Enhanced Digital Twin Solution for Continuous Casting

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Digital twin solutions are set to play a very active role in many digital transformation and Industry 4.0 plans. Existing implementations of digital twins have a wide breadth of scope and usage, from basic data viewing, to large, centralized predictive control setups. Exploring the use of widely available tools in steelmaking to create a combination of modular and specialized interfaces for a pilot process and improving on some existing development may help create designs that help with analyzing data, improve operator understanding of obscure data, and look toward other new tools and possible process implementations.

This project team was the recipient of the 2021 AIST Digital Technologies for Steel Manufacturing Grant.

Many important parameters are used to control and monitor the continuous casting process to ensure a safe, consistent, high-quality and cost-effective product. Some examples include monitoring of the steel chemistry, flowrates, steel levels, liquid and surface temperatures, casting speed, mold heat removal, secondary cooling flowrates, and mold oscillation. The majority of this data can and is collected in real time directly from sensor feedback. Some factors also may be partially or entirely human controlled, such as the addition of tundish and mold fluxes,[1] but can still be monitored in real time by sensors on the casting machine. See Fig. 1 for an overview of the major sections of the process.

One parameter that is not practical to actively measure during the casting process is the condition of the rolls and bearings in the casting machine. Roll gap, roll gap tapering and machine alignment are paramount for internal quality in traditional slab casters but are generally measured when the casting machine is down or turning around. There are many solutions that have been developed by multiple companies worldwide to provide discrete measurement options.[4] Some of these measurements can range from surface and internal structure checks of individual rolls using eddy current probes and ultrasonic transducers to detect flaws in the roll surface, to larger-scale ultrasonic sensors that can check internal structure almost all the way to the center of the roll. See Fig. 2 for examples of different measurement systems from a couple of these companies. They are advertised to provide measurements of the active strand rolls and measure things such as roll alignment, outer roll condition, roll bending and roll rotation.[5,6]

Accurate geometry and adjustments to the casting strand rolls have been viewed as very important to both final slab quality and to overall process health in particular for some time now.[7] While the technology to take these measurements has improved over time, it falls on operators and engineers to evaluate the data coming in from these measurement systems. The goal of this project is to integrate the gap and alignment data into the caster digital twin model for

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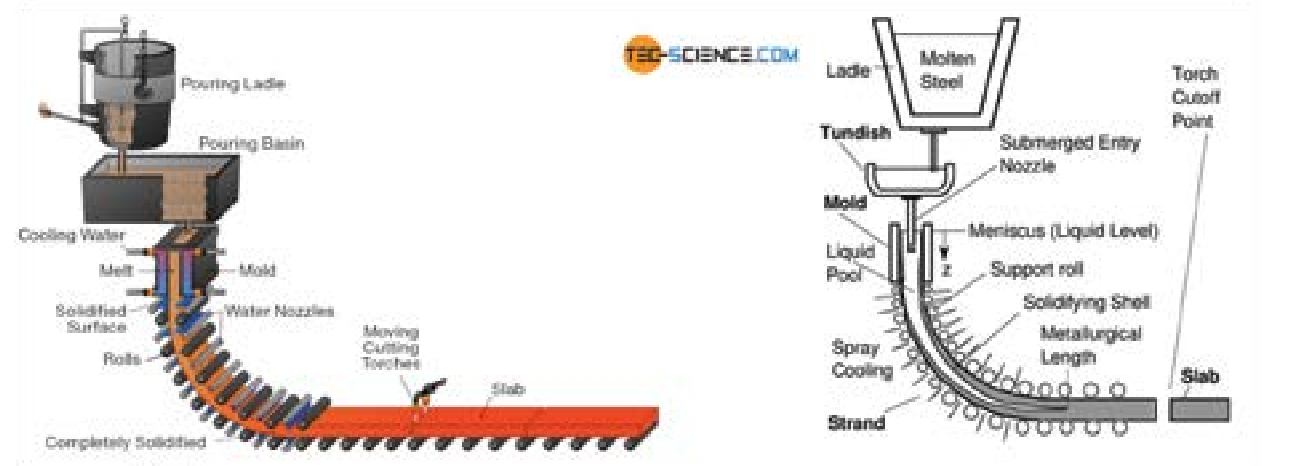
Figure 1



