Multidisciplinary Design Optimization of a Series Hybrid Electric Vehicle (HEV) Powertrain

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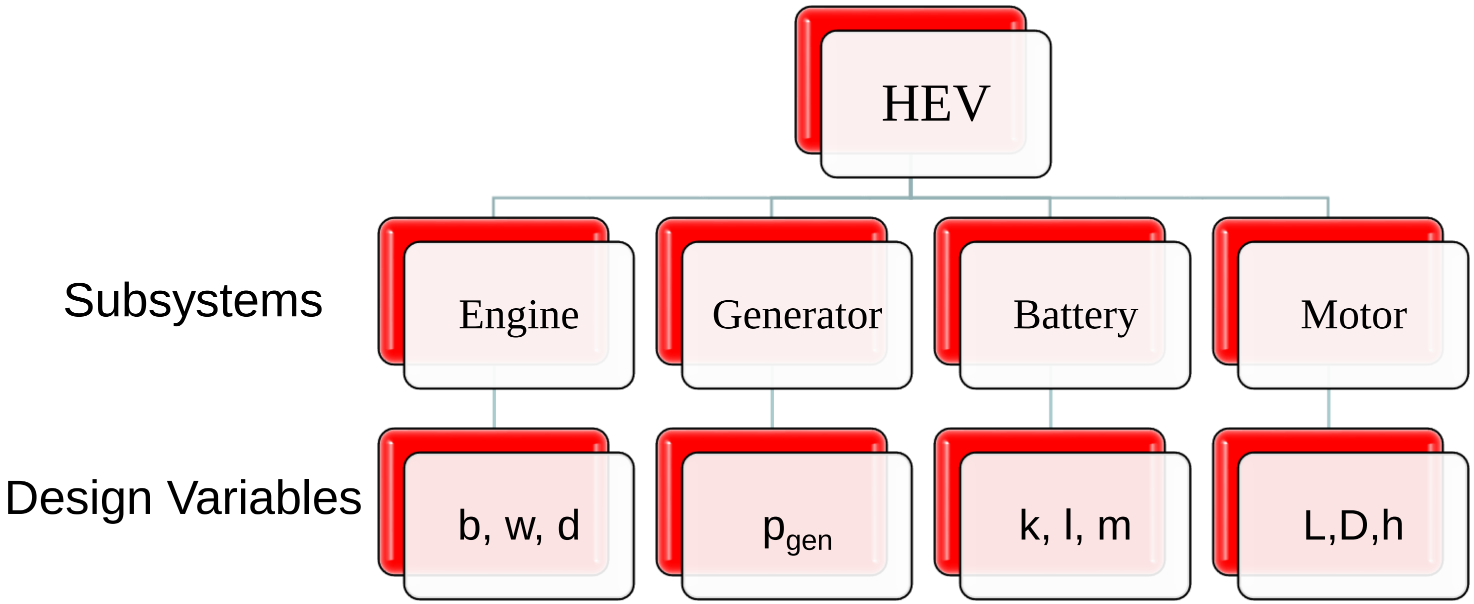
Introduction

- A Hybrid Electric (HEV) is a type of vehicle that combines a conventional internal combustion engine (ICE) propulsion system with an electric propulsion system
- HEVs are becoming increasingly common among the automakers
- HEVs can reduce the fuel consumption as well as emissions
- A HEV is a large-scale, complex system in which each of the components may have a large impact on the overall performance of the system.
- A system level optimization is needed to improve the overall performance of the design.

Photo: chevrolet.com

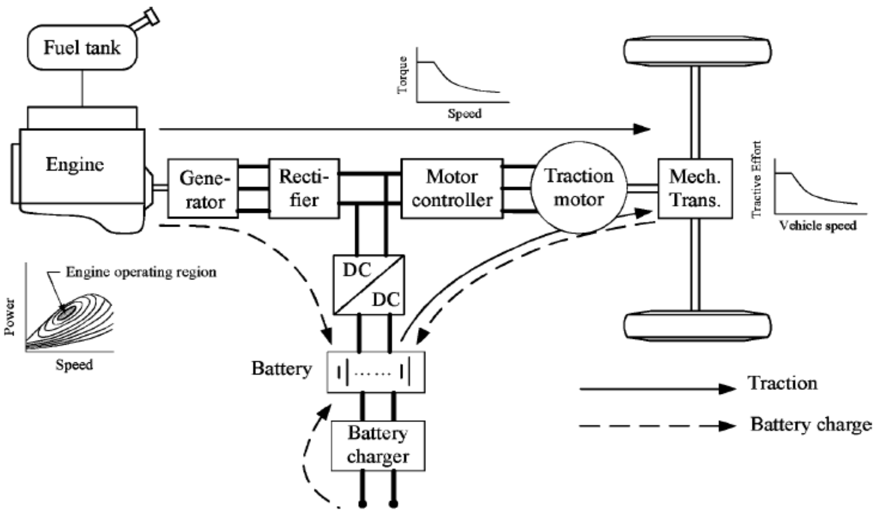
Overall System Decomposition:



Overall System Objective

- **System Level Objective**:
  - Minimizing the mass of the car (motor, engine, and battery)

- **Tradeoffs**:
  - Subsystems are connected to each other through the voltage (output voltage of the generator is a function of the engine power, and voltage is the input to the motor and battery)
  - System level objective conflicts with the subsystem objective (mass of the system and power of the engine)

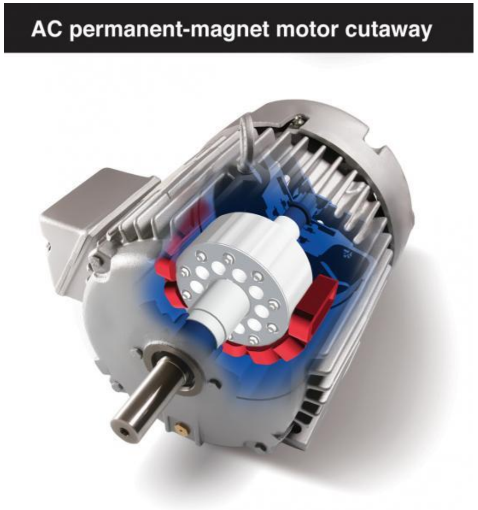


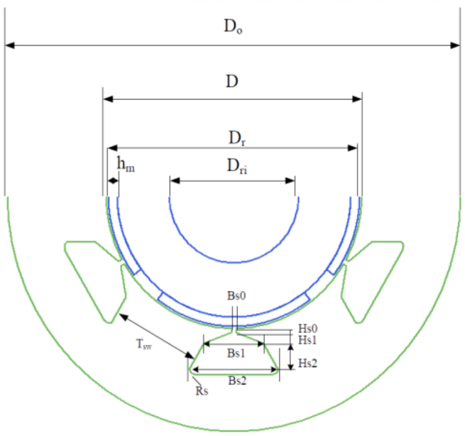
Series HEV architecture

Series hybrid electric veicle (Ehsani, Mehrdad, Yimin Gao, and John M. Miller. "Hybrid electric vehicles: architecture and motor drives." *Proceedings of the IEEE* 95.4 (2007): 719-728.)

Subsystem: Electric Motor

- Motor Type: AC Permanent Magnet Synchronous Motor (PMSM)
- Objective: Maximizing the Efficiency while minimizing the mass and volume
- Challenges: Complicated equations, large number of design variables, effect of topology on the performance of the system, and nonlinearities.





SMPM machine geometry parameters

Subsystem: Electric Motor

Objective:

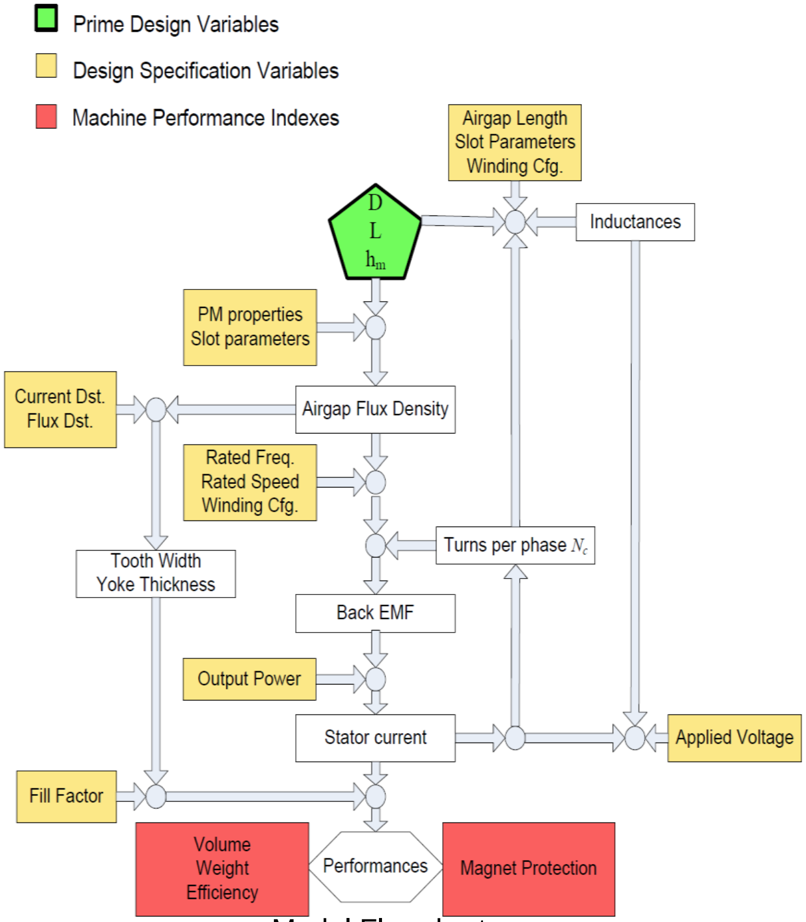
$$\min f = 0.33 * mass + 0.33 * (1 - eff) + 0.33 * Vol$$

s.t:

$$g1: \; D - 300 \leq 0$$
$$g2: \; L - 200 \leq 0$$
$$g3: \; h_m - 12 \leq 0$$
$$g4: \; -D \leq 0$$
$$g5: \; -L \leq 0$$
$$g6: \; -h_m \leq 0$$

Design Variables	
D	Stator diameter on the airgap side
L	machine axial length
h	thickness of the permanent magnet in the radial direction

Design Parameter	Chosen Value
Slot opening B_{s0}	2mm
Slot tip height H_{s0}	1mm
Steel lamination factor	1
Slot fill factor	40%
Power	15000 w
Air gap	1mm



Model Flowchart

Subsystem: Electric Motor

Monotonicity Analysis

	D	L	h_m
f	N/A	N/A	N/A
g1	+	NA	NA
g2	NA	+	NA
g3	NA	NA	+
g4	-	0	0
g5	0	-	0
g6	0	0	-

By MP2: g1 and g4 are active w.r.t D
By MP2: g2 and g5 are active w.r.t L
By MP2: g3 and g6 are active w.r.t h_m

Results:

Numerical methods used in the model to solve and find some of the unknowns. As a result a derivative free algorithm (PSO) was implemented to solve the Optimization problem.

Design Variables	Optimum Value	Objective Function	Optimum Value
D(mm)	112	Weight(kg)	36.5
L(mm)	90.7	Eff	95.7%
h_m(mm)	5.6	Volume	0.0047
		Output Equation (objective)	91.2

Optimal design found by PSO

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Summary Model- Subsystem: Battery

Minimize (f) $W_{pack} = k * n * m * w_{cell}$

Subject to (g_1) $201 - k * n * 1.2 \leq 0$

(g_2) $6500 - m * 232 \leq 0$

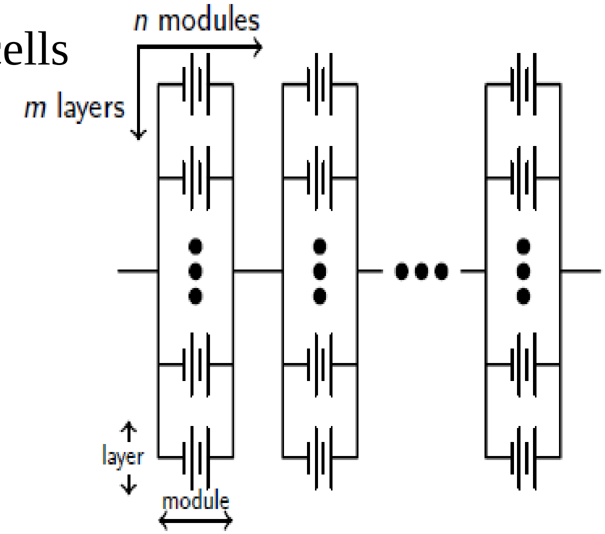
(g_3) $38.15 - k * n * m * 0.2784 \leq 0$

