Automatic Control of Colour-Coating Lines

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A System for Automatic Control of Colour-Coating Lines

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Surface finish plays an important role in the metal processing industry. Galvanised strip is coated on both sides with one or more layers of paint to obtain certain desirable surface properties such as colour and corrosion resistance. The strip is then used for the manufacture of washing machines, electrical control cabinets, car parts, etc. for which the paint has to fulfil certain requirements regarding adherence to the galvanised strip, resistance to environmental conditions, and colour. In addition to other parameters, the uniformity of the paint profile is of critical importance in determining the quality of the paint finish.
This article describes a system for the automatic control of colour coat lines. It explains how the use of this advanced control technology can significantly reduce paint profile variations, thereby resulting in considerable reductions in paint consumption. The article also provides a brief overview of colour coat technology and describes the mathematical models that have been developed for use in paint coating weight/thickness control.

One important way of exploiting the potential of production lines more effectively is to optimise control and automation systems. This measure is aimed at improving the yield of products which are subject to ever narrower tolerances, increased throughput, demands for better energy conservation and lower material consumption – with associated reductions in cost.
Using strip coating as an example, this article shows how an advanced (model-based) control system can reduce paint profile variations significantly thereby reducing paint consumption considerably. It also outlines the technology of colour coating and describes the mathematical models used.

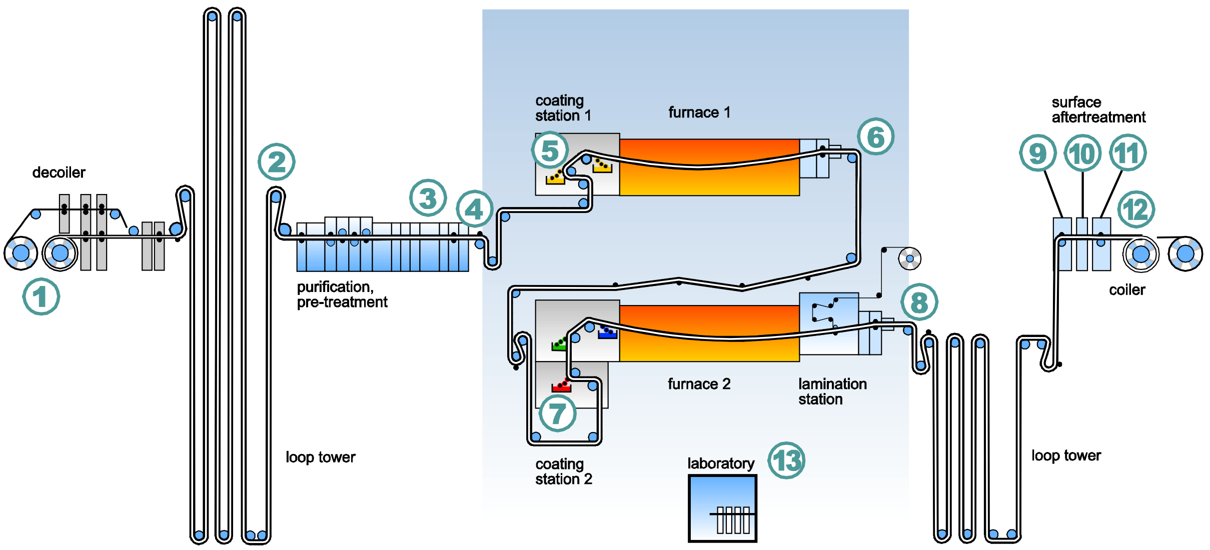

Fig. 1. Typical layout of a colour-coat line

Industrial strip coating

Process description. The term “colour coat” describes the application of organic protective coatings on metal strip in coil treatment lines, see **fig. 1**. In preparation for the application of colour-coat paints, the strip is cleaned and coated with an intermediate layer of a non-metallic material. Thereafter the coating materials are applied in liquid or solid form, one or more times, and oven-dried. This can be followed by further steps such as embossing, printing and coating with protective films.

Beginning with cold-rolled, multiple metallic-coated strip, this process produces a coated semi-finished product in just a few minutes. It can then be recoiled at its original width, slit into several narrow strips, or cut to length in sheets and stacked.
Basically, all steel coils with metallic coatings (tin or zinc electroplated, chrome-plated, hot dip galvanised, or hot dip aluminised), and aluminium coils, can be used as base materials. Organic coating materials are thermoplastic and thermosetting (cross-linked, duoplastic) paints in the form of solutions or dispersions as well as thermoplastic films; see also [1].

