



US 20180161839A1

(19) **United States**(12) **Patent Application Publication**
McGahan(10) **Pub. No.: US 2018/0161839 A1**(43) **Pub. Date: Jun. 14, 2018**(54) **METAL THICKNESS CONTROL MODEL
BASED INFERENCE SENSOR**(52) **U.S. Cl.**CPC **B21B 37/58** (2013.01)(71) Applicant: **Honeywell International Inc.**, Morris
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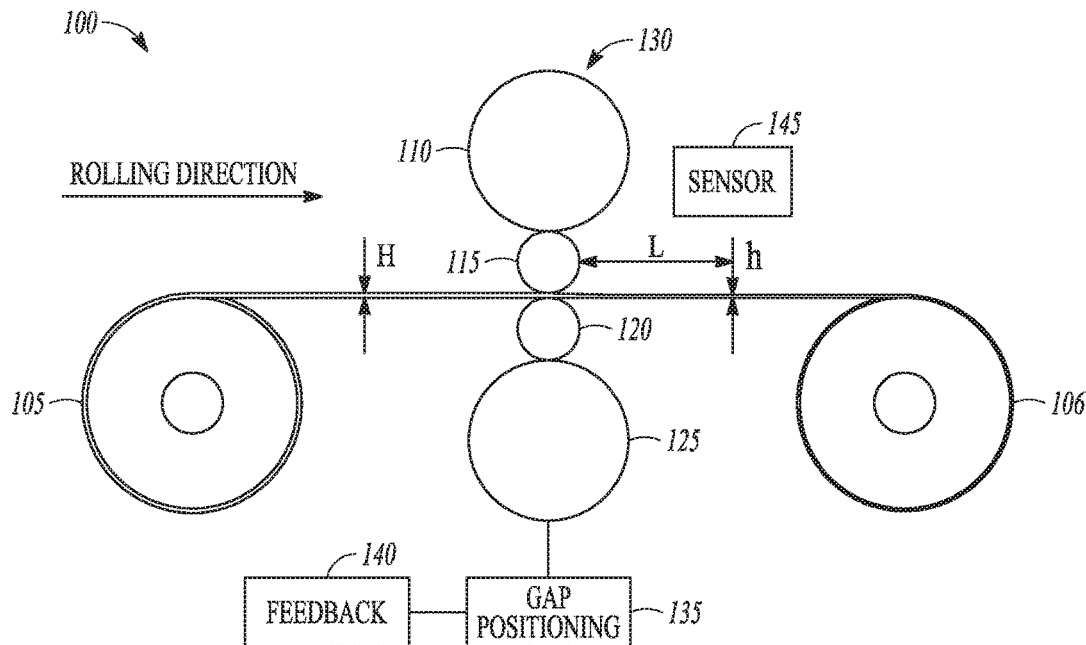
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ABSTRACT

A rolled sheet metal mill controller for controlling thickness of sheet metal produced by rolls of the mill, the controller comprising one or more processors and code stored on media readable by the one or more processors to control the thickness of the produced sheet metal, the controller including an input coupled to receive multiple measured mill parameters including produced sheet metal thickness that is time delayed from the production of the sheet metal, multiple models of the sheet metal mill, wherein the sheet metal thickness is modeled as an input varying delay, and at least one internal disturbance model based on one or more of the multiple measured parameters coupled to the input, a Kalman filter based on the multiple models, and an output coupled to control a gap between the rolls that produce the rolled sheet metal.

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(2006.01)



