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CONCEPTUALIZATION AND DESIGN OF A LOW-COST MTCONNECT-ENABLED REFRACTOMETER FOR COOLANT HEALTH MONITORING

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ABSTRACT

Monitoring of the health of water-based coolant used for machining requires measurement of various parameters of the coolant, including refractive index, temperature, pH, and turbidity. One of the primary parameters that is used to determine the concentration of the coolant is the refractive index, which is typically measured manually by an operator at regular intervals during machine operation. This paper describes the conceptualization and preliminary design of a coolant health monitoring system that will automatically measure the refractive index of the coolant and will digitize the resulting measurement for communication to a factory supervisory control and data acquisition (SCADA) system. To enable rapid integration into a factory's network architecture, the coolant concentration measurement will be transmitted by the monitoring system using the MTConnect format. Having an MTConnect-enabled sensor will allow the data to be remotely aggregated and compared to other machine data to help give a better understanding of overall machine health. The economical approach to its design allows the coolant health monitor to be realizable for both small manufacturing enterprises (SMEs) and large manufacturers alike. This widespread implementation will further benefit industry's movement toward Internet-of-Things (IoT)-equipped manufacturing facilities.

INTRODUCTION

It is widely recognized throughout the metal machining community that cutting fluids play a major role in the metal cutting process. The coolant and lubrication properties associated with their use have been shown to enhance tool life, surface finish, and the accuracy of finished work [1]. It has also been shown that variables such as the concentration of the coolant emulsion, presence of tramp oils and solids, pH levels, microbial counts, emulsion stability, and additive stability are important parameters to be monitored [2-4]. Although new metal cutting machines may be equipped with some sensing capabilities to monitor the health of the cutting fluid, many already-deployed and legacy machines do not have such functionality and instead rely on manual coolant health monitoring. Additionally, even for machinery with integrated coolant monitoring capability, the availability of coolant health measurements may only be to the computer numerical control (CNC) system itself, and the data may not be accessible from the factory network.

Popular data transmission standards, such as MTConnect, allow manufacturers to collect process data from their equipment to enable online and offline analysis, control, and status tracking [5]. Researchers have shown that manufacturers of all sizes can benefit from higher data availability from their processes, which enables process improvement by plant personnel or a SCADA system [6-8]. Published MTConnect deployments have enabled machining process improvement in real-time [9], demonstrated the use of fog and cloud computing technologies for machine monitoring [10], and provided a mechanism for correlation of intended and realized product information [11, 12]. The MTConnect standard has enjoyed such popularity that numerous commercial solutions exist for the collection of data from MTConnect-compatible devices, such as System Insights VIMANA and Memex MERLIN [13]. This paper discusses the design and development of a low-cost MTConnect-enabled refractometer that is built using various pieces of off-the-shelf hardware for the purposes of coolant health monitoring. Inclusion of additional sensing devices beyond those that are typically included in a CNC system will enable generation of higher intelligence in process control systems by large and small manufacturers alike.

BACKGROUND

Coolant Concentration Measurement

Machining lubricants are exposed to intense heat and contamination in daily grinding and machining operations, and thus their health is prone to change continuously. Modern metalworking synthetic or semi-synthetic coolants are mixtures of water and an assortment of chemical additives including oils, emulsifiers, rust inhibitors, and biocides. This mixture is critical to effective and efficient machining performance [1]. If the coolant concentration is too high, manufacturers lose money by using an excess of the concentrate, and the cooling properties of the lubricant are reduced. Likewise, insufficient concentration could have adverse effects on lubrication and tool life.

Every coolant concentrate has its own unique refractive index factor (also known as a Brix factor) which is a multiplier utilized in conjunction with a digital or optical refractometer reading. These factors are only meaningful as a multiplier as they do not indicate anything about a solution's water content. Likewise, a refractometer reading is meaningful only as a number to be multiplied by a refractive index factor. Refractive index factors typically range from 0.9 for emulsions to 3.4 for synthetics [14]. Typical metalworking concentrations are from 4%-10% but specific recommended Brix or concentration values are provided by the manufacturer. To verify this concentration, it's important to continuously measure it since coolant health is continuously changing.

Refractive Index

Refractometers are based on the Gladstone-Dale principle of fluid optics and are the most common and effective concentration measurement instrument. By measuring the light-bending characteristics of fluids, the refractive index can be calculated from Snell's law [15]. Snell's law states that the ratio of the sines of the angles (θ) of incidence and refraction is equivalent to the reciprocal of the ratio of the indices of refraction (n). For water-based fluids, higher concentrations increase the angle of light that is bent as it passes through the fluid [15]. Thus, higher concentrations have a higher refractive index. Snell's law is given in Equation 1.

$$\frac{\sin(\theta_1)}{\sin(\theta_2)} = \frac{\eta_2}{\eta_1} \qquad (1)$$

As shown in Figure 1, a refractometer has a light source that emits light at the interface between a prism and the sample. Some rays undergo a total internal reflection depending on the angle, while the rest of the light is refracted into the sample. As a result, a shadow is formed on a linear image sensor (such as a charge-coupled device, or CCD) placed on the opposite side of prism from the light source. The angle corresponding to the shadow line is called the critical angle of the total internal reflection. This angle is a function of the refractive index and therefore the concentration of the solution.

