Multidisciplinary Design Optimization for Novel Offshore Systems

openMDAO Workshop
NASA Glenn Research Center, Cleveland, Ohio

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Systems Engineering, Cornell University

October 25, 2022

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Topics

1. Offshore systems are complex, coupled systems.
2. Integration of offshore modeling tools with openMDAO.
3. Design statement and optimization problem formulation.
4. Disciplines and governing equations
5. eXtended Design Structure Matrix - MDF Architecture
6. Optimization results discussion.
7. Benefits of using openMDAO platform.
8. Conclusion and future work.

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Offshore systems are complex, coupled systems

Traditional offshore systems

- Oil and gas platforms, very large offshore structures (floating airports, etc)

Novel offshore systems

- Defined as having new functionalities, requirements, objectives, constraints and coupled with new disciplines.
- For example: floating wind turbines, wave energy converters, aquaculture vessels and marine robotics

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Integration of offshore modeling tools with openMDAO

Hydrodynamics is central to offshore design. It models the ocean waves.

Different modeling methods:

Hydrodynamic Modeling in offshore systems	
Methods	Application
Analytical approximation (Morrison's formula)	Regular geometries
Surrogate modeling (Kriging models, GPRs)	WEC arrays, geometry configurations
Linear hydrodynamics (Numerical solvers)	Applicable to any geometry (novel or traditional)

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Integration of offshore modeling tools with OpenMDAO

These tools are boundary element method (BEM solvers) based on potential flow theory. They assume that systems are linear time invariant systems and solve the problem in frequency domain(much faster).

Tools to calculate hydrodynamic parameters		
Tool	Availability	Reliability
WAMIT	Commercial	Robust, no irregular frequencies
Nemoh	Open source (Fortran)	Irregular frequencies
BEMuse	Open source (C++)	No irregular frequencies
Capytaine (and Mesh-Magick)	Python (+Fortran)	Irregular frequencies

Although these tools have been coupled with heuristic optimization methods in the past, none of have been used extensively with gradient-based optimization. (Irregular frequencies arise due to direct solvers solving the singular matrix formed in boundary integral equations)

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To integrate with openMDAO (Gray et al., 2019) for gradient-based optimization, we need gradients of the hydrodynamics solver.

Different approaches to computing gradients.

- Continuous adjoint formulation for the BEMSolver.
- Finite difference through the solver and hope for the best.
- Discrete adjoint method.

Having a differentiable solver for hydrodynamics opens door to couple many disciplines (shape, structure, aerodynamics, propulsion,etc)

The efforts for such implementation is underway.

Today - Design optimization of a marine system with Capytaine + openMDAO (using fd for the partial calculations)

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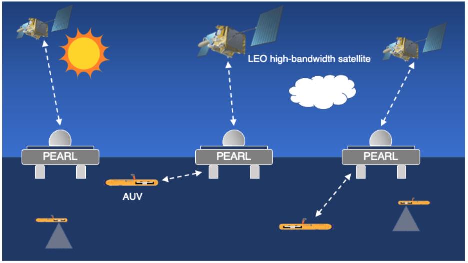
Design optimization integrating openMDAO + Capytaine

What is PEARL?

PEARL is an autonomous floating platform that can service autonomous underwater vehicles by recharging them via solar energy and uploading their data back to shore in near-real time by leveraging new generation high-bandwidth low-Earth orbit (LEO) satellite constellations. (Haji et al., 2020; Rolland et al., 2021)



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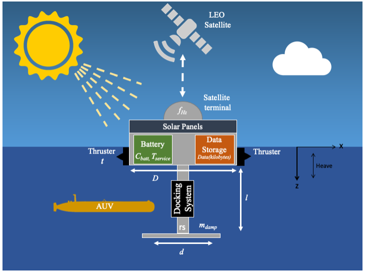
Design statement and optimization problem formulation

Considering the system requirements of PEARL, the platform must:

- Float stably to minimize antenna misalignment loss.
- Be able to generate enough power from PV (assuming 8 hrs/day of sunlight) for all functions.
- Be able to transfer data from 1 AUV (1GB) per day
- Recharge 1 AUV (1900Wh) per day.
- Move itself 0.4 m/s for 1 hr per day (assuming current speed 0.3m/s.
- Stay 'up' for 24 hr.



