ADVANCED CONTROLS FOR WEB HANDLING: READY FOR PRODUCTION?

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ABSTRACT

The science of web handling has numerous control challenges. Longitudinal control is especially challenging because the machine is a distributed, high order, tightly coupled flexible system. Advanced controls were developed in the last few decades, and have been widely applied in several fields, most notably aeronautics, robotics, navigation, and extremely large-scale high-value industrial processes, such as petroleum refining. There have been numerous advanced web handling control strategies papers previously presented at this conference. However, there are few implementations of advanced controls in commercially available web handling equipment.

The Proportional-Integral-Derivative (PID) controller was originally developed in the 1920's. The PID controller dominates web handling controls to this day; virtually all web handling is controlled by variations of the PID algorithm. While an optimized PID controller can perform well, there are superior control algorithms that have higher performance and more flexibility, but they have yet to displace even a small number of PID systems

While this paper is fundamentally on control topics, this presentation is targeted towards a general web handling audience; a general broad overview will be presented. This paper will provide a brief history of control, emphasizing the role of PID in industry. It will illustrate some of the circumstances that have limited the adoption of advanced web handling control strategies, and propose potential solutions to increase the rate of adoption of advanced web handling controls. In addition, several high value web handling problems that may greatly benefit from these strategies will be discussed.

NOMENCLATURE

- A state transition matrix, frequency domain
- a state transition matrix, time domain
- a_{nm} state transition matrix element, time domain
- B state input or forcing function, time domain
- b_{nm} state input matrix element, time domain

G_n plant transfer function
G acceleration, 9.8 m/s^2
J cost function
K_P proportional gain
K_I integral gain
K_D derivative gain
m mass
PV process variable
p_k position at kth step
SP setpoint
s Laplace complex variable
T time step, seconds
U controller output
u_k controller output at kth step
v_k velocity at kth time step
w_n weighting factor
x_n state x sub n, states 1-n
Y process variable
Φ state transition matrix, discrete time series format
Γ input matrix, discrete time series format

INTRODUCTION

To understand the state of current web handling controls, a brief history of controls engineering and the PID controller is required. Simple feedback controls were known in antiquity. The Greeks developed water float regulators for clocks prior to 300 BC. Pressure and temperature control devices employing feedback were developed in Europe in the late 1500's and early 1600's. The first automatic feedback device used in an industrial process was James Watt's flyball governor developed in 1769 for controlling the speed of a steam engine. Efforts to improve upon the flyball regulator exposed some control challenges such as transient behavior and instability, and led to the first efforts to develop a mathematical foundation for control theory. James Clerk Maxwell's seminal paper in 1868, "On Governors" used differential equations to explain the instabilities in these flyball regulators, and began the use of mathematical analysis in control systems, however trial and error approaches still dominated.

The Proportional-Integral-Derivative (PID) controller was originally developed in the early 1920's. It was recognized at the end of World War 1 there was a need to automatically steer large naval ships in order to improve the accuracy of the large guns. Nicholas Minorsky [1] developed a PID controller for use on the battleship New Mexico in 1923. His paper "Directional Stability of Automatically Steered Bodies" analyzed and discussed the properties of a three term controller.

It is claimed that the first general industrial use of PID controllers was by the Taylor Instrument Company in 1936 when "preact" (their term for derivative) was added to their "double response" controller. The derivative term was initially fixed, but in 1939 a version with an adjustable derivative term was introduced. The use of PID in industrial control rapidly expanded.

Control theory in the United States was driven predominantly by the development of the telephone system and the requisite amplifiers. Distortion in telephone amplifiers was a major issue in the early 1920's. Harold Black at Bell Labs first developed the concept of negative feedback, wherein a portion of the amplified signal was subtracted from the input. This greatly improved the signal quality, and made the amplifier more immune to changes in the components. Two other scientist at Bell Labs made major contributions in the 1930's and 40's. Harry Nyquist developed stability theory and the plot that bears his name. Heinrich Bode developed the concept of root locus, and developed the Bode plot (a plot of how the closed loop system poles move based on a system's gain). World War II generated a critical need for a wide range of control systems, such as gun turrets, airplane autopilots, and radar antenna control.

Control system analysis using the integral-differential equations proved difficult to solve. These difficulties led to the development of a variety of techniques to help simplify analysis and provide better controller designs. Frequency based techniques were emphasized in the period immediately after WWII. The techniques developed include the use of Laplace transforms, complex frequency plane analysis, Nyquist and Bode plots, s-plane analysis, and root locus design. These techniques would become known as "classical" control theory. PID controller design is firmly founded in these techniques. In Russia, time domain based formulations tended to be emphasized at this time.

The technical competition between the Soviet Union and the United States provided a huge impetus to develop more advanced control algorithms. The advent of the space age with the drive to develop highly complex weapon systems such as ICBM's, supersonic aircraft, submarines, radar, and of course the race to the moon provided many demanding challenges for control system development.

In about 1960, the development of the solid state digital computer began the age of modern controls. These systems are implemented as discrete time equations solved in real time on a digital computer. Classical controls were previously implemented on analog computers. The creation of the microcontroller and Digital Signal Processor (DSP) has enabled an exponential increase in computing performance and decrease in the cost and size of computers. This in turn has enabled these advanced control techniques to be employed in a wide variety of applications.

Spurred by Rudolph Kalman's famous 1960 paper on noise based adaptive filtering and control, additional developments occurred in stochastic, robust, adaptive and optimal control methods.