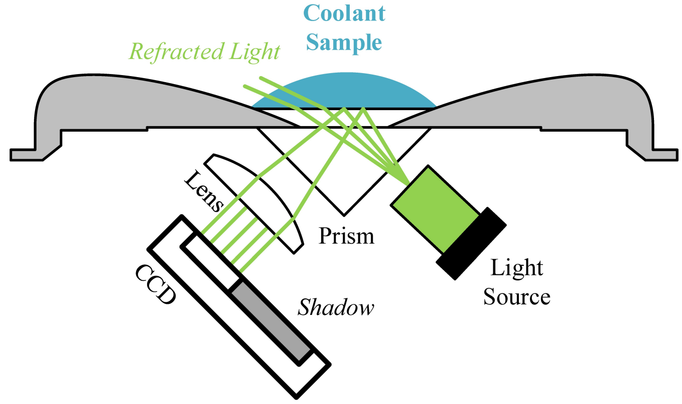

Figure 1. Measurement of Refractive Index

MTConnect

To perform analysis of machining processes, machine tool builders have been embracing MTConnect as the method of choice for transmitting manufacturing data [16]. MTConnect is an open, royalty-free communication protocol that allows for collection of sensor data through a network connection [17]. The MTConnect standard is a read-only format which allows communication from machine to machine and machine to operator. A typical MTConnect implementation consists of two important components: an adapter and an agent. The adapter is responsible for interfacing with the hardware device directly and converting relevant data to an intermediate format which is interpretable by the agent. The agent serves as a simple database and webserver. It also constructs an eXtensible Markup Language (XML) file from data collected from the adapter which is accessible through a normal web browser on a networked external device. The MTConnect standard specifies the format and terminology of data on the webpage and uses the Hypertext Transport Protocol (HTTP) to return data to the browser in response to specific commands that are encoded into the Uniform Resource Locator (URL) that is accessed with the browser [18-20]. A partial example of MTConnect XML data that is publicly available for a Mazak 5-axis milling machine is shown in Figure 2 [21]. While this data is for the B and C axes of a machine tool, discrete sensors can supply data in the MTConnect format as long as they follow the MTConnect standard.