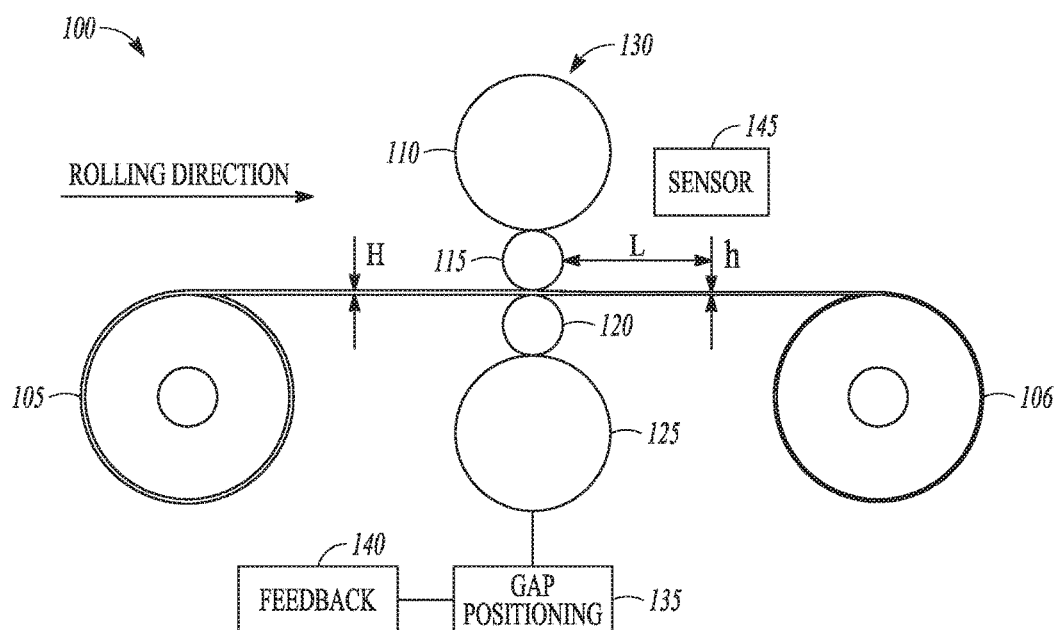


FIG. 1

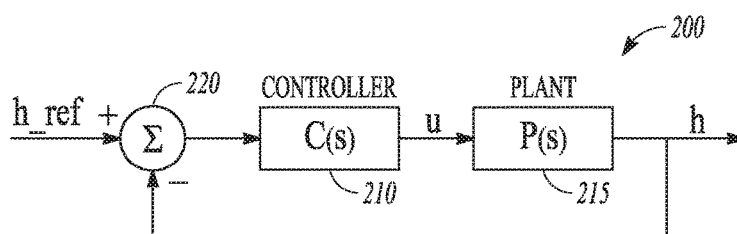


FIG. 2

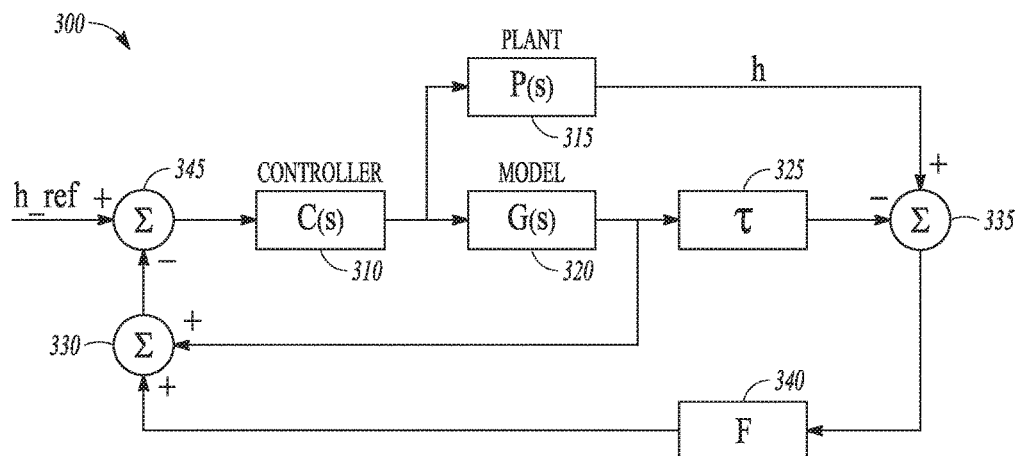


FIG. 3

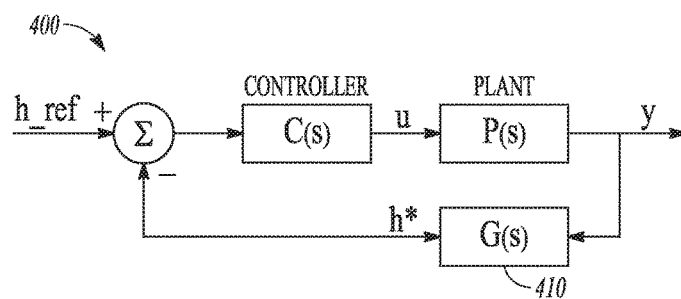


FIG. 4

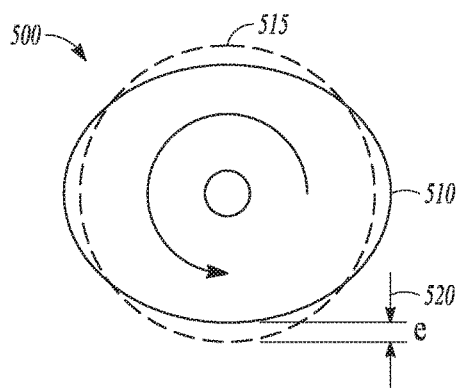
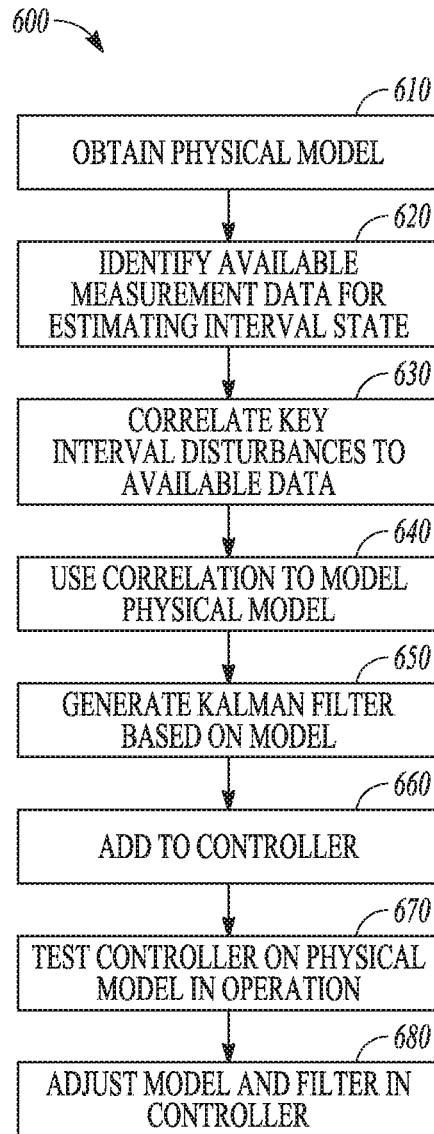