Fields of use. Surface finish plays an important role in the metal processing industry. Painted strip is used in many fields, for example in the automotive industry (auto bodies), in the home (washing machines, refrigerators), in the building industry and in packaging lines.

Coating weight/thickness measurement.
A coating weight gauging system (**fig. 2**, see also [2]) measures the individual coating layers.
For this, it is necessary to measure the infinite thickness values of the base material and the coating material. The following gauging equipment is needed for the top side strip measurement, as shown in **fig. 3**:

- measuring point for steel base material and galvanised sheet steel
- measuring point for conversion layer (e.g. chromate)
- measuring point for primer coat
- measuring point for finish coat

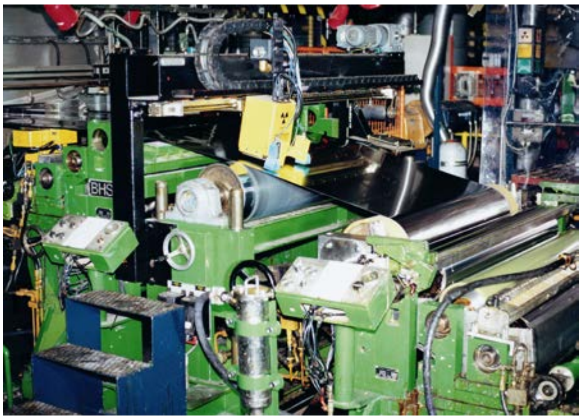

Fig. 2. Paint coater – scanning gauge

To illustrate this, a multi-layer paint coating is shown in **fig. 4**. Each individual measurement needs the data from the previous measurement and the infinite thickness value of the coating material in order to determine the coating weight.
The infinite thickness value of the coating material is determined by measurement in a test gauge (laboratory gauge) directly before application in the coating line. It is measured in a wet state (wet index) and dry state (dry index). It is also possible to calculate the dry index from the wet index.

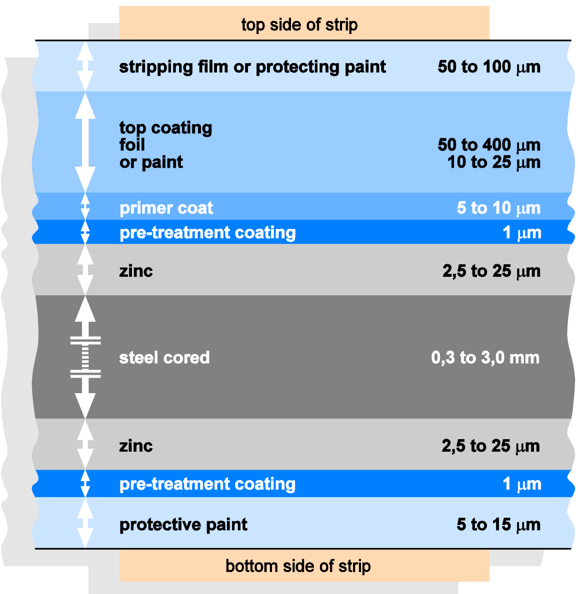

Fig. 3. Schematic presentation of a layered paint coating on galvanised steel strip