MTConnect was developed on the idea of having a common-language such that data can be collected from any device that complies with the standard [17]. The refractometer described in this work will output data on a network connection in the MTConnect format. This enables its data can be easily gathered and analyzed by any compatible external device, whether that device is a computer or another machine tool.

```
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</Samples>
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Figure 2. Example MTConnect Data

Prior Work in Coolant Health Monitoring

Previous research has shown that MTConnect-based machine tool monitoring systems can help manufacturers understand and utilize the data that they gather from their processes [16, 22, 23]. Research has also been shown that that sensors can be easily implemented with machine tools to improve the cutting process [16]. Yet, prior works have not explored using MTConnect to monitor coolant health with a system that is suitable for SMEs. With refractometers costing thousands of dollars, it is not cost effective to automate coolant health monitoring. The coolant health monitoring system discussed in this paper is novel because it utilizes economical off-the-shelf components. Manufacturers of all sizes will now be able to automate their coolant health monitoring without costly equipment or having to manually monitor it.

SYSTEM DESIGN

The coolant health monitoring system was designed such that it would be both economical and compatible with any machine platform. An economical solution is more attractive to SMEs who may not have the available funds for expensive measurement and network hardware. The use of standard protocols and interface hardware enables the deployment of a system on any CNC machine tool. This increased flexibility will allow factories of all sizes to easily implement a networked monitoring system without a large investment.

Upon completion of the design of the subsystems of the coolant monitoring device, all the components will be manufactured and assembled in house. The finished assembly will be implemented on the Okuma Multus B300II at Georgia Institute of Technology's Advanced Manufacturing Pilot Facility (AMPF). This machine is the most highly utilized machine tool in the AMPF, and thus will provide the most dynamic coolant behavior.

Commercial System Analysis

Initial research work was done to evaluate digital refractometers available on the market. A Milwaukee MA871 refractometer was selected for its capability and simple design. At a price of approximately $100, it is an economical choice that provides a source of sensor optics. On the stock device, the included LCD screen displays both the sample temperature and the temperature compensated Brix factor. The sensor itself is based on a Toshiba TCD1304 linear charge-coupled device (CCD) and associated signal conditioning electronics. The CCD and its accompanying optics (the light source, prism, lens, and housing shown in Figure 1) were extracted from the assembly and used as the basis of the new refractometer system. As shown in Figure 3, a microcontroller was connected to the CCD for the initial data collection and signal conditioning circuit development.

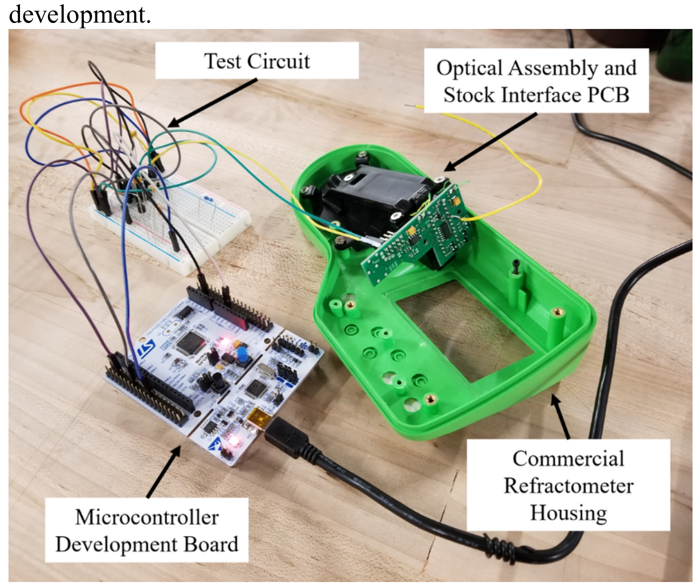


Figure 3: Test Circuit for Initial Data Collection