Images of the continuous casting process taken from a Tec-Science.com segment on different types of casting (a), and a paper published online by O'Malley and Thomas (b).[2,3]

Figure 2

Examples of caster strand measurement systems taken from their respective manufacturers' websites: Sarclad's Strand Condition Monitor (a)[5] and Power MnC's Strand Monitoring System (b).[6]

better visualization combined with the solidification point from the secondary cooling computer model. The secondary cooling model was previously tuned for high accuracy utilizing an array of strain gauges, linear variable displacement transformers (LVDTs), two color pyrometers and line scanning pyrometers.[7] The combination of the roll gap information and the solidification information into the digital twin will enable better real-time decisions to made by operators and engineers to select casting speeds to avoid solidification in potentially compromised areas of the machine. Proper interpretation of the data provided by measurement tools such as these can help to decrease defects and any time spent not manually taking measurements or analyzing is money saved.[9]

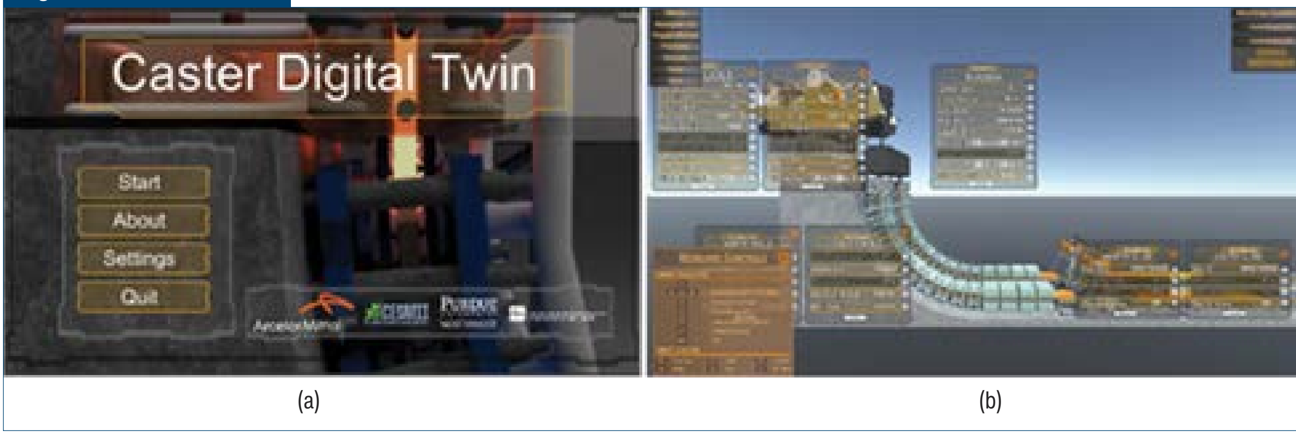
Motivations

While some experienced individuals can see raw data or graphs and come to fast or near-immediate conclusions, newer or less experienced individuals can take much longer to reach the same conclusions, or worse, misinterpret the data. This project has been developed in order to take current data and create new ways to help visualize the issues that may not be obvious when using the current display methods. Any time that can be saved in a decision-making process, or in some cases, a better understanding before making decisions in steelmaking, can help create better products, keep equipment in better shape for longer and save money.

Background Information and Previous Work

This project is funded through the AIST Digital Transformation Grant and comprises a team of students and staff at Purdue University Northwest's Center for Innovation Through Visualization and Simulation (CIVS) and staff at Cleveland-Cliffs Burns Harbor. The current project is developed on a previous project that was presented at AISTech 2021 in a paper titled "Developing a Framework for Process Digital Twin Using Unity 3D."[10] The previous paper detailed the general methodology of how the software was being developed using tools meant for the video game industry to create some basic interfaces to view data supplied from external files queried from plant

Figure 3



Images from the prototype digital twin caster from the AISTech 2021 paper:[9] main menu (a) and process data overview (b).

databases and provide that in a format that allow for both 2D and 3D visualization of the process data. A prototype digital twin software was developed that covered some pieces from areas regarding production data, machine health indices, cooling information and drive roll calibration information (Fig. 3).

