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2018 Altair Optimization Contest

Robot Arm Optimization

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1. Introduction

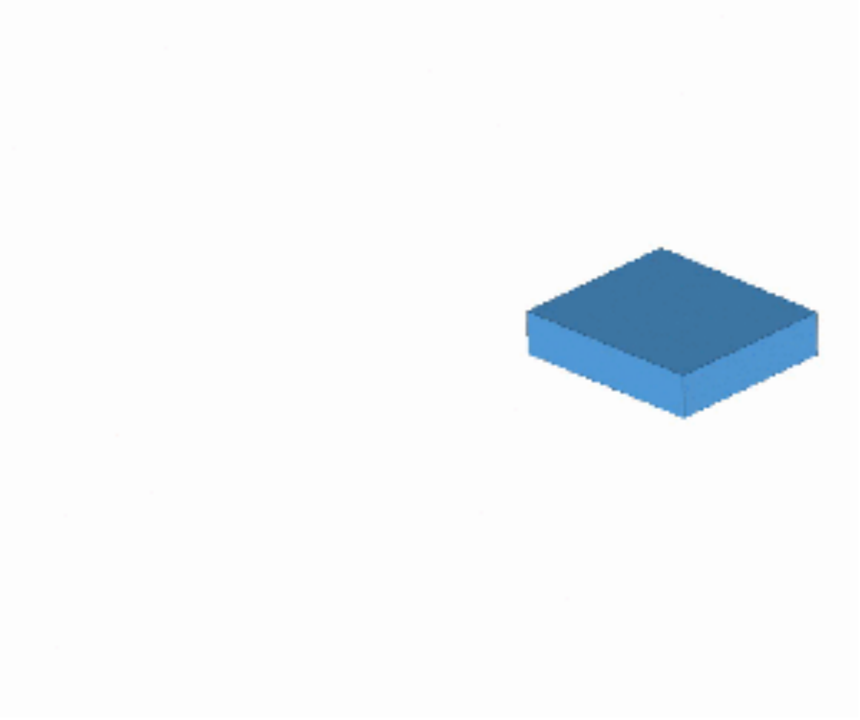
- Background
- Design Goal

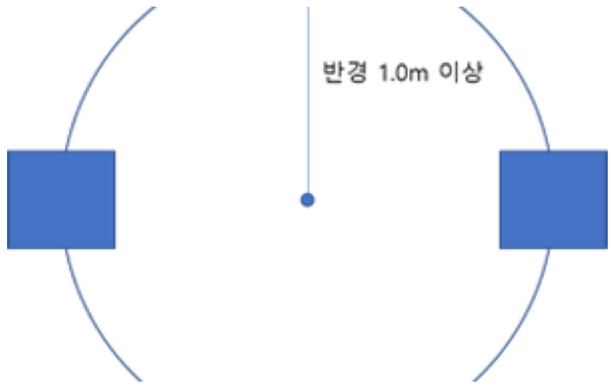
1. Background

- Industrial robots are used to improve productivity and reduce labor force.
- Many robots in the plant operate without stopping for 24 hours a day.
- These factories suffer a great loss even if they stop operating for a while.
- Therefore, It should not occur like fatigue failure and large deformation

1. Design Goal

- Minimize robot operating energy – Mass reduction & Joint reduction
- High accuracy of work
- Infinite life
- Product production possibility