The optical subsystem, which was extracted from the off-the-shelf Milwaukee digital refractometer, is shown in Figure 4. The relevant components are labelled corresponding to the system diagram in Figure 1. The LED in the subassembly is used to generate a 589.3 nm wavelength light which is shined through the prism into the coolant sample. 589.3 nm light is used because it is the wavelength specified by the International Commission for Uniform Methods of Sugar Analysis (ICUMSA) to measure Brix rating [24].

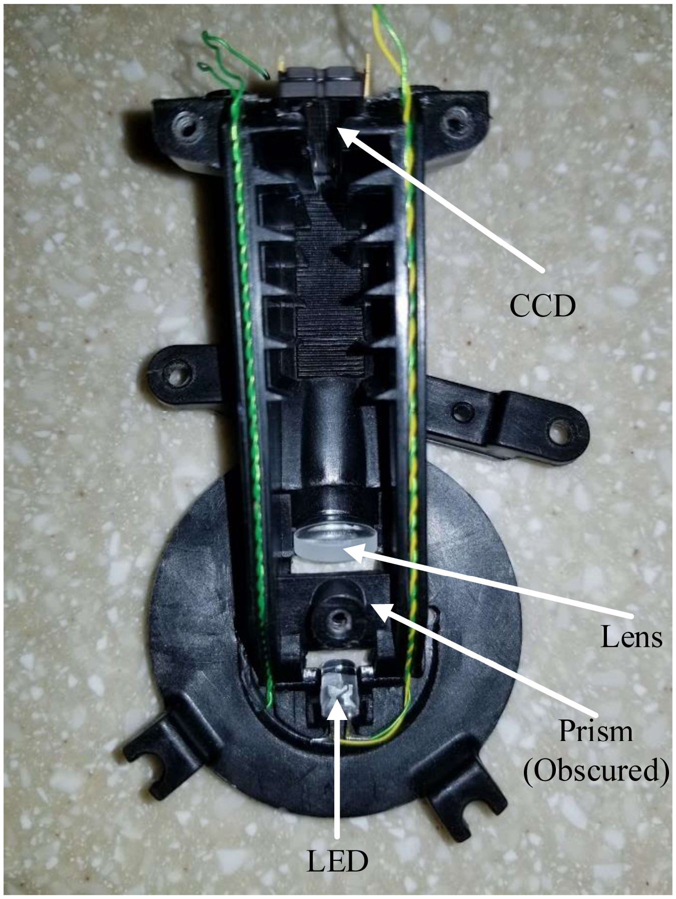


Figure 4. Optical Subassembly

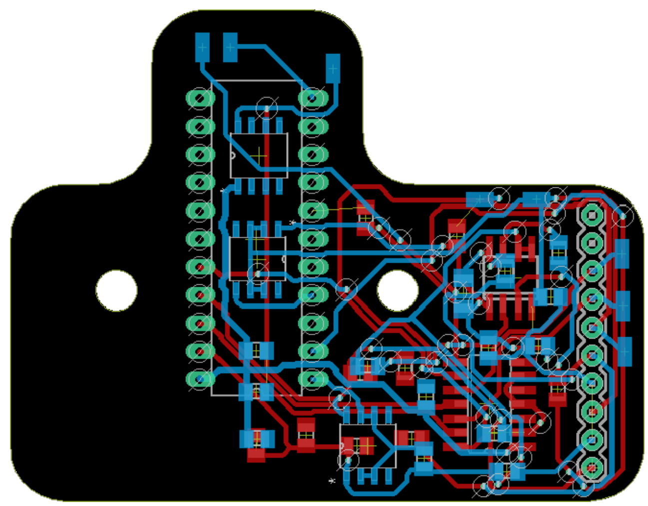
Microcontroller-Based Data Acquisition

The data acquisition setup utilized was heavily influenced by a TCD1304 interface implementation shown by Rossel [25]. The CCD's clock, shutter control, and integration clear signals are generated using hardware timers on a STM32F401RE microcontroller board using timings taken from the datasheet of the CCD [25]. The 32-bit timer on the microcontroller allows for long integration times, and therefore better resolution and accuracy. This microcontroller was primarily chosen because its analog to digital converter (ADC) is a high-speed 12-bit 2.4 MS/s model; the high sampling rate of the ADC is necessary to sample the output of the CCD, whose pixel rate is one quarter of the input clock rate.

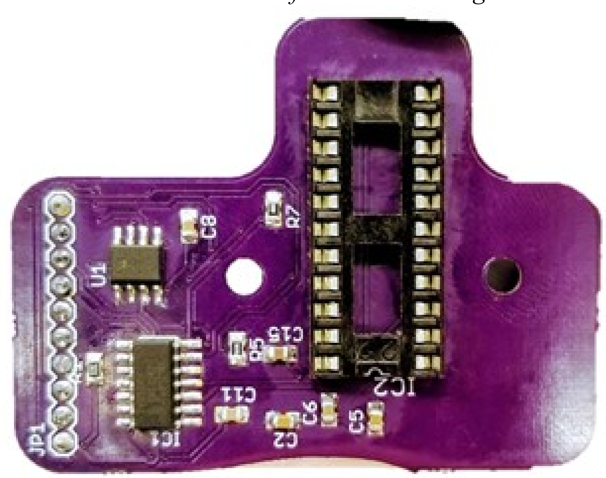
Electrical Subsystem

The CCD required a 1MHz clock rate which is generated by the external microcontroller board. Transmitting this clock signal over 24 AWG wire generated significant oscillations about the 0 and 3.3V levels, resulting in unread clock pulses. To remedy this, a 74 series inverter was used as a low-cost Schmitt trigger. Additionally, the output from the CCD needed to be inverted and scaled from its 0-5V signal to the 0-3.6V signal that the microcontroller board can read. An op amp in an inverting configuration was biased by half the rail voltage to achieve this without clipping 0V.

The TCD1304 interface circuit design shown in Figure 5a was assembled into the prototype board shown in Figure 5b to integrate with mechanical packaging constraints. Pin headers were used to increase robustness and enable easier assembly as compared to solder pads. The final implementation will use keyed connectors to minimize opportunities for inverted or mistaken connections.



a. TCD1304 Interface Circuit Design



b. Completed TCD1304 Interface Circuit
Figure 5. Designed and Fabricated Circuit

This circuit, along with the microcontroller board itself, are to be connected to a 24VDC switched-mode power supply (SMPS) in the control cabinet of the Okuma Multus. The noisy output of the SMPS will be filtered to minimize the impact of these spikes on the analog system using a multi-stage power conditioner designed for this work. The power conditioner, shown in Appendix A, consists of a buck converter and a series of linear regulators. The buck converter brings the 24VDC supply to 12VDC, which is further split into ±6 VDC and a virtual ground for the analog circuits. The +6 VDC is linearly regulated to +5 VDC and +3.3 VDC to power the CCD and the microcontroller board, respectively. The -6V rail is linearly regulated to -5 VDC through a L79L negative linear regulator, and the +5 VDC line is regulated by a L78L regulator.

Mechanical Subsystem

