Development of Metaheuristic Algorithms tuned Artificial Intelligence-Based Models for Prediction and Optimization of Process Parameters of Metal Additive Manufacturing

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Abstract

Metal Additive manufacturing (MAM) is one of the most advanced and non-conventional manufacturing techniques for metals whose popularity is steeply increasing day by day. In MAM, layer-by-layer metal deposition takes place on the basis of the information directly obtained from the 3-D computer aided design (CAD) file of the part to be manufactured. Amongst numerous variants of MAM, wire and arc additive manufacturing (WAAM) has been experiencing huge lime lights among the researchers over a past few years. This method of MAM can be realized as a manifestation of gas metal arc welding (GMAW), wherein, electric arc is used to melt the metal in the form of wire feed. It is then followed by its layer-by-layer deposition with the help of a robotic manipulator. Another popular variant of MAM, direct metal deposition (DMD) is regarded as one of the most promising classes of MAM technology, where metal parts are manufactured directly out of a 3- D CAD model using micro particles of metal powders injected into a melt pool created by a high energy laser source. To enhance the automation in MAM processes, the modelling and prediction of process parameters plays an important role. Two aforementioned popular MAM processes, WAAM and DMD are ever-emerging fields in metal additive manufacturing spectrum because of their higher build-up rate with flexibility at multiple scales and minimum wastes. However, in spite of the existence of these technologies over close to three decades, they have not been able to attract industrial applications primarily because of the ill-understanding of the process parameter contribution towards final parts geometry and mechanical and thermal properties.

The aforementioned fact has necessitated the development of accurate predictive models for establishing relationships between the input and the output parameters of the process. In addition to the conventional forward mapping models, backward models capable of estimating input conditions based on the targeted responses are also in demand. Statistical and empirical models have been developed for forward mapping in these domains in past. Those techniques however have had the limitations to decipher the complex non-linear relationship inherent in the input-output data. Moreover, the statistical regression-based methods are not readily invertible,

and hence, cannot essentially lead to the formation of backward models. Analytical and numerical models which work on physics-based simulations have been also built quite successfully. But these methods shave limitations too as they rely too much on prior knowledge of materials properties often not possible to have for newly developed materials under dynamic process changes and oversimplified assumptions of geometries, boundaries and interactions. It has been observed that artificial intelligence (AI) and machine learning (ML) based methods have been overwhelmingly applied successfully of late either solely or in conjunction with the other techniques to solve many issues met with the existing traditional approaches.

In this work, two different MAM processes, namely WAAM and DMD instances have been modelled considering both forward and backward mappings using two AI and ML techniques, namely artificial neural network (ANN) which has been widely used across all manufacturing domains and extreme gradient boost (XGBoost) which has emerged as a very powerful regression and classification technique. In the first case study as regards to WAAM, travel speed and current have been selected as control/input parameters while measuring geometry features, namely bead height, bead width, primary depth, secondary depth and toe angle as the set of responses through a single bead deposition gas metal arc welding process with an assistance of six degree-of-freedom robotic control system. In the second case study also pertaining to WAAM, micro-structural properties, namely dendritic arm gap and phase fraction have been modelled as outputs considering the same set of input parameters. In the third case study related to DMD, the responses have been identified as the clad height, clad width and capture efficiency while building austenitic steel part by cladding with variations in input parameters namely laser power, scan speed, and powder flow rate.

A large number of data samples, often required for training AI and ML based models, has been generated fitting the statistical regression equations on the experimental data. First, ANN-based architecture using feed forward topology has been leveraged for building input-output mapping from the training data samples. A small part of the total data samples which exclude the training samples has been used as validation data for choosing the best configuration for the models. A separate set of test cases has been also prepared along with the desired outcomes for checking the prediction accuracy. The back propagation algorithm in the form of stochastic gradient descent (SGD), which has been applied for training the models tends to get stuck at local optima. With an aim to enhance the mapping performance, the model has been trained turn-by-turn with different state-of-the-art metaheuristic algorithms namely genetic algorithm, particle swarm optimization,

firefly algorithm, bio-geography based optimization, flower pollination algorithm, dragonfly algorithm, and grey wolf optimization. The backward mapping has been also established similarly using the same hybridization schema and all the approaches have been comparatively studied.

The bi-directional models have been further investigated by applying a relatively new technology extreme gradient boost (XGBoost) for training. Extreme gradient boost is a relatively new machine learning paradigm consisting of an ensemble of decision trees, which has been able to emanate complex relationship between the input and output parameters of any process. extreme gradient boost technique. The parameters in XGBoost are very crucial for obtaining accurate models. Different state-of-the-art algorithms have been tried for tuning the parameters for this purpose. Backward mapping models have been similarly developed with similar kind of hybridized approaches.

Bio-inspired meta-heuristic algorithms have become a buzzword in recent time and new algorithms inspired by natural phenomena and biological species have been emerging in tandem to successfully solve real life regression, classification and optimization tasks. Firefly algorithm (FA) has been one of the most fascinating algorithms with lots of potential. A partition-cum-unification based genetic firefly algorithm (PUBG-FA) has been proposed. This essentially has been formulated by taking the essence and merits of both FA and genetic algorithm (GA) to take the balance between exploration and exploitation. Inspired by the successful application of grey wolf optimization algorithm (GWO) in solving real life problems, a novel modification of the same has been proposed. The improvement in covariance matrix adapted grey wolf optimization (cmaGWO) algorithm has been accomplished by changing the initial perspective prey location guided by the covariance matrix adaptation and recombination. Inspired by the havocs caused by COVID-19 pandemic, a multi-wave corona virus algorithm (MuCOVID) has been developed. All the new optimization algorithms have been tested and compared with some of its variants and several other state-of-the-art metaheuristics quite exhaustively on benchmark objective functions. The new optimizers have been further validated on some real engineering case studies.

Finally, the newly developed metaheuristics have been applied for the already developed hybrid models using both ANN and XGBoost for bi-directional mappings. Once, the forward models have been precisely developed, optimization for the responses have been carried-out by applying all the different metaheuristics including the newly developed ones. The overall mean absolute percentage errors in testing forward mapping and backward mapping using the model, which have been within the tolerable limits, have been found to be the least with the

new optimizers. The cmaGWO algorithm has been found to be the most successful considering bi-directional mappings and optimizations. The adequacy of the developed models has also been found acceptable. The results clearly recommend the application of hybridized AI based approaches for modelling different cutting edge manufacturing processes.

Keywords: Metal additive manufacturing, wire and arc additive manufacturing, direct metal deposition, artificial neural network, extreme gradient boost, bio-inspired metaheuristic algorithm, firefly algorithm, grey wolf optimization, covariance matrix adaptation, corona virus algorithm, forward mapping, backward mapping, optimization