The previous project had mixed results from expectations due to a drastically reduced development time, but the general idea sparked some discussion and ideas on how to proceed. Using what was learned from the work done on the project with Cleveland-Cliffs, the next step was to target specific parts of the prototype and begin to develop them to be more fully featured and user-friendly.

Currently, this project is utilizing Burns Harbor Continuous Caster #1 as the reference caster moving forward for continued development. Relevant to this project, this caster is utilizing battery-powered computerized roll gap sleds to conduct various measurements that are then analyzed and assessed by personnel to determine roll conditions and strand compliance to known target values. Some of these values include the following:

- Roll gap — Measured distance between the outer face and inner face rolls.
- Outer roll condition — Deviation of the outer face rolls from a straight edge reference.
- Roll bending — Eccentricity of a roll during rotation.
- Roll rotation — Freedom of rotation with a known load and minimal friction.
- Outer roll alignment — Deviation of caster alignment used for identifying misaligned segments.

During downtime, the roll gap sled is attached to the starter bar and sent up and down the strand, resulting in the generation of two data sets per full run. Once completed, the information is downloaded and then published for interpretation by maintenance or operations personnel, who determine compliance of the strand. Data is displayed using a few varieties of 2D graphs. Data regarding some of the measurements and the casters in question was published by some of the co-authors previously in *Iron & Steel Technology*.[10]

Objectives — The goal of the project is to refine a selected section of the previous prototype software and make it more viable in possible day-to-day use cases. This would also include research into some additional features or implementations that could be included in the future across multiple targeted updates.

The objectives of this project covered a few topics, but those targeted in the proposal mainly focused on the following areas:

- Exploring new visualization methods for the digital twin prototype's roll data sections based on selected readings from Burns Harbor's Continuous Caster #1.
- Supplementing and improving existing roll graph data generated by the software.
- Improving data-loading methods and user options for loading data.
- Exploring database access functionality to work alongside discrete file loading.
- Researching viable methods for creating machine-learning model predictions.
- Having students involved in the project development work to expose them to the steel industry.

Overview of Software Development Methodology and Tools

Since a detailed version of the previous methodology for the software can be found in the previous paper, this will only cover it at a high level, and then detail new parts or focuses for this particular project.

Unity 3D is being used as the primary development platform for the software. It provides many tools and integrations to allow for different applications of both 2D and 3D visualization, incorporation of user-defined functions, user interface elements, needed plugins, etc. Some original visualizations will also be built using built-in features and assets.

Microsoft Visual Studio is utilized for the integrated development environment (IDE) platform for any developed or modified code in the software, primarily staying in C# since both C# and Visual Studio are directly supported in Unity.

Autodesk 3ds Max is used for any models that need to be created or modified as needed for the project, which may be needed as more model adjustments are made toward making the used models closer to the actual geometry of the targeted caster.

A big part of this project is the generation of new visualization methods for the data being supplied; so to start with, at least being able to replicate or recreate something similar to some of the existing graphs would be needed. In order to do so, a data visualization plugin is being used for Unity called XCharts, which supports the use of parsed data sets in a variety of graph templates with some customization elements that can be changed per graph, all of which can run in real time. This becomes especially important for loading new data sets at runtime. See Fig. 4 for an example of a simple line graph generated from the plugin in Unity with a sample data set read in from a .csv file.