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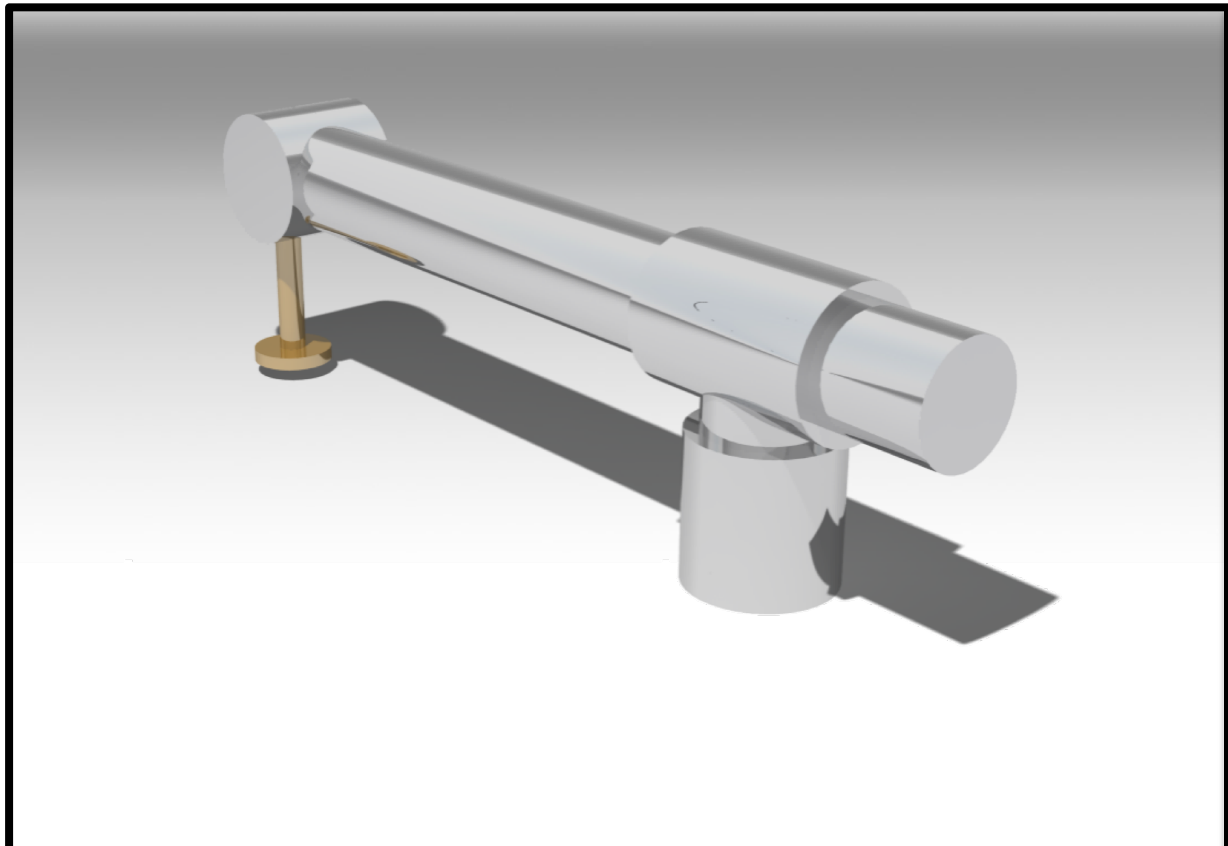
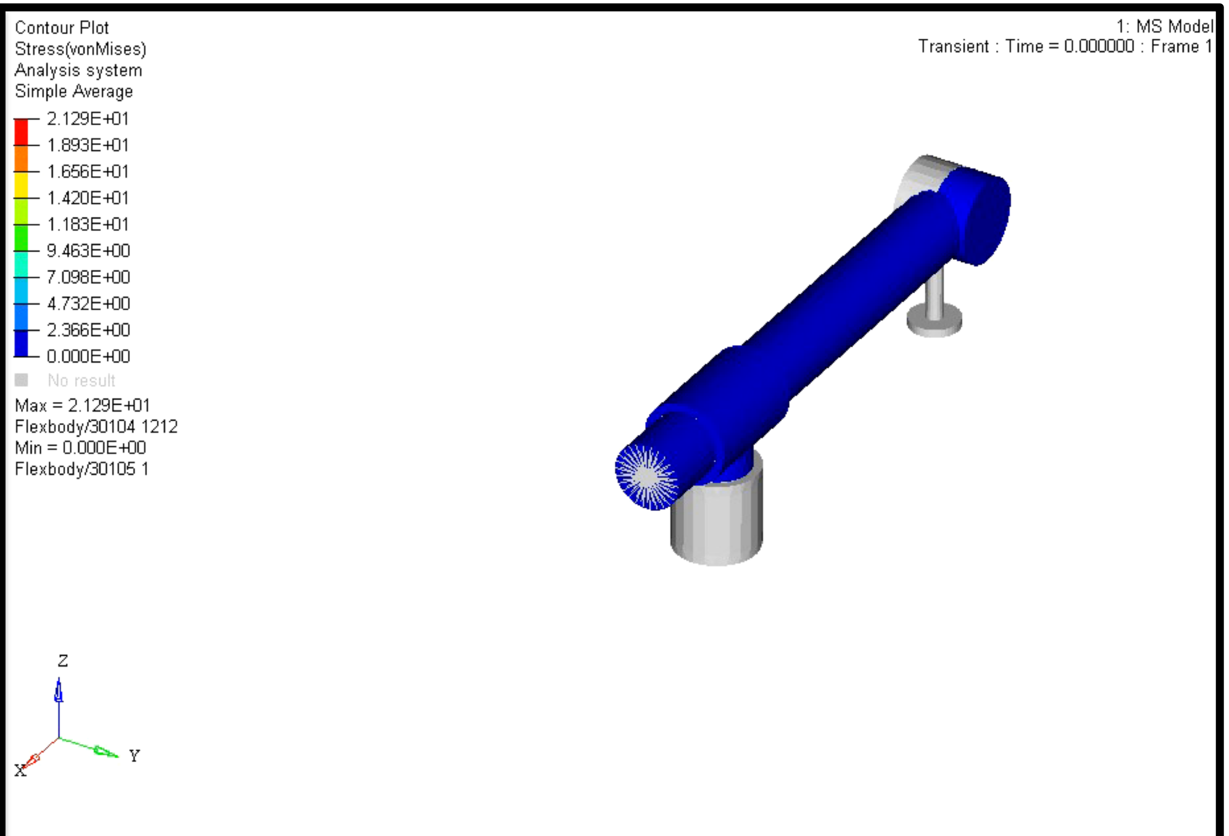
2. Modeling