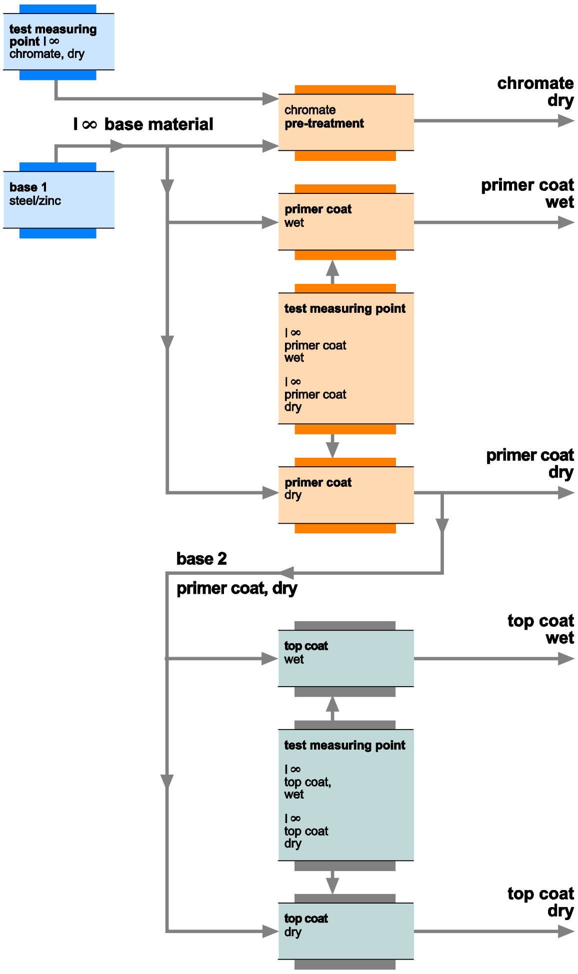

Fig. 4. Signal flow diagram – multi-layer measurement

The coating weight can be determined on the top and bottom sides of the strip, in a wet or dry condition. The wet measuring points are situated directly after the coater and transmit measured values for fast-acting coating weight control. Dry measuring points are located after each drying oven. The primer coat and finish coat are measured separately. Due to the small distance (air gap) between the coated strip and the measuring head, for primer coat and finish coat measurements (approx. 20 mm), a weld-seam detection system is built into the gauging system.

Control - in practice. There is not a great deal of literature describing the control of colour-coat processes. Most paint lines are still operated inmanual mode, or equipped with simple PI controllers. Both these methods of control produce unsatisfactory results because of the complexity of the process and the long time-lags inherent in the process. In [3] the author speaks of computer-based presetting, without discussing this in greater detail. In any event, it seems that automatic control of paint coating weight has not yet reached a particularly advanced state, let alone become standard practice.

Mathematical process modelling

Model coater. The multi-roll coating system used for top and bottom side paint coating (fig. 5) is operated in so-called "reverse" mode, see [4]. In this process, the pick-up roll R_2 'lifts' paint out of the bath. This flow of paint is referred to as Q_0. Q_0 is divided into flows Q_1 and Q_2 by the action of the dosing roll (measuring roll) R_1 pressing against the pick-up roll R_2 with force F_{n12}. Flow Q_1 is wiped off with a blade and returned to the paint bath. The applied force F_{n12} is not identical to the piston force F_P, measured by the load cells in the hydraulic actuators. It depends far more on both the positions of the rolls with respect to each other, and the diameters of the rolls, R_1 and R_2, and on the friction conditions between the dosing roll and the pick-up roll.
Considered in greater detail, the flow Q_2 is divided into flows Q_{2n} and Q_3 as a result of force F_{n23} applied between the pick-up and coating rolls, R_2 and R_3. (The flow Q_{2n} will be ignored for the time being in the further examination below.)
Accordingly, Q_2 is picked up completely by the coating roll R_3 on first convergence, and applied completely to the coated strip carried by the transport roll, R_4. The thickness of the paint coating therefore depends on the forces between the rolls, on the direction and speed of rotation of the rolls, and on the viscosity, density and temperature of the paint.
Seen from a process point of view, the applied force between the dosing roll and pick-up roll, and/or the position of the dosing roll, appear to be the appropriate manipulated variables for colour-coat thickness control. Disturbances caused by the flow conditions between the dosing roll and pick-up roll can be eliminated by the action of the pick-up roll and coating roll. In addition to this, the flow conditions between coating roll and the strip are kept constant, as a result of which a more uniform paint coat thickness profile is achieved.

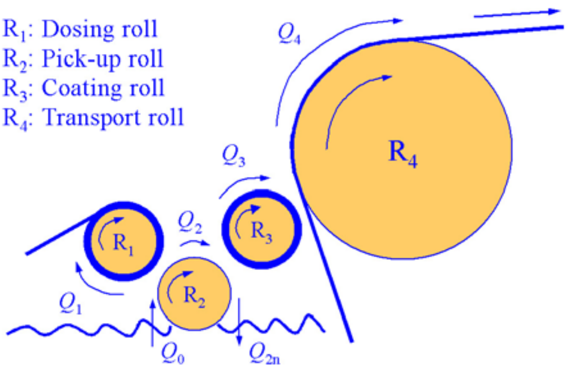

Fig. 5. Schematic presentation of a four-roll coater operating in reverse mode

As far as the authors are aware, at the time of designing the paint coating system there was no model available describing the non-linear dynamics of a coating system operated in reverse mode. For this reason, a data-based model was developed. Subsequently, data was collected over a period of approximately one month and analysed.