The mechanical design of the coolant health monitoring system is comprised of two aluminum flow plates that are clamped together with a gasket sandwiched between them. Each plate is 8 inches long, 6 inches wide, and 3/8 inches thick. The top plate, shown in yellow in Figure 6, holds the refractometer optics and CCD, in addition to printed circuit boards (PCBs) for the microcontroller and power supply.

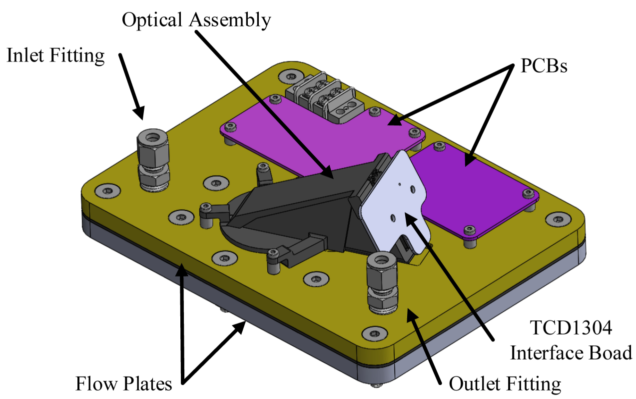
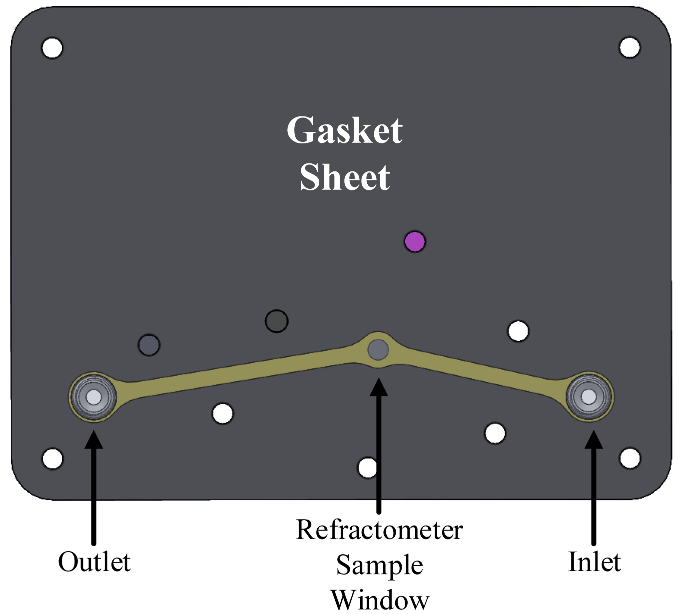
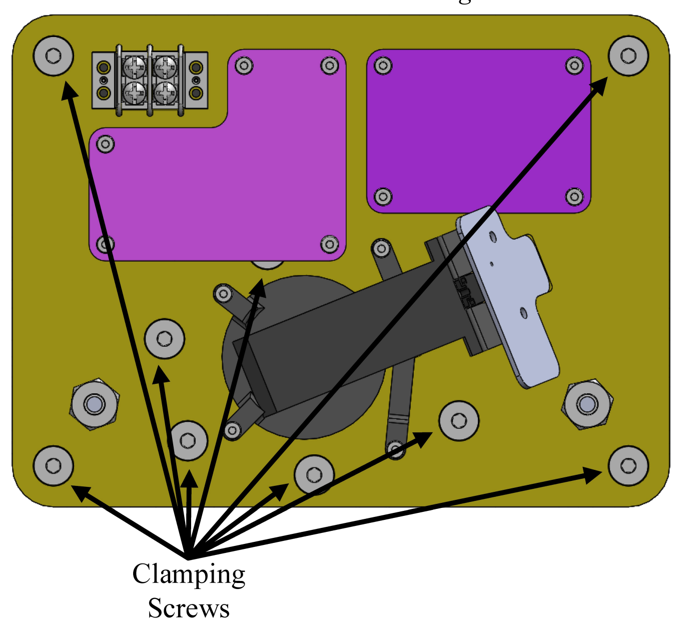


Figure 6: Mechanical System

The inlet fitting is connected to the coolant supply from the machine and coolant flows through a machined channel in the top flow plate during system operation. A hole leading to the sample window of the refractometer optical assembly is machined into the coolant channel, and the coolant passes by the sample window while flowing through the device. The outlet fitting is connected to tubing that returns the coolant to the machine's sump. Figure 7a shows the yellow coolant channel and the sample window of the refractometer optical assembly. The rubber gasket that is sandwiched between the two flow plates is shown in gray in Figure 7a. To further promote sealing, a series of screws along the channel and around the periphery of the assembly were added to provide adequate preload pressure between the gasket and plates. These clamping screws are shown in Figure 7b.



a. Coolant Channel and Sealing Gasket



b. Top Flow Plate and Clamping Screws

Figure 7: Top Flow Plate Details

Threaded pot magnets were added to the four corner bolts such that the system could be attached to any magnetic surface, such as the sheet metal enclosure of a machine tool. The use of magnets also mitigates any needs to add mounting holes or hardware to existing equipment. Since this system will be mounted near the coolant tramp with low-force magnets, there is little concern for interference with any of the electrical components of the equipment.

Machine Interface Plumbing

The interface plumbing of the coolant monitoring system is used to connect the device to the coolant system of a machine tool and was designed for user control and easy implementation. The design shown in Figure 8 shows the plumbing design for deployment on an Okuma Multus B300II millturn machine; however, the plumbing design can be easily modified for implementation on other machines as long as the necessary components are included.

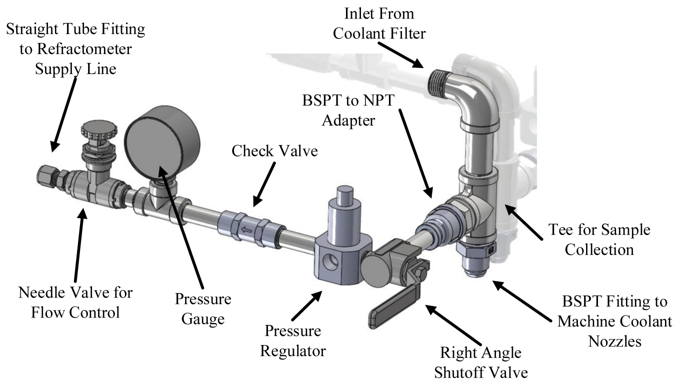


Figure 8: Plumbing System

The inlet to the coolant monitoring system was teed off after the coolant filter that was supplied with the machine's coolant system to avoid ingestion of particulate matter into the refractometer optics. In the Multus coolant system, the filter is attached directly to the output of the flood coolant pump, so teeing off the filter outlet line provides full pump pressure less the drop across the filter. The coolant lines on the machine use British Standard Pipe Taper (BSPT) fittings, so adapters were used to convert the fittings to National Pipe Taper (NPT) threads for compatibility with typical American pipe systems. In case the system needed to be bypassed for maintenance purposes, a shutoff ball valve was added immediately after the outlet from the coolant system. The coolant pumps provide much more pressure than is required to create flow through the monitoring system, so