SISSA mathLab

New Research topics: examples of new projects in the group

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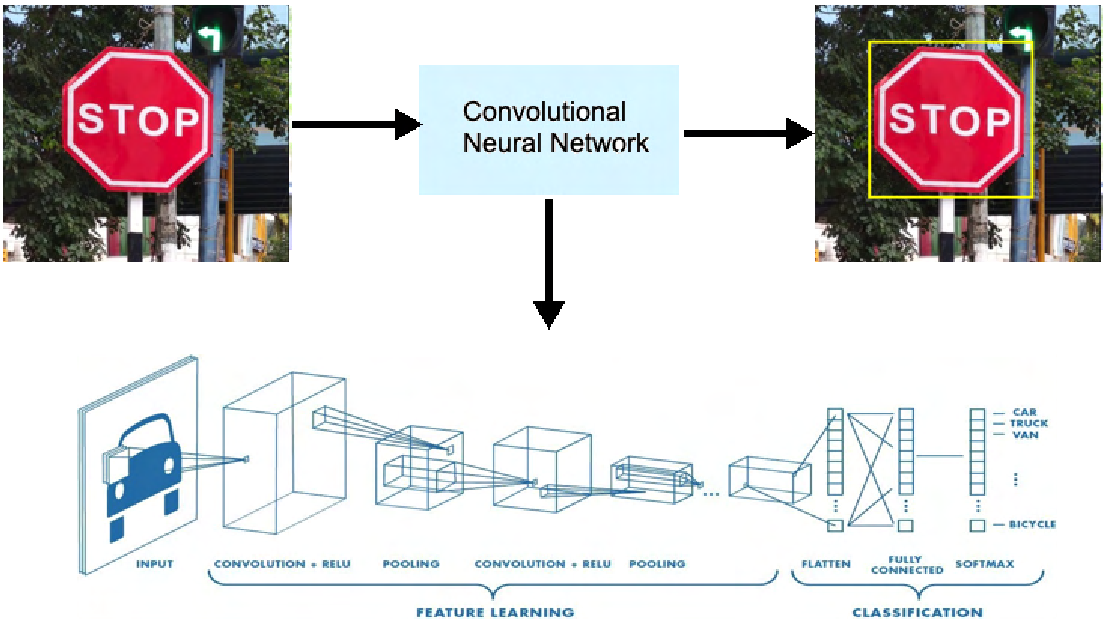
There are several projects completed and currently running in cooperation with different companies in the field of Machine Learning:

