With a worldwide production capacity of 40 million metric tons per year, primary aluminium for 95 billions US$ enters each year into the economy and is processed in industries estimated at a market capitalization of 225 billion US$. Among these, firms processing flat aluminium products, including recycling, are estimated to have a market capitalization of 74 billions US$. A dramatic fall for primary aluminium prices occurred in 2008, when from a high of 3200 US$/ton in the first quarter, prices went down to 1300 US$/ton in the fourth quarter. Although prices have been slowly increasing since then and reaching now 2380 US$/ton, there is an estimated overproduction capacity of 12%, which is projected to increase to 22% until 2012. Under these conditions, both greenfield and existing plants can achieve cost benefits only under wisely planned strategies. Using energy benefits is a classical competitive factor in aluminium industry, such as United Arab Emirates capitalizing on their excess of natural gas reserves. The global conditions facing the industry show that in fact a large and expensive production infrastructure needs to be continuously upgraded and maintained to achieve cost benefits that can withstand fluctuating aluminium prices, high energy costs, overcapacity periods and a complex technological competitive climate.

In a mature industry such as aluminium production, it is known that new technology may counteract at some level energy costs, fluctuating prices or overcapacity. Energy costs can be reduced with a production gear that results in less scrap and in products with homogenous properties and strict tolerances. Fluctuating prices and overcapacity can be balanced by a flexible production that eases introduction of new advanced products with reduced set-up efforts and low upgrade costs.

An interesting question then is if some general principle could identify or quantify when is a plant technologically fit to sustain a long-term competitive market position? To identify such a principle we can start with the most important physical objects in a plant: sensors and mill actuators.

At a certain level of abstraction, each sensor has a set of measurement variables that can be described as a mathematical space - e.g. a vector or a matrix of appropriate dimensions. For example, a flatness sensor (e.g. the Stressometer from ABB) used in cold rolling has as output a vector of flatness values that are sampled across a metal strip. In turn, actuators have command inputs which are described again as a mathematical space of appropriate dimension.

The key functionality of a plant is given by the time evolution of the span of the measurement space intersecting the span of the actuation space. This is called the control space, and includes both discrete and continuous process control. A rolling mill is usually both overactuated - several actuators have about the same effect - and underactuated - some control space cannot be covered by any actuator. Especially in hot mills, the sensor space is often under-dimensioned due to difficulties in measuring some physical process parameters. Thus the evolutionary technology by which actuators and sensors cover increasingly higher areas of the control space, quantifies essentially the competitive strength of a plant.
tant sensors in a mill can be used: load sensors for looper tensiometers and roll force measurement sensors. ABB Force Measurement has recently delivered such sensors to the Chinese company Qinghai Ping Aluminium High Precision Machining Industrial Co., Ltd, Xining, Qinghai province.

The input into the rolling process is aluminium slab of 400-600 mm thickness. After pre-heating to 500°C and rolling, the exit strip thickness is in the range of 18-45 mm. This material is heated again to 400°C and then it enters into a tandem hot rolling mill (Figure 3) as strips of 20-45 mm thickness. The output thickness is typically between 2-10 mm and the strip temperature is about 320°C. The material follows a forced cooling and then a cold rolling.

If we concentrate just on the tandem mill, each stand has actuators modifying the roll gap with a rolling force \( P \). A large part of the reduction power comes from a main drive (one per each stand) which turns the working rolls. The speed of the working roll is a controlled variable - a part of the actuation space. As shown in Figure 3, loopers between stands create a buffer of strip that avoids the strip to become too short or too long. Loopers have several sensors. The most important is the force sensor placed in the arm at

A simple example can clarify this. If sensors and actuators are drawn on the X-Y axis, their interaction is the diagonal dotted line shown in Figure 1. Each actuator has few dedicated sensors and a dedicated control system will position actuators based on sensor information. This is the traditional sensor-actuator digital solution introduced some 20-25 years ago. For example, an automated gauge control system measures strip thickness (sensor) and modifies roll forces (actuator) to achieve the target thickness.

By contrast, for modern plants the mapping tends to span over a large area of the actuation and sensor space, and it could appear as shown in Figure 2. The benefits of this trend can be illustrated by the different ways two impor-
solid blocks of metal that can be substantially overloaded both mechanically and thermally without suffering damages. The patented Pressductor principle using magneto-elastic properties of special materials is among the most robust sensor technologies available today due to stability of components, signal energy and bandwidth: sensors that are robust against electrical, magnetic and thermal disturbances.

As a comparative argument for load cells stability, Figure 7 shows a Millmate Looper Tensiometer placed in the hot rolling line of a steel plant. This is one of the most demanding environments found in industry today, environment in which such sensors work for many years without any recalibration or other maintenance.

Let us analyze the Looper Tensiometer as a point in the Sensor - Actuator space. The looper arm is an actuator that maintains a buffer of the strip length within defined limits. The arm is also a sensor: it measures force, angular position and hydraulic pressure.

Different stages in the Sensor - Actuator space, each going further away from the diagonal line in Figure 1, could be as follows:

**Stage 1:** The output is a simple force value and a controller is doing the arm positioning. This is the traditional case, when the sensor gives some raw physical value, without any regard to the application. This would be a single circle in the control space in Figure 1.

**Stage 2:** The arm has an equation:

\[ T_f = \frac{1}{c} (Q_L - aP - bT_b) \]

where \( T_f \) is the forward strip tension, \( Q_L \) is the torque of the mill motor, \( P \) is the rolling force sampled by the roll force measurement system, \( T_b \) is the back strip tension and \( a, b, c \) are constants. If the system can be upgraded to compute on-line the arm equation and if all parameters are known, then the forward tension \( T_f \) can...
Stage 3: Keeping the thickness profile during hot rolling under given tolerances is essential since even small deviations can produce material defects in the downstream processes. Indication about such tolerances can be obtained again from several roll force sensors and looper tensiometer force sensors. Load cells and loopers are placed on the two sides of the mill (Figure 3). This gives indirect information about strip thickness and thickness asymmetries. Parameters for physical models or dynamic state-space models for thickness profile can be identified at this stage from first principles, correlators, learning systems, or state observers. The result is an estimate profile that enters into the sensor space and can be used in the downstream control as feed-forward information. In the other direction, information from the cold rolling process can enter into the hot rolling control space and adjust tolerance parameters to keep the downstream process parameters in a safe range. In this way, the sensor-actuator space has increased to span over both cold-rolling and hot rolling.

Stages can be continued in this way and finally give quality products to customers - such as via post-rolling flatness. Properties of the strip at the customer are used to identify models for post-rolling flatness and the resulting predictors are entered into stages 2 and 3. Thus a large part of the sensor-actuator space has now been covered as shown in Figure 2.

Conclusions

Modern mills are optimizing their costs by increasing the validated information available in the overall stream process. Essential ingredients are reliable and flexible sensors that cover as large an area as possible of the sensor-actuator space. As shown in this article, it is never wrong to have many sensors: over-populating the sensor space turns out to be very useful to improve the performance of the mill. The interplay among sensors, models and system identification methods, increases the control space. This increase is a mark of a modern, maintainable and competitive plant. ABB Force Measurement has a range of measurement products with a standing reputation in industry, ready to be used in such advanced applications.

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