THICKNESS CONTROL STRATEGIES OF PLATE ROLLING MILL

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ABSTRACT. *Thickness accuracy of plate production depends on Automatic Gauge Control (AGC) in the plate mill area. A typical modern thickness control system design and implementation of a steel plate mill are discussed together with the impact on the design of process models, available measurements, available control actuators and material properties. A high-level software design approach provides the ability to make quick and accurate modifications to both control loops and tuning constants. Control loop strategies and theoretical concepts of steel plate rolling are discussed. Performance results achieved during the startup of a steel plate mill are included.*
Keywords: Hydraulic position control, Automatic gauge control, Plate rolling mill, Roll thermal expansion, Mill modulus control

1. **Introduction.** Because of the product diversity and the process complexity, the plate rolling automation system is difficult to develop and apply. It has been a long time that only several international famous automation companies could perform this task, such as SIEMENS, VAI, MITSUBISHI, HITACHI [1-10]. Currently the situation changed. In China more and more companies and research institutions can make it happen by standardization and generalization of automation equipment.

In the steel industry, the production of a hot-rolled plate calls for high accuracy in the product specification and high stability of the process. AGC system is installed in the four-high plate mill, and it is the most important mechanism for dynamic thickness control in conventional rolling mills. Since the AGC system is responsible for maintaining the dynamic performance of the predicted quality of thickness, it is designed to be able to suppress the disturbances of the rolling process such as hardness and temperature fluctuation of the strip. The extremely sophisticated algorithms are developed to fulfill the task of dynamic thickness control; however, the philosophy and the principles for tuning AGC control gains become very complicated and difficult to the operators in seek of improving the quality for specific product and process [11].

The schematic diagram of a plate mill is shown in Figure 1. The mill stand consists of a mill housing containing two cylindrical work rolls, which perform the reduction, and a pair of larger backup rolls, which support them. Gap control includes the control for the top mounted variable speed synchronous motor driven no-load screw-downs and a bottom mounted servo controlled hydraulic cylinders [12]. These two actuators are controlled as required to support roll change, plate rolling and mill testing.

The thickness of the steel is controlled by dynamic roll positioning. Because the reduction of hot steel in the roll bite is sensitive to mill speed changes as well as temperature

1:worm gear reducer
2:screw-down gear
3:load cell
4:upper backup roll
5:upper work roll
6:lower work roll
7:lower backup roll
8:sliding plate
9:hydraulic cylinder
10:ram
11:worm gear reducer
12:screw-up gear
M :motor
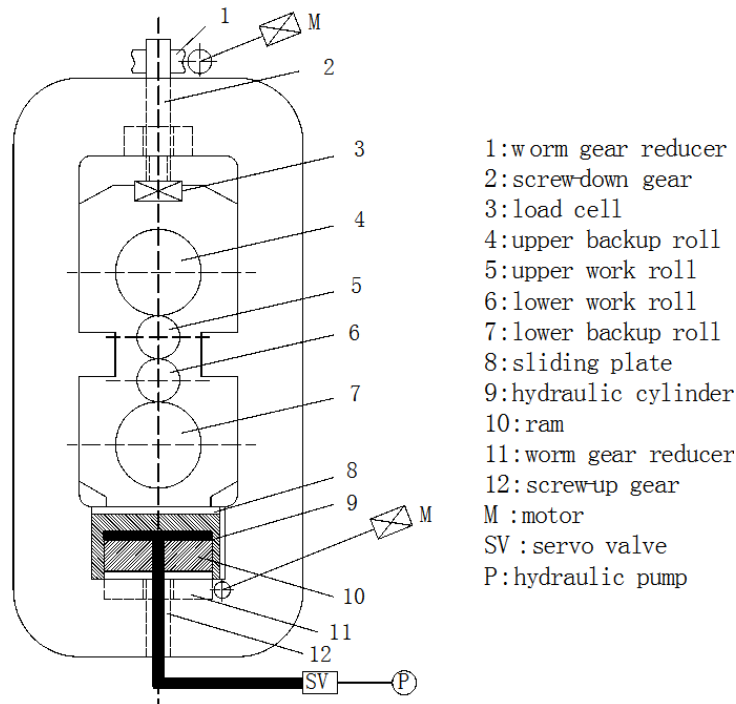SV :servo valve
P:hydraulic pump

