Machine Learning Approaches and Data Driven Control Design Strategies Applied to Dynamic Systems

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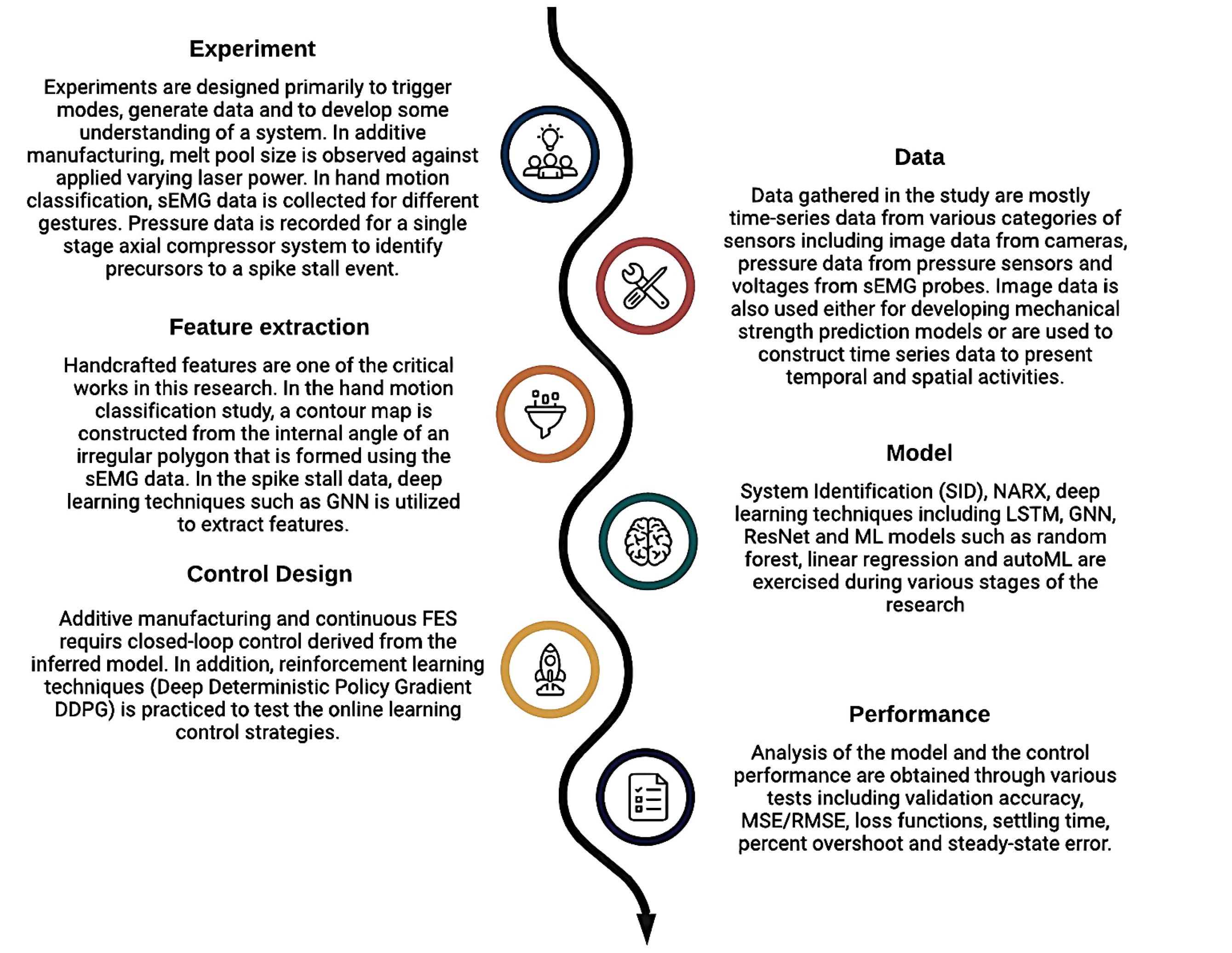
ABSTRACT

The utility of Machine Learning (ML) approaches to solve non-linear systems are gaining attention within the research community. As computational capacity improves, penetration of ML applications increases as well. The vast majority of the systems people interact with are dynamic in nature. ML approaches often solve a complex dynamic system with limited or no domain knowledge but have shown success by applying deep learning techniques that capture the system's characteristics as a black box model. Numerous popular artificial neural networks deliver a high performance with or without transfer learning but without much explanation as to why deep learning efforts show frequent successes in a particular application. The study investigates several ML techniques for a wide spectrum of applications to address effective workflow and adaptation of ML approaches along with control strategies applied to complex problems. **The study described here is segmented into six separate research works.** Efforts are made to identify merits and challenges associated with ML learning and data-driven control strategies applied to dynamic systems. These processes are found across several engineering fields including biomedical, materials, and advanced manufacturing.