FIG. 5

**FIG. 6**

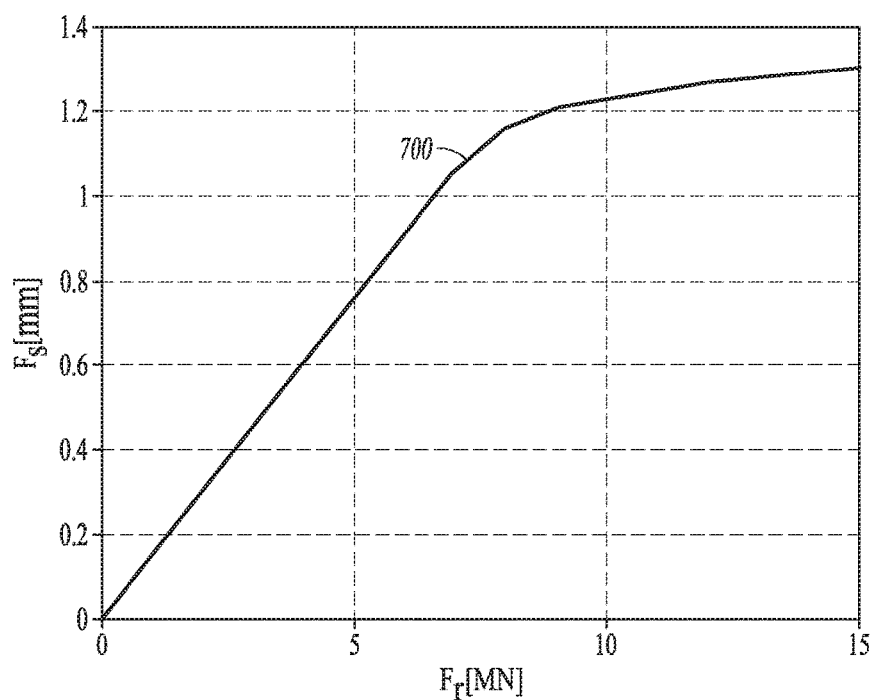


FIG. 7

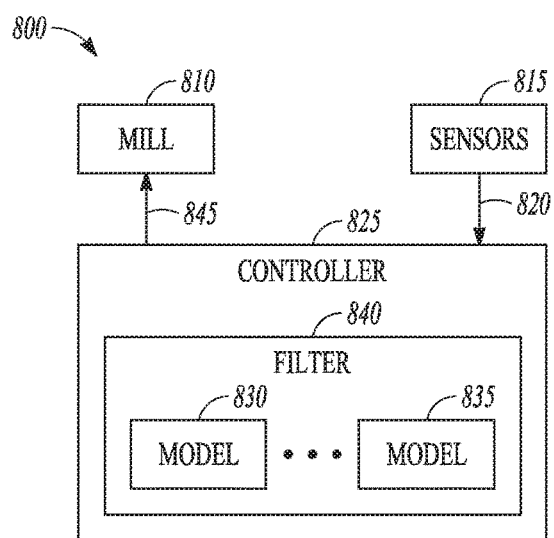


FIG. 8

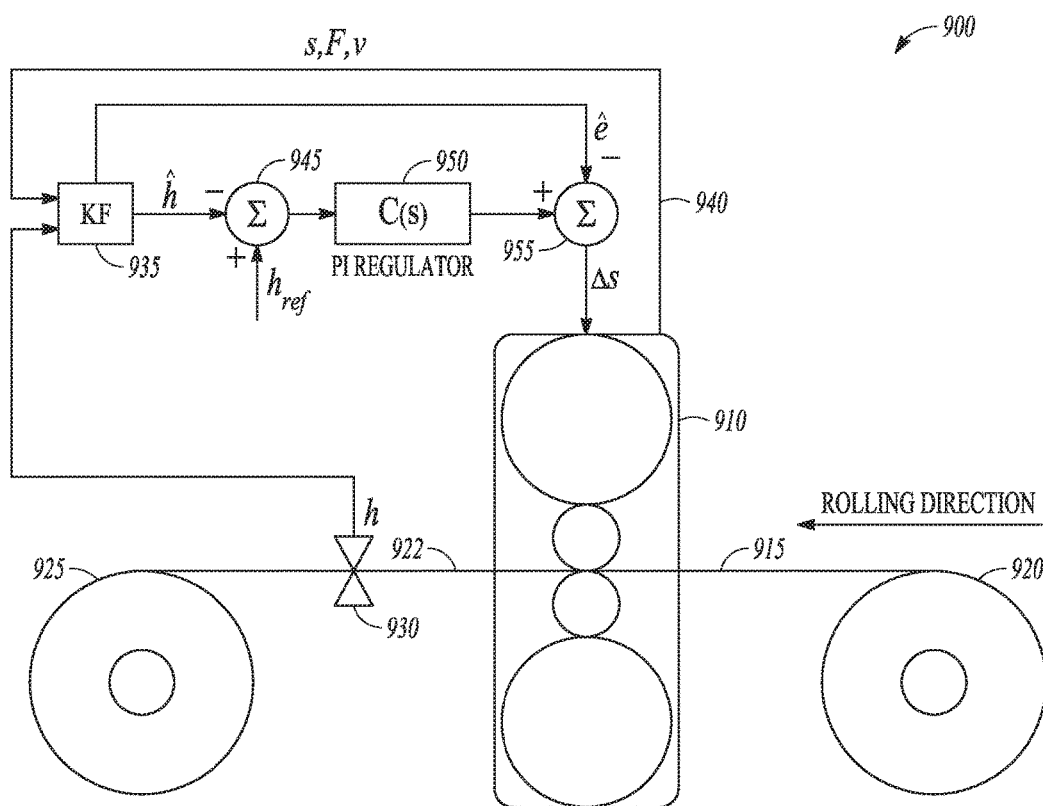


FIG. 9

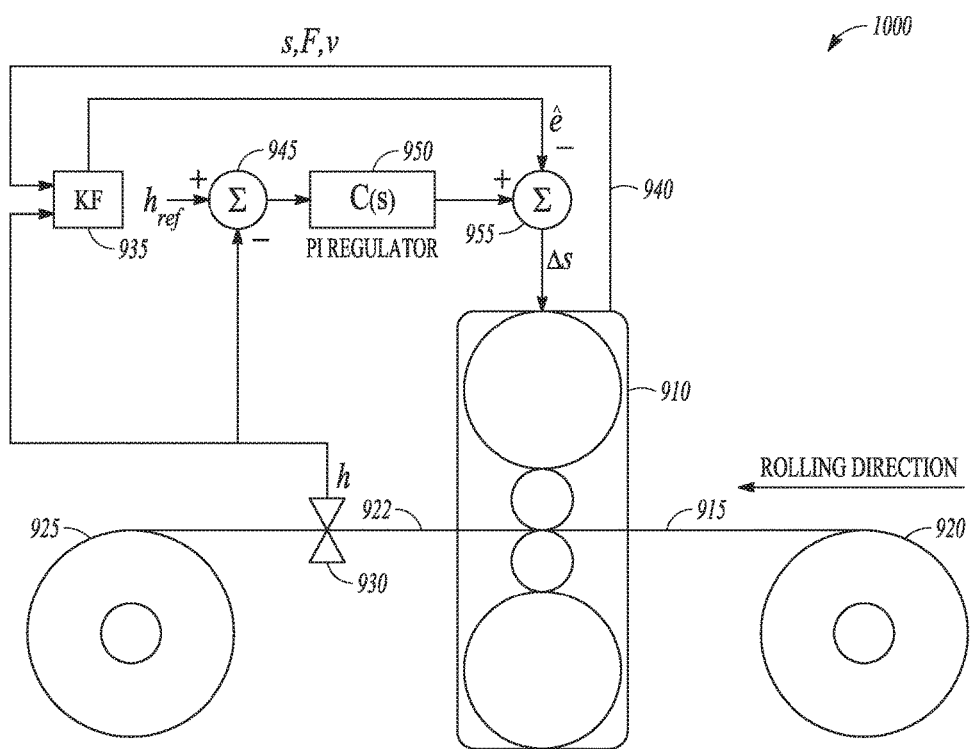


FIG. 10

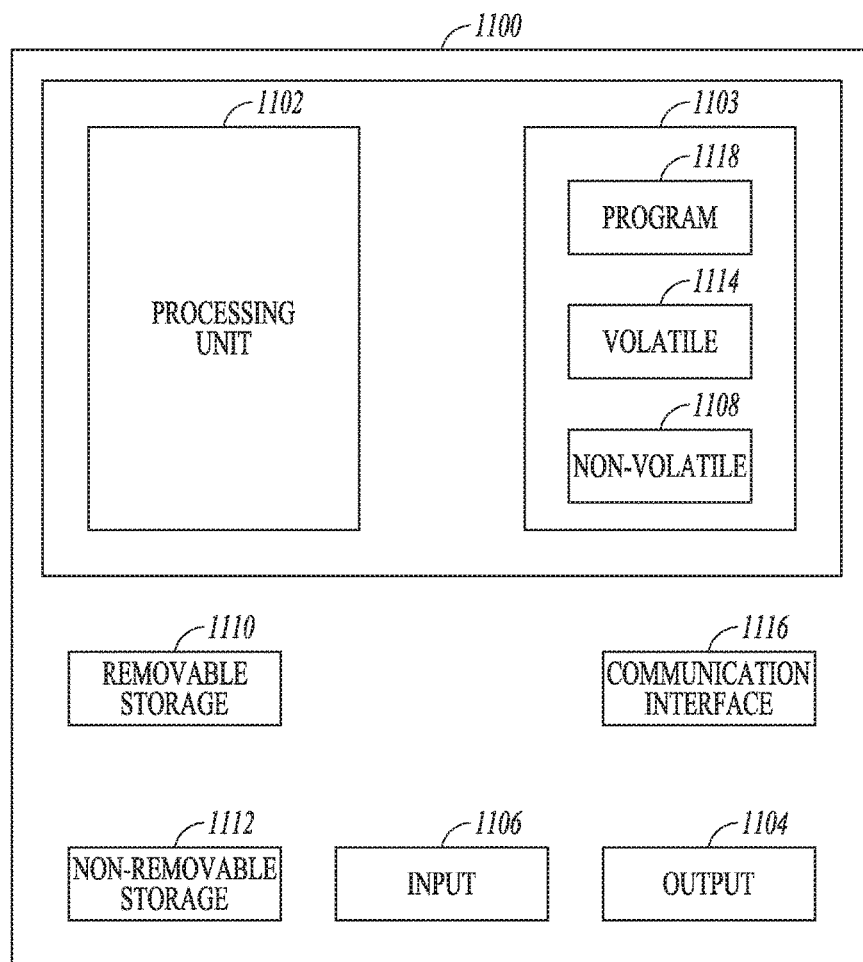


FIG. 11

METAL THICKNESS CONTROL MODEL BASED INFERENCE SENSOR

BACKGROUND

[0001] When rolling metal into sheets, the thickness of the resulting sheet is difficult to control. A rolling mill stand typically has four or more rolls mounted in a vertical plane with two smaller diameter work rolls supported between larger-diameter back-up rolls.

