A NEW FPGA AND MULTI-CORE SYSTEM ARCHITECTURE FOR AUTOMATIC GAUGE CONTROL [1]

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Abstract

A new architecture based on high-speed, real-time control techniques carefully coordinated with embedded, programmable hardware has been developed. The architecture employs Field Programmable Gate Array (FPGA) hardware coupled with the recent advancements in multi-core processors and real-time operating systems. Hardware-In-The-Loop signal processing and closed-loop control functions can now be fully implemented in programmable hardware elements. Multi-core processors allow real-time operating systems and controls to be implemented in one core, with Windows based Supervisory and HMI functions residing in the other core. This new architecture allows complete systems, including signal processing, real-time control and commercially available Windows HMI systems, to reside within a single computer. This new strategy has been successfully installed and is now fully operational on 5 mills, employing vertical stack (2-high/4-high) and Sendzimir/cluster roll arrangements. These systems have been well received, exceeding customer performance and operational specifications.

Key words: Automatic gauge control; Field programmable gate array; Multi-core processors; Real-time operating systems.

Resumo

Este trabalho trata do desenvolvimento de uma nova arquitetura baseada em tecnicas de alta velocidade de controle em tempo real , cuidadosamente combinadas com apropriado hardware programavel. Tal arquitetura utiliza hardware acoplado a recentes desenvolvimentos, compreendendo processadores *multi-core* (multi-nucleos) e sistemas de operação em tempo real, denominada FPGA (*Field Programmable Gate Array*). Processsamento de sinal implementado em hardware e funcoes de malhas fechadas podem agora ser inteiramente implementados em elementos de hardware programaveis. Processsadores multi-core possibilitam sistemas operacionais e controles em tempo-real em um *core* (nucleo), enquanto um sistema supervisorio baseado em Windows e as funções de IHM (Interface Homem Maquina) permanecem em outro *core*. Esta nova arquitetura possibilita que sistemas completos, incluindo processamento de sinal, controle em tempo real e sistemas IHM comerciais baseadas em Windows residam dentro de um único computador. Esta nova estratégia tem sido instalada com sucesso e agora inteiramente operacional em 5 laminadores, empregando arrranjos de cilindros em “colunas” verticais (duos / quadruos) e Sendzmir/”cluster”. Estes sistemas tem sido bem aceitos, excedendo as especificações operacionais e de performance dos clientes.

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1 INTRODUCTION

In the cold rolling of flat strip products, the fundamental objective of an Automatic Gauge Control (AGC) system is to regulate the rolled material thickness about a referenced set-point. The AGC performs this task by the coordinated actuation of the roll gap, separating force, strip tension and/or mill speed. The theories and practices involved in AGC algorithms and roll force cylinder control methods are well understood, and not the subject of this discussion. In this paper, the primary focus is on newly developed technologies in the underlying hardware equipment and software techniques that allow AGC actions to be implemented and carried out in real-time.

Over the past 25+ years, Intergrated Industrial Systems, Inc. (I^2S), has supplied over 270 AGC systems worldwide, starting with one of the first microprocessor controlled AGC systems in 1980. Over the years, we have seen hardware/software technologies and their availabilities change radically, followed closely by the evolving needs of our customers; tighter tolerances, increased reporting, and expanded interconnections between the mill's systems, including a wide range of plant-wide customer provided networks and computer systems.

1.1 Historical Perspective

Through the years, a great many hardware/software platforms and technologies have been employed to implement AGC systems, ranging from commercially available equipment to highly specialized, custom/proprietary arrangements. Early systems employed various combinations of discrete analog/digital components and early microprocessor/computer control technologies (e.g., Z80, PDP-8, etc.). In that era, the lack of commercially available, sufficiently capable hardware was a formidable obstacle. This led some to implement their systems using a combination of available commercial equipment, special proprietary fabricated boards and in some cases, custom, hand-made, wire wrapped cards. These measures were a necessary fact-of-life, given that the available general purpose interface boards were not suited for this class of application, with their associated performance requirements and feature set capabilities.