PID Basics

To understand the application of PID control, and why it is so prevalent, it is important to first have a basic understanding of what it means to control something, and the general structure of PID and other controllers. A very general overview, targeted towards a non-control engineering audience, is included here.

What does it mean to control something? Let's use the well known example of how a driver controls an automobile's speed. There is some variable in the environment, speed in this case, which we would like to maintain at a desired level. This is the setpoint. You cannot change the value of this variable directly; this variable is changed by adjusting another variable (in our example the throttle position), which adjusts how much torque is applied to the wheels. This in turn causes the speed of the vehicle to increase. The automobile's speed is a function of many variables, and this relationship changes over time. Parameters such as the automobile's mass, the road's slope, the wind, gear ratio selected, bearing drag, etc., all affect the relationship between speed and throttle position. The driver must develop some algorithm that the will decide how much to change your controlled variable (the throttle) to achieve and maintain your process variable (the speed) at the desired setpoint. The speed is the *feedback* from the process, and by subtracting it from the setpoint, the *error* signal is generated. The combination of the algorithm and the driver is the controller. In an industrial controller, the hardware would be a computer and the algorithm would be implemented in software for this computer. Virtually all controllers contain this fundamental structure. A block diagram is shown in Figure 1:

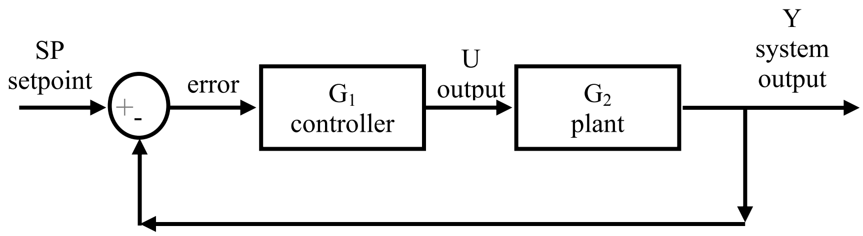

Figure 1

G_1 is a function that represents the control algorithm, and G_2 is the function that describes the output variable, based on the value of the input variable. This block is typically referred to as the plant. The difference between the setpoint and the process variable is the error. For good control, we want the error to be as small as possible, preferably zero at all times. Note the diagram shows a closed loop; the signal flows from the setpoint through the controller and system, and is fed back with negative sign to the input. Most control strategies employ the use of feedback of one or more variables to create one or more closed loop controllers.

The block diagram of Figure 1 can be compactly represented by equation {1}:

$$Y = SP \cdot \frac{G_1 G_2}{1 + G_1 G_2} \qquad \{1\}$$

Recall that G_2 is a function that describes the behavior of our plant. G_1 is a function that implements our control algorithm. We need to choose G_1 in a way to minimize the difference between Y and our SP as much as possible at all times. Note that if we simply make G_1 a large number, much larger than the value of G_2, then the expression is very closely approximated by equation {2}:

$$Y \approx SP \cdot \frac{G_1}{1 + G_1} \approx SP \qquad \{2\}$$

If G_1 is made much larger than G_2, the PV is forced to be the same as our SP. Why not just simply choose G_1 to be very large? We cannot make G_1 arbitrarily large, because at some point our controller will become *unstable.* Consider our automobile example. Nothing can happen infinitely fast; every change in the controlled variable takes time for the effect to be seen in the process variable. As the throttle position increases, it takes time for the engine to increase its power. Time is required for the combustion air flow to accelerate, time for the fuel to atomize and mix, time for the engine shaft speed to integrate up from the force applied, time for the vehicle mass to accelerate to the desired velocity, and so on. As the automobile speed ramps up, it will take time to reverse this acceleration, and we will overshoot our desired speed setpoint. We must adjust our throttle command taking into consideration the time required for the final response to appear. The reader is probably familiar with the example of a microphone. If the amplified sound from a speaker is returned to the microphone, and has positive phase, it will also be amplified, resulting in a positive feedback loop and the annoying squeal. This is a similar effect to the stability issue described above. If, due to time delays of the system, the feedback signal is delayed by more than 180 degrees at any location the gain is greater than 1, the signal will be amplified and as a result the system is unstable.

This delayed response to our control signal is *the* fundamental issue in control engineering; it takes time for the results of our change of a controlled variable to be seen at the process variable. Controls engineering is all about selecting the highest possible controller gain, yet not so high that we exhibit oscillations due to the inherent system response delays. It is further complicated by the fact that our system can have different gain at different frequencies. The gain must actually be adjusted based on the response of the plant at different frequencies. Selecting the "optimum" gain provides the fastest response (bandwidth) and minimum error of our process.

The PID controller actually has three gains that need to be adjusted:

$$U = K_P \cdot error + K_I \cdot \int error + K_D \cdot \frac{d}{dt} error \qquad \{3\}$$

This equation above is the control law, and describes how to adjust our controller variable (output) based on the value of the process error. The terms K_P, K_I, and K_D, are known respectively as the proportional, integral, and derivative gain, hence the name PID controller. The process of determining the "best" adjustments for these three terms is known as "tuning" the controller.

There are many possible ways to arrive at the optimum gain settings for a PID controller. Each of the three terms has a specific action. The proportional term K_P is the most important, as it reduces the response time as well as reduces the amount of error. Note that as the error becomes small, so too must be the corrective action from the proportional term. There will be a steady state error that pure proportional gain cannot remove. The K_I term is used to reduce the steady state error, however it also can increase overshoot to a setpoint change, and decreases the system's stability. The K_D term is the most difficult to tune. It increases stability and helps minimize the overshoot from the integral term, but can also make the system sensitive to noise. Generally a low pass filter is required to ensure the derivative term does not amplify noise. Many applications do not require a derivative term. The algorithm implemented without the derivative term is referred to as a PI controller.