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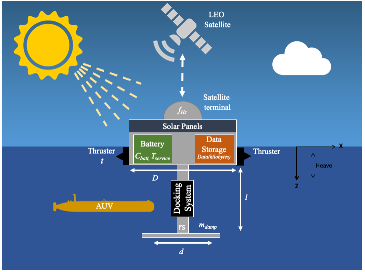

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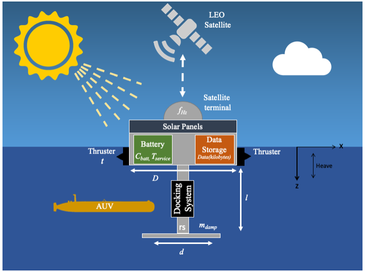

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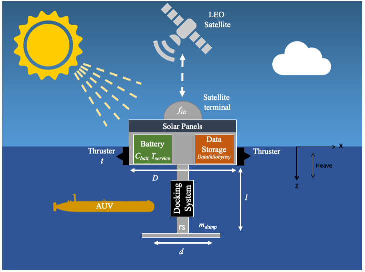

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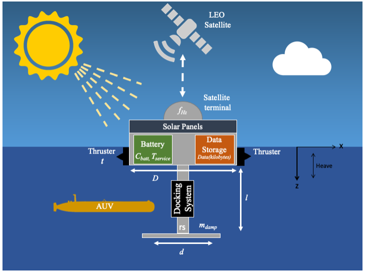

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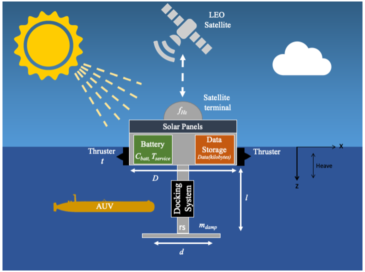

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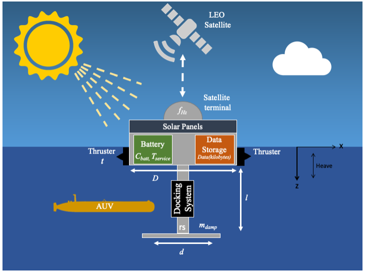

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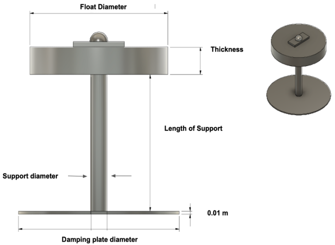
Design statement and optimization problem formulation

	Variable	Lower (m)	Nominal (m)	Upper (m)
Minimize $\widehat{Var}(\int_{0.01}^{4.4} H_{s\eta}(\omega)^2) \times S_{zz}$ (Clauss and Birk, 1996) $H_{s\eta} = f([x_{dvs}])$	where S_{zz} is $jonswap\ spectrum(4m, 3s)$ and $H_{s\eta}$ is transfer function and $\omega \in [0.01, 4.4]$			
with respect to $[x_{dvs}]$	Thickness of top float (tf)	0.5	1.0	2.0
	Diameter of top float (df)	0.5	4.0	6.0
	Diameter of damping plate(dd)	0.5	4.0	6.0
	Length of the support plate(ls)	3.0	3.0	8.0
	Radius of the support plate(rs)	0.2	0.1	0.5
	fraction of area for PV panels	0.1	0.5	0.9
subject to constraints	hydrostatic equilibrium total cost < 3000(USD) $E_{gen} - E_{req} < N_{battery} \times C_{battery}$ minimum link margin for required data transfer $M_{link} > 16dB$ Move PEARL by 1m/s			



Disciplines and governing equations

- Hydro: hydrostatic and hydrodynamics analysis using MeshMagick (Ecole Centrale de Nantes, n.d.) and Capytaine (Ancellin and Dias, 2019)
  - Hydrostatic equilibrium for target displacement.
  - Calculation of response amplitude operator (only for heave).
- Satellite Communication:Link budget analysis for Iridium LEO satellite antenna
  - Minimum $Mlink$ for $>$ 16dB
- Propulsion
  - Power required to move PEARL steadily (0.4m/s assuming current speed 0.3m/s)
- Power Harvest: Calculates total power generated, stored and used.

