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MILL CONTROL SYSTEM AND METHOD FOR CONTROL OF METAL STRIP ROLLING

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See application file for complete search history.

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ABSTRACT
Mill control system and method for metal strip rolling controlled in response to a sequence of controller scans are provided. A sensor suite is coupled to sense a plurality of parameters regarding the strip rolling. A model responsive to the sensed parameters is configured to estimate per scan at least one matrix based on the sensed parameters and indicative of state conditions of the strip rolling. A controller includes an inner control loop configured to effect a control law to generate a control vector per scan. The inner control loop may be configured to have dynamic characteristics, which remain substantially the same for each scan of the controller. The dynamic characteristics of the inner control loop are effective to determine a pointwise online control solution based on the matrix indicative of the state conditions of the strip rolling, without having to compute a Riccati control solution per scan.

17 Claims, 5 Drawing Sheets
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FIG. 3

change in strip thickness

change in strip temperature

FIG. 4
mill and actuators

\[ B \overset{+}{\rightarrow} x \overset{\int}{\rightarrow} x \overset{C(x)}{\rightarrow} y' \]

controller

\[ w \overset{+}{\rightarrow} K(x) \overset{-}{\rightarrow} K_{I,th} \overset{+}{\rightarrow} K_{P,th} \]

trimming functions

FIG. 5
mill and actuators

\[
\begin{align*}
\dot{x} &= Ax + Bu \\
F &= Cx \\
y &= C(x)
\end{align*}
\]

controller

Model e.g., matrices \( A(x), B, C(x) \)

\[
\begin{align*}
x, F &\rightarrow K_i \\
x &\rightarrow y_e \\
y_e &\rightarrow \phi_r
\end{align*}
\]

thickness trims

\[
\begin{align*}
\int &\rightarrow K_{f,th} \\
\int &\rightarrow K_{p,th}
\end{align*}
\]

looper position trims

\[
\begin{align*}
\int &\rightarrow K_{f,m} \\
\int &\rightarrow K_{p,m}
\end{align*}
\]

FIG. 6
FIG. 7

FIG. 8
MILL CONTROL SYSTEM AND METHOD FOR CONTROL OF METAL STRIP ROLLING

STATEMENT REGARDING FEDERALLY SPONSORED DEVELOPMENT

Development for this invention was supported in part by grant No. 0951843, awarded by the United States National Science Foundation. Accordingly, the United States Government may have certain rights in this invention.

FIELD OF THE INVENTION

The invention generally relates to control systems, and, more particularly, to a system for controlling rolling of a metal strip in a rolling mill, such as hot metal strip rolling.

BACKGROUND OF THE INVENTION

A significant process in metalworking is the tandem rolling of a metal strip. The rolling process may be classified according to the temperature of the metal being rolled. If the temperature of the metal is above its recrystallization temperature, the process is generally referred to as hot rolling. If the temperature of the metal is below its recrystallization temperature, the process is generally referred to as cold rolling.

The rolling of a hot metal strip presents substantial control challenges due to the complex interaction of a large number of variables, and may involve many non-linear, time-varying variables. This challenge is heightened by the hostile nature of a hot rolling environment, which, for example, may preclude reliably measuring certain variables that may be needed for control purposes.

Known control strategies tend to result in sub-optimal control since often such strategies shy away from systematically addressing the complex dynamic interactions among the large number of variables of the entire rolling mill and their resulting effect on important process variables, such as strip tension, looper position, strip thickness. A few attempts have been made at considering the entire mill as a single entity, e.g., using advanced control techniques based on linearized models, but often these control techniques introduce unacceptable complexities in a real-world setting, such as lack of user-friendliness in connection with the operation and/or tuning of the concomitant controller. Accordingly, there is a need for an improved system to control rolling of a hot metal strip in a rolling mill.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention is explained in the following description in view of the drawings that show:

FIG. 1 is a schematic representation of an example hot metal tandem rolling mill, which may benefit from aspects of the present invention.

FIG. 2 is a schematic representation of an example looper component, as may be part of the hot metal rolling mill.

FIG. 3 is a zoom-in diagram illustrating example details between corresponding surfaces of a work piece (e.g., metal strip) and a work roll.

FIG. 4 shows respective plots of example control disturbances, such as variations in incoming strip thickness and strip temperature.

FIG. 5 is a block diagram representation intended to facilitate explanation of control trims (e.g., thickness and/or tension trims) embodying aspects of the present invention.

FIG. 6 is a block diagram representation of an example overall control system structure embodying aspects of the present invention.

FIG. 7 is a block diagram representation intended to facilitate explanation of further control trims (e.g., looper operating point trims) embodying aspects of the present invention.

FIG. 8 is a diagram illustrating some example details in connection with an example looper.