a pressure regulator and gauge were added to enable the user to reduce the pressure inside the flow plates. Too high of a pressure would cause leaks and could damage the plastic refractometer housing. Furthermore, the pressure regulator effectively serves as a low pass filter and mitigates concerns of pressure spikes as the coolant system is cycled during cutting operations. A needle valve is used to provide control of the coolant flow through the system. Since the coolant health monitoring system is not rigidly mounted, 1/4-inch clear vinyl tubing is used to connect the system to the needle valve. The clear tubing is also used to return the coolant directly to the coolant sump. To connect this line to the coolant health monitoring system, the inlet and outlet shown in Figure 8a are 1/4-inch straight Swagelok tube adapters. Figure 9 and Figure 10 show the physical implementation of this design on the Okuma Multus B300II.

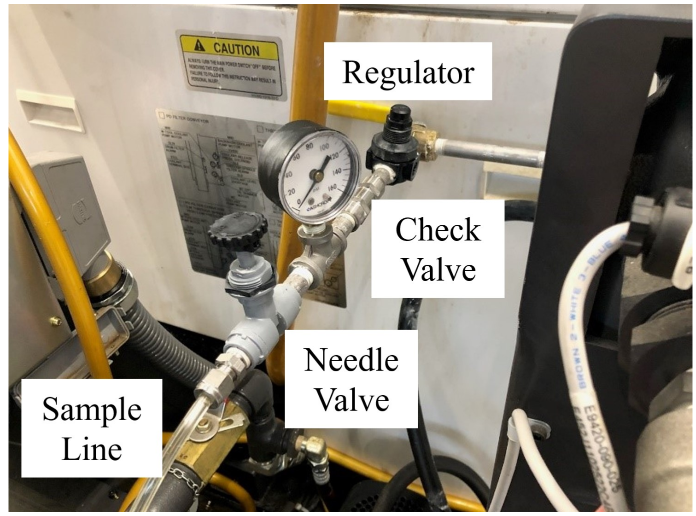


Figure 9: System Plumbing

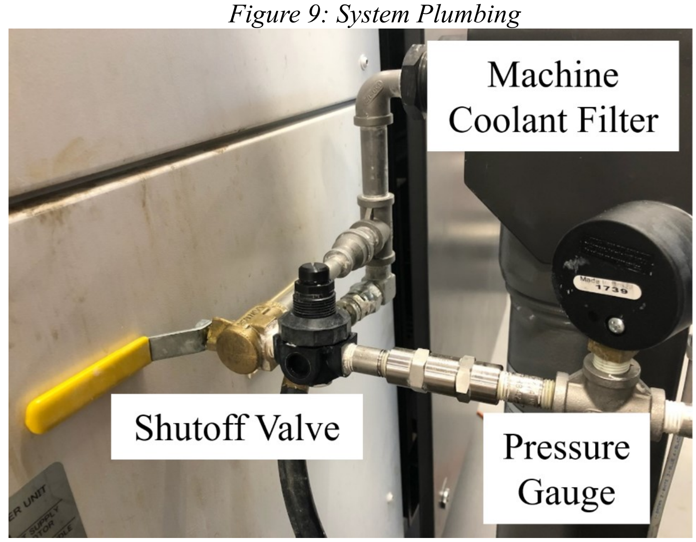


Figure 10: Machine Plumbing

MTConnect Adapter Implementation

The microcontroller will transmit acquired refractive index readings using the MTConnect standard over a Wi-Fi connection to the factory network. An embedded MTConnect adapter will be developed for the STM32F401RE, which will use a unique data tag to send the refractive index reading to an external Wi-Fi module. A Mazak SmartBox will serve as the MTConnect agent for the device, and will listen to the embedded MTConnect adapter over the local Wi-Fi connection that is also used by other embedded MTConnect adapters in the facility.

DISCUSSION AND FUTURE WORK

The development of the MTConnect-enabled coolant health monitoring system directly supports the Industrial IoT (IIoT) movement, where discrete objects on the manufacturing floor are networked together. Using IIoT techniques, data can be gathered and analyzed across machine platforms to enhance the performance of a manufacturing operation. For example, coolant health monitoring data can now be easily shared across the manufacturing enterprise to further understand how its composition changes over time. With more devices connected to the IIoT, there will be a larger pool of data to analyze; this will allow coolant manufactures to study coolant health measurements to further understand their product performance in a range of applications.

This project is part of a larger vision to create a complete coolant monitoring system that can monitor a range of coolant health metrics. The block diagram shown in Figure 11 depicts how the researchers plan to expand this research to monitor a range of different coolant parameters using a suite of networked sensors; other coolant health metrics that will be measured include pH, temperature, and turbidity. These parameters can be measured using various off-the-shelf sensors, or they can be inferred from indirect measurements (e.g., the level of suspended particulate matter can be inferred from pressure drop across the coolant filter). Ultimately, the higher data availability afforded by a complete coolant health monitoring system will enable enhanced control of the machining process.

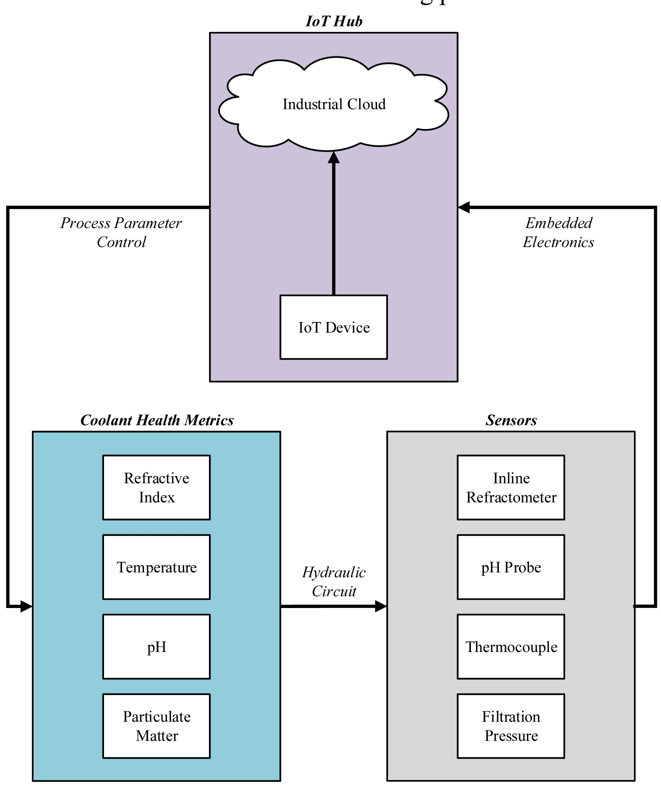


Figure 11: Health Monitoring System Implementation