Specialized techniques were required to determine how to design and optimize PID controllers. Control system analysis had started with Maxwell's initial analysis of the steam engine flyball regulator. The techniques initially developed were in the time domain, i.e. time based differential equations. As systems became increasingly complex, along with the correspondingly more complex describing equations and solutions, the shortcomings of the time domain approach became apparent. It just was not possible, without modern computing power, to generate full solutions to these problems. These limitations drove the development of the techniques that are now known as classical control theory: Laplace transform methods, Routh stability analysis, polar, Bode and Nyquist plots, frequency domain analysis, root locus analysis and design, etc. These techniques allowed very complex systems to be analyzed, and enabled the design of control systems with the required performance.

There is insufficient space in this paper to adequately describe the techniques listed above in detail; however, a simple analogy can help understand them. The mathematical operations of addition and subtractions are relatively straightforward. However, multiplication, and especially division, can be more complex. Before electronic calculators were available, a slide rule was used to perform complex calculations. By taking the logarithm of two numbers, the relatively complex operations of multiplication and division are replaced by the simpler operations of addition and subtraction. In a similar fashion, the Laplace transform is used in the techniques listed above replace more complex integral and differential operations on time based functions to simple algebraic operations on frequency based functions. Instead of time based variables, a complex frequency variable is used. The control analysis and design techniques described above are based on the principles of linearity, superposition, and time invariance (meaning the system's properties do not change dramatically over time). As long as these conditions were reasonably true, these techniques could be used to greatly simply control system design.

There are many analytical techniques to derive the optimum gains for the PID controllers. First a performance index (PI) is chosen optimize, such as minimum response time, Integrated Time Absolute Error (ITAE), or peak overshoot. The closed loop control equation may then be manipulated to solve for the gains that optimize the chosen performance index. This is seldom done in practice in industrial applications, as it requires fairly detailed and accurate knowledge of the plant, which can be time consuming and difficult to determine. In practice, there are two rather simple methods available to determine these gains.

The first is to manually adjust these terms independently, while watching the system's response to a step function to verify performance and ensure stability. First the proportional gain is increased until the system begins to have excessive overshoot, then reduced slightly. Next, the integral gain is increased to improve the rejection of external disturbances, being careful not to induce excessive step response overshoot. Finally, derivative gain is added to help offset the overshoot from the integral term. By optimizing each individual terms in order (K_P, K_I and K_D), and sometimes adding additional feedback and setpoint filters, the controller can be rapidly tuned. Web handling control practitioners rapidly develop an intuition for tuning PID loops, and can obtain surprisingly good results as compared to a thoroughly analyzed and optimized system.

A second technique, known as Ziegler-Nichols, was originally published in 1942. It is based on increasing the proportional gain until the system just starts to oscillate. Based on this "ultimate" gain setting, the optimum gains for all three terms may be calculated. There is an alternate version of Ziegler-Nichols that uses the system's open loop time of response to calculate the proper PID terms. This form may be used when the process is very sensitive to oscillations.

Using these techniques for tuning, and observing the system's time response, the gain and phase margins can be readily determined. Gain margin is how much gain can be added until the system becomes unstable; phase margin is how much less than 180 degrees the system's phase is. Sufficient gain and phase margins ensure system stability, even if the plant characteristics change slightly, which is often occur the case for a web handling process.

Several reasons contribute to the wide use of the PID controller in web handling:

- The PID is widely known and well understood.
- The PID can be rapidly optimized by adjusting three well understood parameters to achieve good system performance.

- Confidence in system stability is assured by simple step response measurements.
- Detailed knowledge of the plant is not required.

As we have just seen, to precisely determine the optimal gains for this three term controller to precisely optimize a specific performance index requires a very detailed knowledge of the plant's structure and response, which is more difficult and time consuming. The simple procedures available to rapidly obtain a reasonably optimal tuned controller without detailed plant knowledge is why the PID controller dominates web handling control.

Modern Control: What is it?

In the early 1950's, much more difficult control problems were being presented, especially in aerospace and autonomous navigation. While the techniques developed to date were powerful, their limitations began to become apparent. Classical techniques are applicable only to linear systems. Non-linear systems could often be controlled by linearizing them around an operating point, or even multiple operating points, but at added complexity. Classical techniques only apply to time-invariant systems Aircraft and missile dynamics change dramatically, depending on speed, altitude, changing mass due to fuel consumption, and so on. Engineers were frequently required to control extremely complex multi-variable systems. Classical controls are primarily single-input single-output (SISO) systems. The techniques were adapted to allow for multi-variable interactions, but the design techniques did not work well with the large number of variable interactions. Much of the design intuition from classical design expertise was lost on these more complex systems.