DETAILED DESCRIPTION OF THE INVENTION

FIG. 1 is a schematic representation that shows an example hot metal rolling mill 10, as may benefit from aspects of the present invention. Metal slabs 12, which may have been produced in a previous rolling or casting operation, may be placed in a reheating furnace 14 and heated to temperatures suitable for intermediate processing 16 and subsequent entry into a tandem hot strip finishing mill 18 (e.g., the physical plant to be controlled). In mill 18, a working piece 20 (e.g., strip) is passed through a number of stands 21 each including independently driven work rolls 22 (e.g., five to seven pairs), with each work roll supported by a back-up roll 24 of larger diameter. As shown in FIG. 2, one or more load-sensing cells 37 may be used to monitor the load at the stands. As further shown in FIG. 2, between each pair of work rolls there is a looper 26, which is a mechanism including an arm 28 and a roll 30, as may be driven by a suitable actuator 32 (e.g., hydraulics device or electric motor). For example, arm 28 may be controllably pivoted about a pivot point 33 to keep the strip 20 at a reference tension.

As the strip 20 passes through the individual pairs of work rolls 22 in the finishing mill, the thickness of strip 20 is successively reduced to a desired thickness value (e.g., ranging from approximately 1.5 mm to approximately 12 mm). The reduction in thickness is caused by a substantially high compressive stress applied to a small region (e.g., roll bite, or roll gap) between opposing work rolls 22. The necessary compression force may be applied by a suitable compression device 34 (e.g., hydraulic rams, or a screw arrangement as may be driven by an electric motor). After strip 20 exits the last stand, the strip 20 may be cooled in an exit cooling process 36 at controlled rates by the application of water sprays to achieve desired metallurgical properties. Strip 20 is then passed to a coiler 38 for suitable coiling.

A control system embodying aspects of the present invention in one example embodiment may comprise four main control-related entities, which interact with one another in synergistic fashion to effect an innovative control technique to control the tandem hot metal strip rolling mill. These four entities are 1) a nonlinear mathematical model of the hot metal strip rolling, 2) a controller adapted to implement a pointwise, linear quadratic optimization technique, 3) one or more trimming control loops, which enhance the performance of the controller, and 4) an overall control strategy, which is implemented by way of interactions among the foregoing three entities to realize the control system embodying aspects of the present invention. The following provides a description of example aspects of each of these control entities.

Aspects Regarding Mathematical Model of Hot Strip Rolling

As will be appreciated by one skilled in the art, a mathematical model of the physical plant (e.g., the tandem hot strip rolling mill) is a set of mathematical expressions, which when executed by a processor or any suitable computing device allow relating a plurality of physical parameters (e.g., rolling parameters) to one another. It is noted that aspects of the present invention are not limited to the specific model
Specific Roll Force

An estimation of specific roll force is basic to the development of the overall control model. In one example embodiment, the specific roll force may be represented as

\[ F = \frac{\partial Q_p - \partial w R p}{R p} \]

where \( P \) is the specific roll force, \( k \) is the constrained yield stress of the material, \( Q_p \) is a factor which compensates for friction and any inhomogeneity of deformation, \( \partial \) is the mean tension stress of the strip (e.g.,

\[ \sigma = \frac{\sigma_{in} + \sigma_{out}}{2} \]

where \( \sigma_{in} \) and \( \sigma_{out} \) are the strip tension stresses at the stand input and output), \( R_p \) is the deformed work roll radius which is estimated using the well-known Hitchcock approximation, and \( \delta \) is the stand draft (e.g., \( \delta = \frac{h_n - h_{out}}{L} \) where \( h_n \) and \( h_{out} \) are the respective input and output thickness of the strip).

Strip Exit Thickness

The exit thickness \( h_{out} \) may be estimated using the linearized relation for the output thickness as

\[ h_{out} = S + S_0 + \frac{F}{M} \]

where \( S \) is the position of the roll bite position actuator, \( S_0 \) is the intercept of the linearized approximation, \( F \) is the total rolling force (equal to \( PW \), where \( W \) is the strip width), and \( M \) is the mill modulus which represents the elastic stretch of the strip to move between adjacent stands and may be approximated as

\[ \tau_\delta \approx \frac{L}{V_{out,i}} \]

where \( L \) is the length of strip between stands \( i \) and \( i+1 \) considering the looper movement, and \( V_{out,i} \) is the strip speed at the output of stand \( i \).

Forward Slip

The forward slip \( f \) is a measure of the strip speed exiting the roll bite and is defined as the ratio of the relative velocity of the exiting strip to the peripheral speed of the roll,

\[ f = \frac{V_{out} - V_o}{V_o} \]

where \( V_{out} \) is the exit strip speed and \( V_o \) is the peripheral speed of the roll, which is approximately equal to the strip speed at the angle \( \phi \), from the centerline of the mill stand (FIG. 3). An example model representation for forward slip and useful in the development of control may be expressed as

\[ f = \left( \frac{R_o}{R_{out}} \right) \phi_o \]

where...

\[ \phi_o = \frac{\partial k + \alpha \sigma_{in} - \sigma_{out}}{4k R_p} \]

with

\[ \phi_1 = \left( \frac{\partial}{R_p} \right)^{1/2} \]

and where \( \mu \) is the friction coefficient, and other symbols are as defined previously. In the case of hot rolling \( \mu \) is taken as the coefficient for sticking friction, which is approximated by the following empirical relationship \( \mu = 0.00027 T_p - 0.08 \), where \( T_p \) is the temperature of the work piece in degrees F.