AGC systems evolved with the prevailing technologies and soon embraced the emerging VME, Multi-Bus and IBM-PC compatible computer technologies, advanced multi-tasking operating systems, graphical user interfaces (GUIs) and a variety of more sophisticated general purpose interface and communication hardware offerings. Unfortunately, much of the commercial hardware still did not fully encompass the specific performance and feature requirements of a complete AGC system. Even so, it was very possible to utilizes these commercial building blocks to field AGC systems able to meet the broader tolerances of that era. To achieve higher levels of performance, suppliers of high-end systems had to, yet again, bridge the performance/capabilities gap with custom/proprietary boards, some employing embedded microprocessors to off-load the computer system's real-time computational overhead.

Although an acceptable choice to performance minded end-users, custom/proprietary hardware required those same end users to invest in and willingly commit to a potentially perilous *de facto* marriage with the system supplier, who offered an inconvenient, single source pathway to spares and repairs. Yes, the resulting systems were highly optimized for AGC applications and tended to achieve the highest degree of performance. However and unfortunately, fears of the manufacture's potential business failure loomed large in the end-user's view of these seemingly precarious relationships. The system's only spare/repair life-line hung tenuously on the thread of whether the equipment provider would be in existence (into the perceivable future) and would truly be able to support this custom hardware over the system's lifetime.

1.2 The Advent of COTS Technologies

General purpose, Commercial-Off-The-Shelf (COTS) technologies soon became a fixture and an ever present mantra in the market place, suggesting that end-users could free themselves from these *de facto* marriages, and openly purchase spares and repairs from other suppliers and vendors, thereby circumventing the OEM and liberating the end-user from concerns over the long term viability of the AGC system provider. This was an enticing proposition…but one that had to be weighed against the fundamental objective of the high end user (i.e., high performance AGC capabilities).

Early COTS equipment was developed for, and directed towards, a broad spectrum, high volume market, whose needs and capabilities may or may not have been suitably aligned with the requirements of high performance AGC applications. An AGC system's requirement for specialized interfacing and signal handling capabilities were still not common among the needs of the general purpose market place. This led COTS manufactures to bypass these niche AGC requirements. AGC suppliers were left to decide whether their product lines would be fashioned to address the high performance needs of their narrowly intended application (and thereby consciously continue to employ certain amounts of proprietary equipment) or would consciously accept potential performance degradations to embrace a more "market attractive" COTS based system.

Recent advances in COTS based controllers have now reached levels of capability to be suitably employed in high performance AGC systems. This has become a fashionable trend and a seemingly viable marketing strategy. Commercial motion/numerical control modules and high speed counting systems are often combined within commercial, general purpose Programmable Logic Controllers (PLCs). These open architecture systems utilize specialized application programming of the general purpose motion control module hardware to obtain the specialized control structures required in AGC applications. One downside of using PLC based controllers for AGC is that it locks the end user into the specific make/model of PLC (and the contained specialty modules) that the AGC supplier provides irrespective of the customer's plant-wide PLC requirements.

Modern COTS based systems are constrained by the underlying hardware and software architectures developed by their commercial manufactures. These systems are focused on a broad, general purpose, application based market. The underlying issue in all current COTS based systems is that their general purpose hardware arrangements must be suitably reorganized, and their general purpose data flow architectures must be selectively programmed, to meet the fundamental requirements of the computational processing involved in AGC activities. This can lead to a "painted-into-a-corner" architecture that does not lend itself to future development and a great dependence on a limit number of components (which the COTS supplier may change or discontinue at any time).

1.3 Computer Industry Facts-Of-Life

Interestingly enough, the rapid pace of commercial hardware development, and quick product end-of-life obsolescence, became a mainstay in the unstable computer and electronics industries. It was not uncommon for PC and VME interface boards to be obsolete and unsupported within 12-18 months of their initial unveiling. This caused many COTS based AGC system offerings to have the appearance of a patchwork quilt, of ever changing hardware components and supporting software drivers, with every new system incarnation being incompatible with effectively identical systems provided a year or two earlier. In addition, many qualified and seemingly stable hardware/software platforms were abruptly discontinued (e.g., Multi-Bus), leaving those utilizing these platforms in their AGC system with little hope for extended support.