A technique known as state-space control became to emerge. States are variables that describe the behavior of a system. For example, a webline might use the states of web position, web velocity, and web tension. There is one state for each degree of freedom of the system. This set of variables allows the system to be completely described. Knowing the initial value of the states, the inputs to the system, and the equations that describe how the states change based on these inputs, all future values of these states may be determined. The starting point is to formulate a set of equations that describes the system's states based on the inputs to the system as a function of time. For a system with n states and m inputs, these equations would be of the form:

$$\dot{x}_1 = a_{11}x_1 + a_{12}x_2 + \ldots + a_{1n}x_n + b_{11}u_1 + b_{12}u_2 + \ldots + b_{1m}u_m$$

$$\dot{x}_2 = a_{21}x_1 + a_{22}x_2 + \ldots + a_{2n}x_n + b_{21}u_1 + b_{22}u_2 + \ldots + b_{2m}u_m \qquad \{4\}$$

$$\vdots$$

$$\dot{x}_n = a_{n1}x_1 + a_{n2}x_2 + \ldots + a_{nn}x_n + b_{n1}u_1 + b_{n2}u_2 + \ldots + b_{nm}u_m$$

This simultaneous set of differential equations can be written in matrix form as:

$$\frac{d}{dt}\begin{vmatrix} x_1 \\ x_2 \\ x_{...} \\ x_n \end{vmatrix} = \begin{vmatrix} a_{11} & a_{12} & a_{1..} & a_{1n} \\ a_{21} & a_{22} & a_{2..} & a_{2n} \\ a_{..1} & a_{a_{...2}} & a_{......} & a_{...n} \\ a_{n1} & a_{n2} & a_{n...} & a_{nn} \end{vmatrix} \begin{vmatrix} x_1 \\ x_2 \\ x_{...} \\ x_n \end{vmatrix} + \begin{vmatrix} b_{11} & \dots & b_{1m} \\ \vdots & \vdots & \vdots \\ b_{n1} & \dots & b_{nm} \end{vmatrix} \circ \begin{vmatrix} u_1 \\ u_2 \\ u_{...} \\ u_m \end{vmatrix} \qquad \{5\}$$

This may be more compactly represented by:

$$\dot{x} = Ax + Bu \qquad \{6\}$$

This equation simply describes how the system's states (the variables we want to control) will evolve with time, based on their past values, as well as the values of the system's inputs. The equations above are in the continuous time domain. For control purposes, they are reformulated in discrete time format equations:

$$x_{(k+1)} = \Phi x_{(k)} + \Gamma u_{(k)} \qquad \{7\}$$

Here, the equation is predicting the next set of system states at time sample k+1, based on the Φ (state transition) and the Γ (input response) matrices, the current states and the values of the system inputs u at time step k. This formulation allows a wide variety of control strategies to be implemented as time difference equations.

Using the previous example of controlling the speed of an automobile, the states selected would be position and velocity. The system's state space describing equations would be:

$$\begin{vmatrix} p_{k+1} \\ v_{k+1} \end{vmatrix} = \begin{vmatrix} 1 & T \\ 0 & 1 \end{vmatrix} \begin{vmatrix} p_k \\ v_k \end{vmatrix} + \begin{vmatrix} \frac{T^2}{2m} & 0 \\ \frac{T}{m} & 0 \end{vmatrix} \bullet \begin{vmatrix} F_k \\ 0 \end{vmatrix} \qquad \{8\}$$

The state space description provides a set of low order equations that are more simply manipulated and solved than a single high order describing equation.

Modern control is a broad term that encompasses many techniques. Most are implemented as some form of the discrete time state-space equations described above. The controller is implemented by calculating the current values of the input matrix, based on present and past values of the states. For the purposes of this paper, we are considering modern controls to be essentially non-PID based controller structures.

Modern control is most often implemented in some form of state space. Some of the more popular current modern control strategies, with a brief description, are listed below:

> H_∞ (H-infinity) optimal control theory, which focuses on worst-case controller design for linear plants subject to unknown additive disturbances and plant uncertainties.
>
> Internal Model Control (IMC) incorporates a model of the plant in the control structure. This is useful for rejecting known disturbances in the plant.

The Linear Quadratic Regulator (LQR) is a control strategy that optimizes two performance indices by minimizing the weighted the sum of their squared difference from the desired state.

Optimal control deals with the problem of finding a control law for a given system such that a certain optimality criterion is achieved, such as minimum fuel consumed, minimum error over time, or the minimum time to reach the target is required. To implement optimal control, first a cost function is defined:

$$J = \int_{t_0}^{t_f} \left(w_1 condition_1^{\,2} + \ldots + w_n condition_n^{\,2} \right) dt \qquad \{9\}$$

The cost function is the sum of a weighting factor times the square of the various performance indices you are trying to optimize. The weight factor is chosen to establish the relative priority between the variables. For example, in a machining process, you would want the least amount of error from the desired trajectory (finished part accuracy). However, you must consider manufacturing cost ($) to produce the part, so this accuracy must be counterbalanced by the time required to complete the machining process. Achieving a reduction of 0.1 micron of following error, but requiring three times the processing time, might not make sense. The weighting factors allow the user to assign relative importance among competing parameters. Based on the cost equation, the control law would be implemented to achieve the best balance of performance indices by minimizing the weighted sum of machining time and profile error.

Some of the advantages of modern control techniques over conventional PID control may be summarized as follows:

- modern controls readily support multi-variable systems.
- modern controls are not limited by the strict requirements of linearity and time-invariance.
- modern controls provides multiple degrees of freedom.
- modern controls support performance index and parameter optimization.
- all classical control design techniques may be used in conjunction with Modern controls.

However, modern control techniques have a few disadvantages. Modern controls:

- are more complex.
- are less known and less well understood.
- are harder to prove stability.
- require a more detailed and accurate knowledge of plant.
- may require additional measurements, or extra complexity to estimate states.
- are more difficult to support by traditional customers and manufacturing.
- require additional effort to ensure robustness.
- require more expensive computational hardware (although cost is dramatically declining).