Work Roll Position and Speed Controllers

The position of the actuator (e.g., hydraulic cylinder) that sets the work roll position at the roll bite may be estimated to be a single first order lag as

\[ \frac{dS}{dt} = \frac{U_i}{\tau_s} \]

where \( S(0) = S_o \)

and \( S \) is the cylinder position, \( U_i \) is the position reference, and \( \tau_s \) is the time constant of the first order lag. The peripheral speed of the work rolls may also be estimated to be a single first order lag as

\[ \frac{dV}{dt} = \frac{U_v}{\tau_v} - \frac{V}{\tau_v} \]

where \( V(0) = V_o \)

and \( V \) is the roll peripheral speed, \( U_v \) is the speed reference, and \( \tau_v \) is the time constant of the first order lag.

Interstand Time Delays

The interstand time delay is the time taken for an element of the strip to move between adjacent stands and may be approximated as

\[ \tau_{\delta,i,i+1} = \frac{L}{V_{out,i}} \]

Looper

The arm position angle of a looper may be determined as

\[ \frac{d\theta}{dt} = \omega, \quad \theta(0) = \theta_i \]

where \( \omega \) is the looper angular velocity which is derived from Newton’s second law of motion, and is described as

\[ \frac{d\omega}{dt} = \frac{1}{I_{looper}} \left[ M_{looper} + M_{friction} + M_{load} \right], \quad \omega(0) = 0 \]

where \( I_{looper} \) is the looper moment of inertia, \( M_{looper} \) is the torque applied to the looper mechanism (e.g., using a controlled hydraulic cylinder), \( M_{friction} \) is the friction torque of the looper mechanism, \( M_{load} \) is the load torque which is

\[ M_{load} = M_{strip, bending} + M_{strip, tension} + M_{strip, weight} + M_{looper, max} \]
where $M_{\text{strip tension}}$, $M_{\text{strip weight}}$, $M_{\text{looper mass}}$, and $M_{\text{strip bending}}$ are the torques resulting from the strip tension force, the strip weight, the mass of the looper mechanism, and the bending of the strip at the looper roll. The torque $M_{\text{looper}}$ is approximated as a single first order lag, which for example, includes the looper hydraulic cylinder with its controller,

$$\frac{dM_{\text{looper}}}{dt} = \frac{U_{\text{looper}}}{\tau_M} M_{\text{looper}}, \quad M_{\text{looper}}(0) = M_{\text{looper0}}. \tag{13}$$

where $U_{\text{looper}}$ is the torque controller reference, and $\tau_M$ is the time constant of the first order lag. The friction torque of the bending of the strip at the looper roll. The torque $M_{\text{looper}}$ is approximated as a single first order lag, which for example, includes the looper hydraulic cylinder with its controller,

$$\frac{dM_{\text{looper}}}{dt} = \frac{U_{\text{looper}}}{\tau_M} M_{\text{looper}}, \quad M_{\text{looper}}(0) = M_{\text{looper0}}. \tag{13}$$

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$$\frac{dM_{\text{looper}}}{dt} = \frac{U_{\text{looper}}}{\tau_M} M_{\text{looper}}, \quad M_{\text{looper}}(0) = M_{\text{looper0}}. \tag{13}$$

where $U_{\text{looper}}$ is the torque controller reference, and $\tau_M$ is the time constant of the first order lag. The friction torque of the bending of the strip at the looper roll.
The magnitude of the uncertainty in the mill modulus may be reduced to less than 2% by standard techniques, as would be known to one skilled in the art. It is also presumed that roll eccentricity effects may be appropriately compensated so that these effects may be considered to be negligible.

Example notable disturbances may be variations in incoming strip thickness and temperature, e.g., due to skid chill in the reheating furnace, as illustrated in FIG. 4. The temperature disturbances in the incoming material may be tracked pointwise on a basis. The following provides a description of certain example controller aspects.

A typical operating point of the tandem hot strip rolling mill may be at a threaded condition and at operating speed, with a strip tension of approximately 0.01 kN/mm² between each pair of adjacent stands, and with each looper at an angle of approximately 15 degrees. Table II lists an example operating point strip thickness (hₘₐₓₜ), example average strip temperature (T) at the mill entry and at the exit of each stand, example peripheral speed of the work rolls (Vₑ), and example undeformed work roll radius (R) of each stand. It will be appreciated that aspects of the present invention are not limited to any specific operating point values and the operating point values listed below should be construed in an example sense and not in a limiting sense.

### Controller Aspects

A controller may be configured to perform a linear quadratic optimization technique that may be solved on a pointwise basis. The following provides a description of certain example controller aspects.

**Linear Quadratic Controller Aspects**

As will be appreciated by those skilled in the art, the term linear quadratic controller refers to a control technique wherein a performance index J may be minimized to realize an optimal controller. The controller is optimal in the sense and not in a limiting sense. The following provides a description of certain controller aspects.

Pointwise Controller Aspects

In the typical control of a tandem hot mill, the algorithm for control of the mill is written in computer-readable code, which may be executed on a digitally-based processor. The execution of the various portions of the code may be performed in a sequential fashion in accordance with a predetermined sequence that is programmed by the control designer. The sequential execution of the entire control code is denoted as a scan of the control code during which the various portions of the code are executed, so that the complete control code is executed in the predetermined sequence during one scan. The scan is then continuously repeated to control the mill during the processing of the present strip.