So much for the alluring and enticing “Sirens’ Call” of the COTS philosophy…

These computer industry facts-of-life led many equipment providers to still develop and employ dedicated, proprietary hardware in certain specific facets of their systems. We have been among them. This is not always a bad thing, time has shown that many proprietary systems have yielded longer (and more stable) product lifetimes and a higher potential to be supported for extended periods of time (i.e., greater than 5-10 years and upwards of 20 years, in some cases of the equipment supplied by I^{2}S). However, the attractive philosophy of COTS based systems is still a mainstay in the marketing ploys of those suppliers choosing to accept and contend with the “ebb and flow” and uncontrolled whims of the commercial hardware manufactures. And, to be sure, COTS is not only a desire by the end user, there are advantages to the AGC supplier as well. COTS can aid in reducing cost and development time by utilizing the component manufactures expertise and capabilities.

1.4 Contemplating The Realities

So, where does this leave us? Customers dislike custom parts available only from single source suppliers. Suppliers are not fond of inflexible, commercial system architectures that limit adaptability and constrain the design. What other options are there?

As noted previously, over the years, I^{2}S has sold/installed/maintained hundreds of AGC systems in both domestic and international settings. We owe it to our customers and ourselves to find and develop systems that are maintainable and can be systematically upgraded to satisfy the needs of the metals industry. The bottom line is that the chosen hardware platform must provide the necessary capabilities and performance. The chosen software platform must provide the required real-time responsiveness, while also supporting the chosen Human Machine Interface (HMI) and Internationally Standardized network interfaces.

In the past few years, a new COTS based alternative has presented itself. One that does not constrain the resulting system with a given manufacture’s preconceived views of what hardware arrangements and data flow architectures will be provided or not provided. But one that offers a general purpose, programmable hardware environment, through which software based control, signal processing and data flows can be implemented with ease. This same COTS based alternative supports hard, real-time control and operating system software to assure deterministic responses to real world events and conditions. Further, all standardized network interfaces are

supported, allowing a broad spectrum of commercial HMI software packages (often selected/directed by the customer) to be employed.
This is very welcome news.

2 NEW TECHNOLOGIES AND INNOVATIVE CAPABILITIES

Two(2) new technologies have now become viable candidates for consideration to AGC applications. Technologies that offer:

- General Purpose, Software Programmed Hardware Arrangements
- Closed-Loop Control, Signal Processing & Data Flows ALL Implemented in High Speed Hardware (Hardware-In-The-Loop)
- Support of Hard, Real-Time Control & Real-Time Operating System Software
- Strict Deterministic Responses to Real World Events & Conditions
- Simultaneous Support of Multiple Operating Systems & Parallel Processing
- Standardized Network Interfaces & Data Bases
- Broad Spectrum of Commercial HMI Software Packages (often selected / directed by the end-user)

2.1 Field Programmable Gate Arrays

A new programmable hardware technology provides the ability to implement application optimized hardware with the flexibility of programming. This technology is Field Programmable Gate Arrays (FPGA). FPGA's are programmable hardware. Integrated, single chip circuits containing millions of programmable gates that can be configured and interconnected for any need, ranging from simple logic to complex mathematical sequences and pipe-lined processing arrangements.
The hardware's signal / logic interconnections and routings are completely defined by software schematics, block structured functions, procedural codes and / or Hardware Description Language (HDL). When the code is compiled and downloaded to the target FPGA, the result is a true hardware implementation of the software application. The software configured / programmed hardware operates in a truly parallel nature. NO processor bottlenecks or execution sequence restrictions exist…NONE!!! The hardware subsystems operate with complete independence, at extremely fast execution rates (parallel operations at 40 MHz clock speeds). Essentially, this is real-time, hardware multi-tasking. Figure 1 provides an illustration of the internal components / architecture of a typical FPGA integrated circuit.