To appreciate why advanced control has not been more widely applied in the web handling industry, it is useful to compare how these applications have been developed and applied in other industries.

The field with the most applications of advanced control (and the first field to have modern controls implemented) is the aerospace industry. These applications are high order, multi-variable, and often highly non-linear and time variant. These systems often operate over several orders of magnitude. Most importantly, these techniques were generally first developed by government agencies, and government sponsored university research for specific applications. An application such as the control design for a new fighter aircraft will employ literally hundreds of highly talented control engineers, and the application is thoroughly simulated, verified, and tested before the aircraft ever takes flight. An example will help illustrate this. The current F35 Joint Strike Fighter has an extremely complex flight control strategy. The root model for the system has 421 inputs and 337 outputs! The development of a new fighter aircraft is a multi-billion dollar project. Aircraft and missile control and guidance routinely employ modern control techniques. No web handling application can justify this level of resources.

Another field with many advanced control implementations is extremely high volume data storage equipment, such as magnetic and optical disks storage systems. These system employ extremely complex controls strategies in a finished product that only costs hundreds of dollars. Challenges include controlling the thin flexible structure that holds the read heads, moving their position and settling as fast as possible, and maintaining head position within microns relative to the data tracks on a rapidly spinning (>15K RPM) disk while rejecting external shocks and vibration. The read heads have substantial flexible dynamics and are difficult to control. Disk drives are manufactured in volumes of tens of millions, and increased control complexity to replace a ten cent component is justified. The number of web handling applications implemented on a particular platform is dwarfed by these volumes.

The petroleum industry is an example of where the web handling industry may be heading. Refining petroleum is a very complex process, and increasing yields by a few tenths of a per cent can mean an increase of millions of dollars per year in profits. The high value of petroleum products and manufacturing complexity has attracted investment in some sophisticated advanced control strategies. Similar applications are found in the paper industry, but at present these are mainly on non-web handling operations, such as the boiler and liquor processes.

A Note on the Complexity of Advanced Controls

The Airbus A320 is a short to medium range commercial passenger aircraft manufactured by Airbus. It was the first commercial airliner designed with a digital fly-by-wire flight control system, where the pilot controls flight surfaces through the use of electronic signals rather than the conventional mechanically linkages and hydraulic systems. The new control technology items introduced include:

- The first fully digital fly-by-wire flight control system in a civil airliner
- The first civil airliner to use sidesticks instead of control columns
- 2 man crew (compared to typical 3-man crew of the 727)
- Fully featured glass cockpit
- Centralized maintenance diagnostics systems from the cockpit

One of the extremely novel features of the advanced controls on the A320 was the control system could override the pilots command. For example, commands that could cause too fast a rate of climb and possibly create a stall condition are ignored, as well as commands that would exceed a 2.5 G acceleration limit.

An early version of the Airbus A320 crashed during an early public demonstration at an air show in Habsheim, France, killing three passengers. The plane was performing a very low altitude fly by. Due to an earlier data entry error by the pilot, , the plane misinterpreted the pilot's actions as an attempt to land. When the pilot applied full throttle, the plane ignored the commands, and the plane crashed into trees at the end of the runway and burned.

While a web handling control system failure would certainly not be as catastrophic, this example demonstrates the importance of having a control system that has been simulated and tested as thoroughly as possible when placed into production. While modern controls are certainly more powerful than classical implementations, there exists a greater risk that an unexpected mode of operation may be encountered. Advanced controls will provide improved capabilities, but will require more time to implement and to allow users to gain experience.

Future Opportunities for Advanced Control in Web Handling

There are several areas of web handling that present especially challenging control problems. The author believes advanced control methods will provide superior solutions to these problems, as compared to the existing classical control solutions.

One present challenge is the nature of transport rollers coupled by the web. Each roller and each web span adds a degree of freedom; with typical weblines having hundreds of rollers and web segments this clearly results in a very high order system.

Various IWEB papers have discussed this problem and proposed potential solutions. Perhaps the most important paper in this area is "Limitations to Sensing of Web Tension by Means of Roller Reaction Forces" by J. J. Shelton presented at IWEB 5. This paper thoroughly lays out the fundamental physics and equations for describing the longitudinal web behavior. Some of the important results include prediction of resonances for web spans, and severe loss of phase across multiple rollers.

Several other notable papers describe strategies for dealing with the difficulties:

"New Decentralized Control in Processing Machines with Continuous Moving Webs", W. Wolfermann and D. Schroeder. This paper presented at IWEB 2 in 1993 suggested distributed coupled controllers to address this issue.

"Matrix Interpolation Based Self-Tuning Web Tension Regulation". B. T. Boulter and Z. Gao proposes a self-tuning control scheme for tension regulation in a web transport.

"Non-Interacting Tension Control in a Multi-Span Web Transport System", K. H. Shin, K. N. Reid, and S. O. Kwon proposes a non- interacting tension control algorithm to reject the disturbance due to the interaction between neighboring processing sections.

"The Effect of Speed Loop Bandwidths and Line -Speed on System Eigenvalues in Multi-Span Web Transport Systems", B. T. Boulter. This paper discusses the natural frequencies of web spans, and its impact on controller design.

"Multiple-Tension Control Using a New Approach in Signal-Processing", S. Krebs. This paper describes a control structure that enables utilize related process variables from different zones to coordinate control. The system is configurable; allowing the user to leverage the embedded advanced control strategy.