As an example, during a scan, the code may be executed to perform functions in the following sequence to determine the control vector u: 1) acquiring data from plant measured variables, 2) computing the vector x based on the acquired data, 3) determining a control vector u, (e.g., solve equation 20), 4) iteratively performing the previous steps until the processing of the present strip is finished. Thus, when a function, such as a solution to a particular equation, is said to be implemented pointwise, it will be understood that such a function is performed during every scan of the mill controller, unless otherwise indicated.

**Pointwise Linear Quadratic Control Aspects**

It will be appreciated that pointwise linear quadratic control is generally referred to in the art as a state-dependent algebraic Riccati equation (SDARE) technique. In this technique, the coefficient matrices of the state equation and state-weighing matrices Q and R, become functions of the state vector x, so that the above equations may be rewritten as

where x and u are respectively the state and control vectors, A and B are the coefficient matrices of the linearized process model, and Q and R are constant, state-weighing matrices whose elements may be selected by the control designer to determine how the function to minimize J may be respectively distributed (weighed) between the state and control functions. The determination of a control law to implement such a controller may be achieved in one example embodiment by solving an algebraic Riccati equation (ARE)

\[
AK + KA^T - BK + QR^{-1}BK = 0,
\]

where and is the solution to equation (19) and \(R^{-1}\) denotes the inverse of the matrix R. The resulting control law may be expressed as

\[
u = R^{-1}Bu,
\]

where x and u are respectively the state and control vectors, A and B are the coefficient matrices of the linearized process model, and Q and R are constant, state-weighing matrices whose elements may be selected by the control designer to determine how the function to minimize J may be respectively distributed (weighed) between the state and control functions. The determination of a control law to implement such a controller may be achieved in one example embodiment by solving an algebraic Riccati equation (ARE)

\[
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\]

where and is the solution to equation (19) and \(R^{-1}\) denotes the inverse of the matrix R. The resulting control law may be expressed as

\[
u = R^{-1}Bu,
\]

where x and u are respectively the state and control vectors, A and B are the coefficient matrices of the linearized process model, and Q and R are constant, state-weighing matrices whose elements may be selected by the control designer to determine how the function to minimize J may be respectively distributed (weighed) between the state and control functions. The determination of a control law to implement such a controller may be achieved in one example embodiment by solving an algebraic Riccati equation (ARE)

\[
AK + KA^T - BK + QR^{-1}BK = 0,
\]

where and is the solution to equation (19) and \(R^{-1}\) denotes the inverse of the matrix R. The resulting control law may be expressed as

\[
u = R^{-1}Bu,
\]
In one example embodiment for control of the hot mill, the
matrices B, Q, and R may be taken as constant matrices,
which may be determined off-line prior to rolling, where
the B matrix is set by the model, and the Q and R matrices
may be intuitively set to achieve a desired performance of the
controller. It is noted, however, that in equations 21, 23 and 24,
the A(x) and K(x) matrices remain functions of the state
vector x. The foregoing aspect has been innovatively recog-
nized by the inventors of the present invention as conducive to
a simpler control strategy while providing appropriate per-
formance.

Trimming Control Loop (Trims) Aspects

Aspects of the present invention provide trimming func-
tions, or trims, which are single-input-single-output (SISO)
functions, as may be configured to implement one or more
counter control loops. The controller configuration for the hot
mill may be arranged so that these SISO functions form an
outer control loop constructed around an inner multi-input
multi-output (MIMO) control loop.

FIG. 5 is a block diagram illustrating a simplified controller
configuration coupled to a hot rolling mill 42 (e.g., the
plant). This simplified configuration is intended to facilitate
explanation of trims embodying aspects of the present inven-
tion. In FIG. 5, an inner control loop 44 includes matrix B
represented by block 46, matrix A(x) represented by block 48,
an integration function 50, and a control law K(x) (e.g.,
MIMO) represented by block 51.

In one example embodiment, an outer control loop 52
includes inner loop 44 (e.g., closed via control law block 51),
matrix C(x) represented by block 54, and one or more trim-
ing functions, which in this simplified representation may
be made up of an integration gain block 55 (block labeled
KPr) and an associated integration block 56 (e.g., mathemati-
cal integration) and a proportional gain block 58 (block
labeled KP).

In one example embodiment, integration gain block 55
and proportional gain block 58 may comprise constant diagonal
matrices whose elements each represent a respective tunable
constant gain for a SISO trim, with inputs from appropriate
elements of the vector y. Integration gain block 55 represents
the gains for a plurality of integral trims, and proportional
gain block 58 represents the gains for a plurality of propor-
tional trims.

It will be appreciated that the functionality of the respective
trims provided by outer loop 52 is conducive to improving the
performance of inner control loop 44. More specifically, the
trims may reduce the error in the control of the associated
variables represented by elements of the output vector y, may
improve the mitigation of disturbances and uncertainties, and
may provide a relatively uncomplicated means for controller
adjustments during commissioning.

