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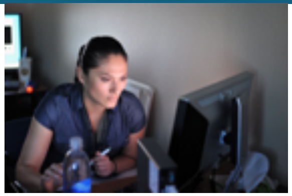
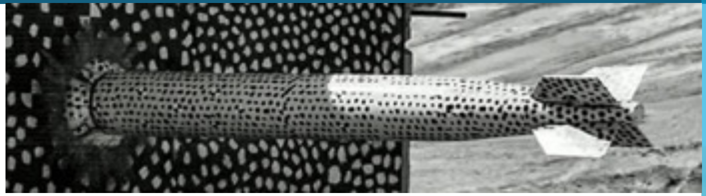
WEC Design Optimization (“WecOptTool”)





Presented by

Ryan Coe, Giorgio Bacelli, Sterling Olson, Vince Neary, & Mat Topper

Sept. 29 2020

U.S. DEPARTMENT OF ENERGY NNSA

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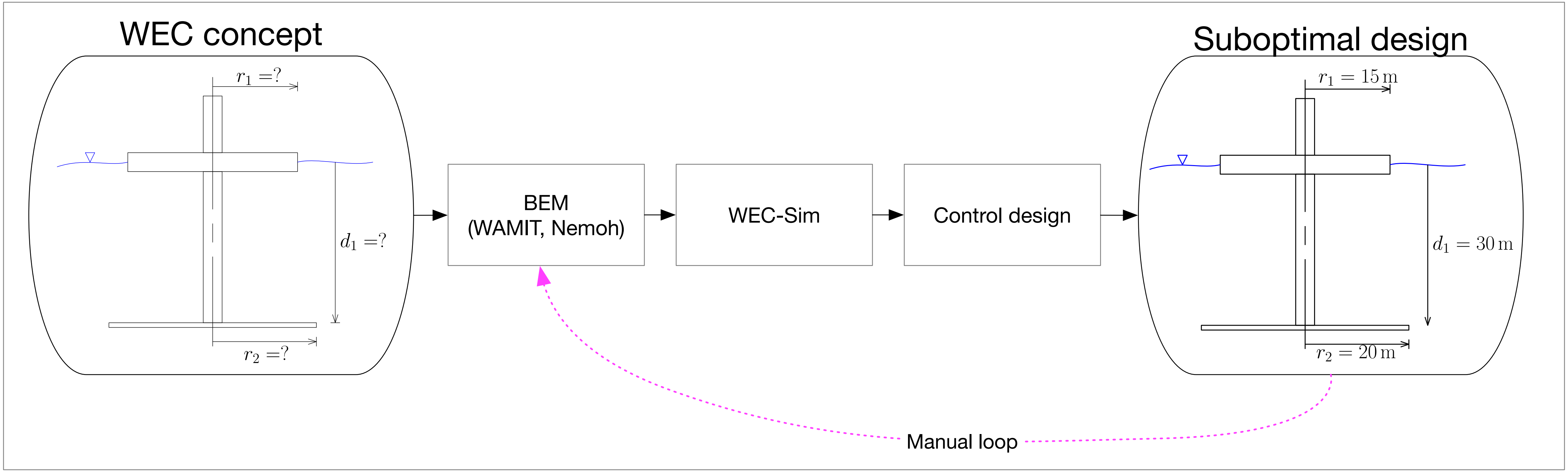
SAND2020-10553 PE

Problem statement

Problem: there are many decisions required to design a WEC , and limited understanding of how these interact and play a role in performance

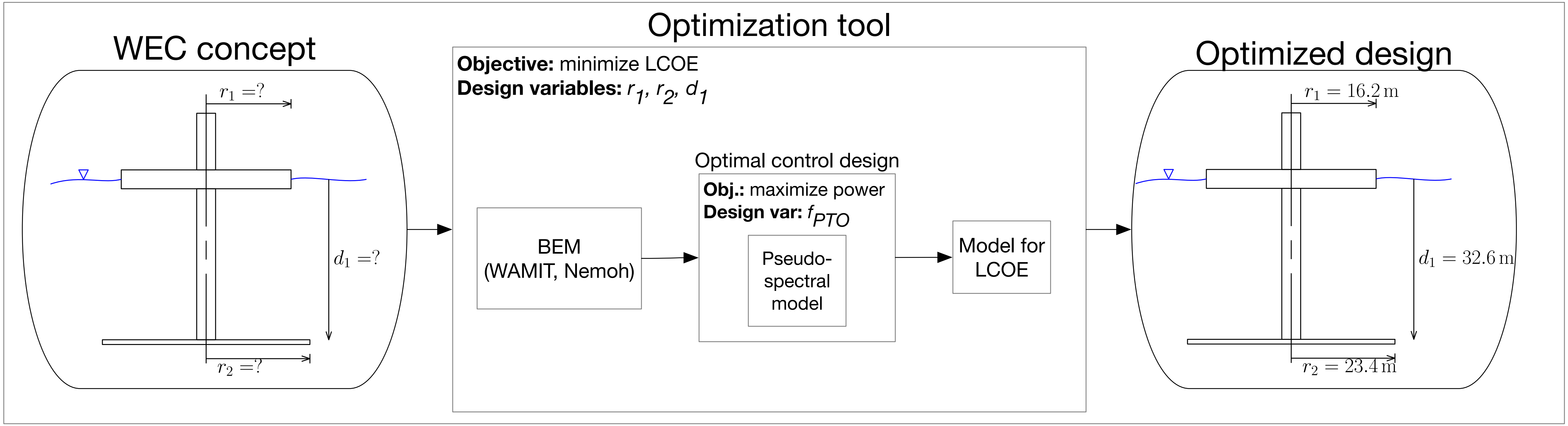
Current process



Problem statement

Solution: enable systematic design optimization studies using efficient models and arbitrary objective functions to suit specific users' needs

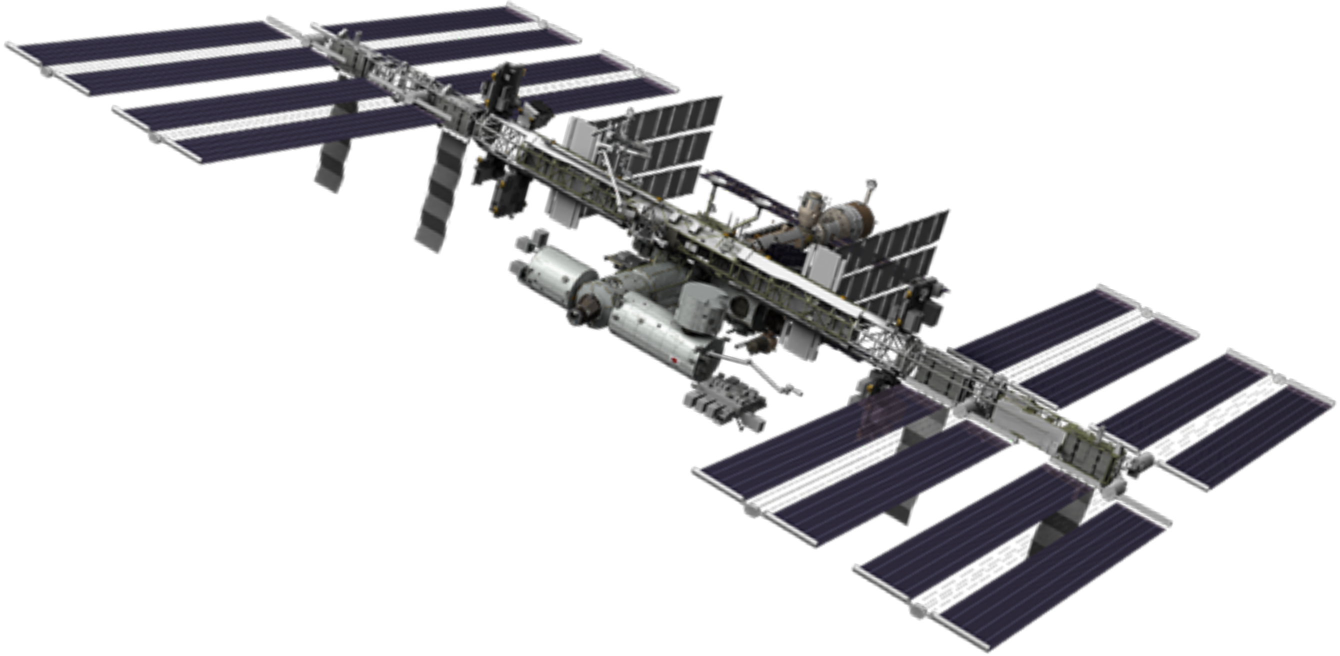
Improved process



Technical Approach

- **Pseudo spectral method[1] allows for <u>efficient optimal control solution with constraints</u>**