[0002] Centerline thickness (gage) deviation is arguably the most important Key Performance Indicator (KPI) in any metal rolling application (ferrous, non-ferrous metals, hot or cold rolling). Despite the relative maturity of the metal rolling process and indeed the control technology that is adopted, mill operators constantly strive for improved process performance. Indeed this is driven, in part, by the ultra-competitive economic market conditions in the metals industry in general.

[0003] There are many challenges to design of robust yet high performance thickness control strategies. The main challenges range from the presence of varying time delays between a mill stand and measurement device, to significant non-linearities across the operating range. Furthermore, the requirement of fast disturbance rejection of measured disturbances such as entry thickness and entry speed or un-measured internal disturbances such as roll eccentricity, thermal growth and thermo-mechanical wear of work rolls presents a further challenge. Although each of these challenges are well known and reasonably well understood, there is a lack of a coordinated and systematic approach to thickness control design, which can incorporate all of the above features effectively.

SUMMARY

[0004] A rolled sheet metal mill controller for controlling thickness of sheet metal produced by rolls of the mill, the controller comprising one or more processors and code stored on media readable by the one or more processors to control the thickness of the produced sheet metal, the controller including an input coupled to receive multiple measured mill parameters including produced sheet metal thickness that is time delayed from the production of the sheet metal, multiple models of the sheet metal mill, wherein the sheet metal thickness is modeled as an input varying delay, and at least one internal disturbance model based on one or more of the multiple measured parameters coupled to the input, a Kalman filter based on the multiple models, and an output coupled to control a gap between the rolls that produce the rolled sheet metal.

[0005] A method of programming a controller for a rolled sheet metal mill, the method including obtaining a physical representation of the rolled sheet metal mill, identifying available measurements for generating inferential estimates of internal states of the rolled sheet metal mill, correlating key internal disturbances to the available measurements to model the rolled sheet metal mill, generating a Kalman filter based on the model, and adding the Kalman filter to the controller such that the controller is programmed to provide closed loop control thickness of sheet metal produced by the sheet metal mill.

[0006] A rolled sheet metal mill controller including a processor, a sensor, and a memory device coupled to the processor and having a program stored thereon for execution

by the program processor to receive an input of multiple measured mill parameters from the sensor including produced sheet metal thickness that is time delayed from the production of the sheet metal, process multiple models of the sheet metal mill, wherein the sheet metal thickness is modeled as an input varying delay, and at least one internal disturbance model based on one or more of the multiple measured parameters coupled to the input, execute a Kalman filter based on the multiple models, and provide an output coupled to control a gap between the rolls that produce the rolled sheet metal.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] FIG. 1 is a block diagram of a sheet metal rolling stand with model based thickness control according to an example embodiment.

[0008] FIG. 2 is a block flow diagram illustrating a sheet metal thickness control mechanism according to an example embodiment.

[0009] FIG. 3 is a block flow diagram illustrating a sheet metal thickness control mechanism according to an example embodiment.

[0010] FIG. 4 is a block flow diagram illustrating a sheet metal thickness control mechanism according to an example embodiment.

[0011] FIG. 5 is a block diagram schematic representation of an ideal and actual roll superimposed to show eccentricities according to an example embodiment.

[0012] FIG. 6 is a flowchart illustrating a method of creating a thickness controller for a sheet metal mill according to an example embodiment.

[0013] FIG. 7 is a graph of a stretch curve for a rolling mill stand shown as mill stretch versus roll force according to an example embodiment.

[0014] FIG. 8 is a block diagram illustrating a rolled sheet metal system for inferentially sensing and controlling sheet metal thickness according to an example embodiment.

[0015] FIG. 9 is a block schematic diagram illustrating one example of thickness control for roll eccentricity compensation according to an example embodiment.

[0016] FIG. 10 is a block schematic diagram illustrating an alternative example of thickness control for roll eccentricity compensation according to an example embodiment.

[0017] FIG. 11 is a block schematic diagram of a computer system to implement the controller and methods according to example embodiments.

DETAILED DESCRIPTION

[0018] In the following description, reference is made to the accompanying drawings that form a part hereof, and in which is shown by way of illustration specific embodiments which may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention, and it is to be understood that other embodiments may be utilized and that structural, logical and electrical changes may be made without departing from the scope of the present invention. The following description of example embodiments is, therefore, not to be taken in a limited sense, and the scope of the present invention is defined by the appended claims.

[0019] The functions or algorithms described herein may be implemented in software in one embodiment. The software may consist of computer executable instructions stored

on computer readable media or computer readable storage device such as one or more non-transitory memories or other type of hardware based storage devices, either local or networked. Further, such functions correspond to modules, which may be software, hardware, firmware or any combination thereof. Multiple functions may be performed in one or more modules as desired, and the embodiments described are merely examples. The software may be executed on a digital signal processor, ASIC, microprocessor, or other type of processor operating on a computer system, such as a personal computer, server or other computer system, turning such computer system into a specifically programmed machine.

[0020] A model based inferential sensor may be used in a controller for controlling sheet metal thickness utilizes internal disturbance modelling and compensation. In various embodiments, roll eccentricity is modeled and compensated for by a rolling model. An HGC (hydraulic gap control) model accounts for mill stretch, which is a non-linear function of rolling force. A main drive model is used to model main drive dynamics. The models may be represented as a series of non-linear ordinary differential equations.

[0021] In designing an inferential sensor, available measurements may be identified and written as a measured output function. Thickness measurement, which is available downstream from the mill stand is delayed, and may be modeled as a communication delay which is clearly varying with mill speed. With respect to the internal disturbance modeling, a user can select various internal disturbances to be modeled depending on the type of rolling application. A Kalman Filter may be used for systems with uncertain parameters. Parameter uncertainty may be incorporated in the Kalman Filter description with covariance updated accordingly.

[0022] A physical model of the process under consideration may be combined with available process measurements to provide estimates of unmeasurable process parameters in order to control the thickness of metal produced via the mill stand. In one embodiment, a systematic approach to inferential sensor design, considers the influence of time delays, unmeasurable internal disturbances and parameter uncertainties.