Design Variables:

k – number of cells in series per module

n – number of modules

m – number of layers



\# Variables=3 # Constraints=3

g1: $V_{pack} = n * k * V_{cell}$ *(voltage constraint)*

g2: $I_{pack} = m * I_{cell}$ *(current constraint)*

g3: $P_{pack} = V_{pack} * I_{pack}$ *(power constraint)*

Design Parameters

w_{cell} - weight of each cell

V_{cell} – Output Voltage of individual cell

I_{cell} – Current rating of individual cell

P_{pack} – Output power of battery pack

W_{pack} – weight of battery pack

V_{pack} – Output Voltage of battery pack

I_{pack} – Current rating of battery pack

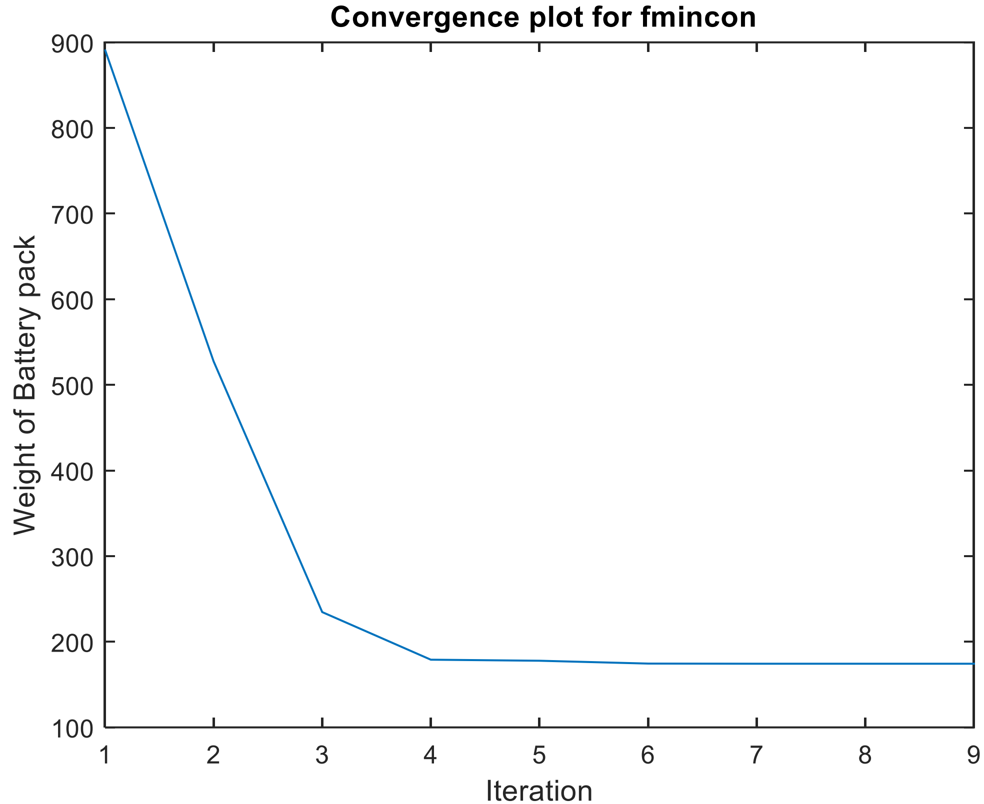
Xue, Nansi, et al. "Design of a lithium-ion battery pack for PHEV using a hybrid optimization method." *Applied Energy* 115 (2014): 591-602.

Solution Process- Subsystem: Battery

	k	n	m
f	+	+	+
g_1	-	-	X
g_2	X	X	-
g_3	-	-	-

Monotonicity Table

- Function is always increasing, but constraints are decreasing, so problem is well bounded.
- Potentially all constraints can be active, but difficult to say which is dominant.
- Used fmincon to obtain solution.