- **Allows for co-design, with arbitrary structure "stand-in" controller**



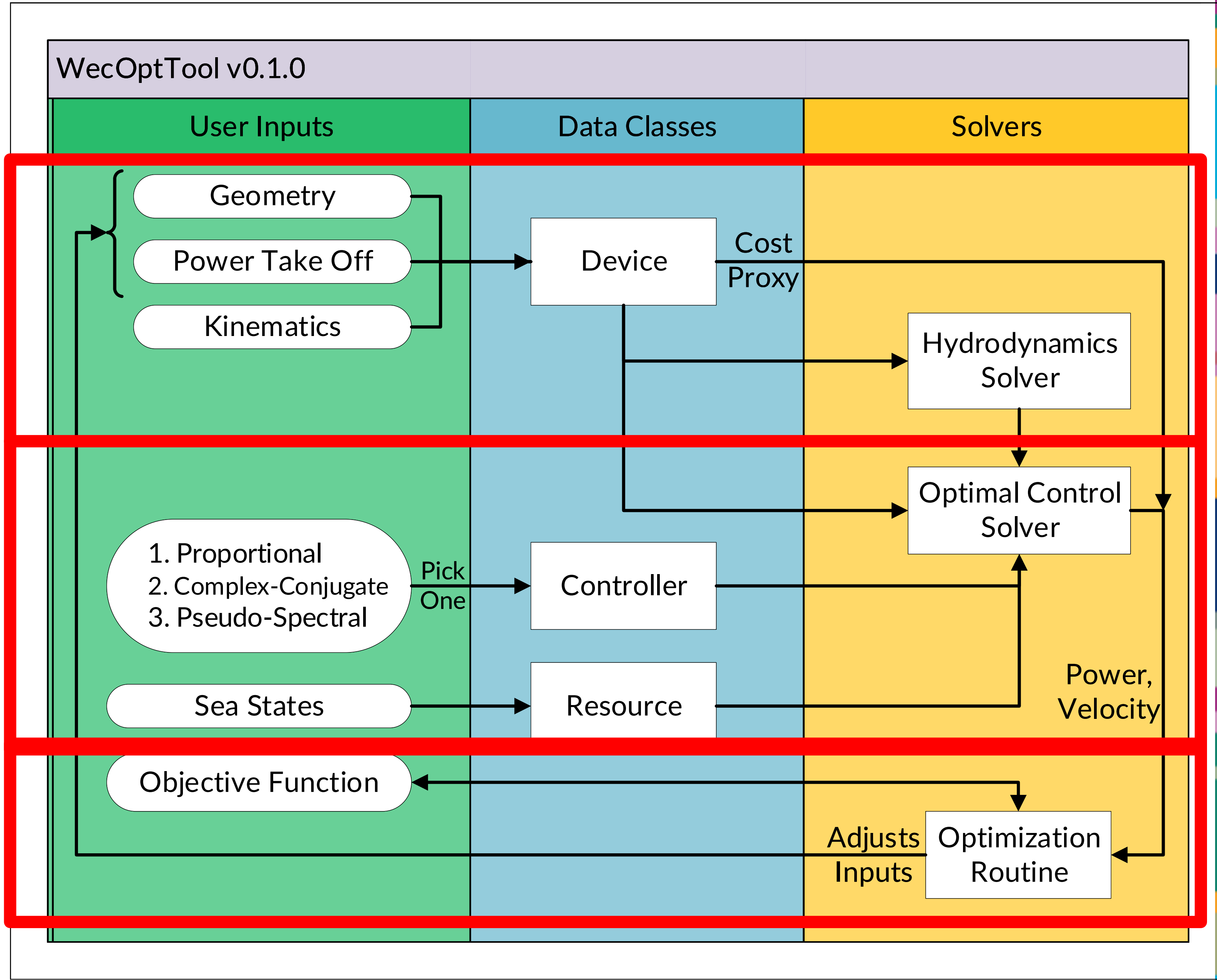
[1]*Recently leveraged for <u>International Space Station</u> maneuver using gyroscopes (no fuel)*

Algorithmic structure

Design device

Simulate performance

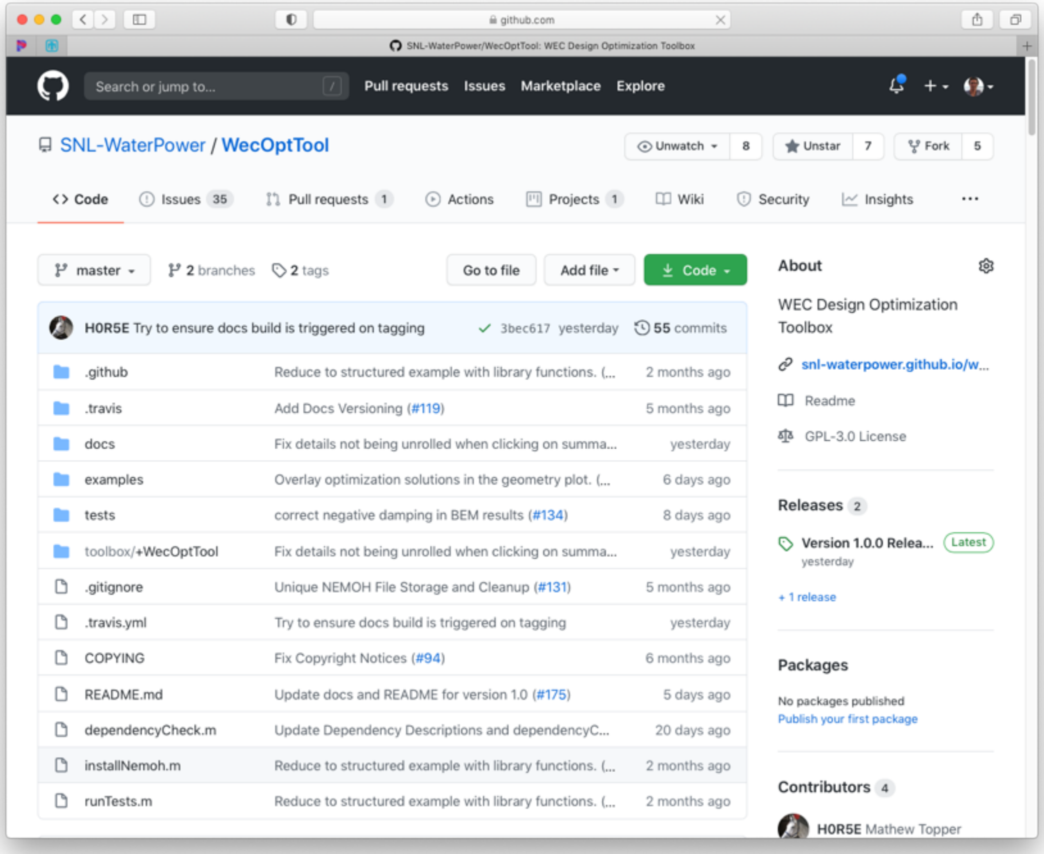
Distill results & pass to optimization solver