Overall Control Technique Aspects

In one example embodiment, a controller embodying
aspects of the present invention may involve at least two
modes of operation: a pre-roll mode and a roll mode. In the
pre-roll mode, preparation is made for the controller to pro-
cess the next strip in the hot mill. In an off-line preparation,
as may be performed prior to the pre-roll mode, the controller
and the process may be simulated to establish appropriate
settings for the elements of the constant diagonal Q matrix
and the initial settings of the tunable trim gains, R may be
taken as the identity matrix. Appropriate simulations may be
performed using the foregoing example model of the hot
metal rolling mill at a typical operating point.

In the off-line preparation the elements of the A(x0) and
C(x0) matrices for a given operating point x0 may be com-
puted based on the values of the states at operating point x0.
The elements of the matrix B may be constants, as noted
previously. A control law may be determined off-line using
the foregoing SDRE technique, and one or more simulations
may be performed to verify steady-state and dynamic perfor-
ance considering example uncertainties and disturbances
(e.g., uncertainties and disturbances typical for the process).
The settings of the elements of the Q matrix and the trim
values may be determined intuitively and may be confirmed
by one or more simulations. The values of the elements of a
matrix denoted as K0 may be determined, where K0 is the
overall gain of the control law at the operating point x0, e.g.
K0 = R−1B(K(x0)).

For strips being considered in the pre-roll mode, it is
unnecessary to solve the state-dependent ARE for each
upcoming strip to be rolled, or to perform further off-line
preparation for each strip to be rolled. This is because when in
the pre-roll mode the incoming strip may require just a change
in the control law gain K0 to correspond with a change in
matrix A(x0), such as may occur from the initial off-line
preparation to the pre-roll mode. For example, matrix A(x0)
as determined by the model for the upcoming strip in the
pre-roll mode, will likely be somewhat different from the
matrix A(x0) determined in the off-line preparation. However,
any such change may be readily accounted for with an
updated control law gain K0.

It is noted that the update to determine K0 in the pre-roll
mode may be similar to the update to determine K0 in the
roll mode. For example, K0 in the pre-roll mode may be deter-
ned as

K0 = R−1B(K(x0)−Aprep(x0))K0,prep

where K0 is the gain K0 in the pre-roll mode, K0, prep is the
gain K0 in the off-line preparation, and Aprep(x0) and Aprep(x0)
are the matrices A(x0) in the pre-roll mode and the off-line
preparation respectively, with the constant matrix B as previ-
ously noted. This is similar to what is noted in (25) for updates
in the roll mode.

It will be also appreciated that the foregoing aspect simpli-
ifies the determination of the initial trim settings for the
upcoming strip. For example, if the inner loop dynamic char-
aracteristics are chosen to be invariant, keeping the overall outer
loop dynamic characteristics very nearly invariant would
involve just straightforward trim adjustments, such as to pro-
vide compensation, if needed, to account for any changes that
may occur in the C(x0) matrix between the off-line prepara-
tion and the pre-roll mode. That is any changes in the C(x0)
matrix may be used to determine any adjustments in the trim
gain matrices KPr and KP in blocks 55 and 58 of the con-
troller 40 as depicted in FIG. 5 to keep the overall outer loop
dynamic characteristics essentially invariant. The differences
between C(x0) in the pre-roll mode and C(x0) in the roll mode
are relatively small so that they can be considered essentially
negligible. During actual operation in the roll mode the devia-
tions between those elements of the C(x) and C(x0) matrices
that apply to the trimming functions also are small so that the
overall outer loop dynamic characteristics remain very nearly
invariant during actual operation. Thus, the desirable perfor-
mance obtained in the off-line preparation would be carried
over to the pre-roll mode and subsequently to the roll mode.
Further detail on keeping the inner loop invariant in the roll
mode is described in the description that follows.

In the roll mode a strip is being processed through the mill.
In this mode, the control law is determined such that the
dynamic characteristics of the inner control loop remain sub-
stantially the same from scan to scan of the controller during
the processing of the strip. This is done by computing the
overall gain of the control law on a pointwise basis, e.g., starting with $K_0$, as determined in the pre-roll mode, as the strip is processed through the mill. One key aspect of the present invention is keeping the matrix difference $(A(x) - BK)$ substantially constant as the elements of the state vector $x$ change from scan to scan, where $i$ represents the present scan. Since the elements of the vector $x$ are measurable, the elements of the matrix $A(x)$ for scan $i$ can be determined based on the measured values of the elements of $x$ for scan $i$. $K_i$ is then computed as

$$K_i = (A(x) - BK) + K_{i-1}$$

where $A_0(x)$ and $B_{i-1}$ are as computed on scan $i-1$, i.e. the previous scan, and $B^{-1}$ is a left inverse of the constant matrix $B$, with $B$ configured, as noted for example in section 1, to assure that a left inverse exists. An example inverse may be the Moore-Penrose pseudo left inverse, which may be computed off-line as

$$B^{-1}(B^TB)^{-1}B^T$$

The ordinary differential equation (ODE) for closed inner-loop 44 (FIG. 5) may be represented by

$$\dot{s} = (A(x) - BK)x + Bu, \quad x(0) = x_0.$$  (27)

As should be appreciated from equation (27), keeping the matrix difference $(A(x) - BK)$ substantially constant from scan to scan (as noted above) keeps the closed loop dynamic characteristics of the inner loop essentially unchanged from scan to scan.