FIGURE 1. Schematic diagram of a plate mill

and hardness changes in strip entry, the gauge control must be able to control to the desired thickness of strip in the face of these disturbances. This control involves the careful coordination of a number of strategies. The rolls are placed prior to entry bar of the mill. It involves predictive models of the steel-rolling process, which will give accurate roll-position settings. To produce output strip of the desired thickness, the roll position is then altered during rolling of the bar. This dynamic roll positioning during rolling of the strip is referred to as automatic gauge control (AGC). The results of rolling each strip are further analyzed and used as adaptive corrections to the predictive models [13].

The success of the thickness control depends on the ability of these various facets of the control to blend in a cohesive system. This blending is particularly evident in the successful development of the absolute, or predicted, mode of automatic gauge control. This mode of control involves an intimate connection between the traditional mill setup and AGC functions. It can prove that a structured system design approach is necessary to ensure the proper integration of the various components of the thickness control [14].

2. Gap Control.

2.1. **Screw-down control.** Screw-down position can be adjusted manually by the operator by a fixed speed reference to the motor drive or in a closed loop position regulator configuration that automatically adjusts the speed reference to the drive. When the clutch is opened each side can be adjusted independently to change the level of the top roll stack. Each screw has a brake that can be set to stop movement.

Normally the screws on both sides of operator and drive are mechanically coupled by an electromagnetic clutch so that both sides move the same amount to maintain average position. For open or close movements the clutch is closed to couple the sides. When coupled, the average position feedback is used and a speed reference is applied to one side while the other side operates as a current follower. For leveling movements the clutch

is opened to allow individual move on each side. During leveling the screw on each side operate as individual position regulators.

2.2. Hydraulic cylinder control.
Cylinder position is controlled by a closed loop position regulator that automatically adjusts the flow according to a hydraulic servo valve. There are regulators on both sides of Operator and Drive respectively. Both sides are coupled together by software control. The control maintains the level of two sides when they move together. Each side has blocking valves that can stop motion of the cylinder and a vent valve that can relieve cylinder pressure. The hydraulic cylinders set the pass line and change gap opening while rolling to maintain strip thickness.

The position regulator calculates the error between the reference and feedback position. The error is used by a speed balance control to keep either the operator or drive side from lagging behind during long movements of both sides. This will prevent excessive tilt of the roll stack during movements. The control acts by reducing the servo valve flow command for the side with the smaller error and increasing it for the side with the larger error. A deadband causes this control to only act when the difference exceeds a specific amount.

Hydraulic cylinder control also includes a total force regulator with a differential position loop to maintain the stand level. The force regulator is only used during special sequences like establishing light force and gap zeroing.

3. Architecture of Automatic Gauge Control System.
Figure 1 shows two kinds of mechanism for roll gap adjustment: one is to control the position of a screw-down by an electrical motor control unit, and the other is to regulate the cylinder position via a hydraulic servo control system. The former is the so-called Electrical AGC system (EAGC), which is popularly adopted in traditional plate mill; the latter is the schema of Hydraulic AGC system (HAGC). The main consideration for selection between these two architectures is the cost and the performance of system's dynamic response. Generally speaking, the bandwidth of HAGC system is larger than EAGC system, so HAGC system produces more accurate control result.

Since the AGC system is responsible for maintaining the dynamic performance of the predicted quality of thickness, it is designed to be able to suppress the disturbances of the rolling process such as hardness and temperature fluctuation of the plate. Consequently, as shown in Figure 2, two kinds of algorithms are supplied to provide suitable gap correction for the AGC control system: (1) AGC compensation function; and (2) AGC control function. In these two control loops, the sophisticated algorithms are automatically calculated to fulfill the task of dynamic thickness control; however, the philosophy and the principles for tuning AGC control gains become very complicated and difficult to the operators in seek of improving the quality for specific product and process. Roll-gap errors and strip-hardness errors are the major sources of disturbances. They must be eliminated in the control of strip thickness. The roll gap is modeled by a number of open-loop models, which are calibrated using mill tests. Residual roll gap errors are isolated using X-ray thickness measurements and the principle of mass flow and are used as adaptive feedback for the roll-gap models. These errors are usually small, also because the roll gap can be modeled accurately, the absolute mode of AGC can operate so successfully.

