

LEARNING ADMISSIBLE SHAPE MANIFOLDS FOR SIMULATION BASED DESIGN OPTIMIZATION

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Abstract

Parametric Model Embedding [1] is a dimensionality reduction technique designed to construct compact representations of parametrized design spaces [2]. The method identifies a reduced set of latent variables capable of reproducing the dominant geometric variability of a family of configurations while preserving a consistent mapping back to the original design parameters. Because the formulation is based on generalized eigenvalue problems, the resulting embedding defines a linear subspace of the original parameter space. Although this approach has demonstrated effectiveness in several shape optimization problems [3-5], linear embeddings may struggle to represent nonlinear correlations between geometric features and design variables in highly coupled parametrizations.

This work investigates a nonlinear extension of Parametric Model Embedding aimed at learning compact manifolds of admissible shapes suitable for simulation based optimization. The proposed framework adopts a supervised encoder decoder architecture that establishes a consistent round trip mapping between geometry, latent coordinates and design variables. The encoder projects high dimensional geometric descriptions into a reduced latent representation, while the decoder reconstructs the original design parameters.

To ensure geometric consistency of the learned manifold, the training procedure integrates a differentiable surrogate of the geometry generation process. This surrogate enables the definition of a geometry aware loss function that evaluates reconstruction errors at the coordinate level instead of considering design parameters alone. In addition, boundary enforcement mechanisms are introduced to guarantee that reconstructed parameters always satisfy the admissible design ranges. As a result, latent coordinates define a reduced control space that generates feasible configurations by construction.

The methodology is assessed on a parametric hydrodynamic configuration characterized by several design variables controlling the geometry of a bio inspired underwater vehicle. Numerical experiments compare the nonlinear formulation with the classical linear Parametric Model Embedding in terms of geometric

reconstruction accuracy, latent dimensionality and compactness of the resulting design space.

The results show that the nonlinear embedding can achieve similar levels of geometric variance recovery using a smaller number of latent coordinates. This leads to a more compact and well conditioned reduced space that is potentially more suitable for global optimization algorithms. The proposed approach therefore represents a step toward the integration of manifold learning techniques within simulation based design frameworks for complex engineering systems.

References

- [1] Serani, A., Diez, M. (2023). Parametric model embedding. *Computer Methods in Applied Mechanics and Engineering*, 404, 115776.
- [2] Serani, A., Diez, M. (2025). A survey on design-space dimensionality reduction methods for shape optimization. *Archives of Computational Methods in Engineering*, 1-28.
- [3] Serani, A., Diez, M., Quagliarella, D. (2024). Aerodynamic shape optimization in transonic conditions through parametric model embedding. *Aerospace Science and Technology*, 155, 109611
- [4] Serani, A., Palma, G., Wackers, J., Quagliarella, D., Gaggero, S., Diez, M. (2025). Extending parametric model embedding with physical information for design-space dimensionality reduction in shape optimization. *Engineering with Computers*, 1-21
- [5] Gaggero, S., Serani, A. (2026). Physics-informed dimensionality reduction for propeller shape optimization. *Applied Ocean Research*, 166, 104932.