Data-based analysis of the influencing factors. Initially the cross profiles were broken down into the following components:

- mean value (g_0)
- slope (g_1)
- crown (g_2)

In order to obtain a better idea of the correlations between the individual profile components and the system parameters, the data was examined further. In order to cope with the immense volume of data to be examined, the software tool DATATools [5], developed by BFI, was used. This tool enables the fast, systematic and clearly-recordable analysis of data.
The first task was to establish the main factors influencing paint coating thickness. Linear correlation examinations proved fruitless. Extended methods of examination were therefore applied. DATATools offers a non-linear correlation analysis based on Kohonen self-organising maps (SOMs), which produce a hierarchical ranking of the main influencing factors affecting paint coating thickness:

- force applied to the pick-up roll
- speed relationships between the individual rolls
- paint density
- paint viscosity

Building on these analyses, a simplified control model was developed.

Simplified control model. Based on the above considerations, it can be shown that the slope of the paint profile depends on the difference between the force applied to the pick-up roll on the operator side $F_{m,o}$ and that applied to the drive side $F_{m,d}$. The mean value of the paint profile depends on the sum of both applied forces, likewise the crown component, see fig. 6. The crown component is ignored for further modelling because it cannot be set independently of the mean value for want of additional actuators.
This results in the following basic model of the adjustment force and the paint coating thickness (measured at the wet measuring point):

$$\begin{aligned} g_0(k) &= K_{go} F_{\Sigma}(k-1) + f_{g0} \\ g_1(k) &= K_{g1} F_{\partial}(k-1) + f_{g1} \end{aligned} \qquad (1)$$

where

$$\begin{aligned} F_{\Sigma}(k) &= 1/2\left(F_{m,o}(k) + F_{m,d}(k)\right) \\ F_{\partial}(k) &= 1/2\left(F_{m,o}(k) + F_{m,d}(k)\right) \end{aligned} \qquad (2)$$