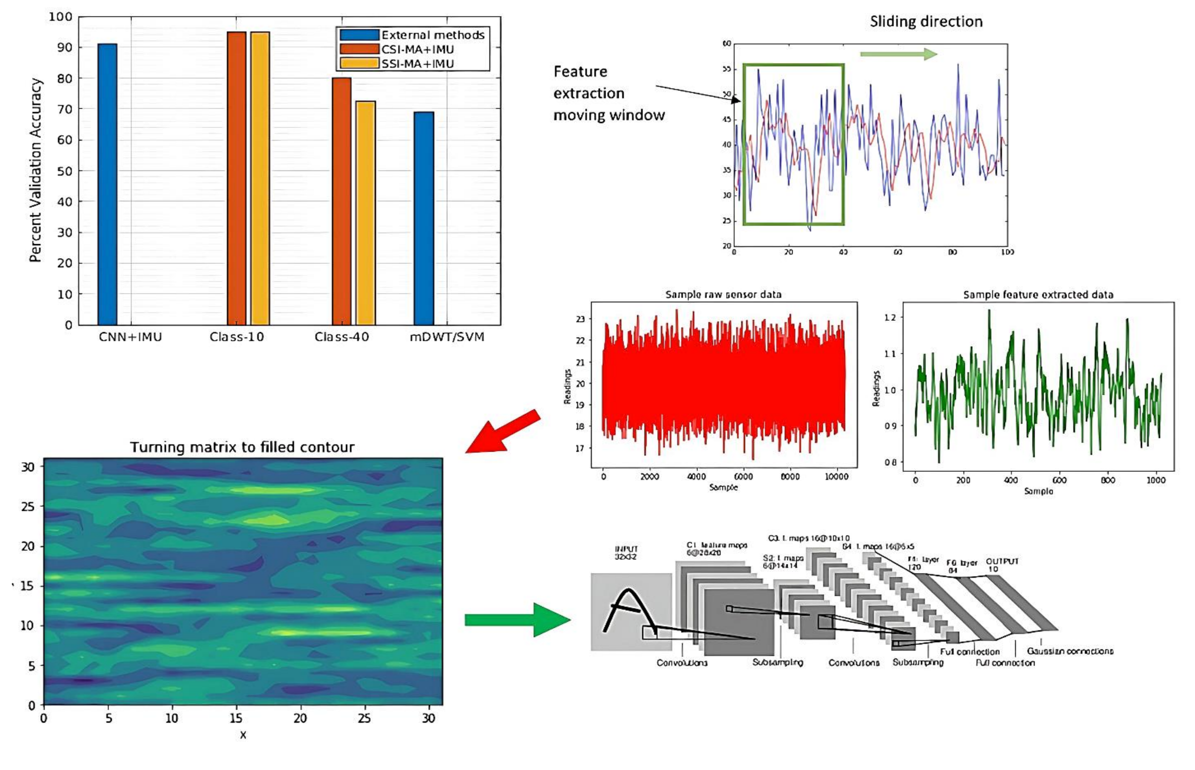


APPROACH

Several ML and Deep Learning techniques are investigated across multiple applications. **The six different applications described in the study are processed through five key design decisions namely, experiment design, data formats, feature extractions, model architecture, and controller design followed by performance analysis.** In the additive manufacturing (AM) and continuous electric field assisted sintering (CEFAS) are the only two applications presented here for which data driven controller design is proposed. At the current state of the research, the hand motion classification techniques, controller design for the AM, mechanical strength parameter prediction in a novel material, and predictive RNN for predicting solidification trajectory in AM, have shown notable performance relative to industry and research standards. The spike stall pre-cursor prediction in a compressor system and the controller design for the CEFAS are in progress.