[0023] Although various embodiments described are focused on thickness, also referred to as gage, control in a single-stand, cold strip mill, it is anticipated that the inventive subject matter may be applicable to any type of metal rolling application. A schematic of a metal rolling mill with thickness control is shown at 100 in FIG. 1. Incoming material of thickness H is provided by a roll 105 of material that reduced through a multiplicity of rolls 110, 115, 120, and 125 (referred to as a stand 130) turning at a known speed w , and collected by a roll 106. The stand 130 is equipped with a gap positioning system 135, which may be mechanical, hydraulic or a combination of both and may be controlled by a feedback device 140. The material leaves the stand at thickness h , which may be measured by a thickness measuring device, sensor 145, at a point indicated by arrows 150. The control objective is to regulate this outgoing thickness h as closely as possible to the target h_{ref} . Many different sensors 145 may be used to measure thickness, with common devices including x-ray type gauges.

[0024] The control problem is significantly complicated by the presence of a (varying) transportation delay between and exit thickness measurement device, sensor 145, and the

stand 130. This time varying transportation delay is characterized by the distance between stand centerline L and the stand speed ω_r . It is well known that such time delay can have a destabilizing effect on control behavior and therefore it is critical that the delay is considered at control design stage.

[0025] One common, simple approach used is to directly deploy a proportional/integral (PI) regulator or controller to control thickness via hydraulic positioning system that controls the positioning of the rolls. As a consequence of the time delay, the controller is de-tuned therefore leading to closed loop performance with limited bandwidth. This simple control structure is shown in block diagram form in FIG. 2 at 200. Control structure 200 includes a controller 210 coupled to a representation of a plant or stand 215 corresponding to the hydraulic or gap positioning system 135 and thickness sensor to control the provision of sheet metal with measured thickness h , with a thickness feedback summed at 220 with a desired or reference thickness provided as input to the controller 210.

[0026] Slightly more advanced control techniques, incorporating delay compensation, have also been applied. An example of such delay compensation loop is the celebrated Smith Predictor, shown at 300 in FIG. 3. Although this delay compensation structure allows for improved closed loop bandwidth, it suffers from well-known issues related to robustness with respect to delay uncertainty. A controller 310 is coupled to a plant 315, which also provides sheet metal of thickness h . In addition, the controller 310 is coupled to a model 320 of the plant, which models the plant to provide an expected thickness to both a delay block 325 and a summing block 330. The delay block 325 provides a delay commensurate with timing of the measured thickness h and results in subtraction of the modeled thickness from the measured thickness at 335. The result is feedback 340 that is also provided to the summing block 330 to provide a feedback value subtracted from a reference thickness at 345, which is then provided to the controller.

[0027] Inferential sensing is a commonly used technique in control engineering. An inferential sensor uses information available from other measurements and process parameters to calculate an estimate of the quantity of interest. Typical motivations for construction of an inferential sensor are replacement of costly or impractical physical instrumentation or improvement of control performance through estimation of key (unmeasurable) process parameters. A Kalman Filter, based on statistical inference, is a commonly used software algorithm for implementation of inferential sensing technology. In this case, a physical model of the process under consideration is combined with available process measurements to provide estimates of unmeasurable process parameters.

[0028] Inferential sensing technology is widely used and widely misunderstood in metal rolling applications. Since the British iron and steel research association (BISRA) gauge was reported in the 1950's as a means of avoiding the influence of the time delay from stand to gauge, inferential sensing technology has become standard in most metal rolling automation solutions.

[0029] Despite the plethora of inferential sensor implementations that have been proposed, a systematic approach to inferential sensor design, considering the influence of time delays, unmeasurable internal disturbances and parameter uncertainties remains an open issue.

[0030] In its simplest form, the BISRA gauge utilizes the fact that an expression for roll separating force can be written as

$$F_r = c_g(h-s)$$

Where

[0031] F_r Roll Separating force [N]

[0032] c_g Stand modulus [N/m]

[0033] h Exit Thickness [m]

[0034] s HGC (hydraulic gap control) Screw Position [m]

[0035] In one embodiment, both the roll separating force and HGC screw position are measured, which allows writing of the estimated exit thickness as:

$$\hat{h} = \frac{F_r}{c_g} + s$$

[0036] In a typical application of such a model, the estimated thickness is used in either one of two ways. Firstly, the estimated exit thickness can be used to construct a feedback loop, similar to that shown in FIG. 2. This observer based controller is shown generally at **400** in FIG. 4, in which the estimated thickness feedback is provided at **410**. Error! Reference source not found.

[0037] Secondly, the estimated thickness can be used to construct a feed-forward compensation, which is typically added to the compensation from the original feedback loop shown in FIG. 2. This feed-forward correction can be derived as:

Taking the Derivative with Respect to Thickness:

$$\frac{dF_r}{dh} = c_g - c_g \frac{ds}{dh}$$

It is observed that

$$\frac{dF_r}{dh} = -c_m,$$

which allows for a simplification and rearrangement as

$$\frac{ds}{dh} = 1 + \frac{c_m}{c_g}$$

The screw compensation may be rewritten as:

$$\Delta s = \frac{ds}{dh} \hat{h} = \left(1 + \frac{c_m}{c_g}\right) \hat{h}$$

[0038] Massflow control is based on the observation that massflow is conserved through a single stand. If it is assumed that there is no lateral spread (a reasonable assumption in hot strip finishing mill applications, or cold strip rolling applications), then it is possible to write the conservation of massflow in simplified form as

$$VH = v\hat{h}$$

Where:

[0039] V Entry Strip Speed [m/s]

[0040] Exit Strip Speed [m/s]

[0041] In this case it is assumed that the entry and exit strip speeds are measured using e.g. laser speed velocimeter. It is further assumed that the entry thickness is measured. It is therefore possible to write the thickness estimate as

$$\hat{h} = \frac{V}{v} H$$

[0042] This thickness estimate can then be used in a similar way as described with respect to FIG. 4.

[0043] In one embodiment, internal disturbance modelling and compensation may be performed. Unmeasured, yet observable disturbances are of significant importance to thickness control in metal rolling applications. These disturbances are referred to as internal due to the fact that they manifest themselves on the internal states of the plant/model as opposed to appearing at either input/output directly. Reasons for such internal disturbances are typically non-uniform cylindrical grinding on the mill stand rolls, thermo-mechanical variation in the mill stand rolls and hydro-dynamic effects of Back-Up Roll bearings (depending on bearing type and construction).

[0044] Roll Eccentricity Modelling and Compensation

[0045] In one embodiment, roll eccentricity is modeled and compensated. Roll eccentricity may be caused by grinding inaccuracies during the manufacture, or preparation of rolls for use, deviations between the axis of the roll barrel and the roll neck or by non-uniform thermal expansion. A simple schematic of eccentricity on a roll is shown at **500** in FIG. 5 as an actual roll shape shown by solid line **510** and an ideal roll shape as shown by broken line **515** which are effectively coaxial. The amount of eccentricity is shown at a maximum eccentricity, e , at **520** as a difference between the ideal and actual radius.