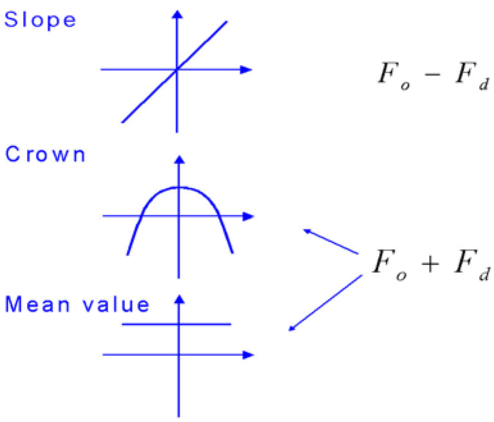

Fig. 6. Breakdown of paint profile into separate components

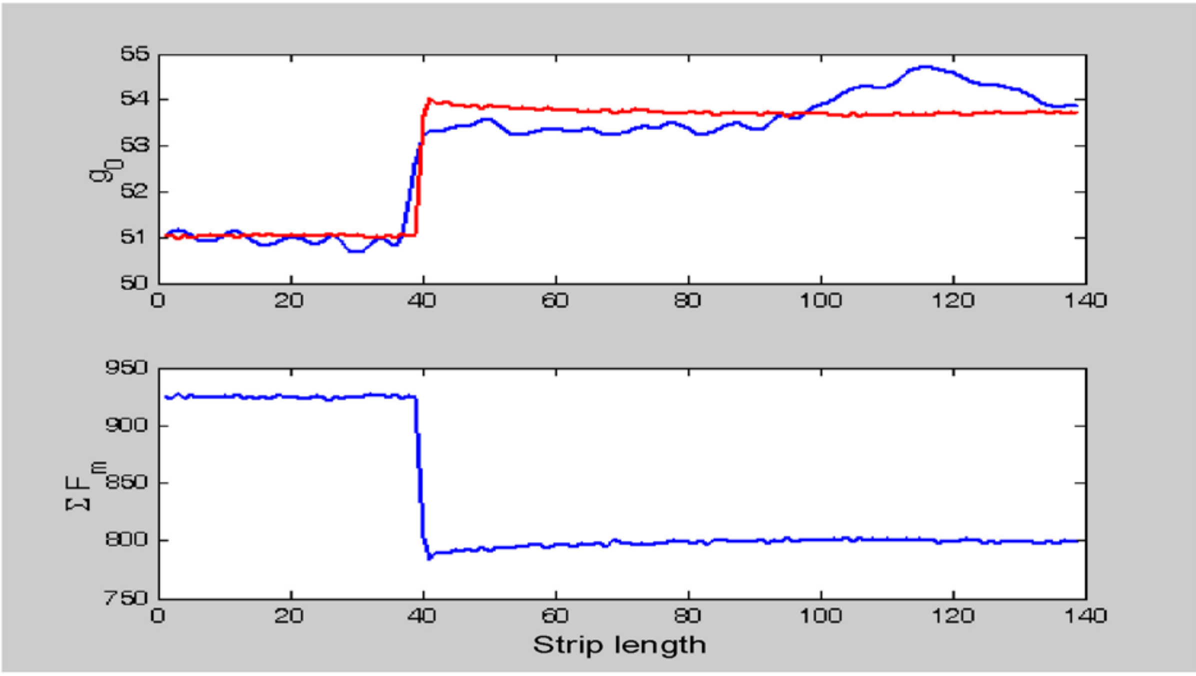

Fig. 7. Step response trial for parameter determination

To determine the model parameters, data was collected over several months. Every time the operator has to correct the paint coat thickness by hand, step changes in the manipulated variables and paint coat thickness occur, as shown in fig. 7.
The data were used to determine the model parameters. The case shown in fig. 7 resulted in the following parameters:

$$K_{g0} = -0.0216 \frac{\mu m}{N} \qquad f_{g0} = 70\ \mu m \tag{3}$$

The parameters for all cases examined lay in the intervals:

$$\begin{aligned} K_{g0} &= [-0.024 \quad -0.001]\ \mu m/N \\ K_{g1} &= [-0.029 \quad -0.004]\ \mu m/N \end{aligned} \tag{4}$$

Due to large variations in the parameters, control with fixed parameters is unsuitable to achieve the quality of control required by paint manufacturers.

Model drying oven. The oven located downstream of the coater can be described more or less as a dead time section

$$\begin{aligned} g_{t,0}(k) &= K_{t,g}\, g_{0,c}(k - T_t) \\ g_{t,1}(k) &= K_{t,g}\, g_{1,c}(k - T_t) \end{aligned} \tag{5}$$

where the dead time, i.e. the transport time from the wet measuring point to the dry measuring point, depends on the strip speed:

$$T_t = \frac{L}{v(t)} \tag{6}$$

The reduction of wet coating thickness to dry coating thickness (wet-dry factor) depends both on the density of the wet paint and the dry paint, and on the solids content:

$$K_{g,t} = \frac{\sigma_{wet}}{\sigma_{dry}} \frac{\eta_{solid}}{100} \tag{7}$$

These values are already known from laboratory trials and can generally be taken to be safe parameters, with the result that no model uncertainties arise in this sub-model.
Building on the models developed during this phase, an automatic controller was then designed.

Modern paint coat thickness control

Controller structure. Due to the time-dependent dead time between dry coating measurement and wet coating measurement, a multivariable cascade controller based on Morari's Internal Model Control principle [6] was developed. The control structure is shown in **fig. 8** [7; 8].

To allow for different operating conditions (type of paint, wear and tear), the controller gains are adapted with the help of a robust gain scheduling method (i.e. a gain changeover strategy). Since the process gain changes during the application of a particular type of paint, the controller must be robust to this. The controller was therefore designed in such a way that it did not overshoot, even with a parameter error of up to 30 percent, and simultaneous falls below a minimum response time.
The gain factors were calculated beforehand on the basis of recorded data, and stored in a table. The factors for paints not entered in the table could be determined by simple preliminary tests.

Mode of operation. To simplify the control task, the operator runs the coating system close to the desired working point. The operator selects the roll speed and the forces between the rolls to achieve a good paint surface quality. The controller then moves the coating system to the working point and stabilises it against disturbances caused by changing roll speeds, temperature and paint viscosity. The controller also manages the desired changes in the nominal paint coating thickness.