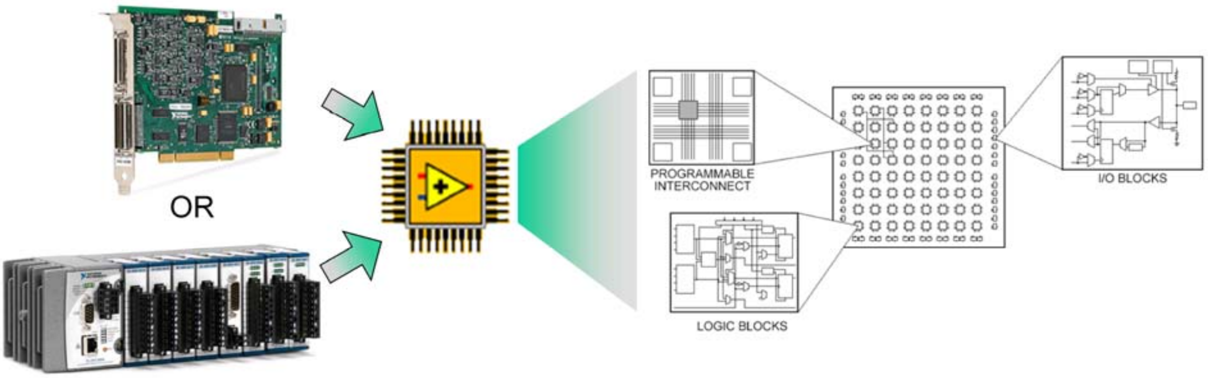


Figure 1 – Illustration of the FPGA internal architecture and component arrangement.

Complex, real-time, closed-loop servo controls and signal processing, formerly implemented only with discrete components or within real-time software environments, can now be completely implemented in a precise digital / numerical format, within this single chip hardware (often with cycle periods of 250 microseconds or faster!). This "hardware-in-the-loop" (HIL) concept is shown in Figure 2.

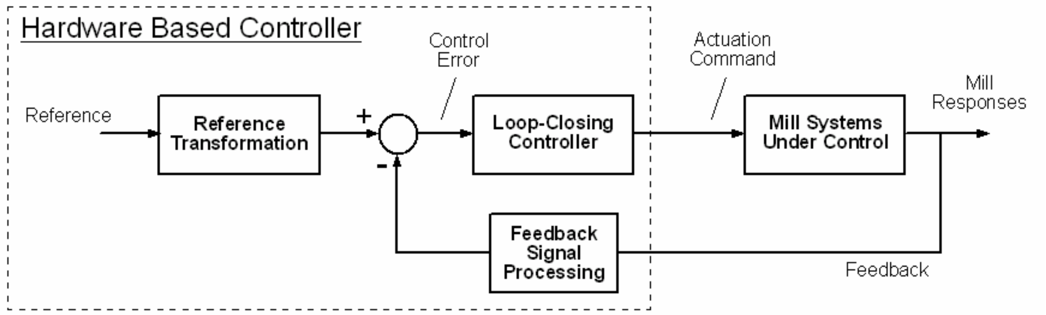


Figure 2 – Illustration of a typical Hardware-In-The-Loop (HIL) closed-loop digital control application.

The fact that the hardware is field programmable means that flexibility and future expandability is ensured. The program for the FPGA is downloaded to the chip on system power up, so hardware updates are as simple as copying a file. Further, identical commercial boards containing the FPGAs, can be placed within the same computer and independently programmed with completely different hardware applications.

This means that only a single, commercial hardware component will support the entire needs of the intended application, requiring only a single spare.

The approach presented here employs commercially available programmable hardware to specifically implement optimized signal processing and control architectures. This allows focus specifically on the issues and requirements inherent to AGC activities. There is no need to distort and contort general purpose commercial hardware (e.g., PLC, motion control equipment, etc.) to provide the required AGC capabilities. Formerly proprietary hardware and software are now replaced with programmed, general purpose commercial hardware, programmed via a commercial, open-architecture development language (i.e., National Instruments LabView).

A great advantage to this approach is that the system is not restricted to unyielding single hardware system architectures. With very little setup time, this same system can be implemented as a PCI bus based computer solution or as a distributed, modular, self-contained, compact remote I/O system (as shown in Figure 1).