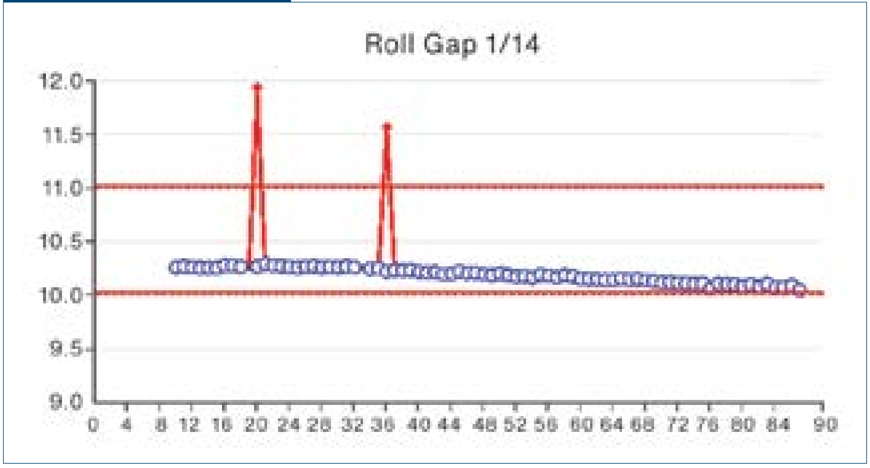
Current Results and Implementations

Graphing and 2D/3D Visualizations — Utilizing some information from the data set, some checks can be established to help post-process the data visually on the graph. The first of these can also be seen in Fig. 4, which is the establishment of thresholds for the data set. Thresholds themselves are pre-set groups of data just like the data being loaded from the .csv files. They can be a static value similar to that which can be seen in Fig. 4, or can be a series of values also provided by an external value set as well. Based on a simple logic that can be performed at runtime, each data point to be put on the graph can be subject to a following check:

$$\textit{Lower Threshold } (n) < \textit{Current Value } (n) < \textit{Upper Threshold } (n)$$

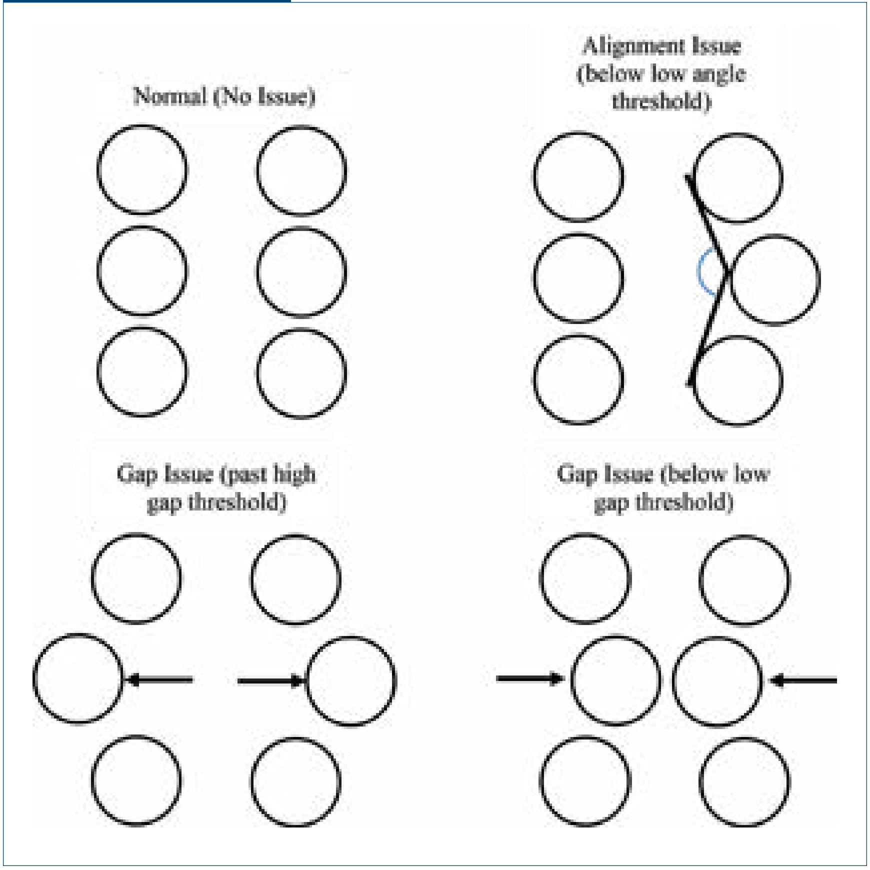
where n is the current roll number value being checked. If the value doesn't comply with the thresholds given, it can be marked as a value that would need more attention. These can be denoted differently from the other data points on the graphs and visualized to make them stand out. Multiple levels of thresholds can be established as well in the event that a difference in severity needs to be highlighted. This functionality has been developed so far with the intention of retaining some of the basic functionality of the existing visualized 2D graphs, but allow some ability to modify as visualization needs and feedback may permit. Toward the end of the project, there may also be some exploration into how color coding, flickering, and other visual indicators can be applied to the graphing to make anomalies and problematic values easier to pick out in the loaded data sets. Trying to leverage some previous visualizations that were utilized for the drive rolls in the caster health monitor in the 2021 paper, there were developments made toward better visual indicators of the types of issues detected in the data from the thresholds or other post-processing. While the final version of the changes should contain some changes in both 2D and 3D visualizations, the current visualization ideas are being prototyped in 2D at the moment. Utilizing a 2D mapping of the top and bottom roll pairs, the outputs from the post-processing of the 2D graphs can be used to apply changes to the 2D mapping.