Advantages. The main advantages of the control system are:

- explicit dead time compensation
- modular design (enabling sequential commissioning of control functions)
- possibility for simple adjustment to the multivariable controller by the operator, on the basis of a single parameter
- Simple bumpless changeover between the three control modes: wet measuring point only, wet and dry measuring points, dry measuring point only

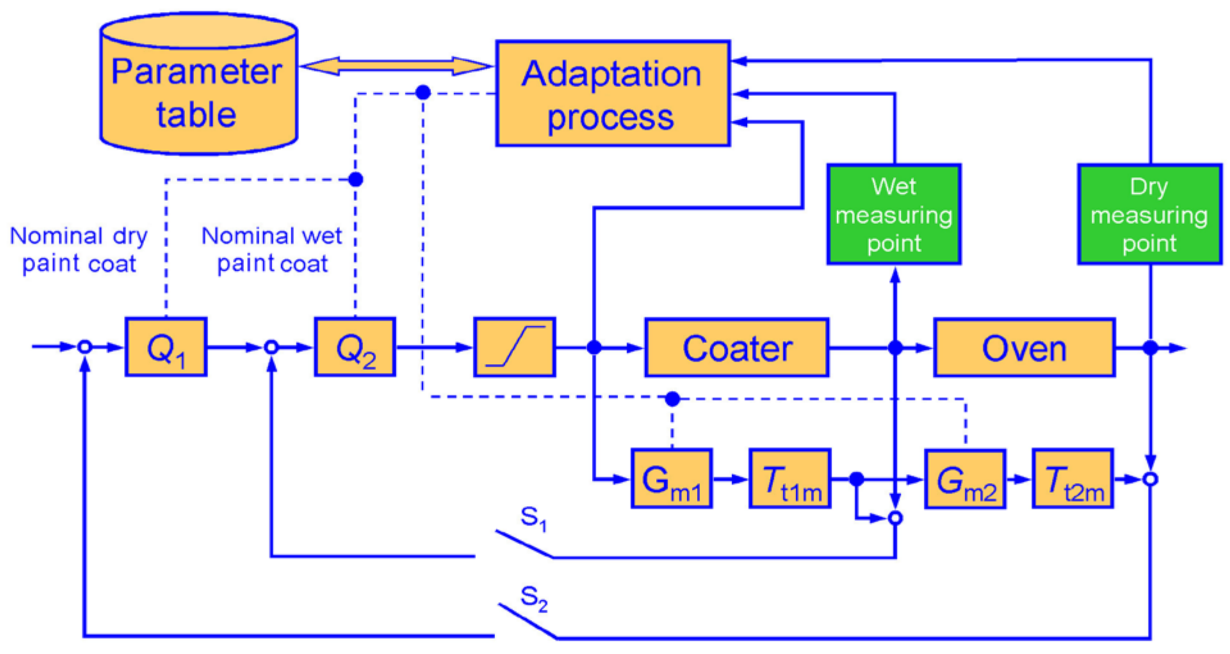

Fig. 8. Selected controller structure

Automation system. The control concept was implemented using the automation system MEVInet from the company IMS Messsysteme GmbH operating under LogiCAD/32, see **fig. 9**. MEVInet is a standardised system for plant automation for the fields of measurement, control, visualisation and quality management. The following main features were taken into account in the development of the system:

- greatest possible transparency of hardware and software (modular design, multiprocessor system)
- use of standard operating systems (Window 2000, CE)
- graphic configuration of the measurement and control functions (IEC 1131-3)
- standardised communication between the individual systems (Ethernet, TCP/IP, InterBus-S, FireWire)
- reaction times in the individual levels adapted to the process
- remote maintenance capability