2.2 Multi-Core Processors

The recent release of multi-core CPUs (e.g., Intel® Core™ 2 Duo Processors) offer some very interesting opportunities to consolidate multiple system responsibilities within a single computer, while simultaneously expanding that single computer's capabilities. These multi-core systems contain two(2) identical processors on a single integrated circuit. These processors operate separately and are fully capable of supporting two(2) completely independent operating systems and functioning in a completely parallel arrangement.

This capability offers a whole new dimension in modularity, flexibility and opportunity.

Classically, the AGC application required (at a minimum), two(2) independent computers, networked / interfaced together, to provide the necessary real-time control performance, supervision and user interfacing.

Former Multi-Computer Arrangement

Computer 1 : Real-Time Controller – This dedicated computer typically employed a real-time operating system and all of the associated interfacing hardware required to perform the loop closing AGC activities.

Computer 2 : Supervisory Computer – This computer typically employed a general purpose operating system (e.g., Windows XP Pro, etc.) and provided a Graphical User Interface (GUI) via a commercial Human Machine Interface (HMI) software package (e.g., Wonderware, WinCC, Intellution, Cimplicity, RS View, etc.).

These computers were typically interfaced together via either a dedicated link (i.e., serial) or a networked data exchange.

Now, with the multi-core technologies, these former multi-computer arrangements can be consolidated into a single computer.

NEW Single Computer / Multi-Core Processor Arrangement

Core 1 : Real-Time Controller – This independent processor core runs a real-time operating system (e.g., PharLap, etc.), executing all critical AGC algorithms and interfacing to the mill's systems via the FPGA hardware systems.

Core 2 : System Supervisor – This independent processor core runs the Windows XP Pro operating system, and supports all supervisory tasks, OPC serving, network interfacing to higher level systems and provides a Graphical User Interface (GUI) via a commercial Human Machine Interface (HMI) software package (e.g., Wonderware, WinCC, Intellution, Cimplicity, RS View, etc.).

This new single computer consolidation of multiple responsibilities offers new opportunities for employing AGC systems in stand-alone applications or as a key member in a fully integrated mill control system.

3 SYSTEM ARCHITECTURE AND IMPLEMENTATION

I^{2}S AGC system is a fully self-contained gauge control system that is capable of operating in a fully stand-alone arrangement or acting as a key participant in a fully integrated mill control system provided by I^{2}S or other automation supplier. The system is fully network-able and provides a high degree of interface-ability via an internationally standardized, onboard OPC Server, allowing the system to seamlessly interface to a broad range of commercially available control and automation equipment and systems. The system is housed in a hardened, industrial, 19 inch rack mounted 4U chassis, incorporating a single board Core 2 Duo computer, passive PCI bus backplane and the pair of National Instruments FPGA boards. External terminal hardware a cable connected to the FPGA board, providing a convenient means of signal connection and mounting flexibility.

Figure 3 provides a block diagram illustration of the I^{2}S AGC system architecture.