	k	m	n	W
Initial	40	40	15	891.6
Final (Optimum)	13	13	28	175.79

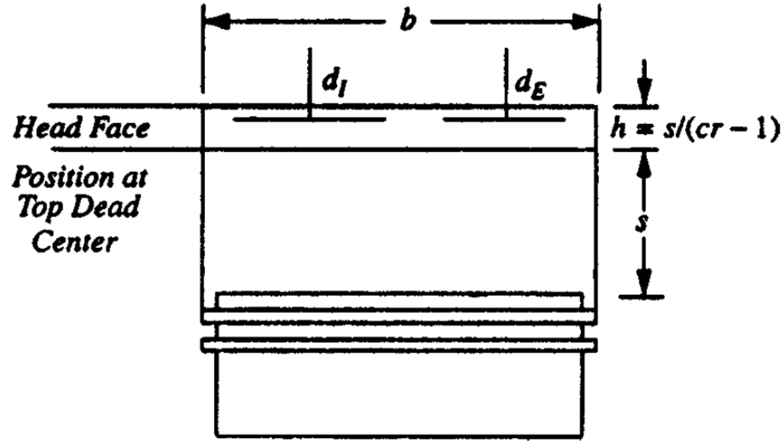
Summary Model- Subsystem: Engine

Objective

$$\min_{b,w,dI} f(b,w,dI) = K_0 * w * [p_{me} - P_0 * \eta_t \eta_v]$$

Constraints

$$g_1(b) = b - P_1 < 0$$
$$g_2(w,dI) = P_3 * w - dI^2 < 0$$
$$g_3(w) = w - K7 < 0$$
$$g_4(cr,b) = cr - 13.2 + 0.045 * b < 0$$
$$g_5(dI) = K4 * dI - 30 < 0$$



Multidisciplinary Robust Design Optimization of an Internal Combustion Engine, Charles D. McAllister, Timothy W. Simpson, Vol. 12, MARCH 2003. ASME.

Variables (3):

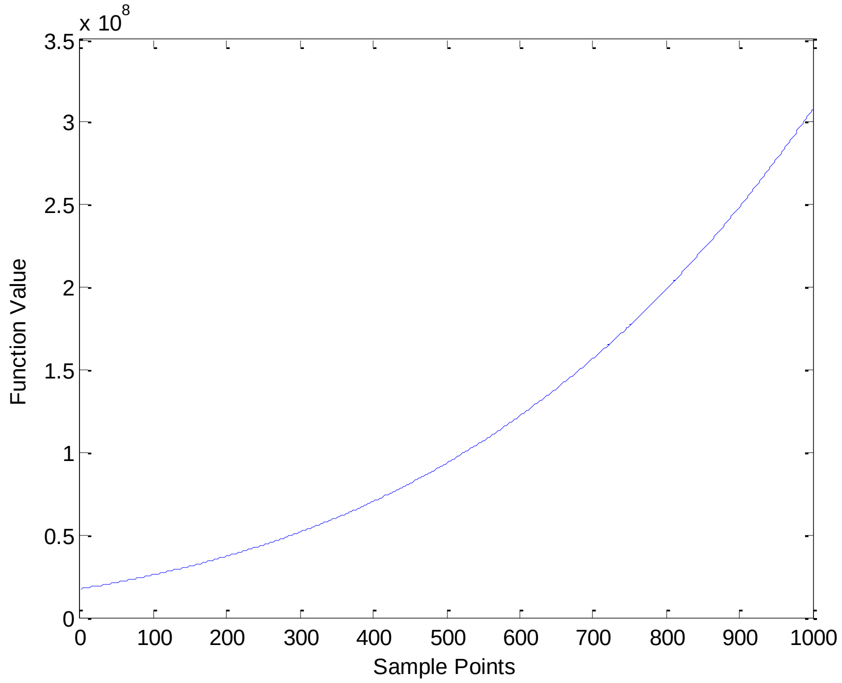
Cylinder Bore, Engine rpm, Intake valve diameter

Parameters

$$P_o = \rho * \frac{Q}{A_f}$$
$$P_1 = \frac{L_1}{K_1} * N_c$$
$$P_2 = 9.428 * 10^{-5} \left(4 \frac{V}{\pi} N_c\right) K_6 C_s$$

Design Variable	Lower Bound	Upper Bound
b (cylinder bore)	70 mm	90 mm
dI (intake valve diameter)	25 mm	50 mm
w (rpm at peak power)	5000 rpm	12000 rpm

Subsystem: Engine



	b	dI	w
f	+	**N/A**	+
g1	+	**N/A**	**N/A**
g3	**N/A**	**-**	+
g4	**N/A**	**N/A**	+
g5	+	**N/A**	**N/A**
g6	**N/A**	+	**N/A**