As would be appreciated by those skilled in the art, use of the word “substantially” in expressions, such as “dynamic characteristics, which remain substantially the same for each scan of the controller” and/or “a matrix difference $(A(x) - BK)$ substantially constant from scan to scan”, means to recognize the presence (in a real-world, practical control system embodying aspects of the present invention) of non-zero uncertainties in modeling and/or measurement typical of those noted herein, which may result in non-zero uncertainties in certain elements of the $A(x)$ matrix with a resulting change in the dynamic characteristics of the inner control loop. However, as has been shown by simulation, the changes to certain elements of the $A(x)$ matrix resulting from such uncertainties, and the corresponding changes to the dynamic characteristics, are on the order of a few percent at most, so that changes to the $A(x)$ matrix and the corresponding changes to the dynamic characteristics remain essentially negligible in the presence of these uncertainties.

In accordance with aspects of the present invention, the algebraic Riccati equation (ARE) need only be solved off-line and, consequently, a controller embodying aspects of the present invention does not need to solve ARE on-line for each strip and at every scan since just the control gain $K_0$ requires a pointwise recalculation to account for the changes in the $A(x)$ matrix. This advantageously reduces the scan time and avoids the difficult design problem of having to determine a new $Q$ matrix at each scan to obtain a desired overall controller gain. For readers desirous of general background information in connection with a hot metal rolling application, a cold metal rolling application may similarly benefit from aspects of the present invention, such as avoiding computation of an on-line ARE solution at every scan. For readers desirous of general background information in connection with a cold metal rolling process, reference is made to US patent application publication No. 2007/0068210 A1, which is incorporated by reference herein in its entirety.
The performance index (22) may be modified to be

$$J = \frac{1}{2} \int_{t_0}^{t_f} (z'Qz + (u - u_0)'R(u - u_0))dt,$$

where for simplicity Q and R are taken as constant diagonal matrices as described previously.

In operation, aspects of the present invention are believed to offer at least the following example advantages:

1) A controller embodying aspects of the present invention is configured to account for a multiplicity of interactions occurring among the numerous variables treated as disturbances. As would be appreciated by those skilled in the art of tandem hot metal rolling, the reduction of interactions between variables treated as disturbances, and uncertainties, (e.g., significant changes in the equivalent carbon content and temperature of the strip being rolled), can have a relatively greater effect on system performance.

2) A controller embodying aspects of the present invention is configured so that effects of changes in the A(x) matrix will have essentially no effect on the dynamics of the inner control loop, and thus changes in the A(x) matrix due to disturbances and unexpected variations in the system performance. This represents a substantial improvement over known control techniques where a loop and its adjacent stands are considered separately, with interacting variables treated as disturbances. As would be appreciated by those skilled in the art of tandem hot metal rolling, the reduction in interactions between variables treated as disturbances, and uncertainties, (e.g., significant changes in the equivalent carbon content and temperature of the strip being rolled), can have a relatively greater effect on system performance.

3) A controller embodying aspects of the present invention is configured so that the time involved for performing a scan is substantially reduced over known control techniques that involve solving an algebraic Riccati equation (ARE). Also, in accordance with aspects of the present invention, the ARE may be initially solved off-line, which reduces the controller complexity with corresponding reductions in design and commissioning times, as considerably less tuning during commissioning is needed to achieve desirable performance over a wide range of products. Control design efforts are also reduced as less design effort needs to be expended to determine suitable controller settings for a wide product range. This ultimately translates into significant cost savings as both the design and commissioning times are reduced with a resulting earlier entry into the productive and profitable operation of the mill.

4) In accordance with aspects of the present invention, a linearized model is not needed, which further reduces the complexity of the controller as coefficients for the linearized model do not need to be computed which further reduces the design effort.

5) In accordance with aspects of the present invention, since the dynamic response of the inner control loop is configured to be essentially invariant between the pre-roll mode and the roll mode, the amount of off-line tuning is reduced. This reduces commissioning time, which also supports faster startups with earlier entry into productive operations.

6) In accordance with aspects of the present invention, the use of SISO trims contributes to the ease of tuning as there is a one-to-one relationship between a tuning parameter and the variable being tuned. This is an improvement over known control techniques, such as H-infinity loop-shaping, wherein controller adjustments involve MIMO and may require familiarity with advanced control techniques. Commissioning personnel are generally unfamiliar with advanced control methods, which would make the tuning of MIMO controllers relatively more cumbersome and often unrealistic for the commissioning of tandem hot mills.

7) In accordance with aspects of the present invention, the closed-loop control action of the trims contributes toward reducing the effects of uncertainties and/or certain unwanted perturbations since these uncertainties and/or perturbations often occur inside the control loops of the trims, and thus trims embodying aspects of the present invention contribute to the robustness of the controller in the event of any such uncertainties and/or perturbations.