- Concept Design
- Setting Joint & Motion

2. Concept Design

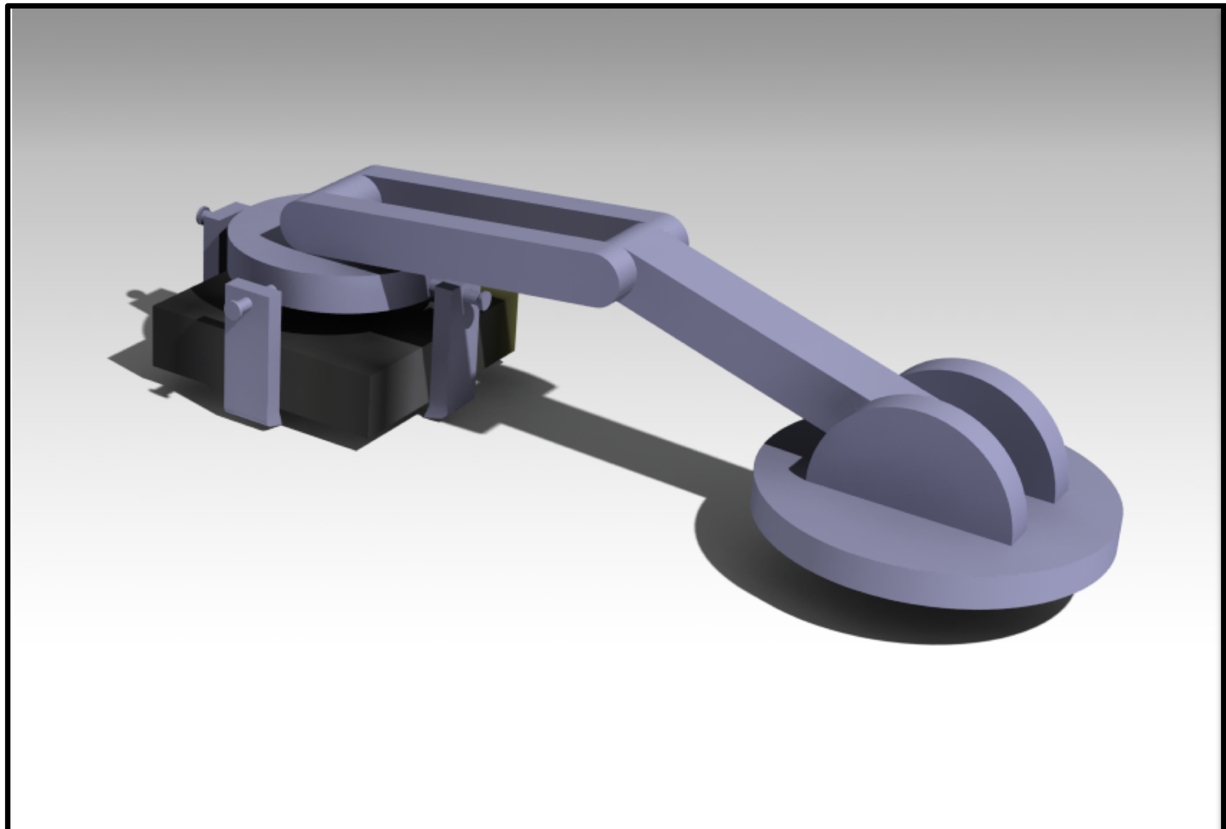


One Arm & Adsorption system

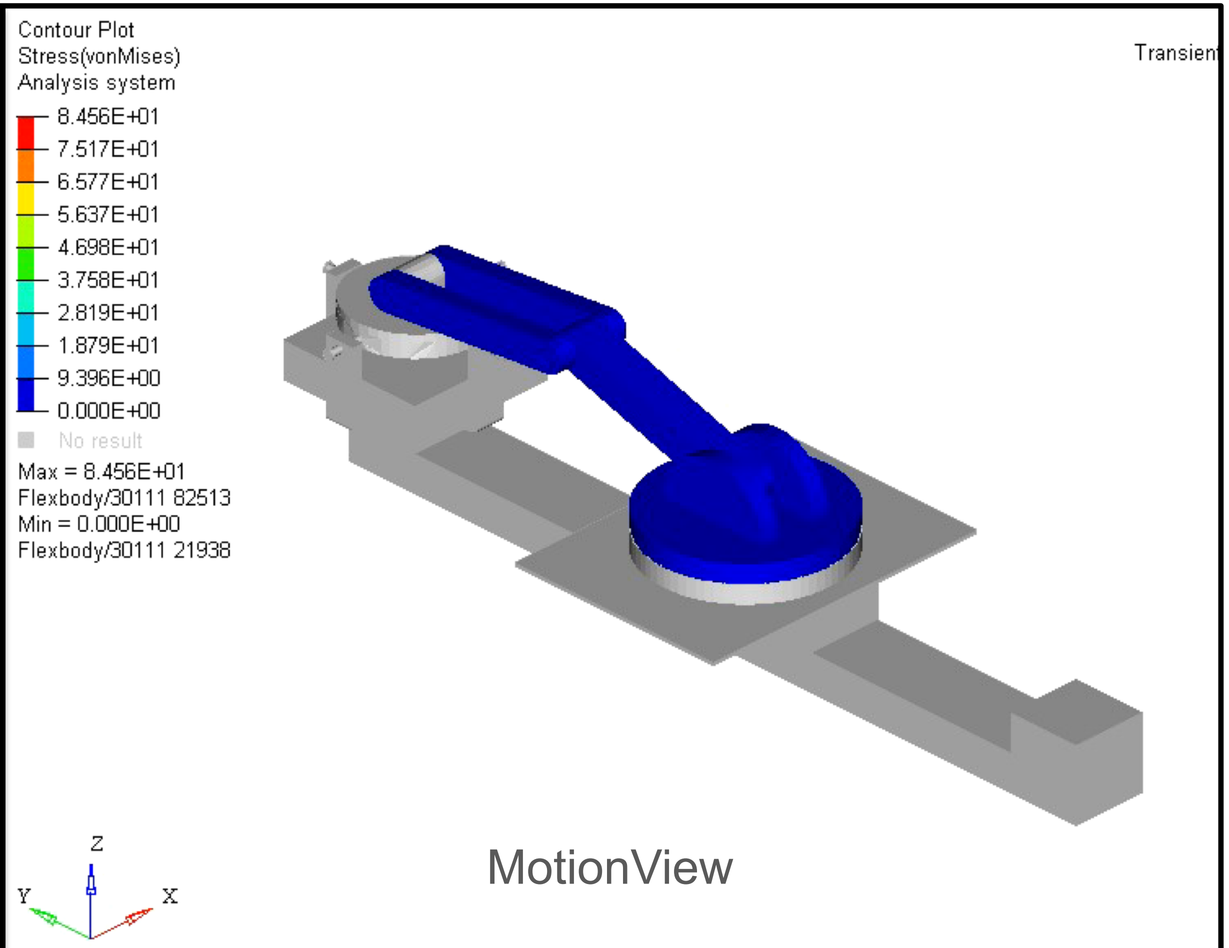


MotionView

2. Concept Design

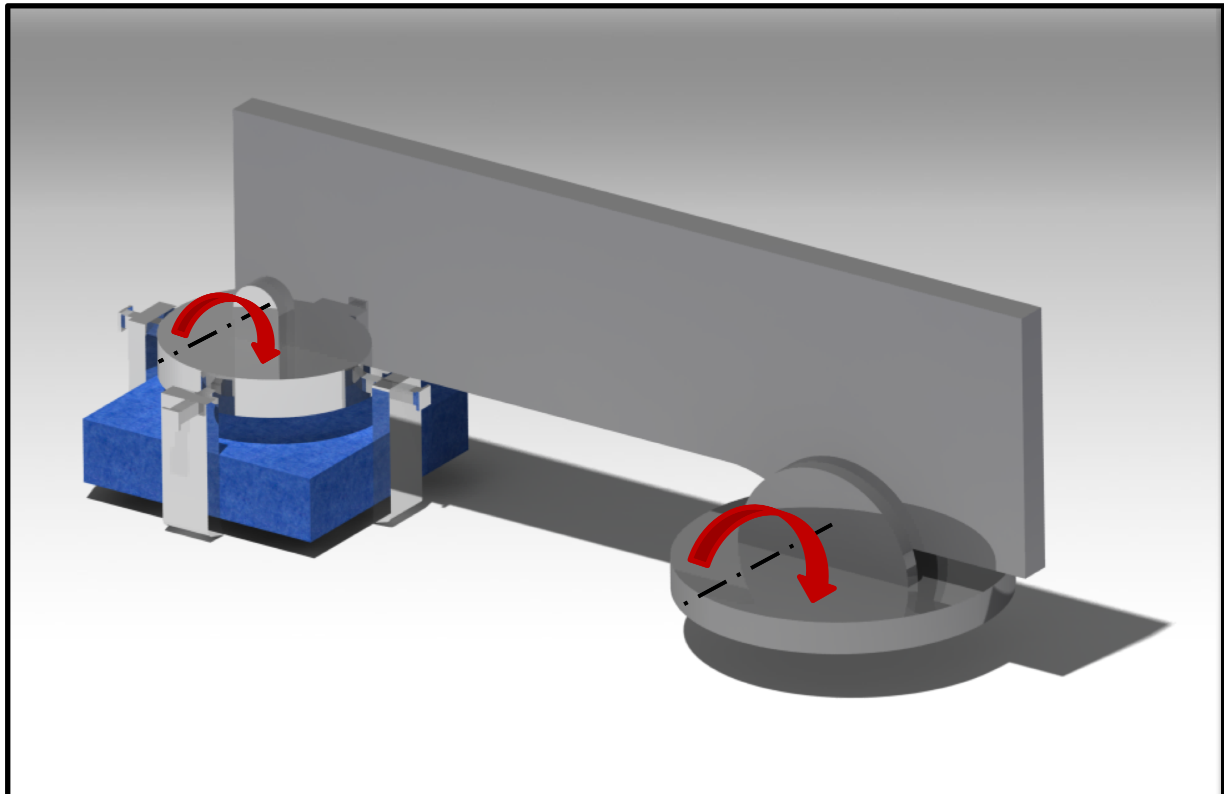