"Recent Advances in Web Longitudinal Control", P. R. Pagilla and D. Knittel. This paper describes recently developed robust control methods for web longitudinal control, as well as potential new directions and future research topics.

Another significant challenge with web lines is that a single machine will often process multiple webs with different material properties, particularly changes in modulus, length, and width. Each new material changes the dynamics of each tension control section. Traditional control strategy has been to either use gain scheduling based on material properties, or more typically, tuning the machine for the stiffest materials, and accepting the corresponding poorer performance for less stiff materials. Advanced control strategies could provide online robust adaptive tuning, ensuring the machine performs at optimum capability at all times, in spite of material changes.

There have been incredible advances in motor controls in the last decade. The AC vector controlled motor has almost entirely displaced the DC motor in most applications. These drive systems employ many examples of advanced control to provide truly surprising performance. Most AC drives employ an advanced control technique known Field Oriented Control (FOC). FOC uses knowledge of the motor's electrical and mechanical characteristics, often using on-line system identification techniques, to properly orient the applied winding voltages to generate the induced field to produce the desired torque. The motor model is dependent on temperature, speed, and loading, and is generally adapted online. Because the controller must manipulate the induced motor flux by manipulating two vector currents, the technique is also referred to as flux vector control. Another example of advanced control common in AC drives is the use of an observer to estimate the motor's rotor position, and is often used in conjunction with the previously described FOC technique. This technique is referred to as sensorless flux vector control, and can be used to regulate motor velocity reasonably well without the use of a position feedback sensor, which can save costs and improve reliability.

The performance of these advanced motor control systems has become so good that in most applications, the system mechanics are the predominantly limiting factor. In spite of employing these very sophisticated modern control algorithms internally, the majority of drive manufacturers only provide the user with a conventional PID based outer loop controller. Many opportunities exist for improving performance and reducing the time to engineer and commission a web handling drive system.

One last example of where advanced controls could improve the baseline of web handling is through increased use of observers and advanced filtering techniques. An observer is an algorithm that estimates or predicts the value of a system variable. The information required to control a system is often corrupted by noise. Sometimes it is impractical or expensive to measure the desired variable. For example, it is often difficult to insert a tension measuring load cell in a long floatation dryer span without the load cell roller touching the wet coated side, or compromising guiding. In these situations an observer can be used to estimate the tension, based on other knowledge of the system. Often an observer blends information from multiple sources to obtain the best control signal. Observers can improve control accuracy, eliminate costly sensors, and measure values that are not directly accessible.

Present web handling control systems have a wide range of traditional filtering techniques available. However, these are generally simple linear filters. Non-linear and statistics based filtering can improve performance.

Notable past IWEB papers describing observer and advanced filtering techniques include:

> "Sensorless Tension Control of Webs," W. Wolfermann at IWEB 4
>
> "Tension Control With and Without Tension Sensors," M. R. Leonard IWEB 5
>
> "Estimating Modulus of Elasticity, Torque Loss, and Tension Using an Extended Kalman Filter," B. Boulter IWEB 5

These past papers suggest a variety of methods to potentially provide better web handling controllers. To the author's knowledge, with the exception of the strategy proposed by Krebs, none of these proposed algorithms have been implemented in a commercially available controller.

CONCLUSIONS

PID control has served industry well for 75 years. It performs well in the majority of applications, and is readily supported by industry. However, there are definitely several areas of web handling that would benefit greatly from modern control strategies.

However, at present there exist substantial barriers to the use of advanced control by the general web handling industry. The most significant of these is the greatly increased level of expertise required to implement this control. Another is the requirement for increased data collection, analysis, and system identification tools.

The author suggests that with some creativity these requirements can be met. Equipment manufacturers and web handling end users cannot often justify the time and cost required to develop and implement these advanced controls in their present state. Computer hardware continues to dramatically increase in performance and decrease in cost, enabling the complex analysis and design of advanced control to be encapsulated.

For the successful application of modern controls, it is imperative that control manufacturers encapsulate as much of the design process as possible. Current control platforms do not require the user to develop a robust PID controller; the user configures an existing PID strategy to their application. Modern control implementations should configurable in a similar manner. Enabling the typical web handling controls practitioner to apply "pre-canned" versions of high performance modern control techniques will push the envelope and enable newer more demanding web handling products.

Some of these features are already beginning to appear in drive systems; predominantly in precision motion applications. Examples include built in FFT functions, embedded signal generators, powerful data collection and system identification functions; advanced filtering techniques such as repeated bi-quad sections; and encapsulated advanced control strategies, such as internal model control. While not generally targeted specifically at the web handling industry, these drives may be adapted, especially in smaller sized machines.

In the near future, it is expected that more advanced control techniques will become readily available in web handling targeted control platforms. Existing Field Oriented Control drives already make heavy use of advanced controls. While this encapsulated expertise and advanced control algorithms will certainly cost more, the savvy user will recognize that the true value is the higher performance, faster commissioning, wider operating windows, and reduced scrap that these strategies will enable. The ability to manufacture more demanding and versatile web based products will more than justify this increased cost.

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APPENDIX A: SUMMARY OF CONTROL PAPERS AT PAST IWEB CONFERENCES

There have been approximately 45 papers presented at previous IWEB conferences that focused directly on control topics. There have been about half this number of papers presented on the dynamics, measurement and understanding of the lateral and longitudinal dynamics of webs. A listing is provided below.