Live demo

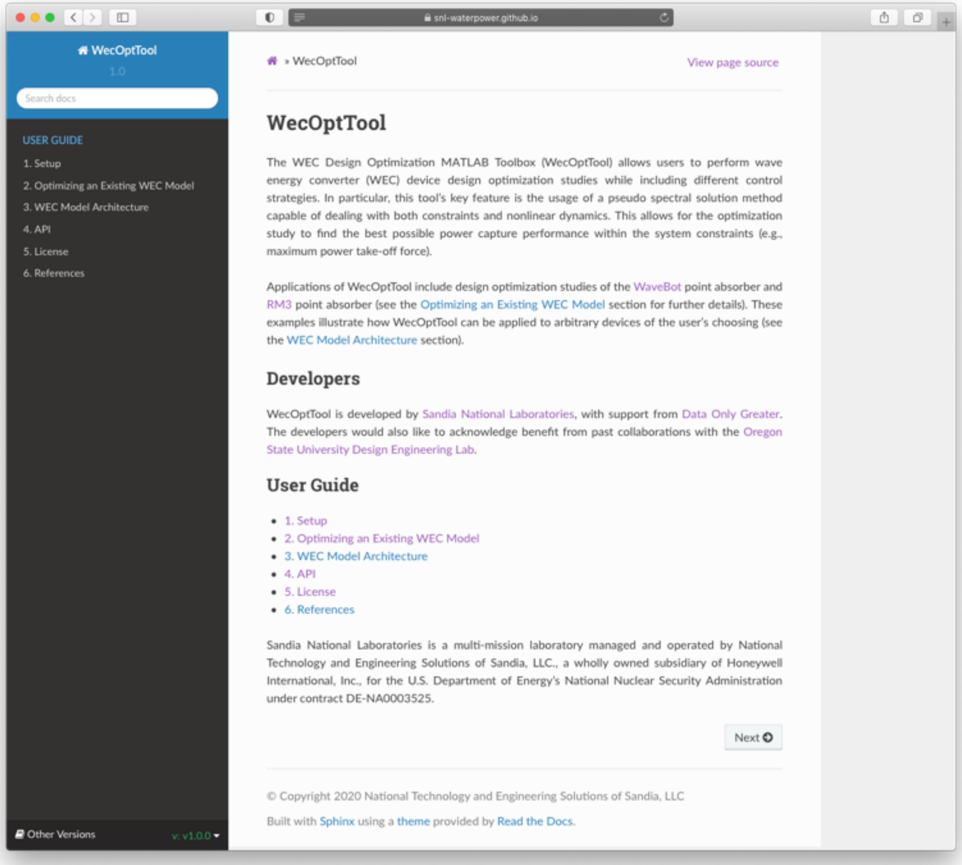
Github repository

https://github.com/SNL-WaterPower/WecOptTool

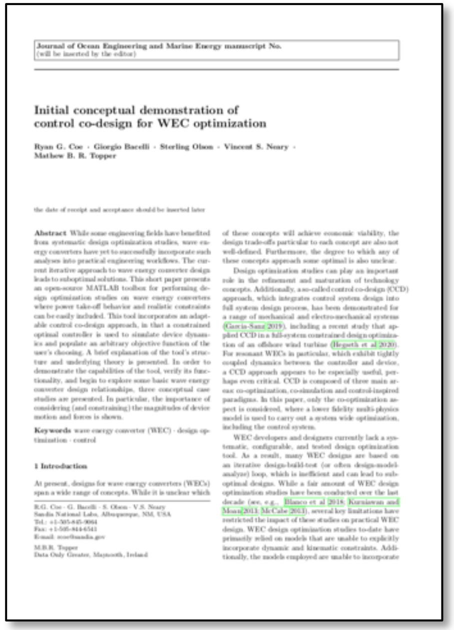


Documentation

https://snl-waterpower.github.io/WecOptTool



Examples


Journal of Ocean Engineering and Marine Energy manuscript No.
(will be inserted by the editor)

Initial conceptual demonstration of control co-design for WEC optimization

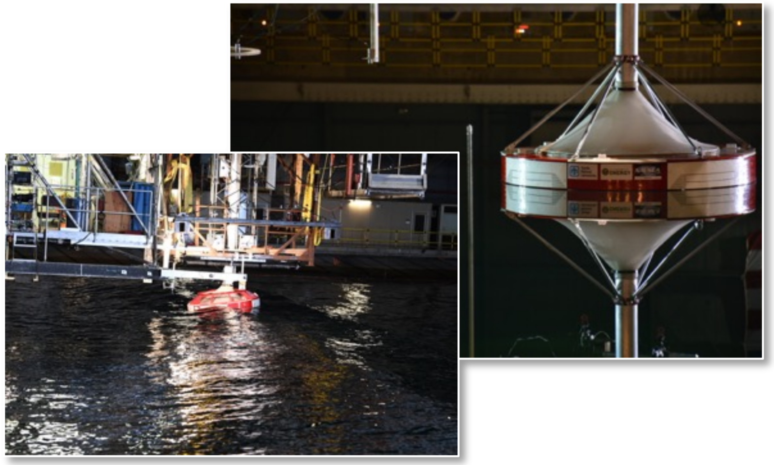
Ryan G. Coe · Giorgio Bacelli · Sterling Olson · Vincent S. Neary · Mathew B. R. Topper

https://doi.org/10.36227/techrxiv.12928898

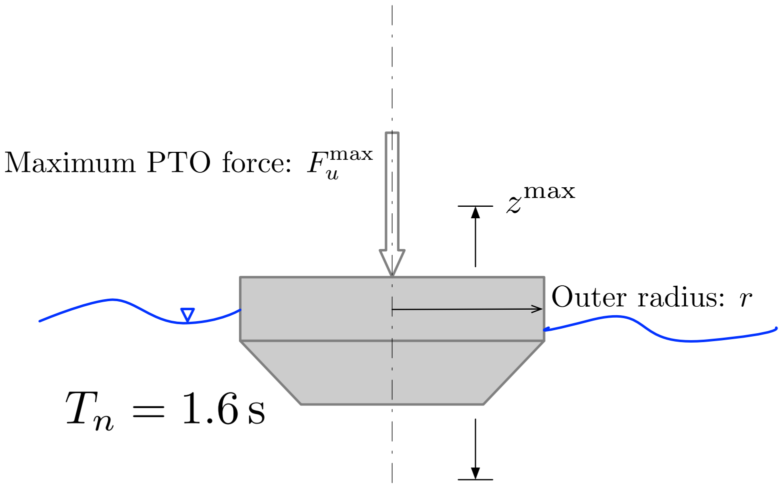
Use WaveBot geometry

- **Case A:** Performance with CC, P, and PS controllers
- **Case B:** Optimal design for CC, P, and PS controllers
- **Case C:** Multi-objective design study

$$\text{Regular wave:}\;\; A = 0.0625\,\text{m},\; T = 3.33\,\text{s}$$



Design variable	Case A	Case B	Case C
Outer radius, r [m]	$r = 0.88$	$r \in [0.25,\ 2]$	$r \in [0.25,\ 2]$
Maximum PTO force, $F_u^{\max}$ [kN]	$F_u^{\max} = 2$	$F_u^{\max} = \infty$	$F_u^{\max} \in [0.1,\ 1]$
Maximum stroke, $z^{\max}$ [m]	$z^{\max} = \infty$	$z^{\max} = 0.6$	$z^{\max} = \infty$



Case A

Performance with CC, P, and PS controllers

Design variable	Case A	Case B	Case C
Outer radius, r [m]	$r = 0.88$	$r \in [0.25, 2]$	$r \in [0.25, 2]$
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Maximum stroke, $z^{\max}$ [m]	$z^{\max} = \infty$	$z^{\max} = 0.6$	$z^{\max} = \infty$

Not a design optimization study

With fixed design, simulate device response using three different controllers

CC: Complex-conjugate

$$F_u(\omega) = -Z_i^*(\omega)\, u(\omega)$$

P: Proportional damping

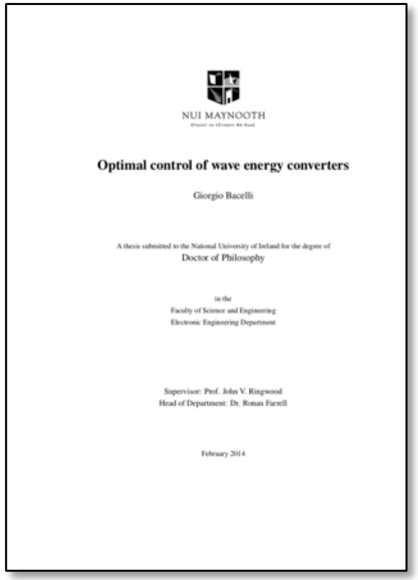
$$F_u = -B_{pto}\, V$$

PS: pseudo-spectral

$$\arg\min_{\nu,\phi,\epsilon} P(X, \Gamma, G, E)$$

- ν,ϕ,ϵ: basis function coefficients
- P: power
- X: velocity
- Γ: PTO force
- G: hydro & constraints
- E: excitation