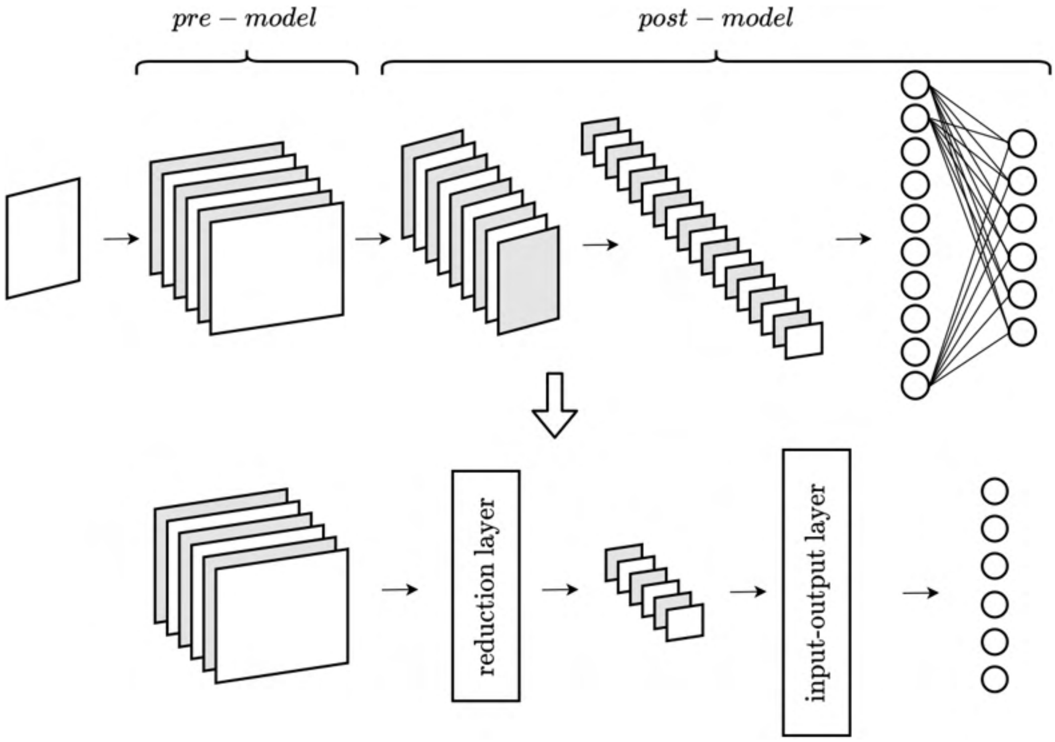
Object Recognition

The goal of this project is to build a Convolutional Neural Network (CNN) able to recognize and detect the position of different types of objects.



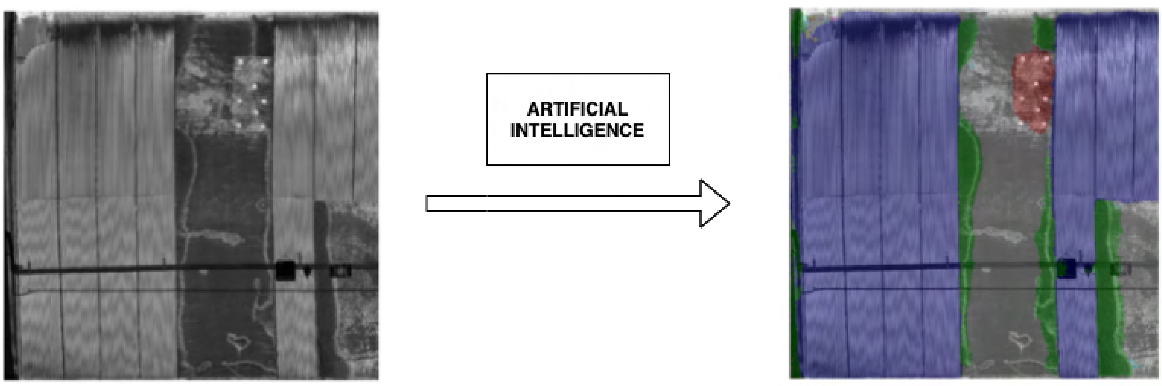
In order to solve such a problem we have constructed a Python library (based on PyTorch) using as architecture SSD300 together with VGG16 as base network.
When trying to apply it inside a professional appliance and in particular in an embedded system, we faced the problem of memory storage since such a net requires a lot of space. Therefore in order to satisfy this memory constraints, we have extended the reduction proposed in **[1]** to obtain a network with few convolutional layers which can easily be integrated in an embedded system **[2]**. We exploit the proper orthogonal decomposition and the active subspace property to perform such reduction, aiming to keep an high accuracy in the network performance even with few layers.

We have thus developed a reduced method for a general artificial neural network (ANN) by retaining a certain number of layers of the original ANN and replacing the remaining ones with an input-output mapping (see the picture below). In this way, the net is splitted in two parts (the original layers of the ANN and the input-output mapping) connected by the reduced method, that aims in reducing the typically large dimensions of the intermediate layers by keeping only the most important information.