IWEB 1 May 19-22, 1991

"Measurement and Control of the Tension Distribution Across the Web in a Newspaper Printing Press," L. Eriksson, Swedish Newsprint Research Center

"Variable Gain Control of Longitudinal Tension in a Web Transport System", K. N. Reid and K. H. Shin, Oklahoma State University

"Concerning Wound Mill Roll Quality and Take-up Tension Control," Y. Kataoka, Kataoka Machine Company, Ltd.

IWEB 2 June 6-9, 1993

"Unwind and Rewind Lateral Control," K. Hopcus, Fife Corporation, USA

"Theory and Application of Draw Control for Elastic Webs with Nipped Pull Rollers," T. M. Spielbauer and T. J. Walker, 3M Company, USA

"Effects of PID Gains for Controller with Dancer Mechanism on Web Tension," P. Lin and M. S. Lan, Rockwell International, USA

"Control of Longitudinal Tension in Multi-Span Web Transport Systems during Start-up and Shut-Down," K. N. Reid and K. C. Lin, Oklahoma State University, USA

"New Decentralized Control in Processing Machines with Continuous Moving Webs," W. Wolfermann and D. Schroeder, Technical University of Munich, Germany

"On the Dynamics of the Web Transfer in the Open Draw," P. Pakarinen, R. Ryymin, M. Kurki, P. Taskinen, Technical Research Center of Finland, University of Jyvaskyla, Valmet Paper Machinery, Finland

"Dynamic Behavior of Dancer Subsystems in Web Transport Systems," K. N. Reid and D. C. Lin, Oklahoma State University, USA

IWEB 3 June 18-21, 1995

"Tension Control of Webs - A Review of the Problems and Solutions in the Present and Future," W. Wolfermann, Technical University of Munich, Germany

”Non-Interacting Tension Control in a Multi-Span Web Transport System,” K. H. Shin, K. N. Reid, and S. O. Kwon, Kon-Kuk University, Korea and Oklahoma State University, USA

“On the Web Tension Dynamics in an Open Draw,” M. Kurki, K. Juppi, R. Ryymin, P. Taskinen, and P. Pakarinen, Technical Research Center of Finland and Valmet Paper Machinery Inc., Finland

“Real Time Tension Control in a Multi-Stand Rolling System,” K. H. Shin and W. K. Hong, Kon-Kuk University, Korea

“Longitudinal Dynamics of a Winding Zone,” J. P. Ries, DuPont Company, USA

“Matrix Interpolation Based Self-Tuning Web Tension Regulation,” B. T. Boulter and Z. Gao, Reliance Electric Corporation and Cleveland State University, USA

“Non-Interacting Tension Control in a Multi-Span Web Transport System,” K. H. Shin, K. N. Reid, and S. O. Kwon, Kon-Kuk University, Korea and Oklahoma State University, USA

“Electromagnetic Lateral Control System of Floating Strip,” T. Kamiyama. H. Uchida, S. Marumoto, H. Yoneda, and N. Suzuki, Nippon Steel Corporation, Japan

IWEB 4 June 1-4, 1997

“Experimental Study of Winding Zone Dynamics,” J. P. Ries, DuPont Company, USA

“The Effect of Speed Loop Bandwidths and Line -Speed on System Eigenvalues in Multi-Span Web Transport Systems,” B. T. Boulter, Rockwell Automation, USA

“Multiple-Tension Control Using a New Approach in Signal-Processing,” S. Krebs, vrp Web Technology Inc., Canada

“Sensorless Tension Control of Webs,” W. Wolfermann, Technical University of Munich, Institute of Electrical Drives, Germany

“Differentially driven S-Wrap Rolls for Improved Tension Isolation,” A. W. Forrest, Jr., A. N. Bennet and M. R. Jones, DuPont and FluorDaniel Engineering, USA

“Non-Linear Tension Control in a Winding Process by Using the Contact Roll,” K. H. Shin, K. T. Kim, and S. M. Cheon, Kon-Kuk University, Korea

“Longitudinal Dynamics,” B. Walton and B. S. Rice, Eastman Kodak Company, USA

IWEB 5 June 6-9, 1999

"Limitations to Sensing of Web Tension by Means of Roller Reaction Forces," J. J. Shelton

"Compensation of Disturbances in the Web Force Caused by a Non-Circular Running Winder," W. Wolfermann

"Tension Control With and Without Tension Sensors," M. R. Leonard

"Theoretical Comparison of Winding Tension Control Methods," J. P. Ries

"Estimating Modulus of Elasticity, Torque Loss, and Tension Using an Extended Kalman Filter," B. Boulter

IWEB 6 June 10-13, 2001

"Online Control of Tension in Web Winding Systems Based on Wound Roll Internal Stress Computation," P. Bourgin, M. Boutaous, and D. Knittel

"Real Time Dynamic Simulation for Control System Software Verification," R. Bettendorf

"The Role of Active Dancers in Tension Control of Webs," P.R. Pagilla, L.P. Perera, and R.V. Dwivedula

"Considerations in the Selection of a Dancer or Load Cell Based Tension Regulation Strategy," D.H. Carlson

"Strip Tension Control Considering the Thermal Strain in Multi-Span Systems with Temperature Change," K. Shin, J. Jang, and K. Kim

"Modeling and H_∞ Robust Control for Winding Systems," H. Koc, D. Knittel, M. de Mathelin, and G. Abba, Siemens AG

IWEB 7 June 1-4, 2003

"Strategies for Competitiveness," Keynote Presentation on drive technologies by J. W. Simons, Rockwell Automation, USA

"Robust Control Design Using H-Infinity Methods in Large Scale Web Handling Systems," D. Knittel