[0046] The effect of eccentricity on thickness in a rolling application can be explained as follows: Normally an increased force means the exit thickness has increased (thus pushing the rolls apart). However, if the rolls are eccentric then when the largest radius passes through the roll gap, the force increases, but the exit thickness actually decreases. Hence a change in force is misinterpreted when eccentricity components are present. This can be easily seen in the following, assuming that eccentricity signal e enters as follows

$$F_r = c_g(h-s+e)$$

[0047] Now, the estimate of the exit thickness is given as

$$\hat{h} = \frac{F_r}{c_g} + s - e$$

[0048] Hence it is clear that the controller would think that the eccentricity variations are disturbances in the output and try to compensate for them.

[0049] The eccentricity signal may be modeled as a compound multi-sinusoidal signal with multiple harmonics as follows

$$e(t) = \sum_{j=1}^H \sum_{i=1}^N a_{ij} \sin j\omega_i t$$

[0050] $e(t)$ Eccentricity signal

[0051] a_{ij} Amplitude of j th harmonic of sinusoidal component i

[0052] ω_i Frequency of sinusoidal component i

[0053] t Absolute time

[0054] N Number of sinusoidal components

[0055] H Number of harmonics of each sinusoidal component

[0056] Eccentricity compensation techniques can be broadly classified into two categories; passive and active. Passive compensation simply attempts to remove the gain effect described above in a mill-stretch compensation loop. Active compensation however generates a signal in the position or force control loop of the hydraulic positioning system in order to reduce the periodic disturbances in the strip.

[0057] Design of inferential sensors for thickness control in metal rolling applications has been rather ad-hoc, utilizing a significant amount of engineer insight and experience. In various embodiments, a systematic approach may be used for inferential sensor design for thickness control in metal rolling applications as illustrated at 600 in a flow diagram of FIG. 6.

[0058] The first step in the Inferential Sensor construction workflow is modelling of a mill stand area as indicated at 610. Although this is valid for any type of mill (single stand, reversing or tandem), embodiments are described related to a mill with the geometry shown in FIG. 1. Model components include a rolling model, an HGC model, and a main drive model.

[0059] Rolling Model

[0060] A classical non-linear rolling model is used to simplify the roll contact area computations. This is of the form

$$[F_r, P_r, f_s]^T = f(H, h, k, R, W)$$

[0061] F_r Rolling Load [N]

[0062] P_r Rolling Torque [Nm]

[0063] f_s Forward Slip [-]

[0064] k Material hardness [Pa]

[0065] R Roll Radius [m]

[0066] W Strip Width [m]

[0067] HGC Model

[0068] As mentioned previously, the strip exit gauge depends on the roll gap s , which is controlled by the hydraulic capsule, and on the mill stretch. The mill stretch is in a turn a non-linear function of the rolling force. A typical example of a stretch curve for a rolling mill stand is shown at 700 in FIG. 7 shown as mill stretch versus roll force. An expression for the exit thickness can then be written as

$$h = s + F_s(F_r)$$

[0069] F_s Mill Stretch [m]

[0070] Note also that

$$\frac{\partial F_s}{\partial F_r} = c_s^{-1},$$

which is an important observation for construction of AGC type controllers. Dynamics of the HGC system are assumed to be governed by the following differential equation:

$$\dot{s} = \frac{1}{T_{hgc}}(s_{ref} - s)$$

[0071] s_{ref} HGC position reference [m]

[0072] T_{hgc} HGC Time constant [s]

[0073] Main Drive Model

[0074] A simple model of the main drive dynamics is of the form

$$\dot{v}_{roll} = \frac{1}{T_{roll}}(v_{ref} - v_{roll})$$

[0075] v_{roll} Work Roll Speed [m/s]

[0076] v_{ref} Work Roll Speed Reference [m/s]

[0077] T_{roll} Main Drive Time constant [s]

[0078] The model components are collected together and represented in compact form as a series of non-linear ordinary differential equations of the form

$$\dot{x} = f(x, u, d, th)$$

$$y = g(x, u, d, th)$$

[0079] x Dynamic states of the model

[0080] u Model Inputs

[0081] d Measured Disturbances

[0082] th Estimatable parameters

[0083] y Model Outputs

[0084] In designing the inferential sensor, at 630 in FIG. 6, measurements that are available for estimation of the system state are determined. The measured output function may be expressed as:

$$z = g_z(x, u, d, th)$$

[0085] With respect to transport delay, L , modelling, in typical cases, a thickness measurement is available downstream from the mill stand. As a consequence of this measurement location, a variable transport delay is present on the output (if exit thickness is selected as a measured output of interest). An expression for this variable transport delay, L , is given as an integral implicit relationship:

$$\int_{t-\tau_h}^t v_{roll}(1+f_s) = L$$

[0086] The variable transport delay may be treated in the Kalman Filter implementation as a communication delay. The delay is at least partially a result of mill speed variations. Slower mill speed results in a larger delay, and faster mill speed results in a shorter delay of the thickness measurement.

[0087] For internal disturbance modelling, the user can select various internal disturbances to be estimated at 630, depending on the type of rolling application under consideration. Although this could in principle be extended to any type of internal disturbance model that affects exit gauge, currently selectable are

[0088] Backup and Work Roll Eccentricity

[0089] Work Roll Thermal Crown

[0090] Work Roll Mechanical Wear

[0091] Backup Roll Bearing Flotation

[0092] The selected internal disturbances are then used to model the mill stand at **640**, utilizing the available data. A Kalman filter is then generated based on the model at **650** and may be integrated into the controller at **660**. At **670**, the controller with the Kalman filter may be parameterized and the corresponding mill stand run to produce sheet metal. The available data may then be collected, including the actual sheet metal thickness measurements. At **680**, the model may be adjusted by adjusting Kalman filter parameters based on the collected data, and the mill stand run again to ensure the model based controller is providing sheet metal of desired thickness.

[0093] Robustness of inferential sensors may be strongly dependent on model quality. An example of this is model dynamics mismatch resulting in fake artifacts in inferred values.

[0094] By assuming some parametric uncertainty in the model (e.g. stand module), and utilizing the concept of equivalent noise, one can design the Kalman filter which is robust to such parametric uncertainties.

[0095] FIG. 8 is a block diagram illustrating a rolled sheet metal system generally at **800**. System **800** includes a mill **810** that utilizes multiple rollers to produce sheet metal of a desired thickness from sheet metal stock. Multiple sensors **815** provide measured data regarding the system **800**, such as actual sheet metal thickness produced, roller speeds, roller forces and other available measurements. The measured data is received at an input **820** of a controller **825**. Controller **825** includes one or more processors and code stored on media readable by the one or more processors to control the thickness of the produced sheet metal.

[0096] Controller **825** includes the input **820** that receives at least a measurement of sheet metal thickness that is time delayed from the production of the sheet metal. The controller also includes multiple models **830**, **835** of the sheet metal mill. The sheet metal thickness is modeled as a communication delay. The communication delay is a function of a variable transport delay input since the thickness cannot be directly measured between the rollers. At least one of the models comprises an internal disturbance model based on one or more of the multiple measured data received at the input **820**. In one embodiment, the models are used to form a Kalman filter **840**. An output **845** is coupled to the mill **810** to control a gap between the rolls that produce the rolled sheet metal.