Strip hardness and deformation characteristics are also modeled for the numerous grades of steel and rolling conditions. Errors in these models are isolated using roll-force predictions during the adaptive feedback process. Any remaining steady-state error is removed by the mill vernier feedback, which compares the desired thickness with the actual thickness. These bar-to-bar control loops work in conjunction with the in-bar automatic gauge control.
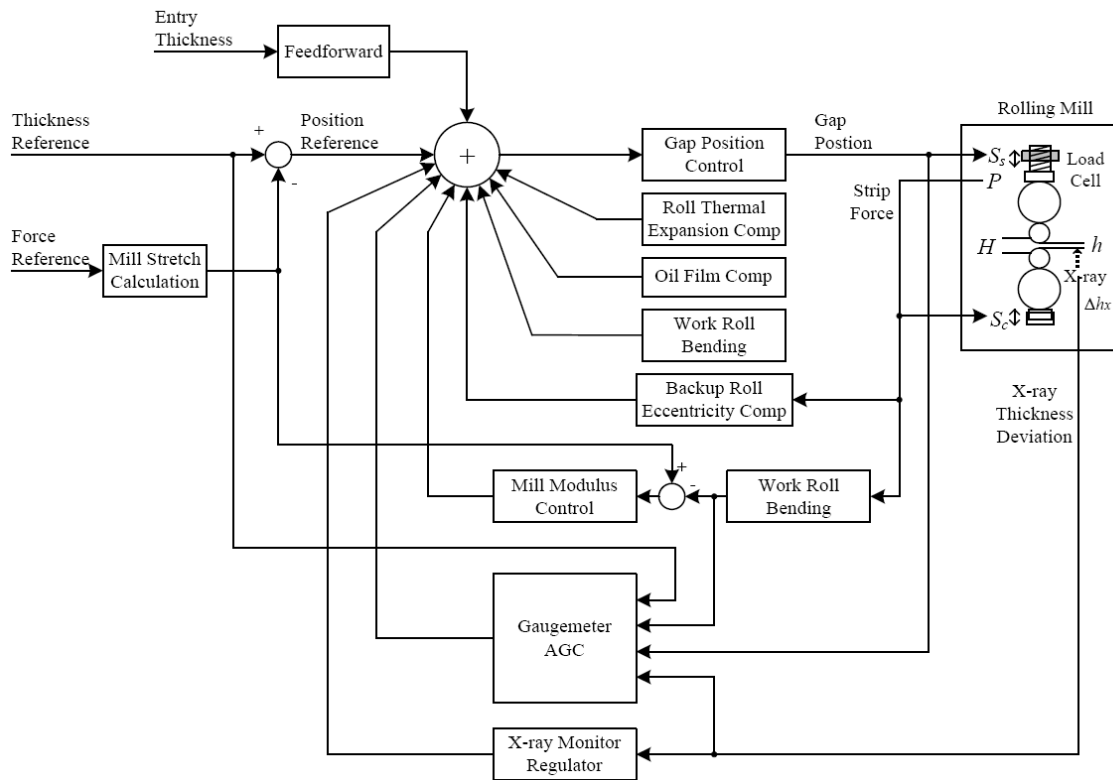
FIGURE 2. AGC block diagram