Surface Electromyography (sEMG) controlled hand prosthesis

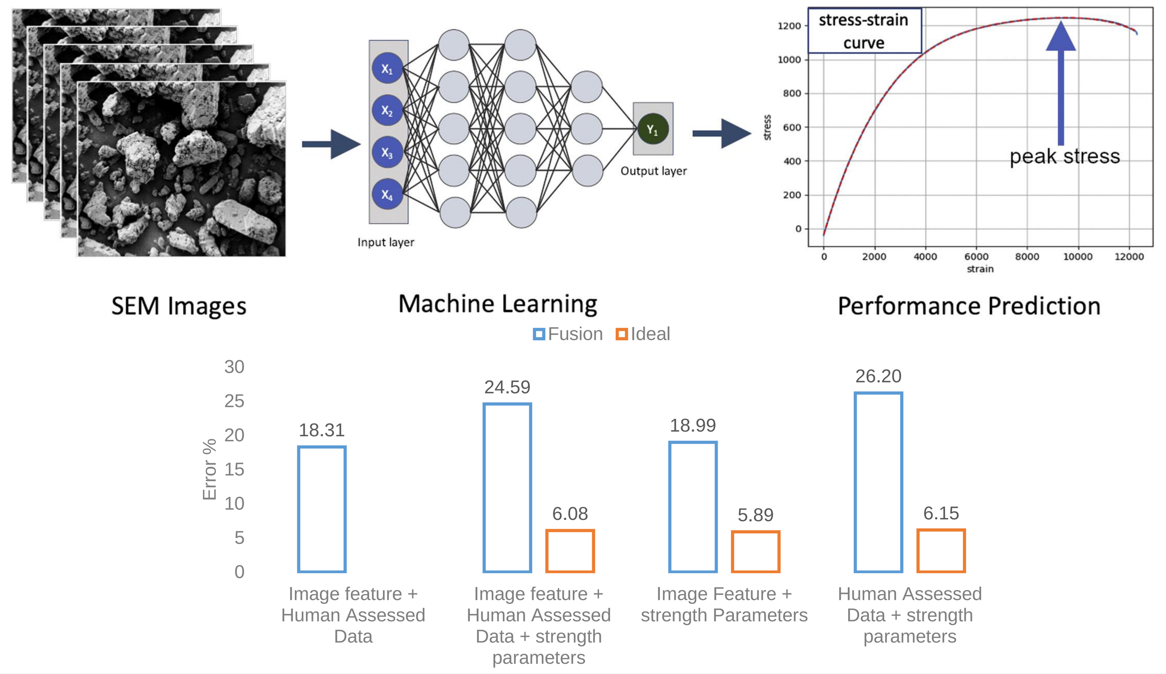
sEMG signals are stochastic in nature and non-invasive data for upper limb prosthesis applications. This research explores sEMG data among others from several sources, internal and external to develop a knowledge domain in hand motion classification in the realm of upper limb prosthetics. Measurement and Control Engineering Research Center facility with MyoMex armband hardware is utilized to form the internal database. Deep learning techniques such as CNN using residual neural networks are tested in conjunction with hand engineer features that capture spatiotemporal elements of the time series signals. The feature engineering practice helps researchers to gain interpretability in a Machine Learning problem. The sEMG study shows outperformance in classification tasks in the datasets relative to recent peer-reviewed results.



CSI: Cross Subject Investigation **SSI**: Single Subject Investigation

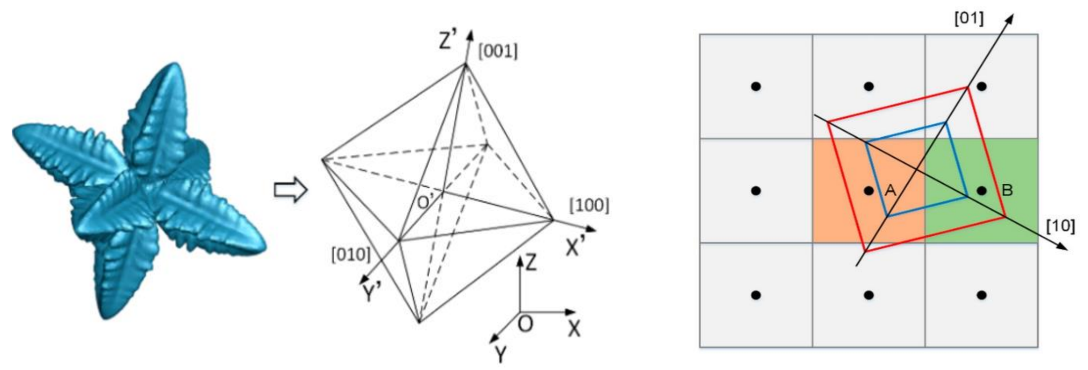
Feedstock Optimization Using Machine Learning Techniques