For more on the pseudo-spectral method


NUI MAYNOOTH

Optimal control of wave energy converters

Giorgio Bacelli

A thesis submitted to the National University of Ireland for the degree of Doctor of Philosophy

in the Faculty of Science and Engineering, Electronic Engineering Department

Supervisor: Prof. John V. Ringwood
Head of Department: Dr. Ronan Farrell

February 2014

http://mural.maynoothuniversity.ie/6753/

https://github.com/SNL-WaterPower/WecOptTool/blob/master/examples/WaveBot/WaveBot_caseA.m

Case A, results

Performance with CC, P, and PS controllers

Design variable	Case A	Case B	Case C
Outer radius, r [m]	$r = 0.88$	$r \in [0.25, 2]$	$r \in [0.25, 2]$
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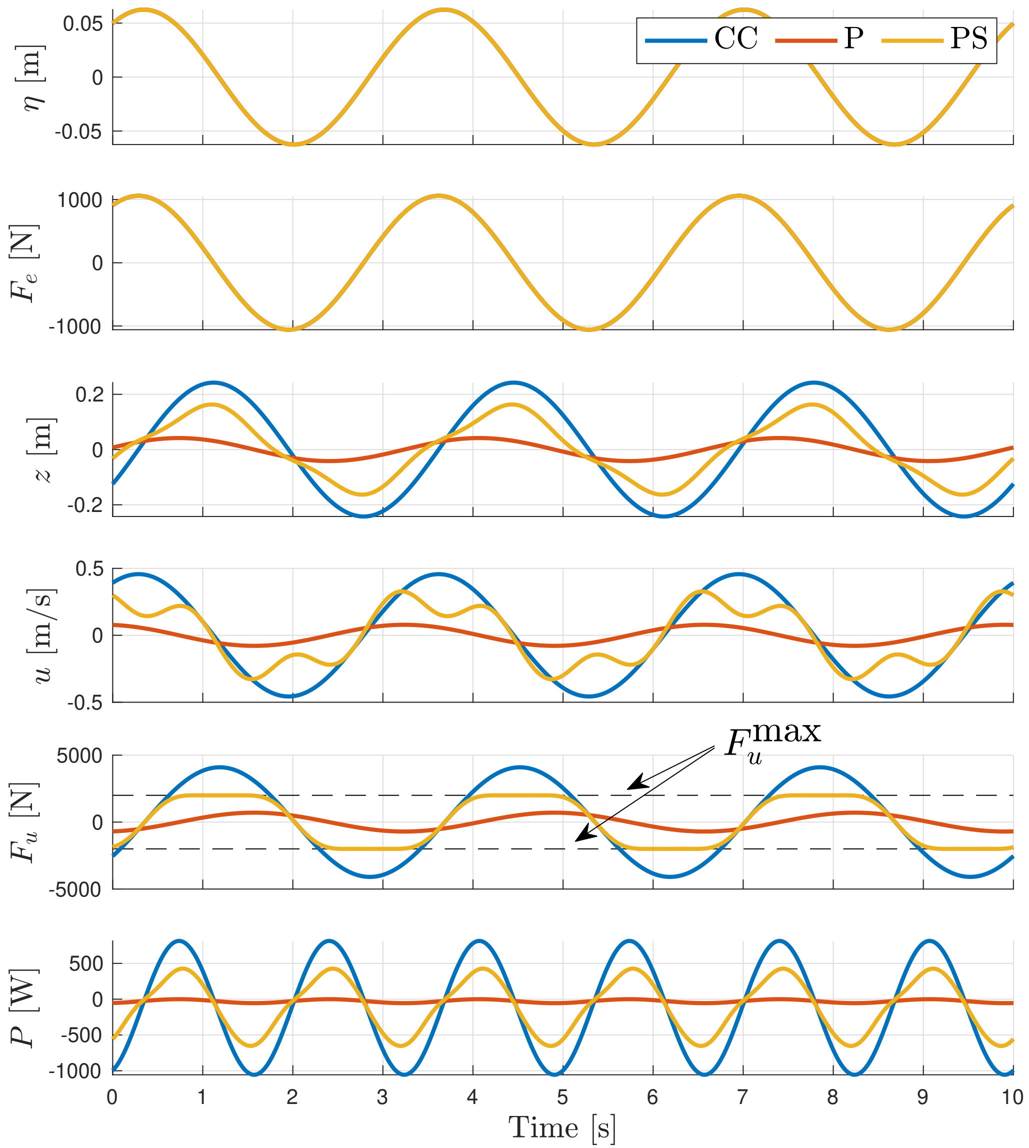


Free surface elevation

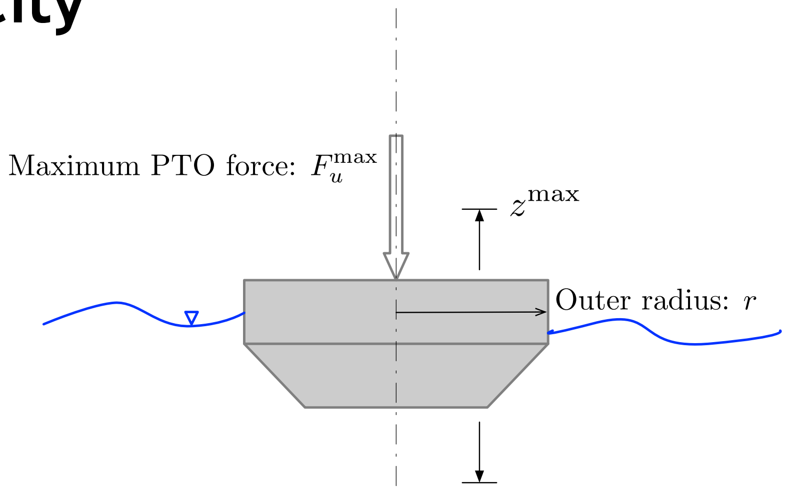
Excitation force

WEC vertical position

WEC vertical velocity

PTO force

Power



https://github.com/SNL-WaterPower/WecOptTool/blob/master/examples/WaveBot/WaveBot_caseA.m

Case A, results

Performance with CC, P, and PS controllers

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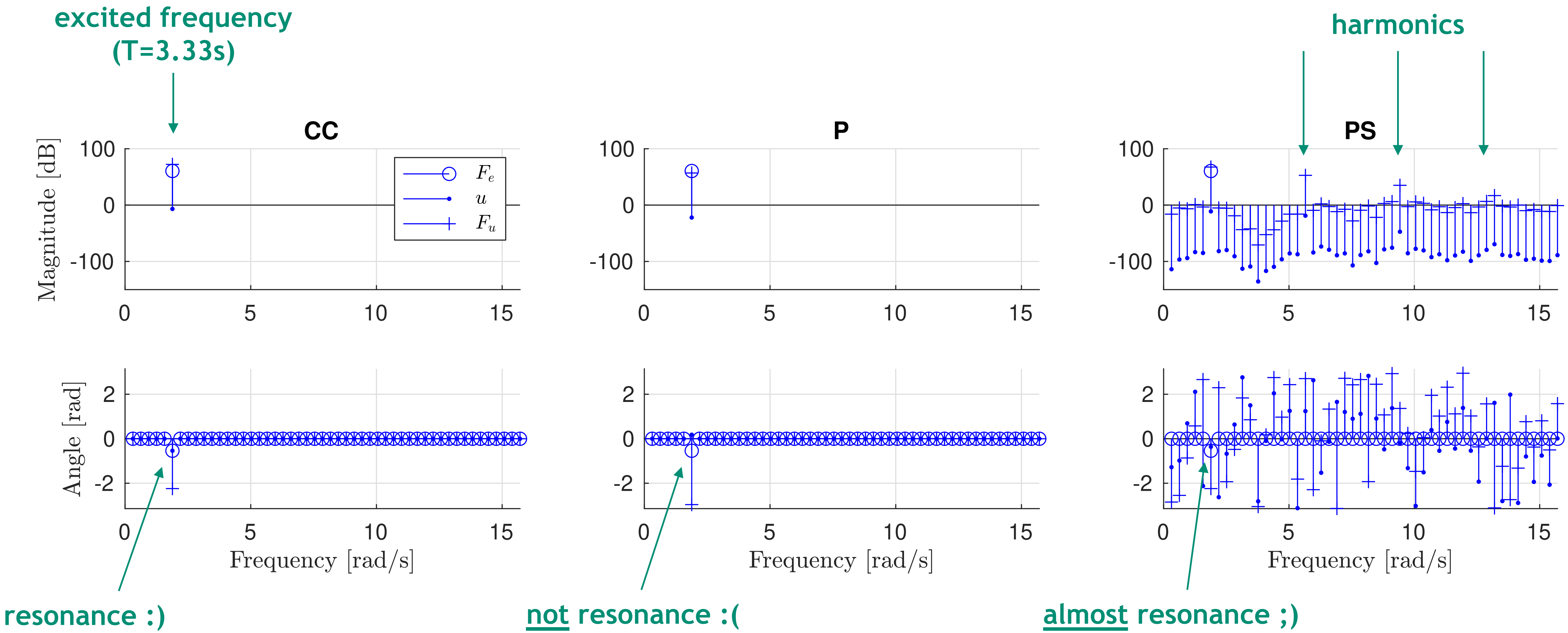