Automatic gauge control uses two methods to measure the strip thickness. The first uses the roll position and force measurements at the rolling mill stand as the basic one. Strip thickness differs from roll position because of various mill housing deflections and roll deformations, which are compositely known as "mill stretch". The total roll force of the stand reacts to this mill stretch but also reacts to changes in the mill stand. Therefore, while roll position and force measurements offer the potential of an immediate measure of strip thickness at each stand, certain prerequisites must be met. Because roll force is one indicator of mill stretch, it is necessary to know how to extract it and convert it to mill stretch by an accurate transfer function. The control of strip thickness using roll position and force measurements is known as Gaugemeter, or BISRA, AGC, named after the British Iron and Steel Research Association. In practice, different control goal requires different mill modulus in the manufacture process of hot rolling mill [15,16]. AGC can compensate elastic deformation of the rolling mill to a certain extent when rolling force fluctuates. In other words, the mill modulus can be controlled. Therefore, there is a concept of the mill modulus control (MMC) to be brought forward. According to different requirement of rolling technology, different equivalent mill modulus can be obtained while changing adjustment coefficients in the AGC system. MMC also uses the Gaugemeter equation to estimate stand exit strip thickness changes. The second measurement of strip thickness is provided by a thickness gauge at the exit of the plate mill. This device accurately measures the strip thickness in a distance from the mill and therefore gives a delayed measurement of the strip thickness. This means that the control that uses the thickness gauge must carefully account for this delay. The control of strip thickness using thickness gauge measurements is known as monitor control. By using the measured thickness, Feedforward AGC is provided to help compensation for known incoming product variations. Feedforward AGC assists MMC and Gaugemeter as

they cannot completely correct gauge due to factors such as window friction and load cell hysteresis.

4. **Model of Automatic Gauge Control System.** In order to predict the dynamic variation of delivery thickness under the correction of roll gap from AGC system, an AGC control model is utilized to calculate the consequent effects of roll gap variation on the strip. In this section, firstly, a popular BISRA (British Iron and Steel Research Association) equation and its linearized model are introduced. And then, for the purpose to simplify the structure of the simulation system, two main control algorithms of the AGC control system are taken into account, and the mathematical model is also introduced.

4.1. **Gaugemeter thickness calculation.** The gaugemeter equation ($h = S_0 + P/M$, see Figure 3) uses gap position and force to estimate stand exit strip thickness. In Figure 3, before metal enters the roll bite the effective roll gap is equal to the setup gap position, S_0. When metal enters the roll bite, force builds up and the mill stretches causing the effective roll gap to open. In the gaugemeter equation P/M is the amount the mill stretches when a roll separating force is applied. Exit thickness is therefore equal to the unloaded gap position plus the stretch.

H: Entry strip thickness
h: Exit strip thickness
P: Strip force
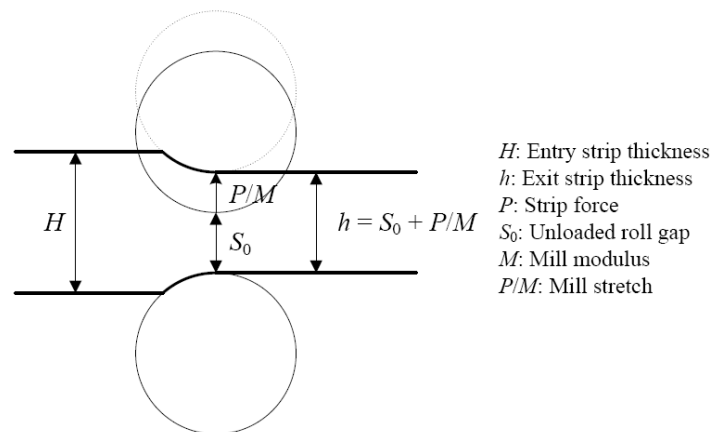S_0: Unloaded roll gap
M: Mill modulus
P/M: Mill stretch

FIGURE 3. Gaugemeter equation

The amount that the mill stretches is not actually linear as suggested in the above gaugemeter equation. The amount of stretch is a combination of stretch in the mill housing and deflection in the roll stack. The mill housing stretch is typically non-linear at low forces and becomes nearly linear with force at high forces. Roll stack deflection includes bending of the roll necks and flattening of rolls at the point of contact with the strip and between backup roll and work roll. Stack deflection is typically linear with force but varies significantly as the strip width changes. Figure 4 attempts to show the relationships between gap position, mill stretch and strip thickness.

Mill total stretch is measured by closing the roll gap with roll on roll while measuring force and gap position. The setup model fits a curve to the data and provides coefficients for an equation that approximates the measured stretch. The setup model provides the coefficients for each product to account for the effect of strip width on stretch.