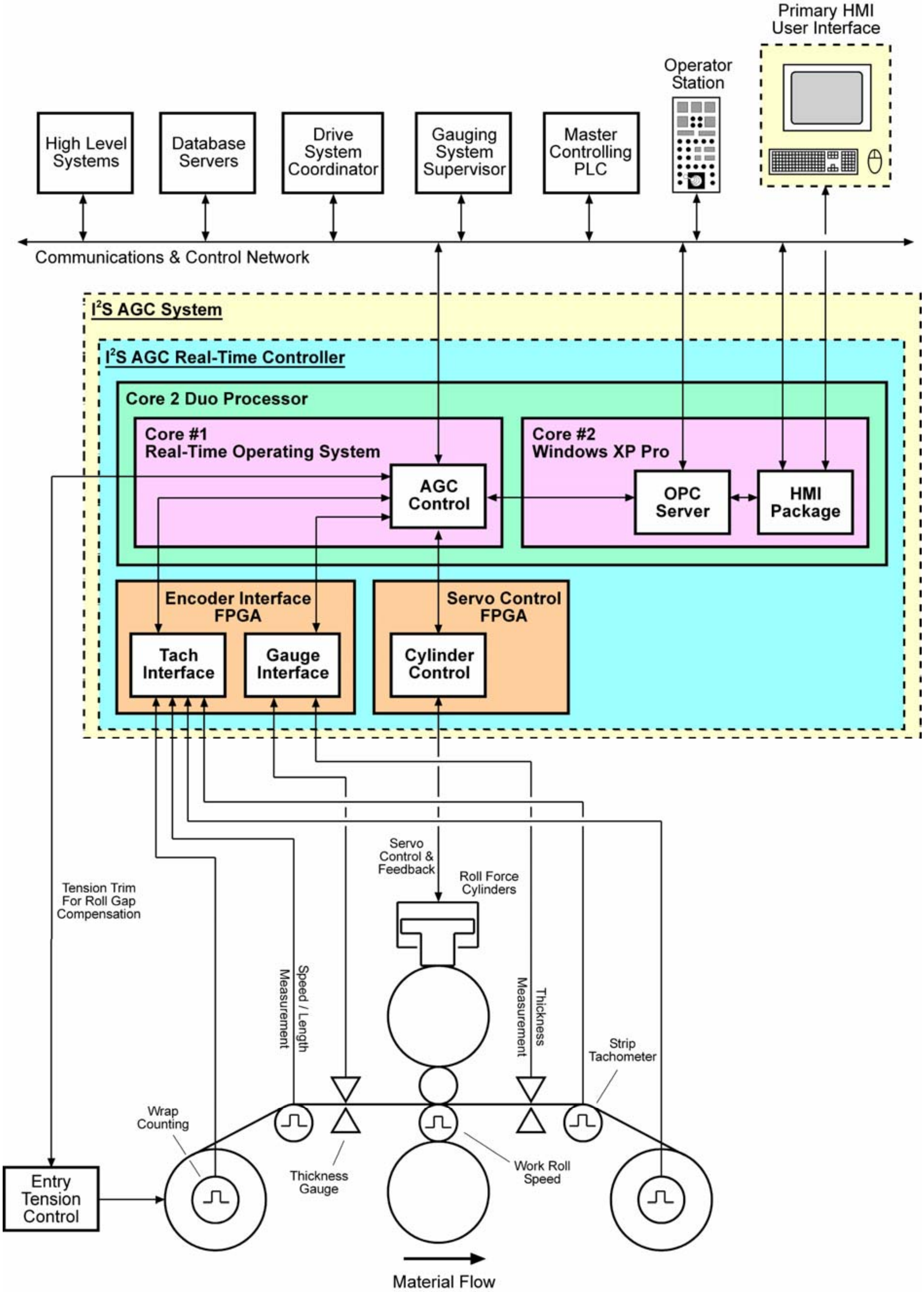


Figure 3 – Simplified block diagram illustration of the typical AGC system components and their interconnection for a reversing, vertical stack, 4-high mill arrangement. It is important that this same architecture is applicable to Sendzimir/cluster, 2-high and 6-high mills.

3.1 Primary Components

The I^{2}S AGC system is composed of two(2) primary components:

AGC Controller – This component provides the real-time AGC functions, algorithm computations, roll force cylinder servo controls, gauging system interface, critical strip length / speed measurements and high frequency data acquisition for SPC analysis, reporting, and general data acquisition (often coupled to IBA data logging systems). The mill equipment interfaces and direct servo controls are provided by two(2) FPGA based subsystems (see Section 3.2) that operate as intelligent, fully autonomous I/O and servo systems beneath a real-time operating system layer that executes within an independent core of the Intel® Core™ 2 Duo Processor. Real-time layer activities are performed by the National Instruments Real-Time LabView ETS software system (executing on a PharLap Real-Time Operating System supporting symmetric multiprocessing for the Core 2 Duo processor).

The gauge control equations used to render exit material thickness correcting roll gap adjustments and entry tension trims are executed within in the system according to their need and processing requirements. Some components (e.g., real-time transport lag buffering) reside in the FPGA, while the more sophisticated and computationally intensive tasks are performed by the real-time software. All standard AGC modes are provided including: Mass Flow, Feedback, Feedforward / Feedback, Extended Feedforward Multi-Mode and all can be actuated via roll gap maneuvers, entry tension trims and mill speed trims, depending on the material characteristics and strip thickness sensitivities. All modes employ mass flow compensation of the entry tension for roll gap maneuvers.