[0097] In one embodiment, the multiple models include one or more of a rolling model with a corresponding input of roll torque, gap control model with a corresponding input of rolling force, and a main drive model with a corresponding input of roll speed. One or more internal disturbances that are modeled are selected from the group consisting of backup and work roll eccentricity, work roll thermal crown, work roll mechanical wear, and backup roll bearing flotation.

[0098] The Kalman filter may include filter parameters adjusted as a function of measured mill parameter values from operation of the sheet metal mill.

[0099] FIG. 9 is a block schematic diagram illustrating one example of thickness control for roll eccentricity compensation generally at **900**. A mill is illustrated in block form

at **910** including multiple rollers and hydraulic gap control (HGC) to change a gap between rollers that changes the thickness of an input sheet of metal **915** from a source roll of metal **920**. The output sheet of metal **922** with changed thickness is collected on a collection roller **925**. The thickness of the output sheet of metal is measured by a thickness sensor **930**, positioned downstream from the mill **910**. Thus, the thickness measurement is made following the roller gap and at a time after actually pressing of the metal sheet that is variable, depending on the speed of the sheet progressing through the mill and the change in thickness.

[0100] The thickness measurement or exit gage in mm, h , is provided to a Kalman Filter (KF) **935**, which also receives measured parameters s , F , and v via **940** measured by corresponding sensors of the mill **910**. S is the HGC position, or gap in mm. F is the rolling load in tons, and v is the mill speed in m/minute. KF **935** provides a thickness estimation,

$$\hat{h} = \frac{F}{c_g} + s - \hat{e}$$

where $\hat{e}$ is an eccentricity estimation, and c_g is a stand modulus in N/m. The thickness estimation, $\hat{h}$, is provided to a summing junction **945** where it is combined with a reference thickness, h_{ref} , corresponding to the desired thickness of the output sheet **922** and provided to a proportional/integral (PI) regulator **950** implementing a combination of proportional and integral control, $C(s)$, to provide a control signal to a summing junction **955**.

[0101] Summing junction **550** combines the control signal with a feedforward eccentricity estimation a from KF **935** to provide a position adjustment signal to the mill **910** to control the gap. Thus, control of the gap is based on estimates of both the thickness at the time the metal sheet is run through the roller gap and an estimate of feed forward eccentricity, both of which are provided by KF **935**.

[0102] FIG. 10 is a block schematic diagram illustrating an alternative example of thickness control for roll eccentricity compensation generally at **1000**. The elements of FIG. 10 have reference numbers corresponding to those of FIG. 9. The difference is that the summing junction **945** in FIG. 10 receives the measured thickness, h , direction from sensor **930** as opposed to receiving it from KF **935**. Otherwise operations performed by thickness control **1000** are the same as those performed by thickness control **900**.

[0103] FIG. 11 is a block schematic diagram of a computer system **1100** to implement the controller and methods according to example embodiments. All components need not be used in various embodiments. One example computing device in the form of a computer **1100**, may include a processing unit **1102**, memory **1103**, removable storage **1110**, and non-removable storage **1112**. Although the example computing device is illustrated and described as computer **1100**, the computing device may be in different forms in different embodiments. For example, the computing device may instead be a smartphone, a tablet, smartwatch, or other computing device including the same or similar elements as illustrated and described with regard to FIG. 11. Devices such as smartphones, tablets, and smartwatches are generally collectively referred to as mobile devices. Further, although the various data storage elements are illustrated as part of the computer **1100**, the storage may

also or alternatively include cloud-based storage accessible via a network, such as the Internet.

[0104] Memory **1103** may include volatile memory **1114** and non-volatile memory **1108**. Computer **1100** may include—or have access to a computing environment that includes—a variety of computer-readable media, such as volatile memory **1114** and non-volatile memory **1108**, removable storage **1110** and non-removable storage **1112**. Computer storage includes random access memory (RAM), read only memory (ROM), erasable programmable read-only memory (EPROM) & electrically erasable programmable read-only memory (EEPROM), flash memory or other memory technologies, compact disc read-only memory (CD ROM), Digital Versatile Disks (DVD) or other optical disk storage, magnetic cassettes, magnetic tape, magnetic disk storage or other magnetic storage devices capable of storing computer-readable instructions for execution to perform functions described herein.

[0105] Computer **1100** may include or have access to a computing environment that includes input **1106**, output **1104**, and a communication connection **1116**. Output **1104** may include a display device, such as a touchscreen, that also may serve as an input device. The input **1106** may include one or more of a touchscreen, touchpad, mouse, keyboard, camera, one or more device-specific buttons, one or more sensors integrated within or coupled via wired or wireless data connections to the computer **1100**, and other input devices. The computer may operate in a networked environment using a communication connection to connect to one or more remote computers, such as database servers, including cloud based servers and storage. The remote computer may include a personal computer (PC), server, router, network PC, a peer device or other common network node, or the like. The communication connection may include a Local Area Network (LAN), a Wide Area Network (WAN), cellular, WiFi, Bluetooth, or other networks.

[0106] Computer-readable instructions stored on a computer-readable storage device are executable by the processing unit **1102** of the computer **1100**. A hard drive, CD-ROM, and RAM are some examples of articles including a non-transitory computer-readable medium such as a storage device. The terms computer-readable medium and storage device do not include carrier waves. For example, a computer program **1118** may be used to cause processing unit **1102** to perform one or more methods or algorithms described herein.

Examples

[0107] Example 1 includes a rolled sheet metal mill controller for controlling thickness of sheet metal produced by rolls of the mill, the controller comprising one or more processors and code stored on media readable by the one or more processors to control the thickness of the produced sheet metal, the controller including an input coupled to receive multiple measured mill parameters including produced sheet metal thickness that is time delayed from the production of the sheet metal, multiple models of the sheet metal mill, wherein the sheet metal thickness is modeled as an input varying delay, and at least one internal disturbance model based on one or more of the multiple measured parameters coupled to the input, a Kalman filter based on the multiple models, and an output coupled to control a gap between the rolls that produce the rolled sheet metal.

[0108] Example 2 includes the rolled sheet metal mill of example 1 wherein the multiple models include a rolling model with a corresponding input of roll torque.

[0109] Example 3 includes the rolled sheet metal mill of any of examples 1-2 wherein the multiple models include a gap control model with a corresponding input of rolling force.

[0110] Example 4 includes the rolled sheet metal mill of any of examples 1-3 wherein the multiple models include a main drive model with a corresponding input of roll speed.

[0111] Example 5 includes the rolled sheet metal mill of any of examples 1-4 wherein the communication delay is a function of a variable transport delay input.

[0112] Example 6 includes the rolled sheet metal mill of any of examples 1-5 wherein one or more internal disturbances that are modeled are selected from the group consisting of backup and work roll eccentricity, work roll thermal crown, work roll mechanical wear, and backup roll bearing flotation.

[0113] Example 7 includes the rolled sheet metal mill of any of examples 1-6 wherein the Kalman filter is based on the models and is robust to known parametric uncertainties.