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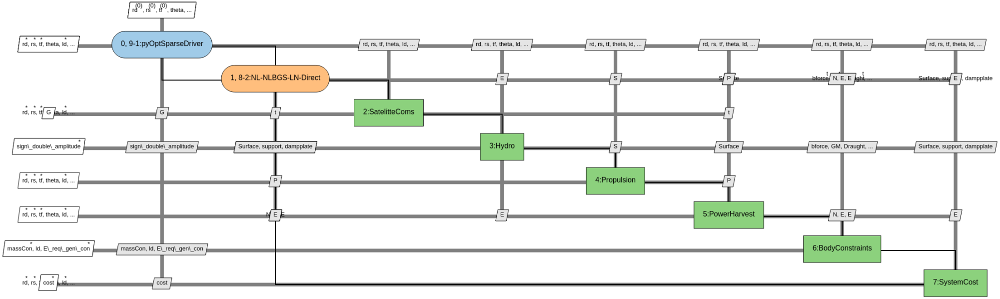
eXtended Design Structure Matrix - MDF Architecture



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eXtended Design Structure Matrix - MDF Architecture

- MDF Architecture
  - "System level states are physically compatible if optimization terminates prematurely" (Martins and Ning, 2021)
- Aitken relaxation for the NLGBS solver
- Total derivative approximated using finite difference (1e-6)

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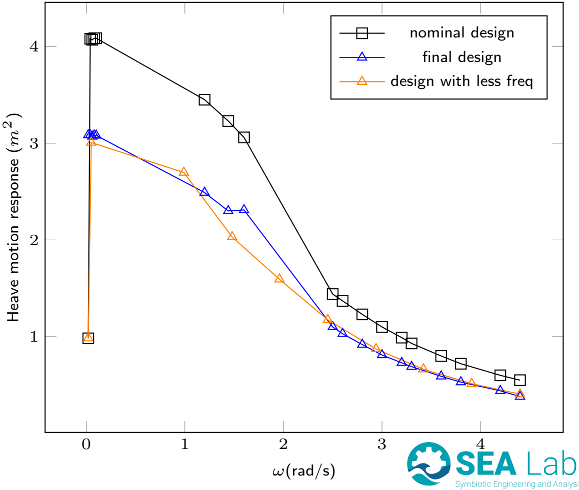
Optimization results

Optimal Dimensions for PEARL		
	Variable	optimum
Minimum	Heave motion response	$0.22m^2$
for design variables	Diameter of top float (df)	3.99 m
	Thickness of top float (tf)	2.0m
	Diameter of damping plate (dd)	1.52m
	Length of the support plate (ls)	8m
	Radius of the support plate (rs)	0.25mm
	solar panel area fraction	0.41
	Number of Battery	2
	Total system cost	2678 (USD)



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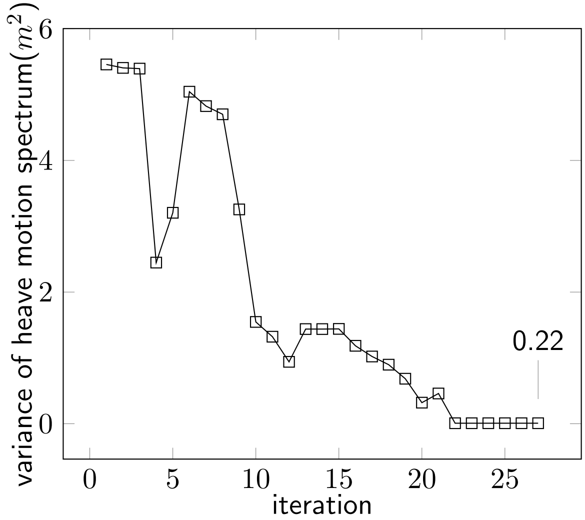
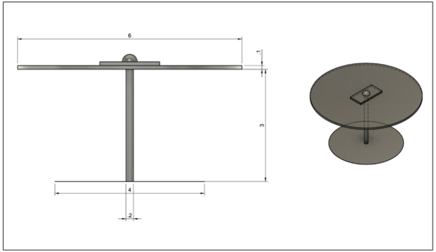
Objective function convergence

Depends on the frequencies sampled which depends on the location to be deployed.