Future work will include manufacture and implementation of the final versions of both the CCD and power conditioning PCBs needed for this system, in addition to software development for both data acquisition and MTConnect data transmission. Upon completion of the electrical hardware for the system, it will be calibrated using a range of samples with known refractive index. Once the initial system is completed and determined to provide accurate data, additional coolant health monitoring systems will be manufactured and deployed on all of the machine tools at the AMPF. Some additional design changes that are envisioned include simplifying the plumbing and creating an enclosed housing for the system to protect the circuitry. Implementing on a larger scale will not only aid understanding of the robustness of the design but will also provide data to explain how coolant health of the machines in the facility changes as the machines are used. This data can then inform the design of a future coolant health *control* system, which will affect coolant parameters to maintain the quality of the coolant over time. Controlling the quality of the coolant will reduce harmful chemical waste that is produced when the coolant is changed on a machine, as coolant changes will be required less frequently.

CONCLUSION

Cutting fluids play a major role in the metal cutting process, and it is therefore important to monitor their health to maintain control of the machining process. This paper has shown the conceptualization and design of a low-cost MTConnect-enabled refractometer that can measure the refractive index of a water-based cutting fluid. Connection of the system to the factory network enables remote monitoring of the concentration of a cutting fluid solution in a machine tool, which directly affects the effectiveness of a machining processes. Additionally, the use of MTConnect enables simple integration with existing facility network infrastructure and allows for data collection in the same format across many different devices. The low cost of this system enables manufacturers of all sizes to leverage the benefits of the coolant health monitoring system.

ACKNOWLEDGEMENTS

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REFERENCES

[1] M. Stanford and P. M. Lister, "The future role of metalworking fluids in metal cutting operations," *Industrial Lubrication and Tribology,* vol. 54, no. 1, pp. 11-19, 2002.

[2] T. Howes, H. Toenshoff, W. Heuer, and T. Howes, "Environmental aspects of grinding fluids," *CIRP Annals-Manufacturing Technology,* vol. 40, no. 2, pp. 623-630, 1991.

[3] P. Sheng and S. Oberwalleney, "Life-cycle planning of cutting fluids—a review," *Journal of manufacturing science and engineering,* vol. 119, no. 4B, pp. 791-800, 1997.

[4] B. Sanjanna, J. Sreedhar, K. N. Rao, and K. Reddy, "Design and Validation of an Oil Separating Accessory employed for Separating Oil Mix from Coolant," *Journal of Advances in Mechanical Engineering and Science,* vol. 3, no. 2, pp. 1-12, 2017.

[5] N. L. Baxter and H. D. Jesus, "Remote Machinery Monitoring--A Developing Industry," *Sound and Vibration,* vol. 42, no. 5, p. 20, 2008.
[6] G. Ćwikła, "Methods of manufacturing data acquisition for production management-a review," in *Advanced Materials Research*, 2014, vol. 837: Trans Tech Publ, pp. 618-623.