The research explores feature engineering practices to address a regression problem in the field of material strength prediction. In particular, BSIF features and CT data of a novel material are utilized to predict mechanical strength characteristics such as stress, strain, and slopes using machine learning techniques with and without ML fusion. 3D CNN is studied on the CT data for the material and the study suggests that the deep learning approach is more effective when the size of the data points is increased. The research is conducted under the LLNL MaCI feedstock optimization studies and published in [1].



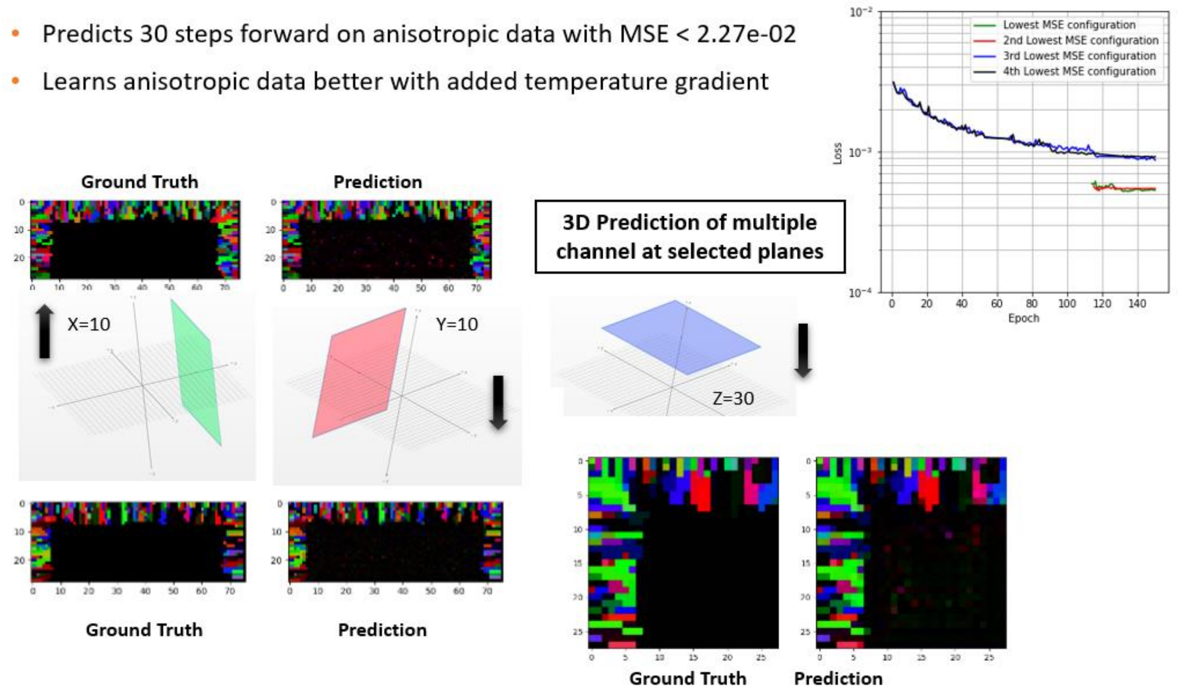
Accelerating ALE3D-CAFÉ using Deep Learning

ALE3D is a popular CFD tool heavily used in the LLNL with added CAFE capacity to simulate the solidification of material during an additive manufacturing process. The solidification simulation generates critical information if known in real-time, and could be applied towards closed-loop control in metal 3D printing. Therefore, acceleration of some parts of the computations in ALE3D-CAFE is necessary. The combined merit of spatiotemporal LSTM and Conv LSTM network is the Predictive RNN or PredRNN. The PredRNN is applied on time sequence data points containing location in cartesian coordinates, Euler angle, states, etc to predict state trajectory.