The equation for mill stretch is of the following form.

$$S_m = \frac{1}{C_2}\left(\sqrt{C_1^2 + 2C_2\frac{P}{K_B}} - C_1\right) \tag{1}$$

where, C_1, C_2, K_B are coefficients provided by the setup model, and P is strip force.
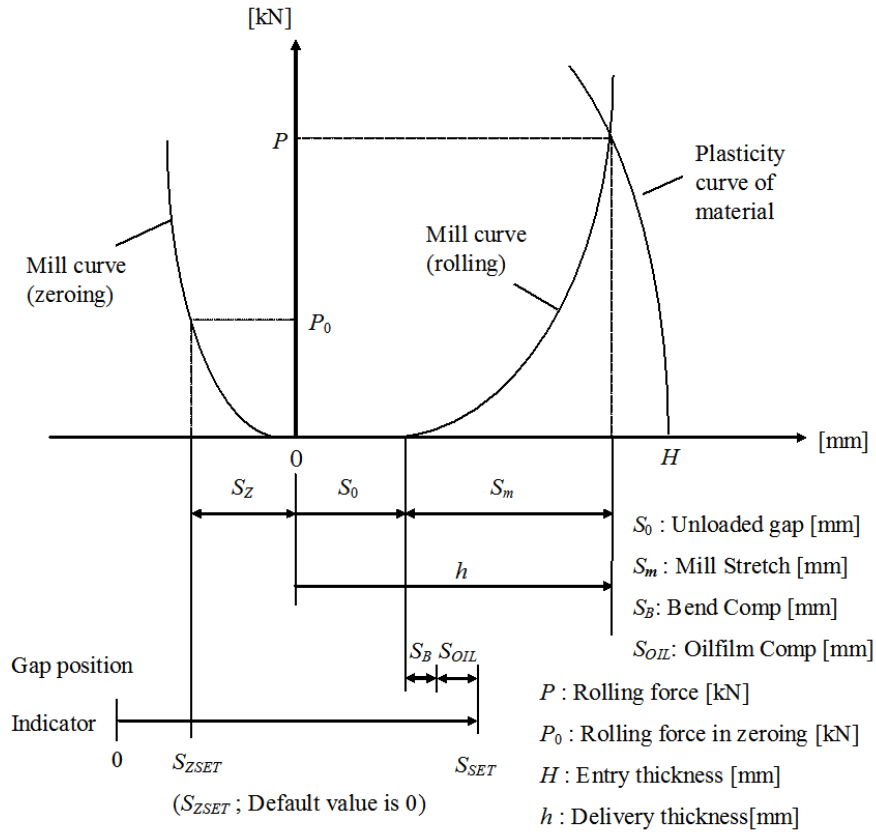
FIGURE 4. Mill stretch characteristics

Then, mill modulus can be derived as follows.

$$M = \frac{\partial P}{\partial S_m} = K_B \left(C_1 + C_2 S_M \right) \tag{2}$$

4.2. **The BISRA's control model.** Figure 4 shows a popular AGC control model, and the main methodology is to predict the strip's delivery thickness (h) and rolling force (P) by the entry thickness (H) of the slab and the gap correction (S_0) from the AGC system.

Nevertheless, as shown in Figure 4, the delivery thickness can be influenced by the process parameters of mill modulus and strip modulus. The former is the representation for the strength of mill's housing which can be estimated by an experiment of mill modulus test; consequently, it is the function of rolling force and roll gap; the latter presents the characteristics of the rolled strip, which is related to the rolling temperature, and strip's geometry and material. Moreover, the rolling results can also be varied by the thickness of entry strip in the case with the same roll gap; and dynamic variation of roll gap from AGC adjustment with the same entry thickness also gives different effects to the delivery gauge.

Although the AGC model shown in Figure 4 is highly nonlinear, a linearized model can possibly be utilized to simplify the calculations, under the consideration of the general operation range, so that the characteristics of mill modulus and strip modulus can be assumed to present a linear behavior. And the expressions for the delivery thickness and the roll force can be presented as follows:

$$h = S_0 + \frac{P}{M} \tag{3}$$

$$F = Q(H - h) \tag{4}$$

where Q and M denote the strip modulus and mill modulus, respectively. And Equation (3) presents the so-called gaugemeter equation or BISRA equation. Therefore, the deviation of thickness and the roll force under the influence from the variation of roll gap and entry thickness can be derived:

$$\Delta h = \frac{Q}{M + Q}\Delta H + \frac{M}{M + Q}\Delta S_0 \tag{5}$$

$$\Delta F = \frac{MQ}{M + Q}\Delta H - \frac{MQ}{M + Q}\Delta S_0 \tag{6}$$

Since the target of the AGC system is to regulate the deviation of the delivery thickness and the roll force of the strip to zero, this control task can be achieved by the adjustment of the roll gap from the computation of Equations (5) and (6).