https://github.com/SNL-WaterPower/WecOptTool/blob/master/examples/WaveBot/WaveBot_caseA.m

Case B

Optimal design for CC, P, and PS controllers

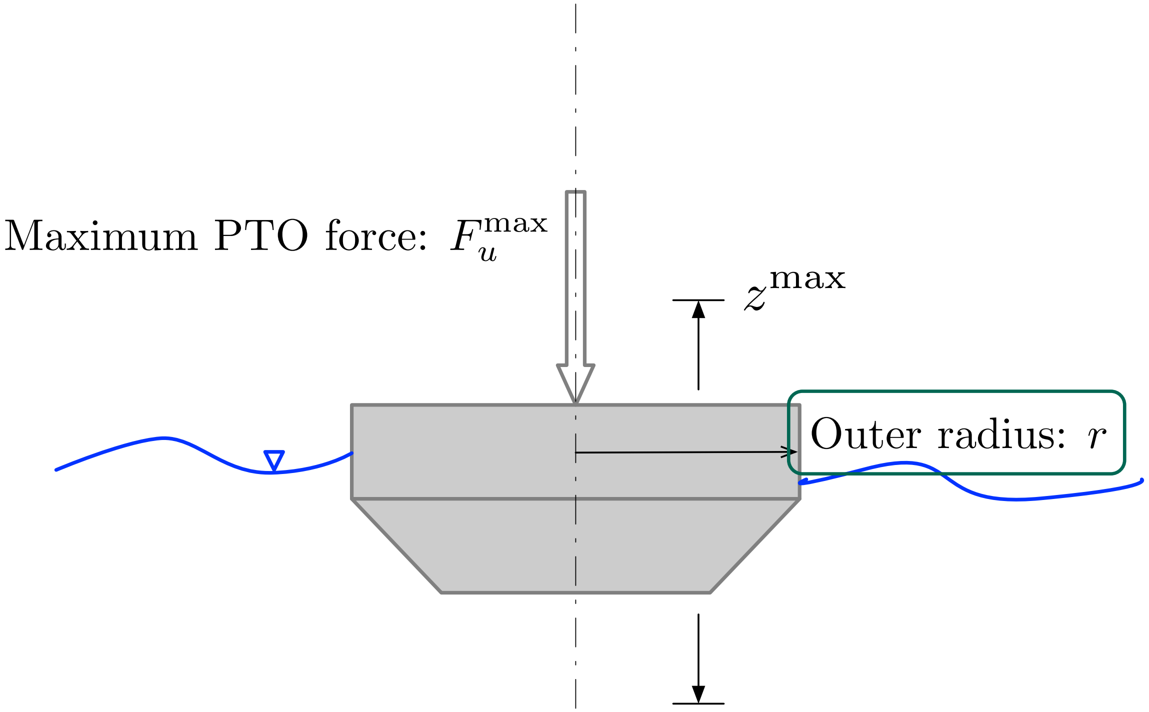
Design variable	Case A	Case B	Case C
Outer radius, r [m]	$r = 0.88$	$r \in [0.25,\ 2]$	$r \in [0.25,\ 2]$
Maximum PTO force, $F_u^{\max}$ [kN]	$F_u^{\max} = 2$	$F_u^{\max} = \infty$	$F_u^{\max} \in [0.1,\ 1]$
Maximum stroke, $z^{\max}$ [m]	$z^{\max} = \infty$	$z^{\max} = 0.6$	$z^{\max} = \infty$

Varying the outer radius, maximize the ratio of average power to volume*

$$\min_{r} \quad \frac{\bar{P}(r)}{(r_0 + r)^3}$$
$$\text{s.t.} \quad r \in [0.25, 2]$$

Does not go to zero quickly

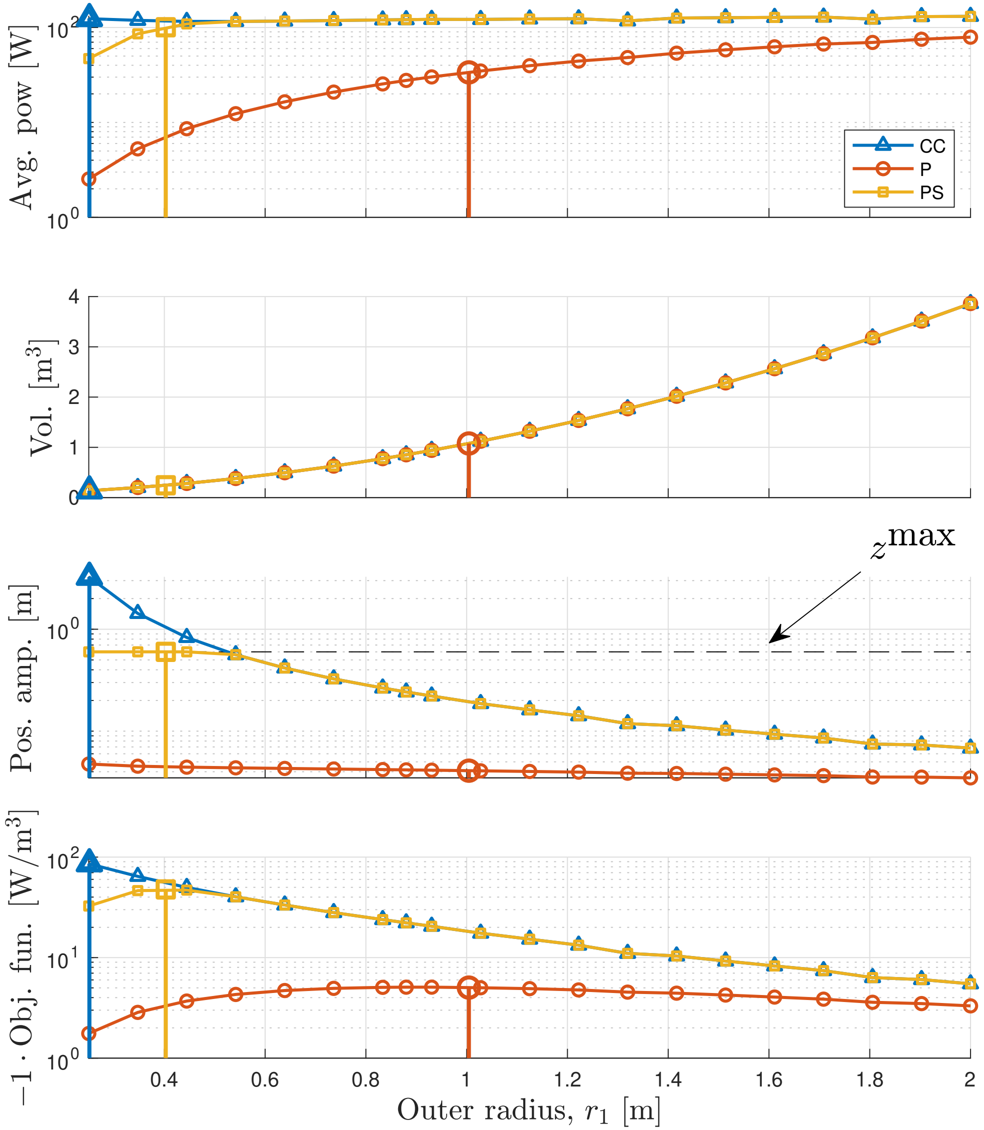
Brute force (“Monte Carlo”) and `fminbnd`