Two Arm & Grab System

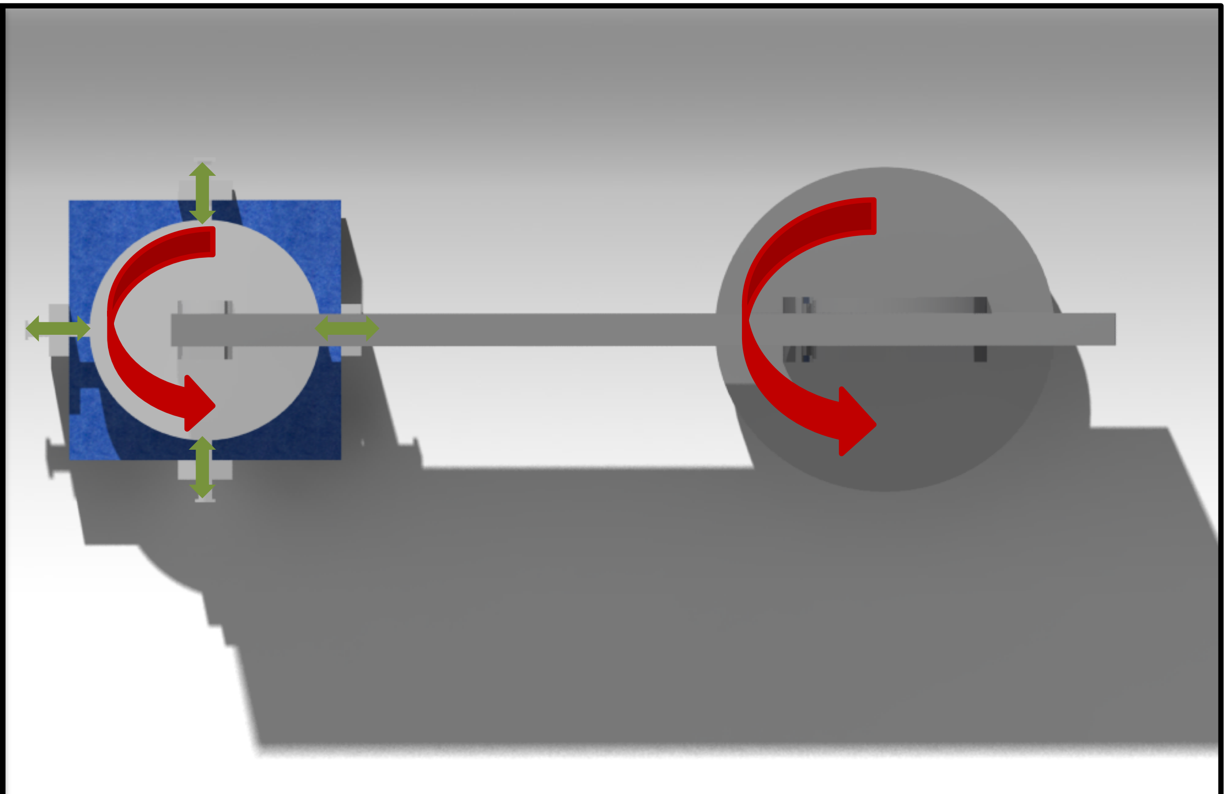


MotionView

2. Setting Joint & Motion



Proto Design – One arm & grab system

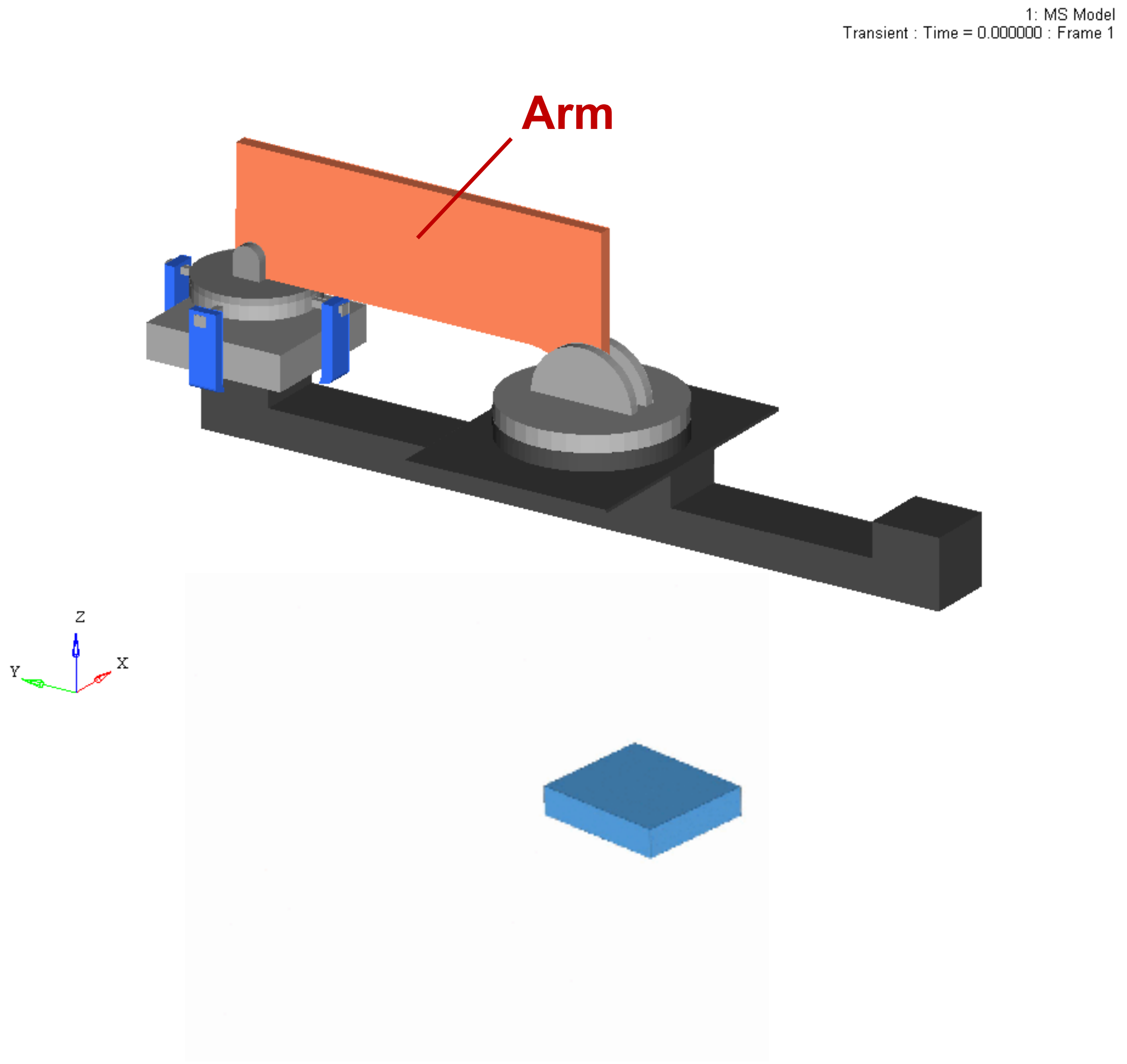


4 revolute joint to move box
4 translate joint to grab box

2. Setting Joint & Motion

- 0 ~ 0.5s(0.5s) for grab box
- 0.5 ~ 1.5s(1s) for raise box
- 1.5s ~ 2.5s(1s) for rotate box
- 2.5s ~ 8s(5.5s) for move box
- 8s ~ 9s(1s) for rotate box
- 9s ~ 10s(1s) for put down box

- Design domain: **Arm**



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3. Analysis & Optimization

- Flowchart
- Dynamic analysis - MotionSolve
- Topology Optimization - Optistruct
- Size Optimization – HyperMorph & HyperStudy
- Check final design – Click2Cast