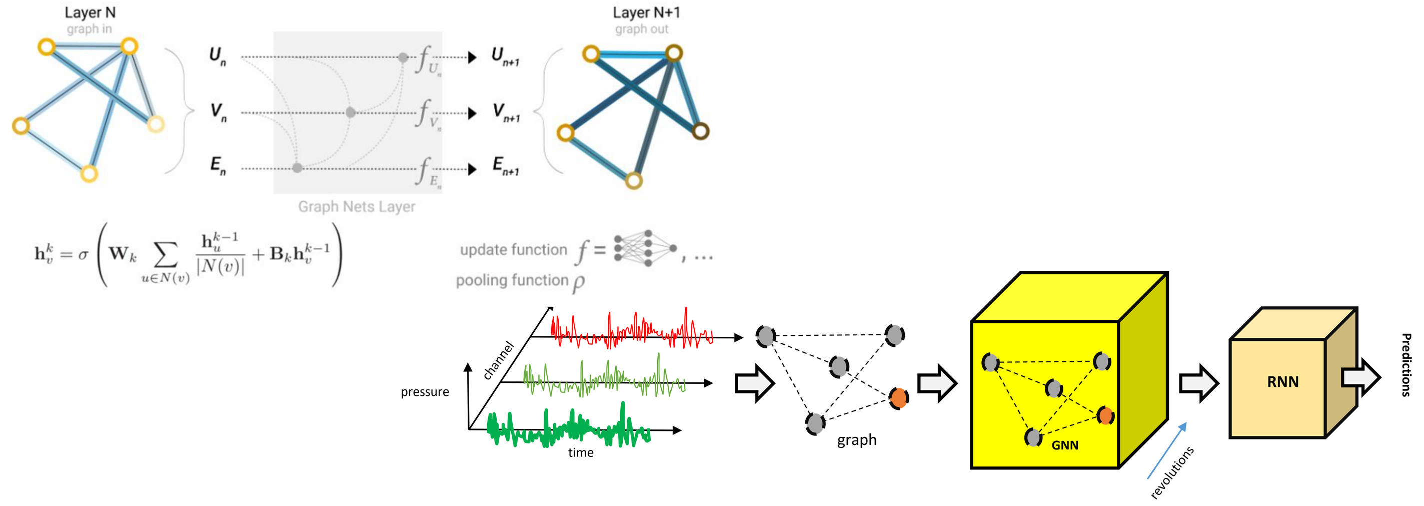
Growth of the Octahedral
= ***f(temperature gradient, lattice orientation, velocity, neighboring cell state, …)***

- Predicts 30 steps forward on anisotropic data with MSE < 2.27e-02
- Learns anisotropic data better with added temperature gradient



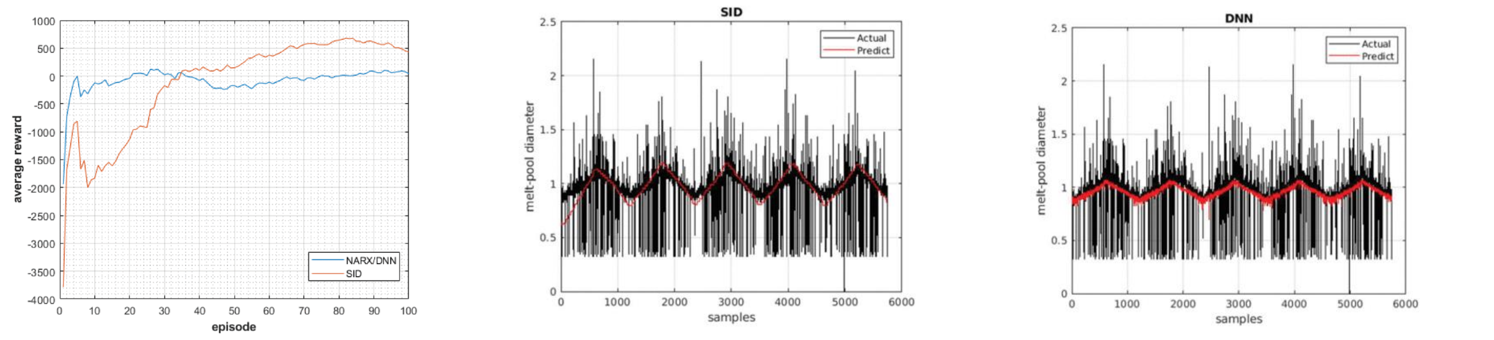
Precursor Detection of Spike Stall in Axial Compressor Systems

Knowledge gathered from the sEMG research, the feedstock optimization work, and the study of accelerating CAFE computations are utilized to explore the spike stall precursor event classification problem applied to the compressor system found in the Jet engine. The data is collected in collaboration with Chinese Academy of Sciences. The research pipeline is set to test GNN for feature extractions followed by LSTM for classification in supervised learning settings.