This controller interfaces to the other control system computers (PLC, HMI, Drive System) via a Gigabit class Ethernet network interface and through the OPC Server executing on the other core. Precision digital wrap counting is provided from the counting of the quadrature pulse trains of the winder motors' pulse tachometers / rotary encoders.

Supervisory and Human Machine Interface System (HMI) - This component serves as the supervisor of the AGC Controller, provides the primary interactive, graphical user interface HMI screens that support the I^{2}S AGC System, and supports an Internationally Standardized OPC Server. This Window XP Pro operating system based component executes on the other independent core of the Intel® Core™ 2 Duo Processor. The supervisory functions and utilities are orchestrated through the HMI screens and include:

- AGC Control & Operational Parameter Monitoring & Adjustment
- AGC Mode Selection, Set-Up & Activation
- Transducer & Roll Force Cylinder Calibration & Monitoring
- Tachometer / Rotary Encoder Monitoring & Operational Verification
- Roll Force Cylinder Servo Tuning
- AGC Performance Tracing & Evaluation

Mill management and performance recording / reporting include:

- Mathematical Modeling & Pass Scheduling
- Coil Set-Up & Customer Information Entry
- Roll Cluster / Stack Utilities
- SPC / QC Data Collection & Reporting
- Fault & Permissive Annunciation & Diagnostic Assistance

Report and document printing is provided via the networked color printer. Depending on the customer selected HMI package's capabilities, multiple language support is typically offered. This system also provides database interactions with ODBC compliant systems.

The user interface typically consists of a high resolution, flat panel video monitor (often mounted on/in the Main Operator Desk), a keyboard and pointing device (i.e., mouse, trackball, etc. – depending on customer preferences). The HMI screens are programmed with commercially available (off-the-shelf) software packages (e.g., WonderWare, Intellution, Cimplicity, WinCC, RS View, etc.) and is open to customer modification and adjustment.

The system performs data exchanges and interactions with the mill's master controlling PLC and other control systems (AGC Controller, Drive System, Gauging System, High Level Systems, etc.) through a networked interface via the OPC Server executing on the same processor core.

3.2 FPGA Implemented Components

The I^{2}S AGC system two(2) National Instruments PCI base, FPGA boards reside in the computer chassis passive backplane in specified PCI slots. These boards are identical, but are programmed differently to orient their internal hardware systems to their required tasks. During the system initialization process, the appropriate hardware configuration is downloaded to the board occupying the predefined PCI slot organization (i.e., depending on which slot a given generic FPGA board is located, that board will be programmed / configured to assume a specific role – slot specific hardware assignment).

Roll Force Cylinder Servo Control FPGA – This FPGA hardware is programmed to interface with and control two(2) roll force cylinders, including position encoders, pressure transducers and servo/proportional valves. The real-time, closed-loop, digital control of the cylinders is performed in the FPGA as a Hardware-In-The-Loop (HIL) component, communicating with the real-time control components via bidirectional DMA transfers. These hardware based controllers operate completely independently (i.e., parallel execution / hardware multi-tasking) with sampling periods of 250 micrseconds.