8) In accordance with aspects of the present invention, the trim functions are effective in reducing the effects of interstand time delays. This occurs by the trims providing immediate outer loop control action for the estimated strip thicknesses at the stand outputs without having to deal with the significant effects of the time delays in the control of these variables, as would be the case if only the inner control loops were used. However, during outer loop control action, the inner MIMO control loop remains effective so that corresponding changes in variables over the entire process are made inherently.

It should be understood that aspects of the inventive system and method disclosed herein may be implemented in any appropriate operating system environment using any appropriate programming language or programming technique. The system can take the form of a hardware embodiment, a software embodiment or an embodiment containing both hardware and software elements. In one example embodiment, the system may be implemented by software (e.g., controls) and hardware (e.g., sensors), which includes but is not limited to firmware, resident software, microcode, etc. Furthermore, parts of the system can take the form of a computer program product accessible from a computer-readable or computer-readable medium providing program code for use by or in connection with a computer or any instruction execution system. Examples of a computer-readable medium may include a semiconductor or solid-state memory, magnetic tape, a removable computer diskette, a random access memory (RAM), a read-only memory (ROM), a rigid magnetic disk and an optical disk. Current examples of optical disks include compact disk-read only memory (CD-ROM), compact disk-read/write (CD-RW) and DVD. The display may be a tablet, flat panel display, PDA, or the like.

A processing system suitable for storing and/or executing program code will include in one example at least one processor coupled directly or indirectly to memory elements through a system bus. The memory elements can include local memory employed during actual execution of the program code, bulk storage, and cache memories which provide temporary storage of at least some program code in order to reduce the number of times code must be retrieved from bulk storage during execution. Input/output or I/O devices (including but not limited to keyboards, displays, pointing devices, etc.) can be coupled to the system either directly or through intervening I/O controllers. Network adapters may also be coupled to the system to enable the data processing system to become coupled to other data processing systems, or remote printers or storage devices through intervening private or public networks. Modems, cable modem and Ethernet cards are just a few of the currently available types of network adapters.
While various embodiments of the present invention have been shown and described herein, it will be apparent that such embodiments are provided by way of example only. Numerous variations, changes and substitutions may be made without departing from the invention herein. Accordingly, it is intended that the invention be limited only by the spirit and scope of the appended claims.

The invention claimed is:

1. A mill control system for metal strip rolling controlled in response to a sequence of controller scans, the system comprising:

   a sensor suite coupled to sense a plurality of parameters regarding the strip rolling;

   a model responsive to the sensed parameters and configured to estimate per scan at least one matrix based on the sensed parameters and indicative of state conditions of the strip rolling; and

   a controller comprising an inner control loop to effect a control law to generate a control vector per the scan, the inner control loop configured to have dynamic characteristics, which remain substantially the same for each scan of the controller, wherein the dynamic characteristics of the inner control loop are effective to determine a pointwise on-line control solution based on the at least one matrix indicative of the state conditions of the strip rolling, without having to compute a Riccati control solution per scan wherein said dynamic characteristics of the inner control loop are established by keeping a matrix difference \( (A_1(x) - B K_1) \) substantially constant from scan to scan, wherein \( A_1(x) \) represents the matrix estimated by the model indicative of the state conditions of the strip rolling for a present scan, \( B \) represents a constant control matrix, and \( K_1 \) represents a control gain matrix for the present scan.

2. The mill control system of claim 1, wherein the control gain matrix for a present scan is defined by \( K_1 = B^{-1}(A_1(x) - A_1(x)+K_{prev}) \), where \( B^{-1} \) represents a left inverse of the constant control matrix \( B \), \( A_1(x) \) represents the matrix estimated by the model indicative of the state conditions of the strip rolling for a previous scan, \( K_{prev} \) represents the control gain matrix for the previous scan.

3. The mill control system of claim 1, wherein the mill comprises a hot rolling mill comprising a plurality of spaced-apart stands each including at least mutually opposing work rolls arranged to apply in response to control signals derived from the control vector respective compression forces to controllably shape a thickness of a metal strip traveling between the opposing rollers, the rolling mill further including a plurality of loopers respectively interposed between adjacent stands and arranged to controllably provide in response to further control signals derived from the control vector respective levels of inter-stand tension to the traveling strip.

4. The mill control system of claim 3, wherein the inner control loop comprises a multiple-input, multiple output control loop, and wherein the controller further comprises at least a first outer control loop and a second outer control loop with respect to the inner control loop, the first and second outer control loops each respectively comprising a plurality of single-input, single output control loops, the first and second outer control loops each including at least one respective tunable gain matrix, the first outer control loop configured to generate a first group of control trims and the second outer control loop configured to generate a second group of control trims, wherein the first group of control trims comprises a plurality of thickness trims and the second group of control trims comprises a plurality of tension trims.

5. The mill control system of claim 4, wherein the controller further comprises a control loop coupled to the inner control loop configured to generate a plurality of looper position trims.