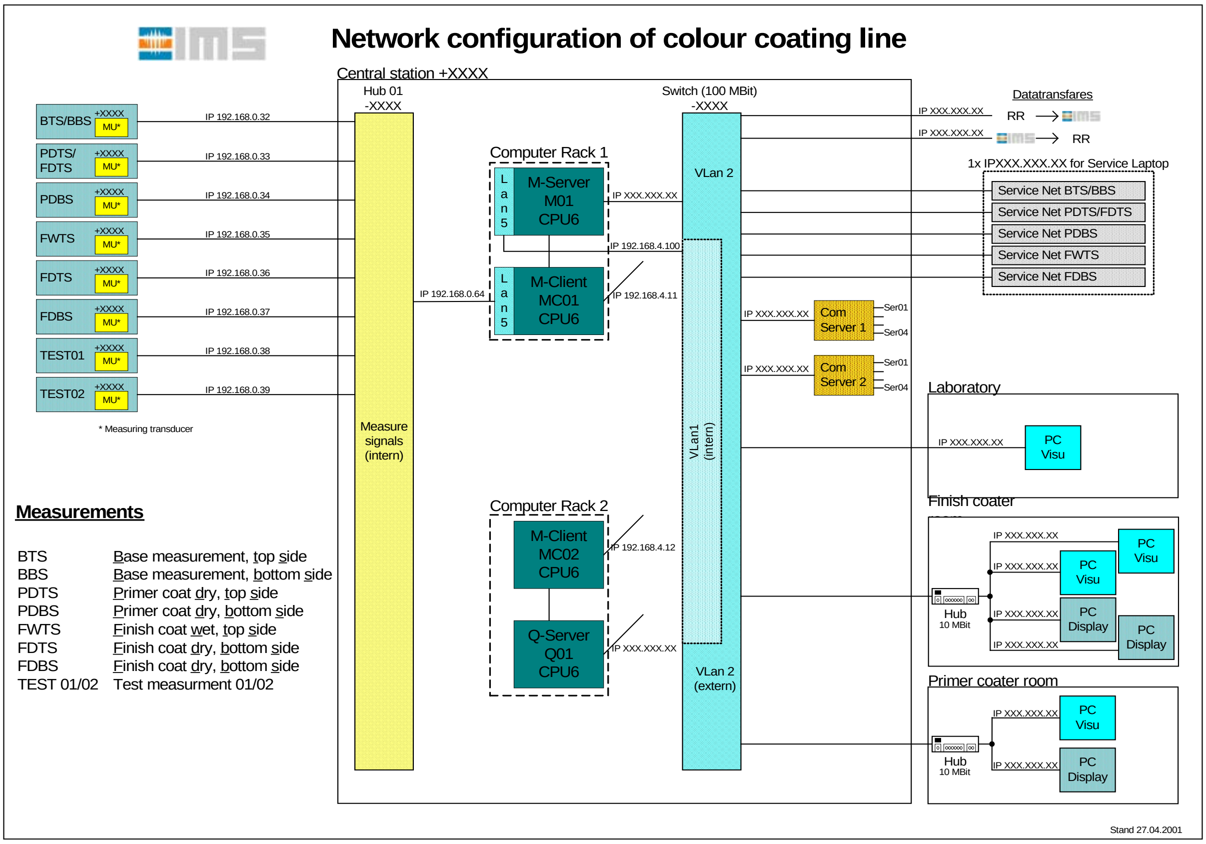

Fig. 9. MEVInet components in a colour-coat line

Initial operating experience

Fig. 10 shows an example of the outstanding results achieved with the control system. The mean dry coating thickness $g_{0,t}$ and the slope $g_{1,t}$ are plotted along the strip length. In addition to this, the applied forces on the dosing roll operator side $F_{m,o}$ and drive side $F_{m,d}$ are also shown. The nominal value of the mean coating thickness $g_{0,t}$ changes at the strip positions $l_1 = 100$ m, $l_2 = 950$ m and $l_4 = 2600$ m.

The temperature of the paint increases between strip positions $l_2 = 1000$ m and $l_3 = 2000$ m because of the high forces applied to the dosing roll. This has an influence on the flow characteristic of the paint between the rolls and, therefore, also on the thickness of the paint. Consequently, the dosing roll is adjusted in order to maintain constant paint coating thickness.