Infrastructure Monitoring

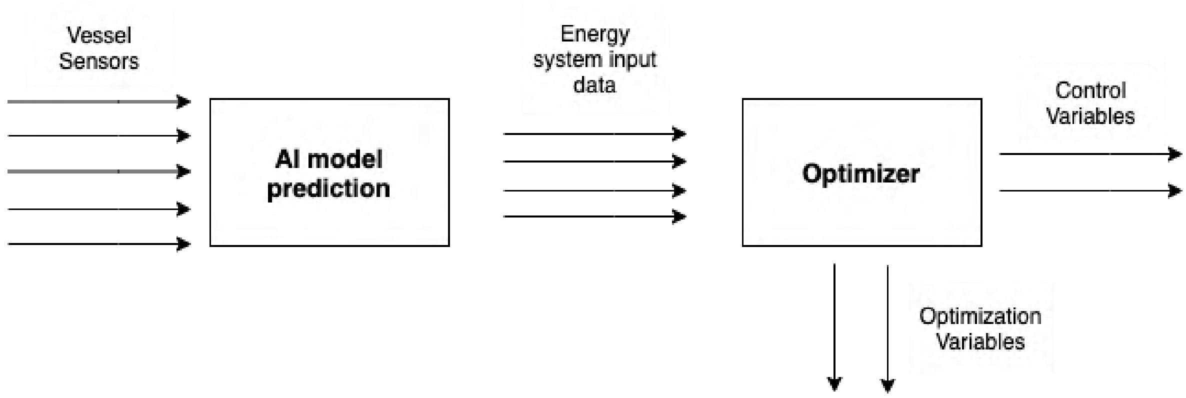
The goal of this project is to improve analysis of road tunnel defects with Machine Learning and Deep Learning in order to support engineers to plan and prepare targeted inspections in advance.



To solve the problem a CNN was used to classify the importance of defects using Keras and Pytorch as main frameworks.

Performance Optimization

The Smart Hybrid Energy Management System (SHEMS) project is capable of optimizing the performances of a hybrid energy system in different working conditions.



The framework manages the operations of an hybrid energy system such that fuel consumptions and emissions are minimized. We can identify two main parts in this project:

- AI prediction
- Optimization.

The first part is in charge for the prediction of the system behavior and takes advantage of acquired knowledge to learn how the system would function in different scenarios.
The second part is instead responsible for the optimization of the same working conditions, focusing on the minimization of emissions, exploiting as much as possible the usage of green energy.

References

[1] Chunfeng Cui, Kaiqi Zhang, Talgat Daulbaev, Julia Gusak, Ivan Oseledets, and Zheng Zhang.
"*Active Subspace of Neural Networks: Structural Analysis and Universal Attacks*", (2020)
SIAM Journal on Mathematics of Data Science (SIMODS)

[2] Meneghetti L., Demo N., Rozza G.,
‘’ *A Dimensionality Reduction Approach for Convolutional Neural Networks”* (2021)
arXiv:2110.09163.

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Main references and open source software for (aeronautical, mechanical, automotive, nuclear, industrial, sport) engineering problems

Rozza Group

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In the following a comprehensive list of the SISSA mathLab publications in different engineering fields together with a brief introduction of each one of them. The next page presents all the open source software libraries developed by the group in the same context.

A presentation of **different <u>geometrical parameterisation techniques</u>** and **data-driven model order reduction techniques** such as POD with interpolation and dynamic mode decomposition (DMD), for an integrated optimization pipeline:

- M. Tezzele, N. Demo, A. Mola, and G. Rozza. ***An integrated data-driven computational pipeline with model order reduction for industrial and applied mathematics***. *Submitted*, Special Issue ECMI (2018). [arxiv].

<u>Parameter space dimensionality reduction</u> through active subspaces (AS) with heterogeneous parameters.

- M. Tezzele, F. Salmoiraghi, A. Mola, and G. Rozza. ***Dimension reduction in heterogeneous parametric spaces with application to naval engineering shape design problems***. Advanced Modeling and Simulation in Engineering Sciences, 5(1):25, Sep 2018. [arxiv] [doi].

<u>Coupling of parameter space reduction and non-intrusive reduced order modeling</u> for structural and CFD problems:

- N. Demo, M. Tezzele, and G. Rozza. ***A non-intrusive approach for proper orthogonal decomposition modal coefficients reconstruction through active subspaces.*** Comptes Rendus de l'Académie des Sciences, DataBEST 2019 Special Issue, 2019. [arxiv].