4.3. **Philosophy of gaugemeter AGC and monitor AGC.** Figures 5 and 6 present the control philosophy of Gaugemeter AGC and Monitor AGC, respectively. In Figure 5, the feedback of roll force from load cell is utilized to compensate the effect of mill stretch, and the gain of the Gaugemeter AGC control loop is used to adjust the correction of roll gap as follows:

$$\Delta S_{GM} = -G_{GM}\frac{\Delta F}{M} \tag{7}$$

where ΔS_{GM} denotes the roll gap correction of Gaugemeter AGC, and G_{GM} presents the control gain of Gaugemeter AGC system. ΔF is the difference between target and actual roll force.
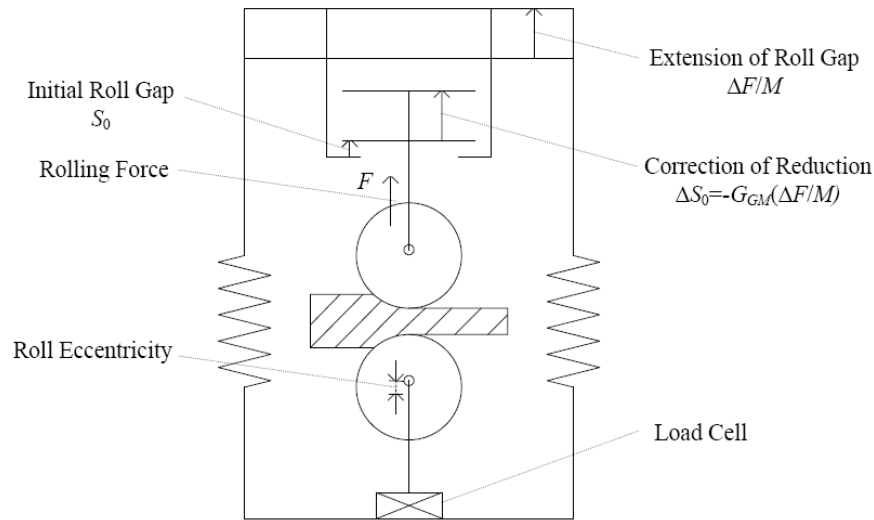

FIGURE 5. Philosophy of Gaugemeter AGC

In addition, the control philosophy of Monitor AGC is shown in Figure 6, and the measuring result of delivery thickness is fed back to regulate the roll gap. In the control loop, the time delay (t_r) of the measurement is considered to reflect the actual sensing situation, and an integrator is used as the main controller to compensate the deviation of the delivery thickness. Moreover, the total correction rate of Monitor AGC is the summation of balance and monitor correction parts, and the loop gain is defined in Equation (8):
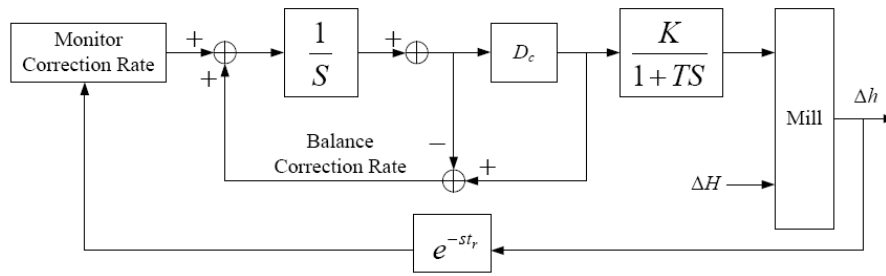
$$K = G_{GM} + (1 - G_{GM})\frac{M + Q}{M} \tag{8}$$

FIGURE 6. Philosophy of Monitor AGC

and a time constant (T) to present the dynamic behavior of the actuator.

