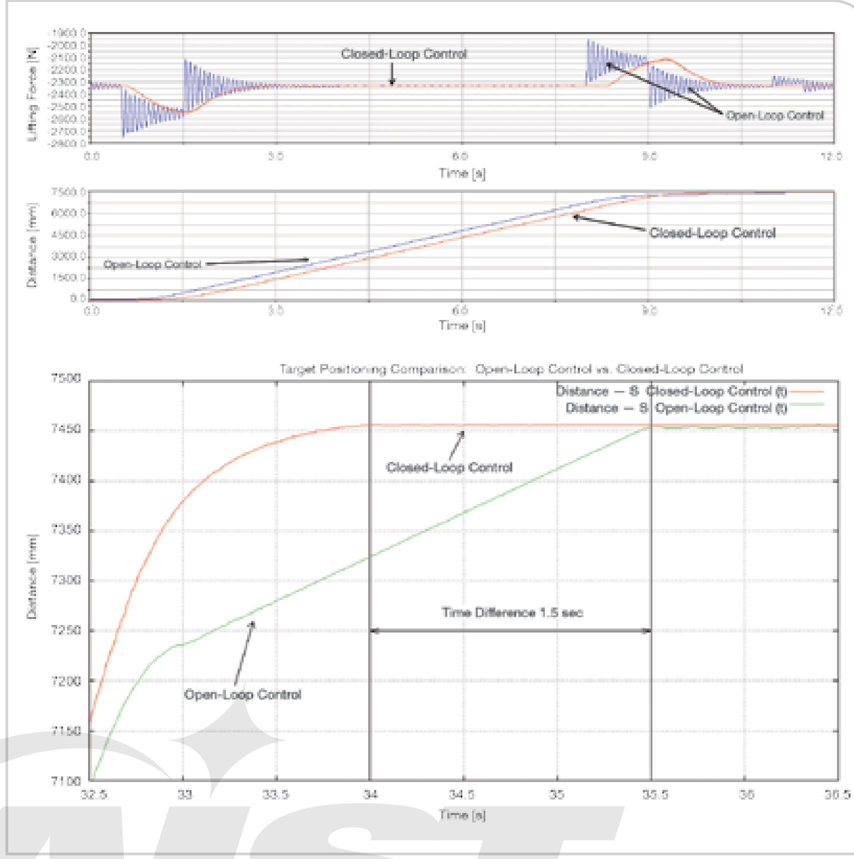
Automated and Ad Hoc Reports — Periodically created automated reports that include predefined key performance indicators or charts are useful tools for evaluating crane condition. Supplemental indicators can be defined to further optimize maintenance activities. They can also serve as important tools for assessing and monitoring the effectiveness of previous maintenance activities. They provide answers to important questions such as: Has the number of incidents decreased? Were maintenance activities planned more efficiently?

In addition, reports should offer the flexibility of being delivered to chosen staff or supervisors on a scheduled basis or be run on an ad hoc basis. A maintenance supervisor may wish, for example, to see what the planned maintenance activities will be for the coming month for each crane in the plant, and may choose to have that information emailed to him/her every other Monday morning.

Important Factors That Contribute to Lowering Maintenance Costs

Easy Access to Graphical Analysis Tools — Graphical analysis tools can substantially promote maintenance efficiency. To this end, data has to be recorded and stored at a dedicated and easily accessible location in a meaningful format that can be easily visualized and analyzed. A variety of data formats that are recorded in different locations can further complicate a comparison. A good strategy is this: all data should be processed and stored in the positioning controller itself, since the most important crane data are readily available from the device. End users should be able to easily access the data via a freely customizable browser-based dashboard.

Figure 6



Machine modeling comparison (open-loop vs. closed-loop control).

Machine Models — Modern drive systems are usually configured and fine-tuned for a specific motor. A closed-loop control system that uses a complete machine model, which includes the crane's mechanical components, makes positioning control considerably more effective. It enables faster positioning by reducing creeping speed. It also reduces machine oscillations and thereby mechanical stresses. This permits a throughput increase of up to 15%, while reduced mechanical stresses translate into lower maintenance costs. The diagrams in Figure 6 illustrate different machine models used for open- and closed-loop control. The graph on top shows machine models relating to the lifting force of a crane system. The graph in the middle shows machine models relating to the distance traveled. The graph on the bottom contains a magnification of the distance graph for open-loop and closed-loop positioning. The closed-loop controller reaches the target position faster with a time difference of 1.5 seconds.

Energy-Optimized Travel Profiles — In crane systems with multiple axes for bridge/gantry and trolley travel, axes can be moved simultaneously, but storage or retrieval processes can take place only after both axes have reached their defined target positions. Since one axis will reach the target first, the velocity of this axis can be reduced so that both axes arrive at the respective target positions simultaneously and in the same amount of time required for regular axis positioning. The synchronized and energy-optimized movement of both axes reduces energy consumption, as less energy is required for positioning. In addition, energy-optimized travel profiles reduce system wear and mechanical losses. Reduced wear, in turn, contributes to lower maintenance costs and increases the life-span of individual system components.

Conclusion

A wide variety of data can be collected during regular crane operation. It can be used for a number of different purposes, including:

- Faster troubleshooting for reduced downtimes.
- Identifying optimization potentials and defining measures to increase throughput.
- Identifying and eliminating weak spots in the crane's motion profile to reduce repair and maintenance costs and to extend usable life of equipment.

- Anticipating the crane condition and identifying vital key performance indicators for a predictive maintenance strategy.

Different types of data — for example, travel distance and crane mileage, velocity and acceleration, setpoint values, target/performance variance — and additional tools, such as recorded frequency converter currents, load weight or temperature information, were presented. An effective data analysis requires a central storage location that provides easy and transparent data access. When combined with empirical, maintenance-related knowledge, past data can be used to predict future events and dynamic alerts can be set up to alert operators and maintenance personnel when threshold values have been exceeded.

These powerful tools contribute to the development of a dynamic, usage-based predictive maintenance strategy. It is, however, important that the results are validated to ensure that the implemented measures have the desired effect. Periodic automated reports that include the trend development of key performance indicators can be used for this purpose.

To date, the above-mentioned tools consistently yielded positive results for PSI Technics. Measures that were implemented in practice based on the results of similar analyses had a noticeable effect on industrial processes and increased the efficiency of crane systems. By reducing positioning time and expenses for maintenance and by increasing system throughput, cost savings of more than 20% could be achieved. Additional cost savings can be realized when manual cranes are retrofitted with an efficient controller for semi-automatic operation without modifying existing components or processes.

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