<u>Shape optimization</u> using OpenFOAM solver, free form deformation for the geometrical parameterisation, DMD to accelerate the single simulation, and POD with interpolation to construct the surrogate model to optimize:

- N. Demo, M. Tezzele, G. Gustin, G. Lavini, and G. Rozza. ***Shape optimization by means of proper orthogonal decomposition and dynamic mode decomposition***. In Technology and Science for the Ships of the Future: Proceedings of NAV 2018: 19th International Conference on Ship & Maritime Research, pages 212–219. IOS Press, 2018. [arxiv] [doi].

Few contributions that employ AS to assess che parameter influence on the target functions and **reduce the dimension of the parameter space**:

- M. Tezzele, N. Demo, and G. Rozza. ***Shape Optimization through Proper Orthogonal Decomposition with Interpolation and Dynamic Mode Decomposition Enhanced by Active***

Subspaces. In The Proceedings of VIII International Conference on Computational Methods in Marine Engineering, pages 122–133, 2019. [arxiv] [doi].

- A. Mola, M. Tezzele, M. Gadalla, F. Valdenazzi, D.Grassi, R. Padovan, and G. Rozza. ***Efficient Reduction in Shape Parameter Space Dimension for Ship Propeller Blade Design***. In The Proceedings of VIII International Conference on Computational Methods in Marine Engineering, pages 201–212, 2019. [doi].
- M. Tezzele, N. Demo, M. Gadalla, A. Mola, and G. Rozza. ***Model order reduction by means of active subspaces and dynamic mode decomposition for parametric hull shape design hydrodynamics***. In Technology and Science for the Ships of the Future: Proceedings of NAV 2018: 19th International Conference on Ship & Maritime Research, pages 569–576. IOS Press, 2018. [arxiv] [doi].
- N. Demo, M. Tezzele, A. Mola, and G. Rozza. ***An efficient shape parametrisation by free-form deformation enhanced by active subspace for hull hydrodynamic ship design problems in open source environment***. In The 28th International Ocean and Polar Engineering Conference, 2018. [arxiv].

Reduction of both the geometries and the output fields, particularly suited for cases where we do not know the actual geometrical parameters:

- N. Demo, M. Tezzele, A. Mola, and G. Rozza. ***A Complete Data-Driven Framework for the Efficient Solution of Parametric Shape Design and Optimization in Naval Engineering Problems.*** In The Proceedings of VIII International Conference on Computational Methods in Marine Engineering, pages 111–121, 2019. [arxiv] [doi].

Reduced order models for CFD problems using the FV method with and without heat transfer, with some applications in industrial flows**:**

- G. Stabile, G. Rozza. ***Finite volume POD-Galerkin stabilised reduced order methods for the parametrised incompressible Navier–Stokes equations***. Computers & Fluids. 2018. [arxiv] [doi].
- S. Georgaka, G. Stabile, G. Rozza, and M. J. Bluck. ***Parametric POD-Galerkin Model Order Reduction for Unsteady-State Heat Transfer Problems***. Communications in Computational Physics, 2019. [arxiv].

Reduced order models for CFD problems using the Discontinuous Galerkin Method, with applications related to weakly compressible flows.

Combination of data-driven and intrusive reduced order modeling techniques for fluid dynamics problem with and without heat transfer, with some applications in industrial engineering field:

- S. Hijazi, G. Stabile, A. Mola, and G. Rozza. ***Data-Driven POD-Galerkin Reduced Order Model for Turbulent Flows***. Submitted, Journal of Computational Physics, 2019. [arxiv].
- S. Hijazi, S. Ali, G. Stabile, F. Ballarin, and G. Rozza. ***The Effort of Increasing Reynolds Number in Projection-Based Reduced Order Methods: from Laminar to Turbulent Flows***, FEF special Volume, 2018. [arxiv].
- S. Georgaka, G. Stabile, K. Star, G. Rozza, and M. J. Bluck. ***A Hybrid Reduced Order Method for Modelling Turbulent Heat Transfer Problems***. Submitted, Computers and Fluids, 2019. [arxiv].