"Real Time Dynamic Simulation of a Paper Winder," R. Bettendorf

"A Comparative Study on Active and Passive Dancers Used for Attenuation of Web Tension Disturbances," R. V. Dwivedula, Y. L. Zhu, and P. R. Pagilla

IWEB 8 June 5-8, 2005

"Control and Online Tension Reference Optimization in Winding Systems: Application to an Identified Three-Motors Simulator," D. Knittel1, P. Bourgin, and M. Boutaous

"Effect of Compliance and Backlash on the Output Speed of a Transmission System," R. V. Ramamurthy and P. Pagilla, Oklahoma State University, USA

"Tension Control in Thin Film Production Lines," G. Oedl, Bruckner Maschinenbau Siegsdorf, Germany

"Recent Advances in Web Longitudinal Control," P. R. Pagilla[1] and D. Knittel[2], [1]Oklahoma State University, USA, [2]Louis Pasteur University, France

Keynote Presentation – *Advanced Controls for Web Handling: Ready for Production?* — **D. Carlson**, 3M Company, USA

Name & Affiliation	Comment
John Shelton, Oklahoma State University	I have a comment which is concerned with how controls problems should be approached. The fundamental problem must always be addressed first, such as backlash. There is not a control algorithm that will fix fundamental problems, such as backlash and poorly damped resonances. Not many people, including myself, are going to learn the details of modern controls. There are fundamentals we still need to look at, whether it is a 1955 vintage web guide which doesn't have PID but it does have PI inherently. The inherent integrator is the servo valve in the old hydraulic units. Whether you have classic, inherent or modern controls, you should eliminate fundamental potential problems first before you apply controls.
Name & Affiliation	**Question**
Karl Reid, Oklahoma State University	Dan, can you give us a brief example where you have used an advanced control technique instead of a PID and tell us what the advantage was?
Name & Affiliation	**Answer**
Dan Carlson, 3M Company	We have an internally developed adaptive control module and it has been very successful internally within the company. In certain applications, it works great. There have been quite a few people that say it is a magic solution and implement it without thought. With the adapter, you have to tell it that it is allowed to adapt. If you break the loop and it is not in control, you'd better tell it, or it keeps saying that it is trying to adjust the output. It says the output is not moving, I've got to adjust more. What I have learned is you don't apply advanced control methods unless you really need it. You do all the other things first. You fix the plant, you do as much as you can, before you apply the advanced control methods. You do get unanticipated consequences when you employ advanced controls methods. I don't want to receive the phone calls that are associated with the unanticipated consequences. What I do is to encapsulate an advanced control model for a less skilled user to use. It is really difficult. In particular it is the unanticipated way things get used. It is always unanticipated uses that cause problems.
Name & Affiliation	**Question**
Tim Walker, T.J. Walker & Associates	The control side of web handling has always been critical and yet the lion share of people attending IWEB conferences are mechanical engineers. We get a little glazed look in our eye. Where do people go to learn about the control side of web handling? I think there are a lot of people like myself who teach the mechanical, the process

	side. I see a lot of equipment suppliers that really could benefit from a next level of knowledge on the control side. Where should they turn?
Name & Affiliation	**Answer**
Dan Carlson, 3M Company	What I have experienced at 3M is that you learn what you can at school and then you learn to apply it to practical examples when you start in industry. Do what your professor said and then apply it and find out what he really meant. Especially at 3M, the way people learn is the mentoring from more senior engineers. There are a lot of courses that are individual or team courses. Often the best way people learn is for them to be partnered with a more experienced engineer.
Name & Affiliation	**Question**
Tim Walker, T. J. Walker & Associates	What do you do if your company doesn't have a more experienced engineer?
Name & Affiliation	**Answer**
Dan Carlson, 3M Company	You probably must rely on the suppliers from whom you are purchasing by attending their classes.
Name & Affiliation	**Comment**
Mark Weaver, Rockwell Automation	I have found that if you are looking for advanced training, definitely mentoring is the way to go. If you are looking for something a little more general, I recommend the University of Wisconsin course of Dynamics of Controls Systems. It will give you a good introduction to the advanced techniques Dan is talking about. They give you the basics of the state control and deal with active control. One of the important things that are taught is that active inertia as a way to handle system resonances. It is all developed in that class and can be taken online.
Name & Affiliation	**Comment**
Prabhakar Pagilla, Oklahoma State University	Basic controls and advanced controls are not foreign to the mechanical engineering programs in the country. It has been like that for at least the last two decades. I think almost all the major state schools in the country now have at least 10-15% of the Mechanical Engineering faculty specializing in the dynamic systems and controls areas. Many courses are taught at the undergraduate and the graduate levels. For example, OSU has four (out of total 22 faculty in Mechanical Engineering) active faculty in the systems and controls area. In addition our Dean also specializes in controls. At OSU, in mechanical engineering we offer a number of undergraduate and graduate courses. For the undergraduate mechanical engineering students, dynamic systems and a measurements lab course are two required courses. We also offer two electives 1) Automatic Control and 2) Mechatronics (lab course) - for seniors. So, if our undergraduates take one of the controls electives in addition to the two required courses, then they should have a basic controls background. Our graduate students with a controls focus take many advanced controls courses. Many

other state schools in the country such as University of Minnesota, Purdue, Georgia Tech, Texas A&M have mechanical engineering programs with similar courses, and in some cases more courses in this area. So, it is very possible for mechanical engineering graduates today to have a good controls background.