5. Applications.

5.1. **Design approach.** This thickness control could only be achieved through proper system design. The most important design objectives were high availability, efficient installation, optimum delivery, and ease of maintenance. A flexible modular approach was chosen to enhance these design objectives. This approach was further enhanced with the extensive use of structured design techniques.

Structured design techniques were used throughout both the hardware and software design. The essential nature of structured design involves breaking down the complex requirements into small modules which are then easily managed. The main design effort is involved in the process of building each of these modules and assembling them together to form the complex set of automation functions. Good structured design promotes the flexible modular approach significantly both during the design phase and for the long-term maintenance of the system.
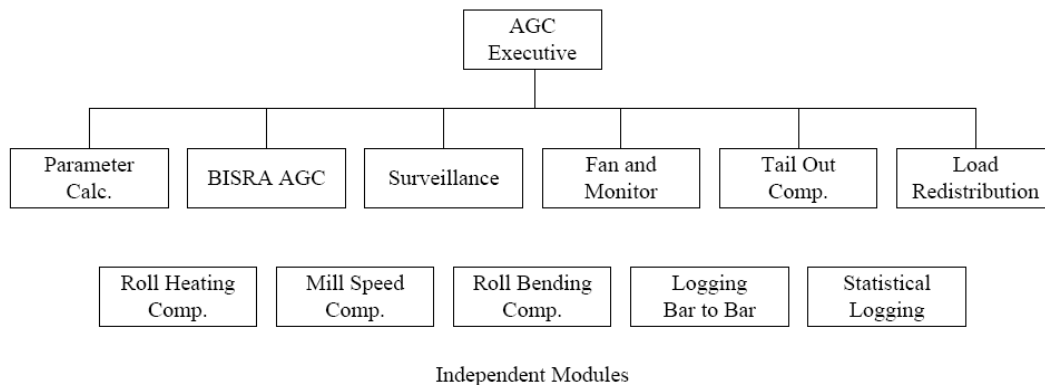

FIGURE 7. Software structure of automatic gauge control

The AGC software was divided into a number of individual control, action, and communication modules. Many of these modules were managed as a coordinated group of AGC functions while other functions were performed as more individual modules separated from this group. The division of the AGC functions is shown in Figure 7.

5.2. **Software planning.** Each of the individual software modules has a similar life history. Figure 8 contains a general view of that history. There is an analysis phase, a design phase, a coding phase, and an individual testing phase. Groups of modules were brought together to provide functional tests. Then many functions were combined together for
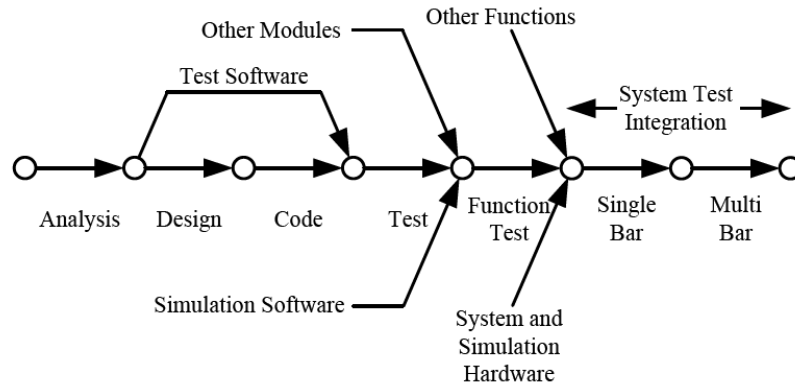
FIGURE 8. Software design planning chart

a total simulation involving both hardware and software integration. Individual module test software was designed. In addition a very flexible and comprehensive software simulation package was developed and used prior to, and during, the hardware and software integration phase.

In the initial analysis phase fully 80-90 percent of the final system documentation was produced. This documentation was subject to a rigorous design inspection and review procedure. This procedure was very successful and ensured at an early stage in the project that all the individual parts would eventually fit together correctly. Both customer and factory personnel worked together during the design phase. Work activities were allocated based on skill and experience among all team members.