Case B, results pt. I

Optimal design for CC, P, and PS controllers

Design variable	Case A	Case B	Case C
Outer radius, r [m]	$r = 0.88$	$r \in [0.25,\ 2]$	$r \in [0.25,\ 2]$
Maximum PTO force, $F_u^{\max}$ [kN]	$F_u^{\max} = 2$	$F_u^{\max} = \infty$	$F_u^{\max} \in [0.1,\ 1]$
Maximum stroke, $z^{\max}$ [m]	$z^{\max} = \infty$	$z^{\max} = 0.6$	$z^{\max} = \infty$



$$\frac{\bar{P}(r)}{(r_0 + r)^3}$$

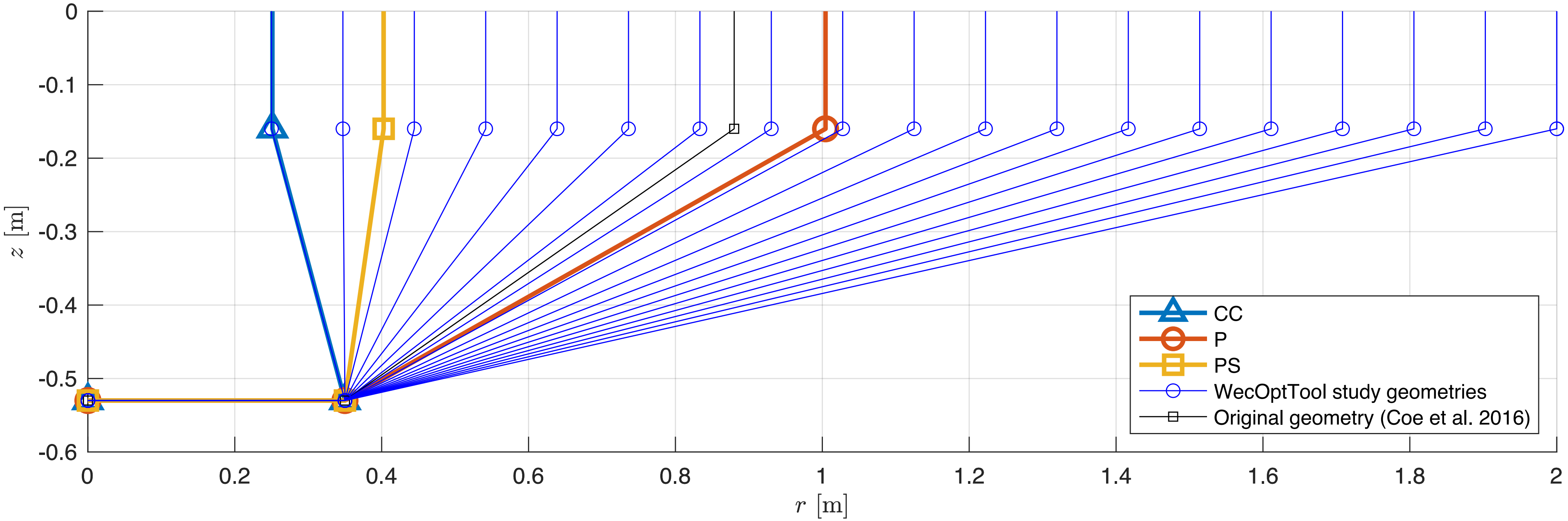
Controller	Opt. radius, r_{opt}	Obj. fun. value
CC	0.25	-86.1
P	1.00	-5.0
PS	0.40	-47.7

https://github.com/SNL-WaterPower/WecOptTool/blob/master/examples/WaveBot/WaveBot_caseB.m

Case B, results pt. 2

Optimal design for CC, P, and PS controllers

Design variable	Case A	Case B	Case C
Outer radius, r [m]	$r = 0.88$	$r \in [0.25,\ 2]$	$r \in [0.25,\ 2]$
Maximum PTO force, $F_u^{\max}$ [kN]	$F_u^{\max} = 2$	$F_u^{\max} = \infty$	$F_u^{\max} \in [0.1,\ 1]$
Maximum stroke, $z^{\max}$ [m]	$z^{\max} = \infty$	$z^{\max} = 0.6$	$z^{\max} = \infty$



$$\frac{\bar{P}(r)}{(r_0 + r)^3}$$

Controller	Opt. radius, r_{opt}	Obj. fun. value
CC	0.25	-86.1
P	1.00	-5.0
PS	0.40	-47.7

https://github.com/SNL-WaterPower/WecOptTool/blob/master/examples/WaveBot/WaveBot_caseB.m

Case C

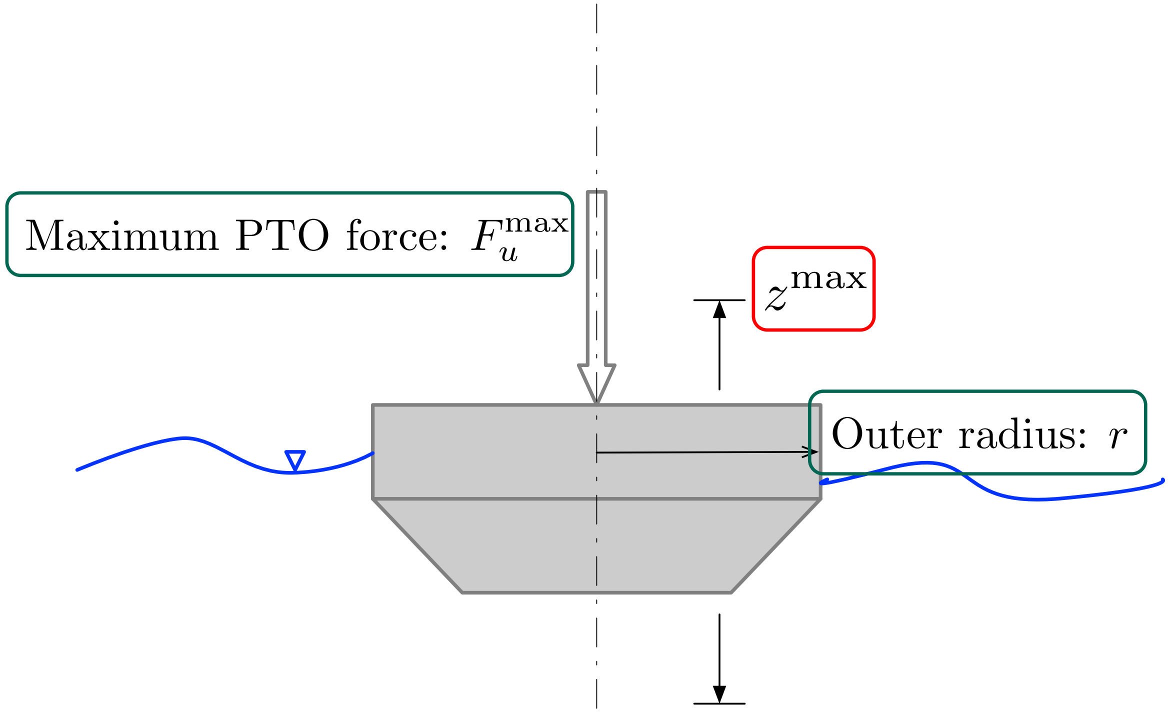
Multi-objective design study

Design variable	Case A	Case B	Case C
Outer radius, r [m]	$r = 0.88$	$r \in [0.25,\ 2]$	$r \in [0.25,\ 2]$
Maximum PTO force, $F_u^{\max}$ [kN]	$F_u^{\max} = 2$	$F_u^{\max} = \infty$	$F_u^{\max} \in [0.1,\ 1]$
Maximum stroke, $z^{\max}$ [m]	$z^{\max} = \infty$	$z^{\max} = 0.6$	$z^{\max} = \infty$