6. The mill control system of claim 1, wherein the model comprises a non-linear model.

7. A rolling mill configured to perform a hot metal strip rolling controlled in response to a sequence of control scans, the mill comprising: a sensor suite coupled to sense a plurality of parameters regarding the hot strip rolling; a non-linear model responsive to the sensed parameters and configured to estimate per scan at least one matrix based on the sensed parameters indicative of state conditions of the hot strip rolling; a controller coupled to the model and comprising an inner control loop to effect a control law to generate a control vector per scan; and a plurality of spaced-apart stands each including at least mutually opposing work rolls arranged to apply in response to control signals derived from the control vector respective compression forces to controllably shape a thickness of a metal strip traveling between the opposing rollers, the rolling mill further including a plurality of loopers respectively interposed between adjacent stands and arranged to controllably provide in response to further control signals derived from the control vector respective levels of inter-stand tension to the traveling strip, and wherein the inner control loop is configured to have dynamic characteristics, which remain substantially the same for each scan of the controller, wherein the dynamic characteristics of the inner control loop are effective to determine a pointwise on-line control solution based on the matrix indicative of the state conditions of the strip rolling, without having to compute a Riccati control solution per scan, and wherein said dynamic characteristics of the inner control loop are established by keeping a matrix difference \( (A_1(x) - B K_1) \) substantially constant from scan to scan, wherein \( A_1(x) \) represents the matrix estimated by the model indicative of the state conditions of the strip rolling for a present scan, \( B \) represents a constant control matrix, and \( K_1 \) represents a control gain matrix for the present scan.

8. The rolling mill of claim 7, wherein the control gain matrix for a present scan is defined by \( K_1 = B^{-1}(A_1(x) - A_1(x)+K_{prev}) \), where \( B^{-1} \) represents a left inverse of the constant control matrix \( B \), \( A_1(x) \) represents the matrix estimated by the model indicative of the state conditions of the mill for a previous scan, \( K_{prev} \) represents the control gain matrix for the previous scan.

9. The rolling mill of claim 7, wherein the inner control loop comprises a multiple-input, multiple output control loop, and wherein the controller further comprises at least a first outer control loop and a second outer control loop coupled to the inner control loop, the first and second outer control loops each respectively comprising a plurality of single-input, single output control loops, the first and second outer control loops each including at least one respective tunable gain matrix, the first outer control loop configured to generate a first group of control trims and the second outer control loop configured to generate a second group of control trims, wherein the first group of control trims comprises a plurality of thickness trims and the second group of control trims comprises a plurality of tension trims.

10. The rolling mill of claim 9, wherein the controller further comprises a control loop coupled to the inner control loop configured to generate a plurality of looper position trims.

11. A method to control metal strip rolling in response to a sequence of controller scans, the method comprising: sensing a plurality of parameters regarding the metal strip rolling; in
response to the sensed parameters, estimating per scan at least one matrix based on the sensed parameters indicative of state conditions of the strip rolling; effecting a control law in an inner loop of a controller to generate a control vector per scan; configuring the inner control loop to have dynamic characteristics, which remain substantially the same for each scan of the controller; in view of the dynamic characteristics of the inner control loop, determining a pointwise on-line control solution based on the matrix indicative of the state conditions of the strip rolling, without having to compute a Riccati control solution per scan; and controlling compression forces to controllably shape a thickness of a metal strip traveling between mutually opposing rollers based on the control vector, and wherein the configuring of the inner control loop comprises keeping a matrix difference (A(x)-BK) substantially constant from scan to scan, wherein A(x) represents the matrix estimated by the model indicative of the state conditions of the mill for a present scan i, B represents a constant control matrix, and K, represents a control gain matrix for the present scan i, and further comprising defining the control gain matrix for a present scan by K,=-B-(A(x)-A,(x))+K,_1, where B-1 represents a left inverse of the constant control matrix B, A,(x) represents the matrix estimated by the model indicative of the state conditions of the mill for a previous scan, K, represents the control gain matrix for the previous scan.

12. The method of claim 11, further comprising control signals derived from the control vector controlling respective levels of inter-stand tension to the strip rolling.

13. The method of claim 12, wherein the inner control loop is a multiple-input, multiple output control loop, and coupling to the inner control loop at least a first outer control loop and a second outer control loop, the first and second outer control loops each respectively comprising a plurality of single-input, single output control loops, the first and second outer control loops each including at least one respective tunable gain matrix, the first outer control loop configured to generate a first group of control trims and the second outer control loop configured to generate a second group of control trims, wherein the first group of control trims comprises a plurality of thickness trims and the second group of control trims comprises a plurality of tension trims.

14. The method of claim 11, further comprising configuring the controller to compute during an off-line preparation a pointwise control solution to a state-dependent algebraic Riccati equation to determine an off-line control gain matrix and off-line trim settings, the off-line preparation being performed prior to the steps recited in claim 11.

15. The method of claim 14, further comprising adapting the control gain matrix and trim settings determined during the off-line preparation to function as an initial control gain matrix and initial trim settings for determining the pointwise on-line control solution, the adapting being performed without recomputing a Riccati-based control solution.

16. The method of claim 12, further comprising configuring the plurality of single-input, single output control loops to provide a one-to-one relationship between a respective tuning parameter of the tunable gain matrix and a variable being tuned by the control trims.

17. A non-transitory tangible computer-readable storage medium having computer-executable instructions for performing the steps recited in claim 11.