UQ techniques for CFD problems using reduced order models:

- S. Hijazi, G. Stabile, A. Mola, and G. Rozza. ***Non-Intrusive Polynomial Chaos Method Applied to Full-Order and Reduced Problems in Computational Fluid Dynamics: a Comparison and Perspectives***. QUIET special volume, 2019. [arxiv].

Geometrical parametrization for heat transfer and fluid dynamics problems:

- G. Stabile, M. Zancanaro, and G.Rozza. ***Efficient Geometrical parametrization for Finite-Volume based Reduced Order Methods***. Submitted, IJNME, 2019. [arxiv].

SISSA mathLab Open Source Software and Tools

The complete list of SISSA mathLab software is available on GitHub and on SISSA mathLab website**,** here we present the most interesting ones from a naval engineering point of view.

PyGeM (Python Geometrical Morphing) is a package that allows you to deform a given geometry or mesh with different deformation techniques such as Free Form Deformation, Radial Basis Functions and Inverse Distance Weighting. [github] [SISSA mathLab].

- F. Salmoiraghi, A. Scardigli, H. Telib, and G. Rozza, ***Free Form Deformation, mesh morphing and reduced order methods: enablers for efficient aerodynamic shape optimization,*** Int. J. CFD, 2018 [arxiv].

EZyRB (Easy Reduced Basis method) is a package to perform non-intrusive model order reduction based on Proper Orthogonal Decomposition. [github] [SISSA mathLab].

- N. Demo, M. Tezzele, and G. Rozza. EZyRB: ***Easy Reduced Basis method.*** The Journal of Open Source Software, 3(24):661, 2018. [doi].

PyDMD is a package that uses Dynamic Mode Decomposition for a data-driven model simplification based on spatiotemporal coherent structures. [github] [SISSA mathLab].

- N. Demo, M. Tezzele, and G. Rozza. ***PyDMD: Python Dynamic Mode Decomposition.*** The Journal of Open Source Software, 3(22):530, 2018. [doi].

ITHACA-FV is an implementation in OpenFOAM of several reduced order modelling techniques. [github] [SISSA mathLab].

- G. Stabile, G. Rozza. ***Finite volume POD-Galerkin stabilised reduced order methods for the parametrised incompressible Navier–Stokes equations.*** Computers & Fluids. 2018. [doi] [arxiv].

BladeX (Python Blade Deformation) is a Python package for geometrical parametrization and bottom-up construction of propeller blades. It allows to generate and deform a blade based on the radial distribution of its parameters. [github] [SISSA mathLab].

- M. Gadalla, M. Tezzele, A. Mola, and G. Rozza. ***BladeX: Python Blade Morphing.*** The Journal of Open Source Software, 4(34):1203, 2019. [doi].

ITHACA-DG is an implementation in HopeFOAM (an extension of OpenFOAM) of reduced order modelling techniques starting from high order simulations based on the Discontinuous Galerkin Method. [github] [SISSA mathLab].

ATHENA is a Python package for reduction of high dimensional parameter spaces in the context of numerical analysis.

ATHENA allows the use of several dimensionality reduction techniques in the parameter space such as Active Subspaces (AS), Kernel-based Active Subspaces (KAS), and Nonlinear Level-set Learning (NLL). It is particularly suited for the study of parametric PDEs, for sensitivity analysis and uncertainty quantification, and for the approximation of engineering quantities of interest with the design of response surfaces. It can handle both scalar and vectorial high dimensional functions, making it useful as a tool to reduce the burden of computational intensive optimization tasks and as a preprocessing step before heavy parametric dependent CFD simulations.

The research in the field is growing towards nonlinear dimension reduction techniques in the context of scientific machine learning and also towards inverse problems and statistical inference in the context of uncertainty quantification and probabilistic modeling.

Projects

ARIA, ERC AROMA-CFD, ROMSOC are H2020 projects funded by European Commission to enhance methodological developments in reduced order methods with a focus in CFD:
http://people.sissa.it/grozza
http://mathlab.sissa.it/projects-list

European Commission
Horizon 2020
European Union funding
for Research & Innovation