Figure 4



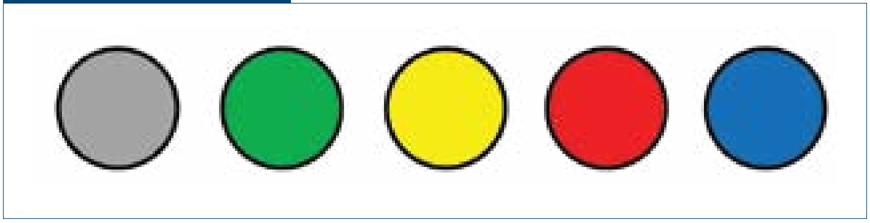
Example chart made using XCharts in Unity 3D with a test data set.

Figure 5



Example mockups of different detected situations using three roll pairs.

Figure 6



Color coding examples (possible examples from left to right: gray = ignore, green = good, yellow = warning, red = alert, blue = masked).

See Fig. 5 for mockup examples of what some of those 2D mappings might look like based on threshold checks.

Issues found in the data typically are difficult to easily convey visually what the issue is, especially in some cases where data is processed into things such as absolute values, where the direct issue requires a user to refer back to raw data to identify the issue. These issues would be dramatized in scale in order to noticeably show where errors are, as some issues could have thresholds in some cases in the thousandths of inches, which would still be near impossible to see if drawn to scale. This could be combined with color coding to indicate the severity of the issue (Fig. 6).

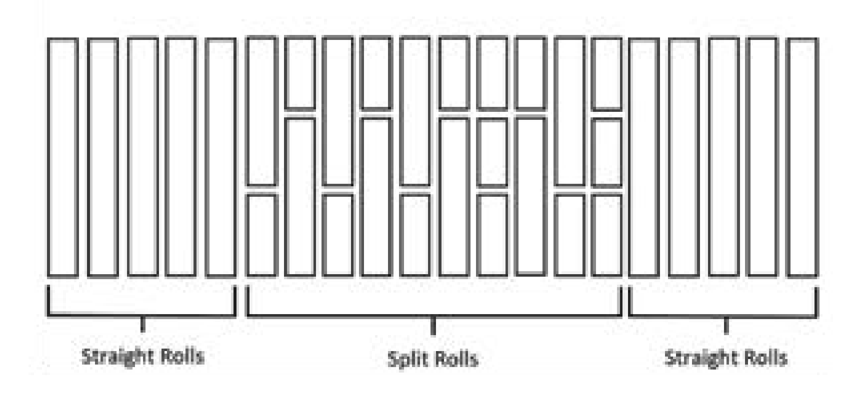
There may also be cases where known specific rollers need to be ignored in the readings (particularly right at the beginning of measurement) and can be marked as such, like the gray in Fig. 6. Also, there are some cases with known non-compliances to set thresholds, or a filter to mask out certain values or ranges that can be addressed separately, like the blue in Fig. 6. Different colors can be used for different purposes, whether it be just marking the severity of detected issues, or labeling different types of known issues, in conjunction with other visual effects that could be similar to things done with data graph points like the graph shown in Fig. 4.