Varying the outer radius and maximum PTO force, find the Pareto front for power, volume*, and maximum PTO stroke

power → $\bar{P}$; volume* → $(r_0 + r)^3$; max PTO stroke → $z^{\max}$

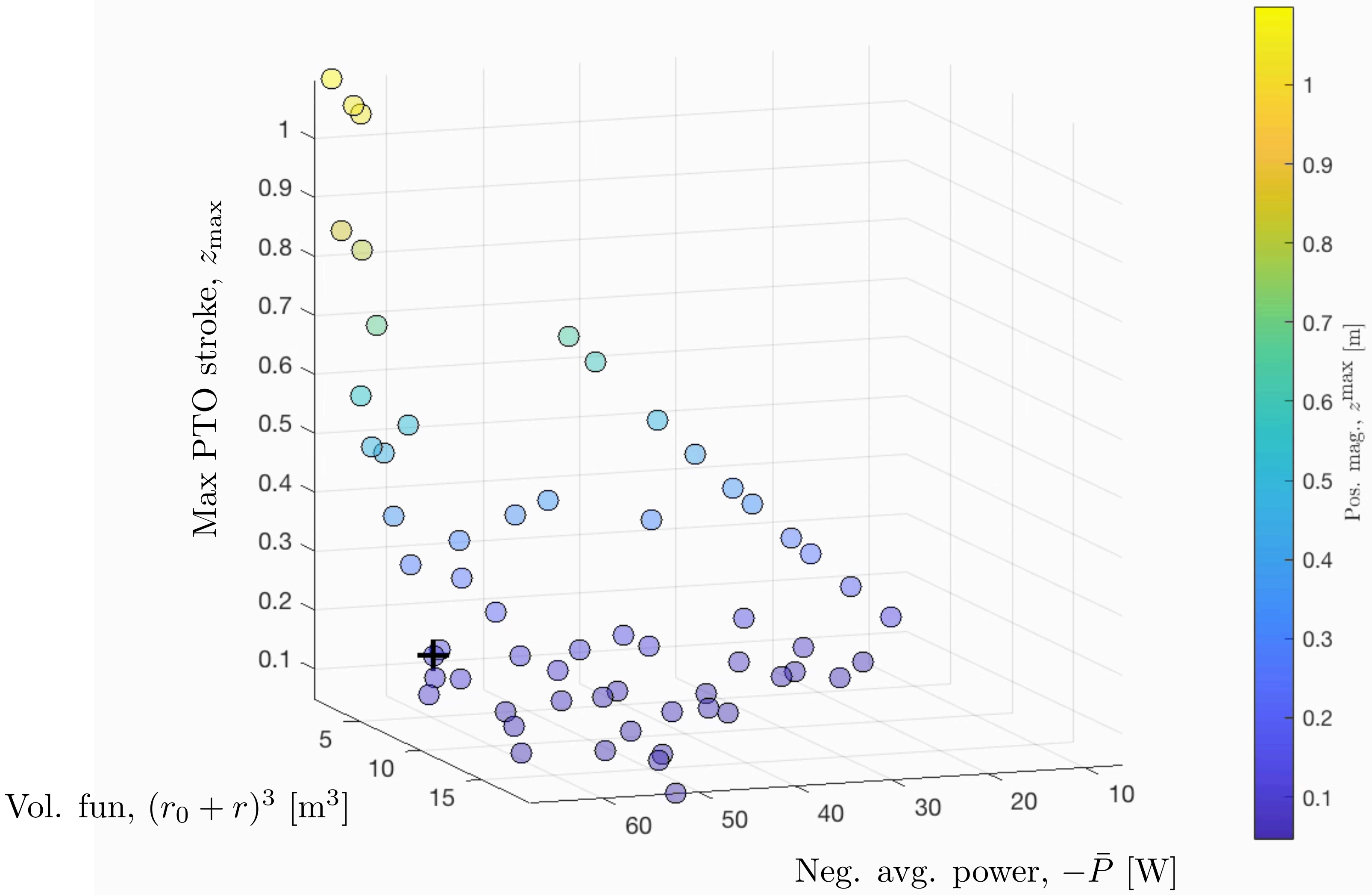
$$\min_{r, F_u^{\max}} \quad \left(\bar{P},\ (r_0 + r)^3,\ z^{\max}\right)$$
$$\text{s.t.} \quad r \in [0.25, 2]$$
$$F_u^{\max} \in [0.1, 1] \times 10^3$$



Case C, results pt. I

Multi-objective design study

Design variable	Case A	Case B	Case C
Outer radius, r [m]	$r = 0.88$	$r \in [0.25, 2]$	$r \in [0.25, 2]$
Maximum PTO force, $F_u^{\max}$ [kN]	$F_u^{\max} = 2$	$F_u^{\max} = \infty$	$F_u^{\max} \in [0.1, 1]$
Maximum stroke, $z^{\max}$ [m]	$z^{\max} = \infty$	$z^{\max} = 0.6$	$z^{\max} = \infty$



https://github.com/SNL-WaterPower/WecOptTool/blob/master/examples/WaveBot/WaveBot_caseC.m