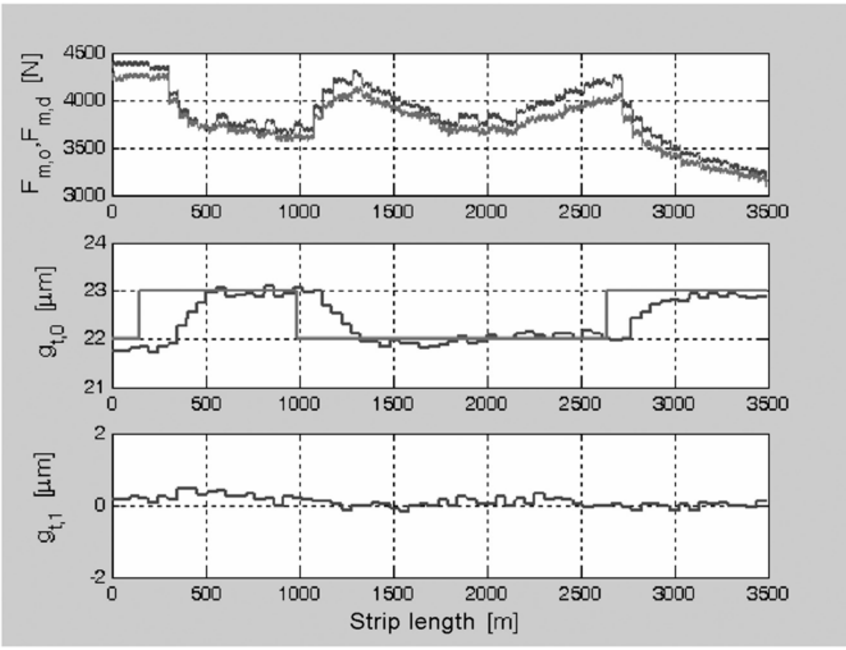

Fig. 10. Typical control results

The paint cools down again from strip position l_3 as a result of the application of fresh, cold paint. As a result of the application of automatic control, it is feasible to reduce the nominal deviation of mean dry paint coating thickness to ±0.3 µm. This compares to a deviation range of -2 µm to 5 µm for an uncontrolled paint line, see fig. 11.

With the installation of a coating thickness gauging system and automatic control system, total annual paint cost savings of up to 10 percent can beachieved. This represents a “return on investment” of approximately 12 months, which is an excellent result.

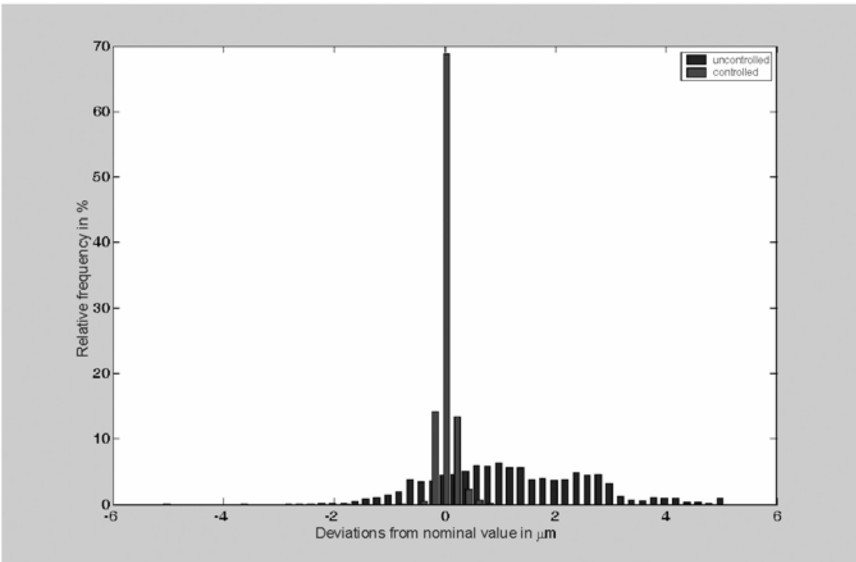

Fig. 11. Typical distribution of paint coating thickness deviation – comparison between manual and automatic operating modes

Conclusion

This article describes a automatic gauging and control system for colour-coat lines developed by IMS and BFI, for which a patent is pending [7]. The system has already been installed and commissioned in one coating line. Initial operating experience has shown the following verifiable customer benefits:

- uniform paint distribution for all paint qualities as a result of high quality measurement and up to date automatic control
- integrated quality measurement and process control in a one complete automation system
- considerable cost savings due to a reduction in the consumption of energy and raw materials
- cost savings of approximately 10 percent through reliable measurement and effective automatic control
- reduced laboratory costs as a result of fewer check measurements

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