As more work is done to fine tune the initial 2D mapping and graphing functionality, there will be work done to transfer the information filtered out to also apply this to the 3D models in the virtual environment, with all the same information displayed as in the 2D mapping. Some additional things to consider when moving in this direction is that the rolls themselves may be a combination of straight rolls and split rolls, and different roll gap sleds may have different sensors in different locations along the length of the rolls, which may add additional dimensions to both the 2D and 3D visualizations. This is something that typically is only really put together on engineering and CAD drawings, so exploring visualization of roll gap data in this way can make some issues much more intuitive. See Fig. 7 for a comparison example of the top-down mapping of the rolls and the difference between straight rolls versus split rolls.

Access to Database Features — Since the software is being developed with C# and utilizing Microsoft System .NET libraries, there is access natively to some different database types, and currently some tests are underway to develop a workflow and back end for SQL databases in the Unity project.

Cleveland-Cliffs is currently looking into options for testing these functionalities and how final implementations would need to be put together to actually use at the plant for further testing and feedback through the rest of the project and going forward.

Figure 7



Top-down view example of a section of rolls.

Machine Learning With Process Data — At the time of this writing, there has not been extensive work done in applying machine-learning techniques to the process data of the caster, but some initial literature review has been completed to investigate potential options to start with if time permits by the end of the grant period. A few different papers and case studies have been consulted as a reference, but the current ones that are being looked at are the use of non-linear techniques such as support vector machines (SVMs) for their success in some time-series prediction applications.[11] The nature of some processes cannot be predicted with the best results using more common linear techniques, and SVM is a technique that generally performs well in processes that are non-linear, non-stationary and in some cases, not defined entirely a priori. In the event that SVM is not a feasible choice for the prediction modeling, some research into the pros and cons of different more common solutions is being made. Currently, published papers evaluating comparisons of different linear and non-linear methods are being reviewed.[12]

Conclusions and Future Work

The project period was set to end in June 2022 and, at the time of this writing, is progressing well based on the original timeline in the project proposal. The visualizations both on the graphing side and the 2D visualization side are progressing to a point where they should be ready for review and revision by people at the plant by April 2022, with continued work on the 3D visualizations happening into the end of the project.

After implementations are put together and verified, the next steps would be to help bring in the implementations for database access and refine the data input methods to allow more user-friendly data access. This is a change that would massively impact the usability of the software for other data sets in the future if handled correctly. The end goal is to make it so the software can directly access database values very much in the same way that it would process offline data files. This would also include the ability to work with varying data sets so changes to target variables on the user interface are easier to iterate and implement as needs change for the caster.

Machine learning continues to be a hot topic in industrial usage, and continuous casting is no different. Finding some starting variables that could be useful for prediction modeling and establishing some models to generate process predictions could in the future not only allow viewing of existing data, but also add a "prediction" mode that would allow users to view "what-if" scenarios. This on its own could change how operators and technicians learn how changes can affect the process and help them to make better-informed decisions in real time on the caster. Prediction modeling using fault scenarios can also be good at potentially finding leading factors in data like the roll gap sled mentioned in the paper or process data and find trends that lead to problematic situations or product quality issues before they appear in the end products. Finding and testing various linear and non-linear models with different variable sets may be a project to tackle in the future with longer-term work, but could potentially show good results.

The interest this project drives both at CIVS and at Cleveland-Cliffs is leading to a bigger, more involved project to take the results and improvements that are being worked on and apply it to other areas of the caster data from the original CESMII work. Eventually, the work would then be made modular enough to make it usable for other casting setups outside the current test site.

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