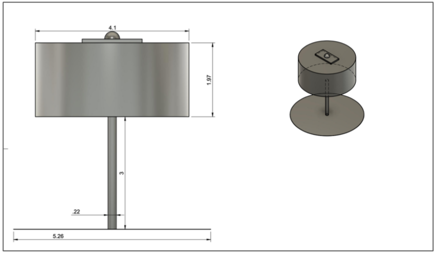


Change in design for minimal heave response

INITIAL DESIGN



FINAL DESIGN



Scale: 1:30
Volume: 3.079 m^3

Scale: 1:30
Volume: 26.289 m^3

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Several issues during the optimization

Things to iterate on for more reliable framework

- For some design, hydrostatic equilibrium fails to converge.
- Irregular frequency effects causes overestimation of hydrodynamic coefficients.
  - Sudden jumps in objective functions (either resonance or irregular frequency effects).
- Meshmagick uses a constant density for the inertia matrix.
- Converges faster with approximated total derivatives but not when derivatives are assembled from component partials.
- Takes more iterations when we have noisy evaluations.
  - Different selection of ω gives different results
  - Needs convergence analysis for both Gauss-Siedel and Newton Solvers for ω choices.

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Benefits of using openMDAO platform

- Decomposition of complexity in system to modular subsystems/components.
- Exploration of data flow, process and interface between subsystems in your system.
- Plug and play for choosing optimizer, MDO architectures, derivative calculations.
- Various disciplinary solvers already available.
- Recording and visualization to understand the behavior of the subsystems during optimization.
- Developers active on Stackoverflow.

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- Various disciplinary solvers already available.
- Recording and visualization to understand the behavior of the subsystems during optimization.
- Developers active on Stackoverflow.

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Conclusion and future steps

- Several existing issues with convergence of the hydrodynamic and hydrostatic solver.
- Differentiable BEM solver for accurate derivatives and to ensure efficient optimization when adding more design variables.
- Develop framework for discrete-adjoint based design optimization for offshore systems.
- Couple underwater shape optimization for hydrodynamic stability and less drag (could be challenging for novel shapes).
- Integrate lower level components in the optimization.
  - Battery SOC, PV panels, docking dynamics, etc.

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References

- Ancellin, Matthieu and Frédéric Dias (2019). "Capytaine: a Python-based linear potential flow solver". In: *Journal of Open Source Software* 4.36, p. 1341. DOI: 10.21105/joss.01341. URL: https://doi.org/10.21105%2Fjoss.01341.
- Charles A. Mader Joaquim Martins, Juan J. Alonso Edwin van der Weide (n.d.). "ADjoint: An Approach for the Rapid Development of Discrete Adjoint Solvers, Year = 2008". In: ().
- Clauss, G.F. and L. Birk (1996). "Hydrodynamic shape optimization of large offshore structures". In: *Applied Ocean Research* 18.4, pp. 157–171. ISSN: 0141-1187. DOI: https://doi.org/10.1016/S0141-1187(96)00028-4. URL: https://www.sciencedirect.com/science/article/pii/S0141118796000284.
- Ecole Centrale de Nantes (n.d.). *Meshmagick*. URL: https://github.com/LHEEA/meshmagick.
- Gray, Justin S. et al. (2019). "OpenMDAO: An open-source framework for multidisciplinary design, analysis, and optimization". In: *Structural and Multidisciplinary Optimization* 59.4, pp. 1075–1104. DOI: 10.1007/s00158-019-02211-z.
- Martins, Joaquim R. R. A. and Andrew Ning (2021). *Engineering Design Optimization*. Cambridge University Press. DOI: 10.1017/9781108980647.

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Thank you for listening!

Thank you team members

Ana Sofia Alonoso Munera and Dr. Arezoo Hasankhani for help with related research and calculations.

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Noisy convergence when some frequencies present

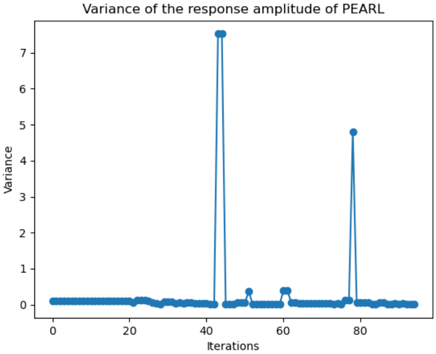

Figure: Convergence when frequencies were sampled randomly within some region

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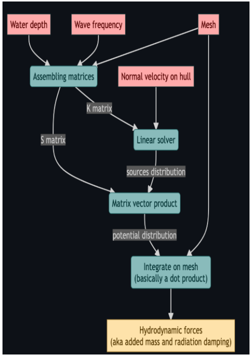
Potential Approach

- Model each of the capytaine components into openMDAO groups/components



(Ancellin and Dias, 2019)

Rapid development of Discrete Adjoint Solvers (Charles A. Mader, n.d.)

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