SQP fmincon implemented for optimization study.

w = 6061 rpm, b = 36.1 mm, dI = 76.9 mm,
Power = 173 kW, Mass = 104.1261 kg

System Level

Objective:

Minimize (f) $M = M_E + M_B + M_M$

Subject to (g1) $100 \le V_{Gen} \le 300$

and all subsystem constraints for engine, battery and motor

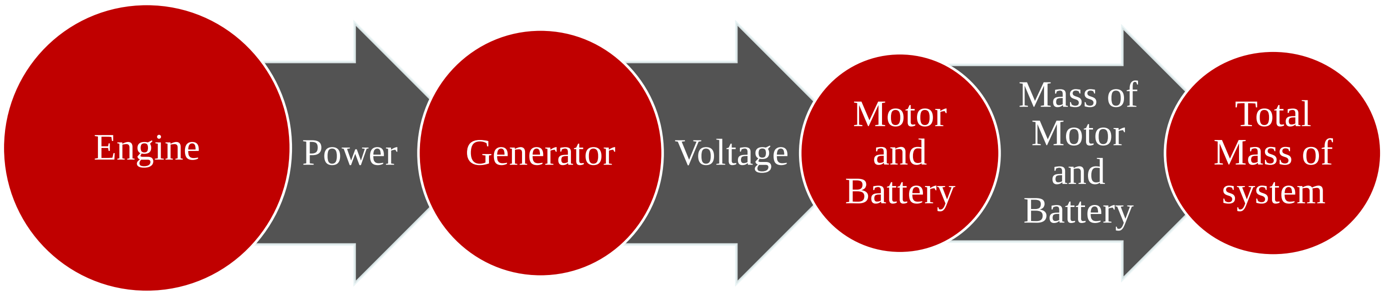
Design Variables:

M_E *Mass of Engine*

M_B *Mass of Battery*

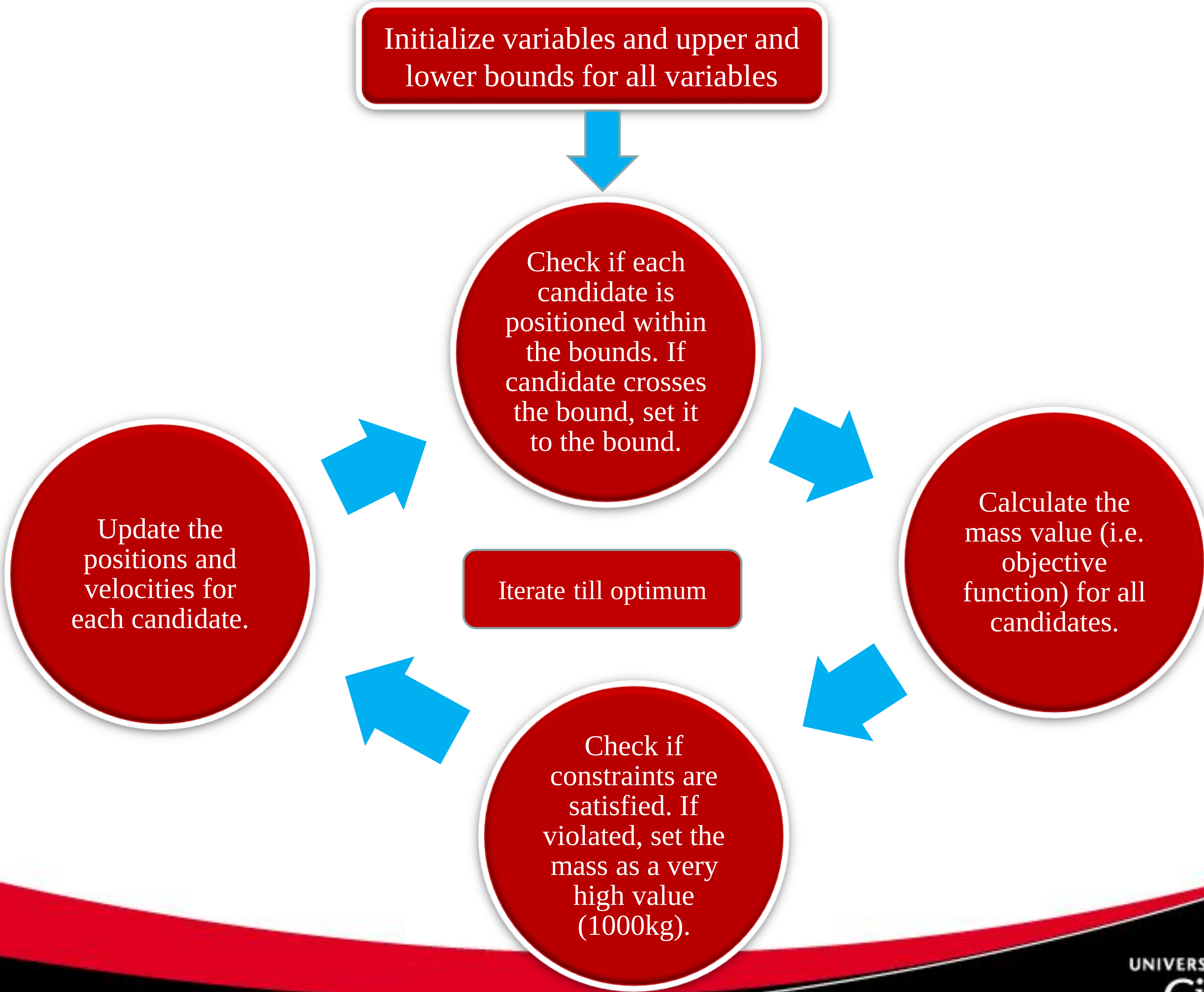
M_M *Mass of Motor*

Variables=10, # Constraints=2, and all variables have bounds



System level design flowchart

PSO Algorithm:



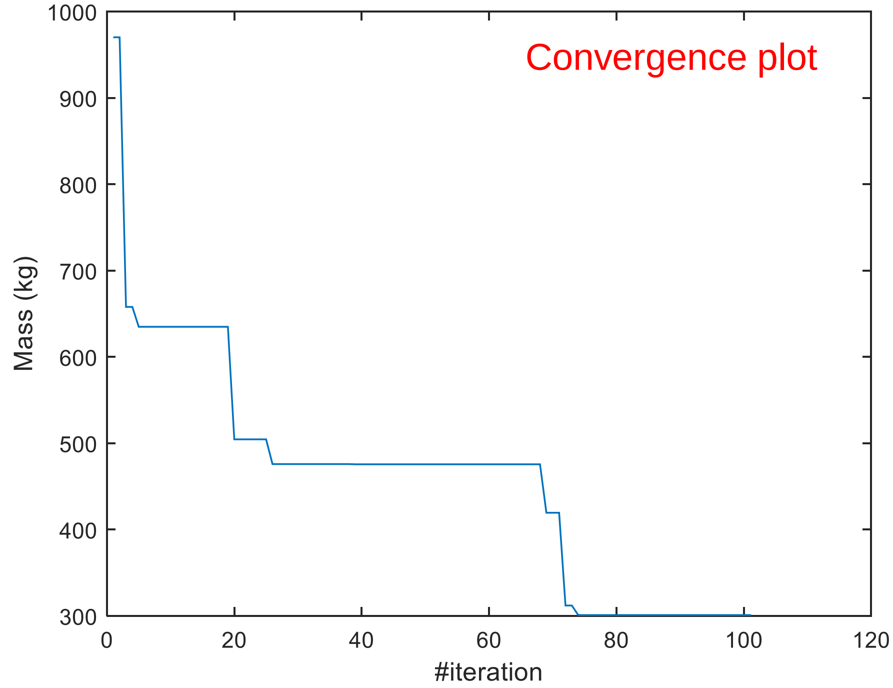
System Level Results:

w	b	di	k	l	m	D	lst	h	Nc	Mass
5000	31.02	87.64	10	10	31	144.83	73.08	11.43	30	249.65
6061	36.1	76.9	13	13	28	112	90.6	5.6	72	316.41

Optimal design variables and objective

Trial	Mass
1	249.64
2	257.26
3	214.09
4	253.68
5	218.48
Mean	238.63
SD	20.63

Optimal mass over iterations



Key Learnings:

- How to break down a complex system into subsystems
- How to optimize a complex system
- Importance of the linking variables on the overall system's objective
- The conflicts that the subsystem objectives may have with the overall system objective
- Using the penalty function