5.3. **Control system structure.** Normally, automation control system to the plate production line is designed as several levels. Level 0 is A-C and D-C digital drives, etc. Level 1 is the base automation. It consists of programmable controllers and microcomputers that manage the functional logic (e.g., PLCs) of the system, the single device control and the interface with the sensors. Level 2 is the process automation. It consists of minicomputers that handle material flow and production targets, and provide the user with tools for plant supervision and diagnostics. Level 3 is the plant wide production automation. It mainly defines the scheduling of production in the whole plant. Level 4 is corporate-wide automation. It consists of business system and quality database, etc. The applied automation control system designed for a plate production line is shown in Figure 9.

6. **Conclusions.** The plate mill thickness control system described herein was successfully installed at the No. 2 Plate Mill of Handan Hongri Metallurgy Co. Ltd., China (Figure 10). The system has surpassed its original performance targets. This success was not the result of a single factor, but of the thorough coordination of the total thickness control system. This included well-developed control strategies, structured design implementation, accurate simulation and calibration of the mill prior to rolling, as well as the availability of fully tested engineering analysis tools for the first day of rolling. The system was quickly brought on-line and has continued to enjoy very stable high performance as a result of these efforts.

The thickness accuracy guaranteed value of the automation system is shown in Table 1. With AGC function in basic automation system, the plate thickness accuracy can be guaranteed.

We have collected statistics data for 7 months, and conclude from the data analysis that the average thickness qualified rate of the No. 2 plate mill is 1.4 percent higher than the No. 1 Plate Mill which was built two years ago.
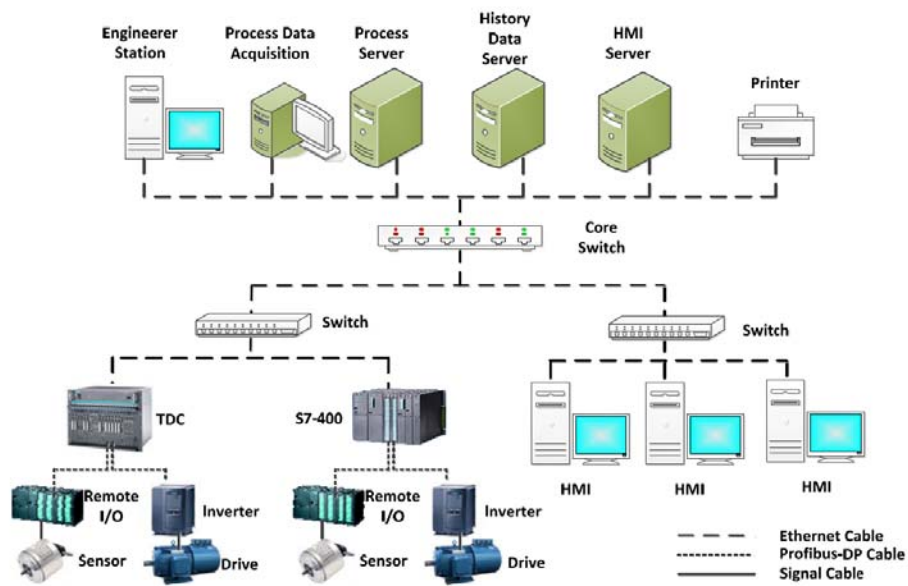
FIGURE 9. Schematic of automation control system for plate rolling

FIGURE 10. Plate rolling process

TABLE 1. Plate thickness accuracy guaranteed value

	Target thickness range (mm)	Thickness tolerance (2σ) (mm)
Thickness accuracy along one plate length	$6 \leq h \leq 10$	≤ 0.08
	$10 < h \leq 20$	≤ 0.10
	$20 < h \leq 30$	≤ 0.12
	$30 < h \leq 50$	≤ 0.16
	$50 < h$	≤ 0.24
Thickness accuracy for different plates	$6 \leq h \leq 10$	≤ 0.10
	$10 < h \leq 20$	≤ 0.12
	$20 < h \leq 30$	≤ 0.15
	$30 < h \leq 50$	≤ 0.20
	$50 < h$	≤ 0.30

Automation of rolling mills is an important and vibrant activity that reaches into every aspect of mill operation and links together a number of academic and commercial disciplines. The role of automation has been well established for a number of years and is likely to expand for many years to come.

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