Case C, results pt. 2

Multi-objective design study

Design variable	Case A	Case B	Case C
Outer radius, r [m]	$r = 0.88$	$r \in [0.25,\ 2]$	$r \in [0.25,\ 2]$
Maximum PTO force, $F_u^{\max}$ [kN]	$F_u^{\max} = 2$	$F_u^{\max} = \infty$	$F_u^{\max} \in [0.1,\ 1]$
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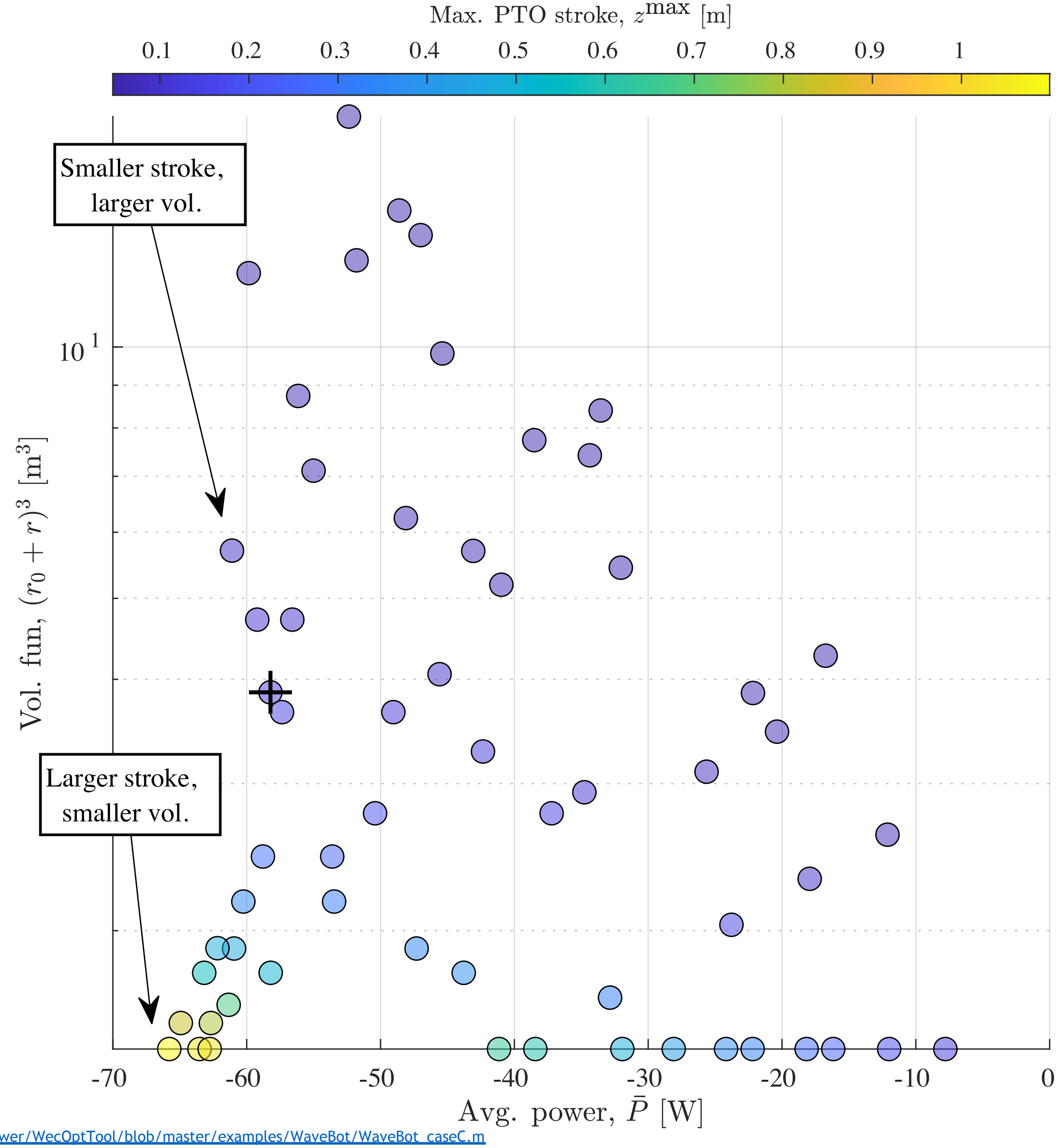
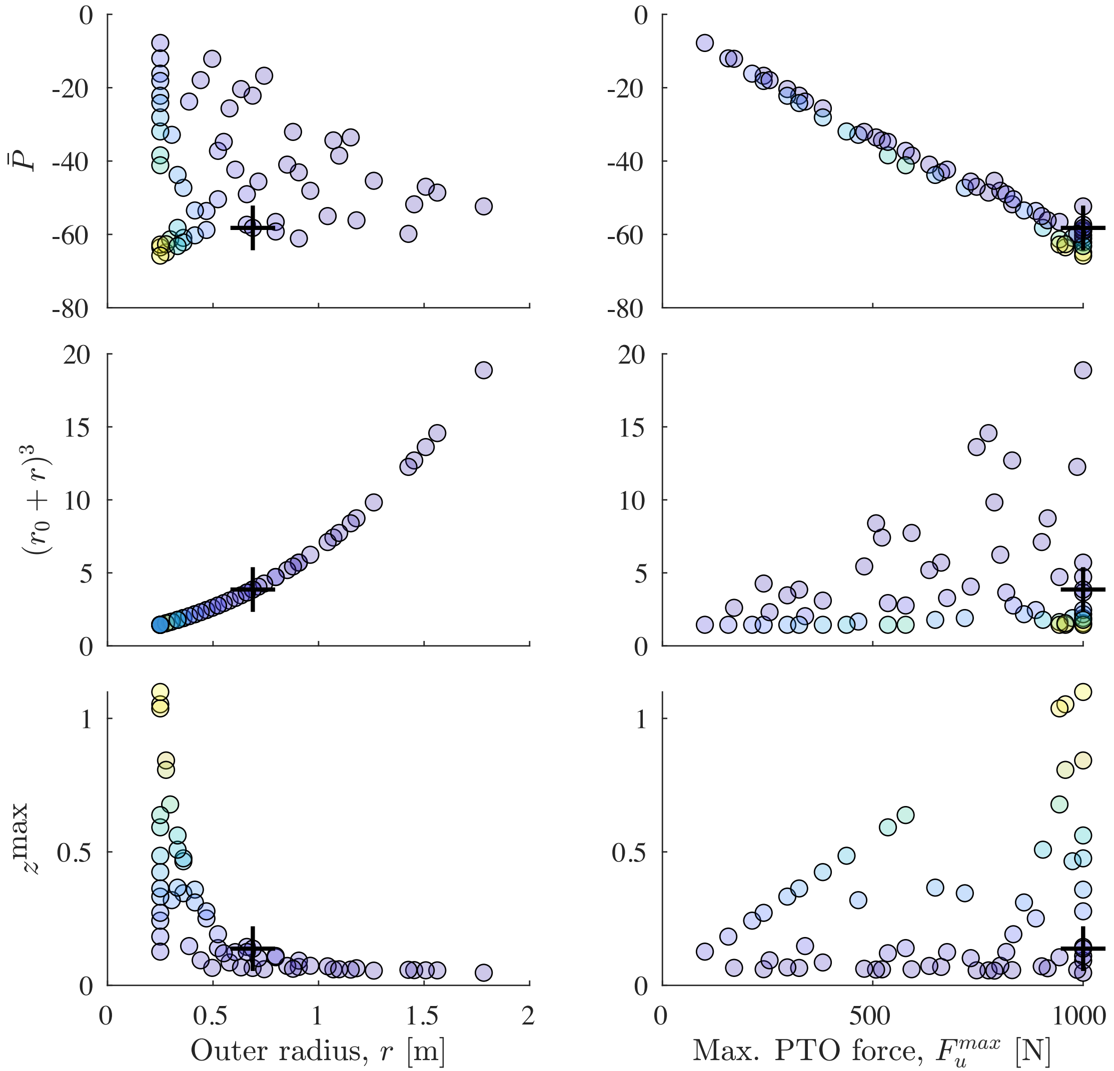
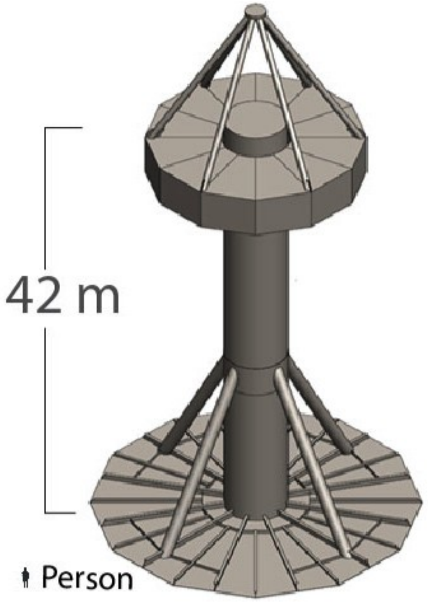


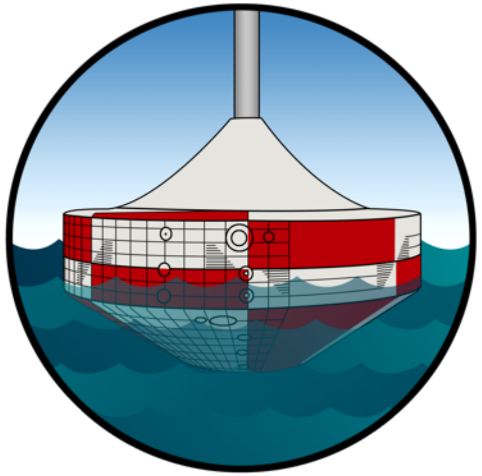


WecOptTool v1.0 and beyond

Existing examples

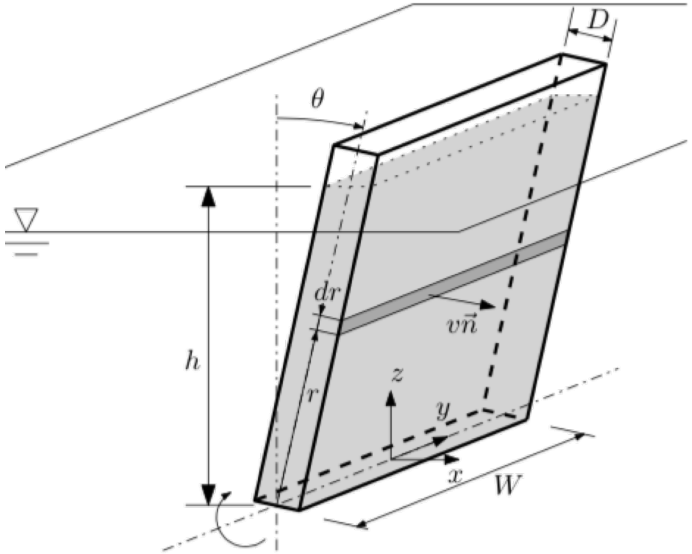


RM3



WaveBot

Upcoming examples



Flapper

WecOptTool v1.0 and beyond (cont.)

- Additional examples
- Automated kinematics generation
  (linearization of a Jacobian)
- PTO dynamics
  (https://github.com/SNL-WaterPower/fbWecCntrl/tree/codesign)
- Fundamental concepts and objective functions
- Fixed-structure controllers

Thank you for your time

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