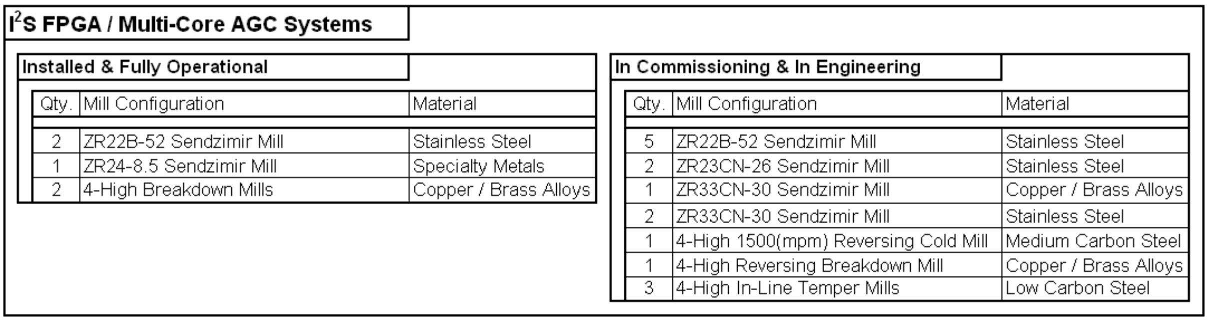
Encoder Interface FPGA – This FPGA hardware is programmed to interface with the rotary encoders on the mill and the gauging system. The encoders include entry / exit strip length / speed, reel motor shaft wrap counters and mill motor shaft (to provide forward slip measurements and roll surface speed indications). The flexibility of the FPGA allows basic counting as well as ratio and speed calculations to be carried out in hardware. (16) bit A/D converters accept gauge deviation signals (from the thickness measurement systems) directly into the FPGA where they are signal processed (via HIL activities) and provided to the AGC algorithms in the real-time software layer. The gauge analog deviations and SPC/QC real-time data acquisition transport buffers are also processed through this board.

4 CONCLUSION

The history and prevailing issues associated with the supply and sustainable support of the hardware and software components of high performance control systems have been discussed. Optimized, proprietary hardware and general purpose COTS technologies have been compared. End users and developer / suppliers must make a difficult decision as to which way to proceed. The key issue has been the lack of commercially available hardware that is appropriately optimized for high performance AGC applications. That is until now…

The new technologies of COTS based FPGA hardware and multi-core processors have emerged and now offer the ability to implement the desired, optimized attributes of customized, proprietary hardware, in the form of commercial, openly available, programmable hardware, while also consolidating formerly multi-computer architectures into a single computer, executing separate operating systems on the independent processor cores.

The new I^{2}S AGC system, described in this paper, has been conceived and developed with the end user and these difficult issues in mind. The first of these FPGA based, multi-core AGC systems have been successfully installed and are now fully operational. These systems have been well received, exceeding the customer specifications, leading to much interest in the industry and a rapid surge in system orders, as shown in Figure 4.



I^{2}S FPGA / Multi-Core AGC Systems

Installed & Fully Operational

Qty.	Mill Configuration	Material
2	ZR22B-52 Sendzimir Mill	Stainless Steel
1	ZR24-8.5 Sendzimir Mill	Specialty Metals
2	4-High Breakdown Mills	Copper / Brass Alloys

In Commissioning & In Engineering

Qty.	Mill Configuration	Material
5	ZR22B-52 Sendzimir Mill	Stainless Steel
2	ZR23CN-26 Sendzimir Mill	Stainless Steel
1	ZR33CN-30 Sendzimir Mill	Copper / Brass Alloys
2	ZR33CN-30 Sendzimir Mill	Stainless Steel
1	4-High 1500(mpm) Reversing Cold Mill	Medium Carbon Steel
1	4-High Reversing Breakdown Mill	Copper / Brass Alloys
3	4-High In-Line Temper Mills	Low Carbon Steel

Figure 4 – Listing of currently installed I^{2}S FPGA / Multi-Core AGC Systems and those systems currently being engineered or installed / commissioned.

This new architecture has fulfilled our design/developmental goals, along with satisfying the performance and supply concerns of the end users, by providing an optimized, high performance AGC system, using commercial, openly available equipment. This architecture is not limited to AGC systems. The pioneering work on these technologies originated in the I^{2}S development of a new series of Isotope and X-Ray Gauging Systems.

Many manufactures of FPGA based, general purpose equipment are introducing a broad spectrum of compatible hardware. This offers an open market of commercially available boards and systems, all of which can be interchangeably used in these classes of applications. This fact alone should alleviate any fears that this equipment is just made for some niche market and may become obsolete in short order.

The present development work is focused on expanding Quad Core Processors (four(4) independent cores). Here, the plan is to employ two(2) cores in the manner described in the paper, the third(3rd) core will accommodate the Isotope / X-Ray Gauging System, while the fourth(4th) core will support the all development, utility, diagnostic and database software. Current results are very promising.