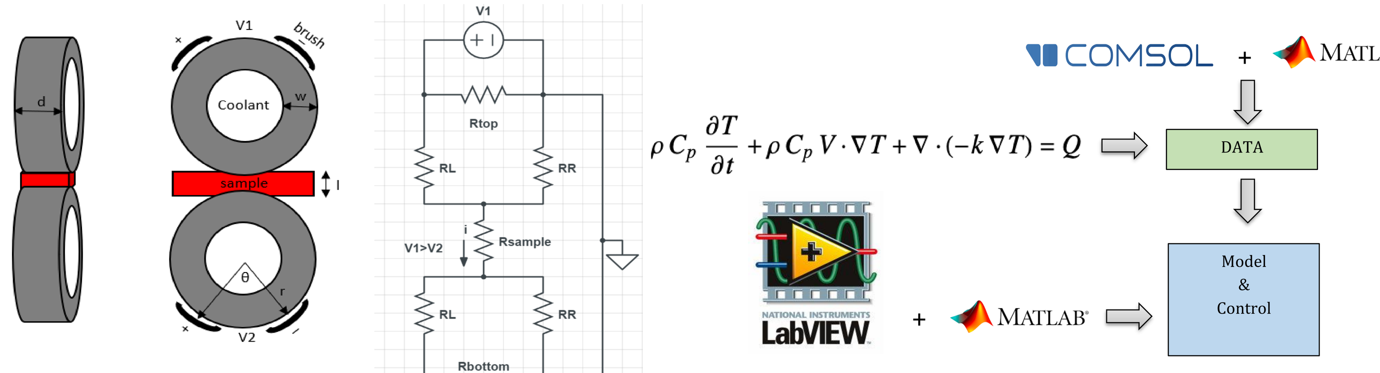
System Identification and Machine Learning Model Construction for Reinforcement Learning Control Strategies Applied to LENS System

Classification and regression models addressed in all of the aforementioned studies except the Predictive RNN, do not capture any dynamics. The research is further expanded to model and design intelligent control for dynamics systems. This study is conducted in collaboration with INL using their LENS DED technology as the primary source of data. The experiment is designed to generate appropriate data that contains system dynamics in the melt pool size in response to laser power. SID, NARX, and fully connected DL are applied to derive linear transfer functions and non-linear plant networks. A linear controller, PID is tuned on the SID model to set a benchmark followed by intelligent control design for the non-linear black box models for the comparative studies. Reinforcement Learning with a Deep Deterministic Policy Gradient approach is considered that utilizes an actor-critic deep network to generate action, state, and performance index in the sequence. The customized cost function determines the online adaptiveness of the controller-based reward optimization efforts by the actor-critic network. Performance observed in Matlab/Simulink relative to PID controller, suggests that RL controller is capable of smaller steady-state error, lesser settling time, and reduced overshoot. RL contains an online policy update capability that learns from mistakes in real time. However, considering the target plant being expensive equipment, some pre-trained work is done on Matlab/Simulink to establish a knowledge domain for the controller. This pre-trained controller can be transferred to further enhance the control policy during the operation of the LENS DED system. The study is published in [2].



Continuous Electric Field Assisted Sintering (CEFAS)

The RL controller pipeline described in the additive manufacturing task or LENS DED system is re-purposed for advanced manufacturing tasks known as CEFAS. Currently, the study is in a plant modeling state where the first principle method is being used to generate data and derive the system dynamics along with other data-driven approaches such as SID, NARX, and DL techniques. In addition, the COMSOL model is also being developed as an alternative data source. Once the plant is finalized, the design of linear controllers such as PID and intelligent controller concept is in the pipeline of work similar to the study described in the additive manufacturing task. This study is conducted in collaboration with the INL advanced manufacturing team.



References

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