[7] B. E. Lee, J. Michaloski, F. Proctor, S. Venkatesh, and N. Bengtsson, "MtConnect-Based kaizen for machine tool processes," in *ASME 2010 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2010: American Society of Mechanical Engineers, pp. 1183-1190.
[8] R. Lynn, E. Wescoat, D. Han, and T. Kurfess, "Embedded fog computing for high-frequency MTConnect data analytics," *Manufacturing Letters,* vol. 15, pp. 135-138, 2018.
[9] F. Ridwan and X. Xu, "Advanced CNC system with in-process feed-rate optimisation," *Robotics and Computer-Integrated Manufacturing,* vol. 29, no. 3, pp. 12-20, 2013.
[10] M. Parto Dezfouli, "A SECURE MTCONNECT COMPATIBLE IOT PLATFORM FOR MACHINE MONITORING THROUGH INTEGRATION OF FOG COMPUTING, CLOUD COMPUTING, AND COMMUNICATION PROTOCOLS," Georgia Institute of Technology, 2017.
[11] P. D. U. Coronado, R. Lynn, W. Louhichi, M. Parto, E. Wescoat, and T. Kurfess, "Part data integration in the Shop Floor Digital Twin: Mobile and cloud technologies to enable a manufacturing execution system," *Journal of Manufacturing Systems,* 2018.
[12] M. Helu, A. Joseph, and T. Hedberg Jr, "A standards-based approach for linking as-planned to as-fabricated product data," *CIRP Annals,* 2018.
[13] M. Helu and B. Weiss, "The current state of sensing, health management, and control for small-to-medium-sized manufacturers," in *ASME 2016 11th International Manufacturing Science and Engineering Conference*, 2016: American Society of Mechanical Engineers, pp. V002T04A007-V002T04A007.
[14] "Coolant Concentration, Facts & Terminology," ed: Master Chemical Corporation, 2016.
[15] P. A. Tipler and G. Mosca, *Physics for Scientists and Engineers Extended Version*. W. H. Freeman, 2007.
[16] R. Lynn, W. Louhichi, M. Parto, E. Wescoat, and T. Kurfess, "Rapidly deployable MTConnect-based machine tool monitoring systems," in *ASME 2017 12th International Manufacturing Science and Engineering Conference collocated with the JSME/ASME 2017 6th International Conference on Materials and Processing*, 2017: American Society of Mechanical Engineers, pp. V003T04A046-V003T04A046.
[17] B. Edrington, B. Zhao, A. Hansel, M. Mori, and M. Fujishima, "Machine monitoring system based on MTConnect technology," *Procedia Cirp,* vol. 22, pp. 92-97, 2014.
[18] (2018). *Smart Manufacturing Systems Test Bed* [Online]. Available: https://smstestbed.nist.gov/vds/current.
[19] W. Sobel, "MTConnect standard. Part 1—overview and protocol," *Standard—MTConnect. http://www. mtconnect. org/standard. Accessed,* vol. 10, 2015.
[20] T. Hedberg Jr and M. Helu, *Design and configuration of the smart manufacturing systems test bed*. US Department of Commerce, National Institute of Standards and Technology, 2017.
[21] (2018). *MTConnect V1.3 Demo Agents* [Online]. Available: http://mtconnect.mazakcorp.com/.
[22] R. Lynn, A. Chen, S. Locks, C. Nath, and T. Kurfess, "Intelligent and accessible data flow architectures for manufacturing system optimization," in *IFIP International Conference on Advances in Production Management Systems*, 2015: Springer, pp. 27-35.
[23] E. Wescoat and R. Lynn, "Monitoring machines using excel and MTConnect: tracking machine utilization using off-the-shelf products," *AMT MTConnect Student Challenge, Chicago, IL,* 2016.
[24] H. De Whalley, *ICUMSA methods of sugar analysis*. Elsevier, 1964.
[25] E. Rossel. (2017). *The TCD1304 Linear CCD* [Online]. Available: https://tcd1304.wordpress.com/.

APPENDIX A

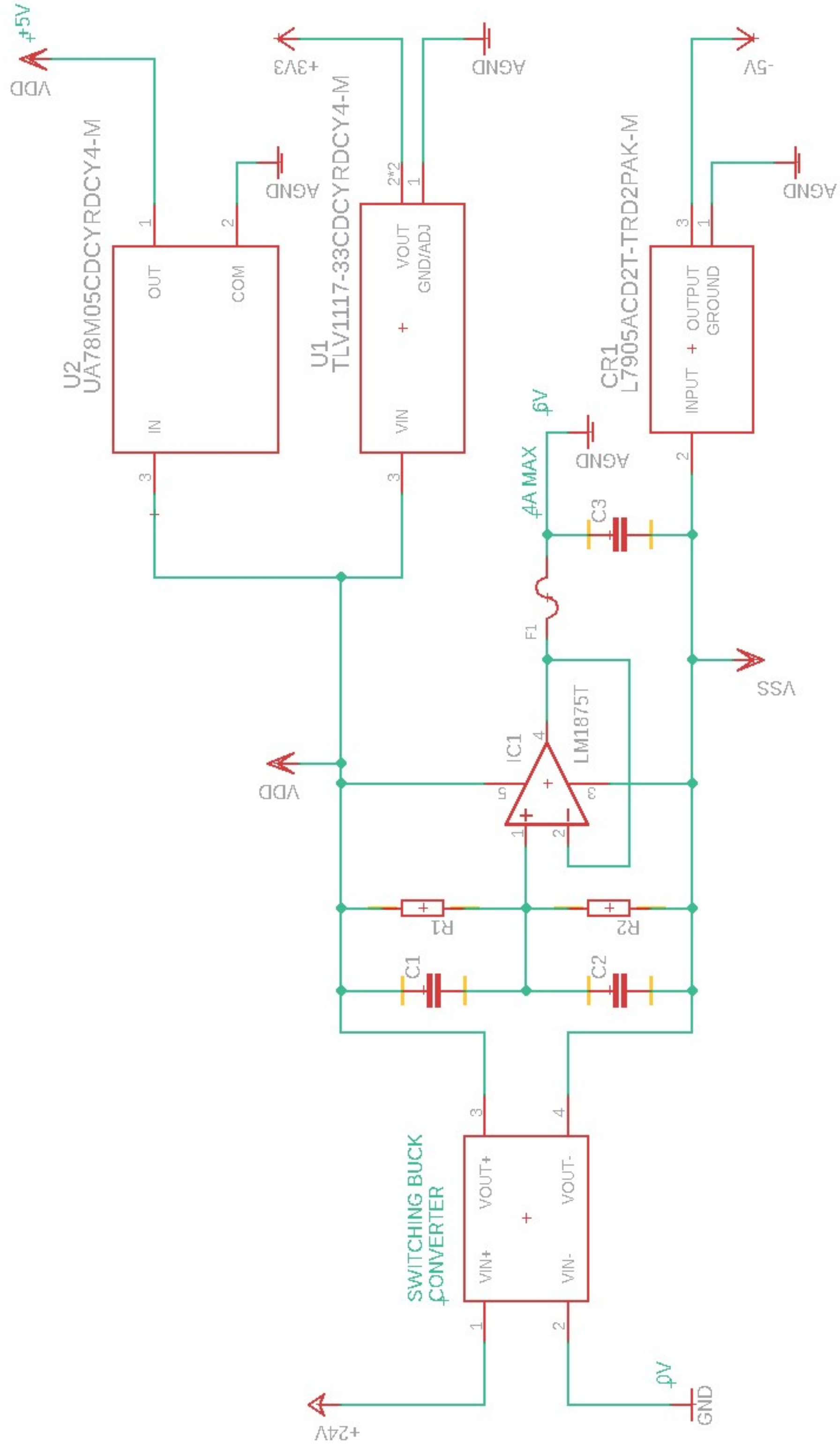

Figure 12. Power Conditioner