[0114] Example 8 includes the rolled sheet metal mill of any of examples 1-7 wherein the Kalman filter includes filter parameters adjusted as a function of measured mill parameter values from operation of the sheet metal mill.

[0115] In example 9, a method of programming a controller for a rolled sheet metal mill, the method including obtaining a physical representation of the rolled sheet metal mill, identifying available measurements for generating inferential estimates of internal states of the rolled sheet metal mill, correlating key internal disturbances to the available measurements to model the rolled sheet metal mill, generating a Kalman filter based on the model, and adding the Kalman filter to the controller such that the controller is programmed to provide closed loop control thickness of sheet metal produced by the sheet metal mill.

[0116] Example 10 includes the method of example 9 and further comprising testing the controller as a function of operation of the rolled sheet metal mill.

[0117] Example 11 includes the method of example 10 and further comprising adjusting Kalman filter parameters responsive to the testing.

[0118] Example 12 includes the method of any of examples 10-11 wherein the multiple models include a rolling model with a corresponding input of roll torque.

[0119] Example 13 includes the method of any of examples 10-12 wherein the multiple models include a gap control model with a corresponding input of rolling force.

[0120] Example 14 includes the method of any of examples 10-13 wherein the multiple models include a main drive model with a corresponding input of roll speed.

[0121] Example 15 includes the method of any of examples 10-14 wherein the communication delay is a function of a variable transport delay input.

[0122] Example 16 includes the method of any of examples 10-15 wherein one or more internal disturbances that are modeled are selected from the group consisting of backup and work roll eccentricity, work roll thermal crown, work roll mechanical wear, and backup roll bearing flotation.

[0123] In example 17, a rolled sheet metal mill controller including a processor, a sensor, and a memory device coupled to the processor and having a program stored

thereon for execution by the program processor to receive an input of multiple measured mill parameters from the sensor including produced sheet metal thickness that is time delayed from the production of the sheet metal, process multiple models of the sheet metal mill, wherein the sheet metal thickness is modeled as an input varying delay, and at least one internal disturbance model based on one or more of the multiple measured parameters coupled to the input, execute a Kalman filter based on the multiple models, and provide an output coupled to control a gap between the rolls that produce the rolled sheet metal.

[0124] Example 18 includes the controller of example 17 wherein the multiple models include a rolling model with a corresponding input of roll torque, a gap control model with a corresponding input of rolling force, and a main drive model with a corresponding input of roll speed.

[0125] Example 19 includes the controller of any of examples 17-18 wherein the communication delay is a function of a variable transport delay input.

[0126] Example 20 includes the controller of any of examples 17-19 wherein one or more internal disturbances that are modeled are selected from the group consisting of backup and work roll eccentricity, work roll thermal crown, work roll mechanical wear, and backup roll bearing flotation.

[0127] Although a few embodiments have been described in detail above, other modifications are possible. For example, the logic flows depicted in the figures do not require the particular order shown, or sequential order, to achieve desirable results. Other steps may be provided, or steps may be eliminated, from the described flows, and other components may be added to, or removed from, the described systems. Other embodiments may be within the scope of the following claims.

1. A rolled sheet metal mill controller for controlling thickness of sheet metal produced by rolls of the mill, the controller comprising one or more processors and code stored on media readable by the one or more processors to control the thickness of the produced sheet metal, the controller comprising:

- an input coupled to receive multiple measured mill parameters including produced sheet metal thickness that is time delayed from the production of the sheet metal;

- multiple models of the sheet metal mill, wherein the sheet metal thickness is modeled as an input varying delay, and at least one internal disturbance model based on one or more of the multiple measured parameters coupled to the input;

- a Kalman filter based on the multiple models; and

- an output coupled to control a gap between the rolls that produce the rolled sheet metal.

2. The rolled sheet metal mill of claim 1 wherein the multiple models include a rolling model with a corresponding input of roll torque.

3. The rolled sheet metal mill of claim 1 wherein the multiple models include a gap control model with a corresponding input of rolling force.

4. The rolled sheet metal mill of claim 1 wherein the multiple models include a main drive model with a corresponding input of roll speed.

5. The rolled sheet metal mill of claim 1 wherein the communication delay is a function of a variable transport delay input.

6. The rolled sheet metal mill of claim 1 wherein one or more internal disturbances that are modeled are selected from the group consisting of backup and work roll eccentricity, work roll thermal crown, work roll mechanical wear, and backup roll bearing flotation.

7. The rolled sheet metal mill of claim 1 wherein the Kalman filter is based on the models and is robust to known parametric uncertainties.

8. The rolled sheet metal mill of claim 1 wherein the Kalman filter includes filter parameters adjusted as a function of measured mill parameter values from operation of the sheet metal mill.

9. A method of programming a controller for a rolled sheet metal mill, the method comprising:

- obtaining a physical representation of the rolled sheet metal mill;

- identifying available measurements for generating inferential estimates of internal states of the rolled sheet metal mill;

- correlating key internal disturbances to the available measurements to model the rolled sheet metal mill;

- generating a Kalman filter based on the model; and adding the Kalman filter to the controller such that the controller is programmed to provide closed loop control thickness of sheet metal produced by the sheet metal mill.

10. The method of claim 9 and further comprising testing the controller as a function of operation of the rolled sheet metal mill.

11. The method of claim 10 and further comprising adjusting Kalman filter parameters responsive to the testing.

12. The method of claim 10 wherein the multiple models include a rolling model with a corresponding input of roll torque.

13. The method of claim 10 wherein the multiple models include a gap control model with a corresponding input of rolling force.

14. The method of claim 10 wherein the multiple models include a main drive model with a corresponding input of roll speed.

15. The method of claim 10 wherein the communication delay is a function of a variable transport delay input.

16. The method of claim 10 wherein one or more internal disturbances that are modeled are selected from the group consisting of backup and work roll eccentricity, work roll thermal crown, work roll mechanical wear, and backup roll bearing flotation.

17. A rolled sheet metal mill controller comprising:

- a processor;

- a sensor; and

- a memory device coupled to the processor and having a program stored thereon for execution by the program processor to:

- receive an input of multiple measured mill parameters from the sensor including produced sheet metal thickness that is time delayed from the production of the sheet metal;

- process multiple models of the sheet metal mill, wherein the sheet metal thickness is modeled as an input varying delay, and at least one internal disturbance model based on one or more of the multiple measured parameters coupled to the input;

- execute a Kalman filter based on the multiple models; and

provide an output coupled to control a gap between the rolls that produce the rolled sheet metal.

18. The controller of claim **17** wherein the multiple models include a rolling model with a corresponding input of roll torque, a gap control model with a corresponding input of rolling force, and a main drive model with a corresponding input of roll speed.

19. The controller of claim **17** wherein the communication delay is a function of a variable transport delay input.

20. The controller of claim **17** wherein one or more internal disturbances that are modeled are selected from the group consisting of backup and work roll eccentricity, work roll thermal crown, work roll mechanical wear, and backup roll bearing flotation.

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