3. Analysis & Optimization Flowchart

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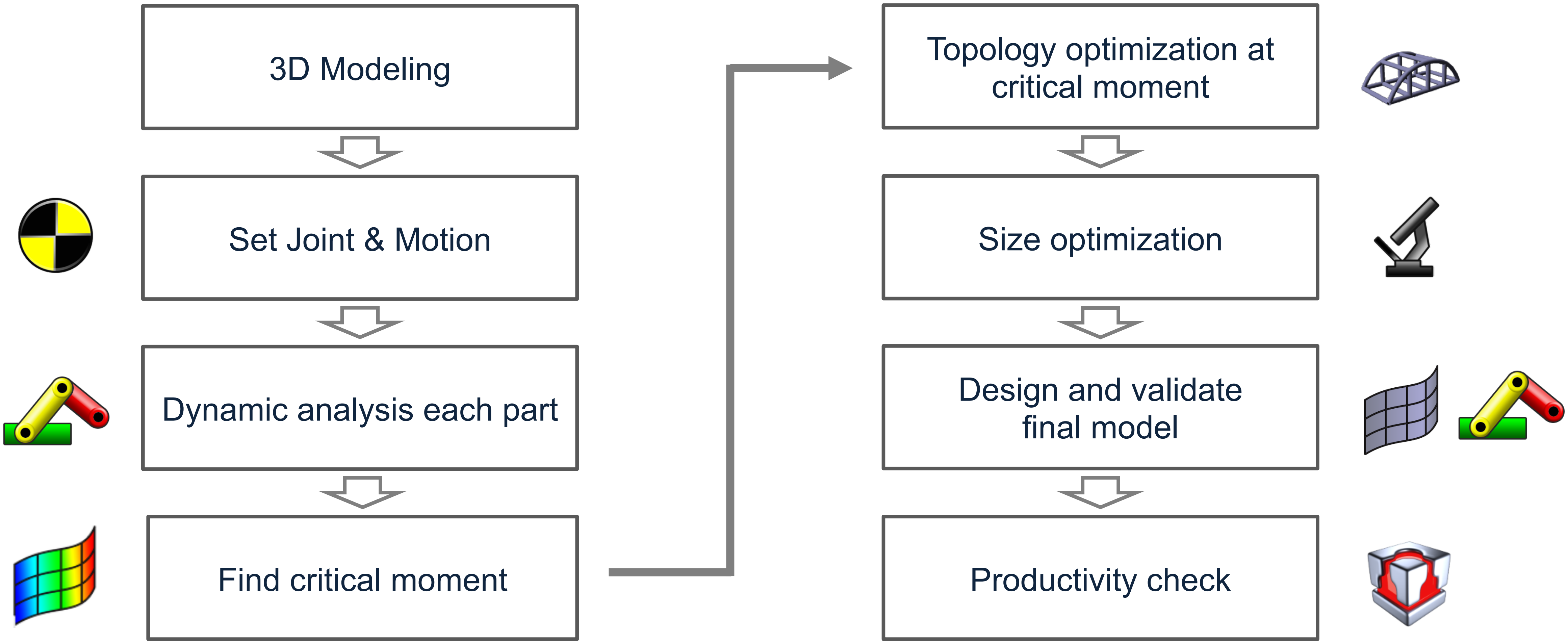
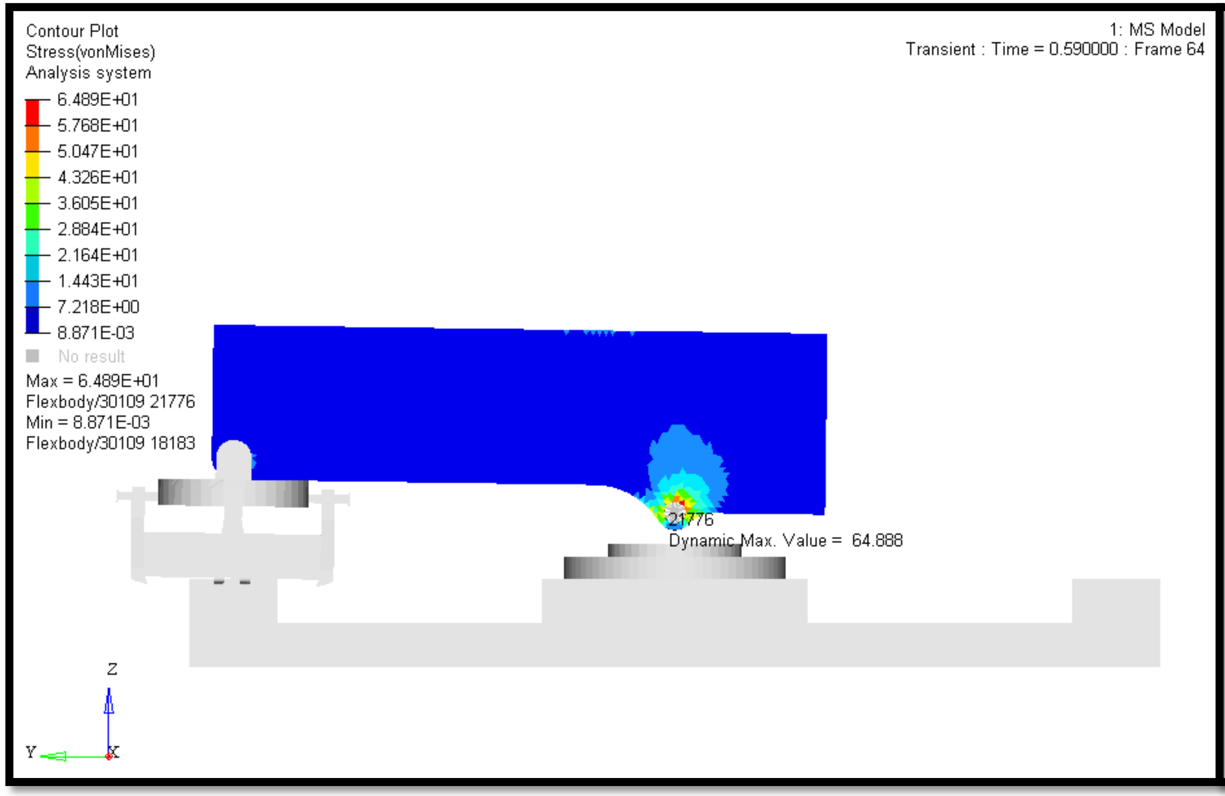
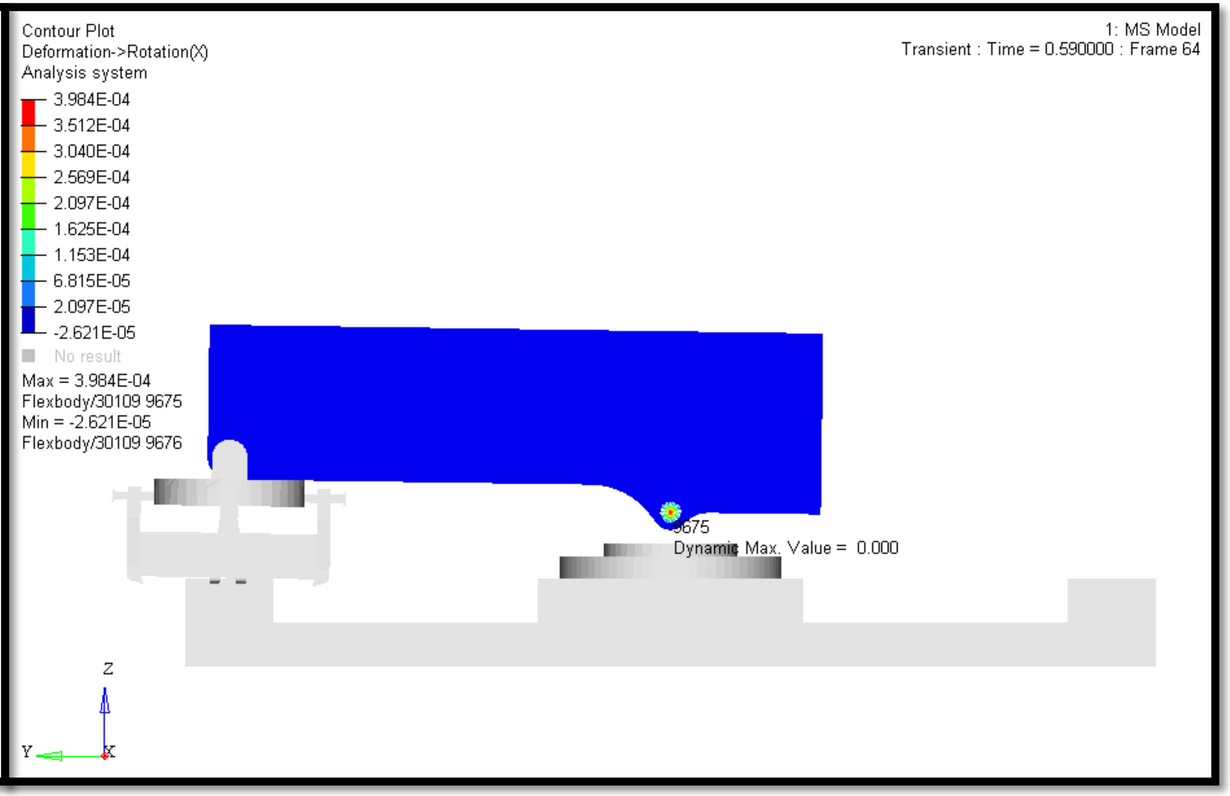


3. Dynamic Analysis - MotionSolve





Maximum Stress = 64.9MPa

Angle of arm with maximum stress = 0.0228°

Maximum stress is applied at the moment of raising arm

3. Topology optimization - Optistruct

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- Topology optimization formulation

$$\min\ m(\gamma_e) = \sum_{e=1}^{n} v_e \gamma_e$$

$$s.t\quad \sigma_{max} \leq 228MPa$$

$$Draw\ \&\ Symmetry\ condition$$

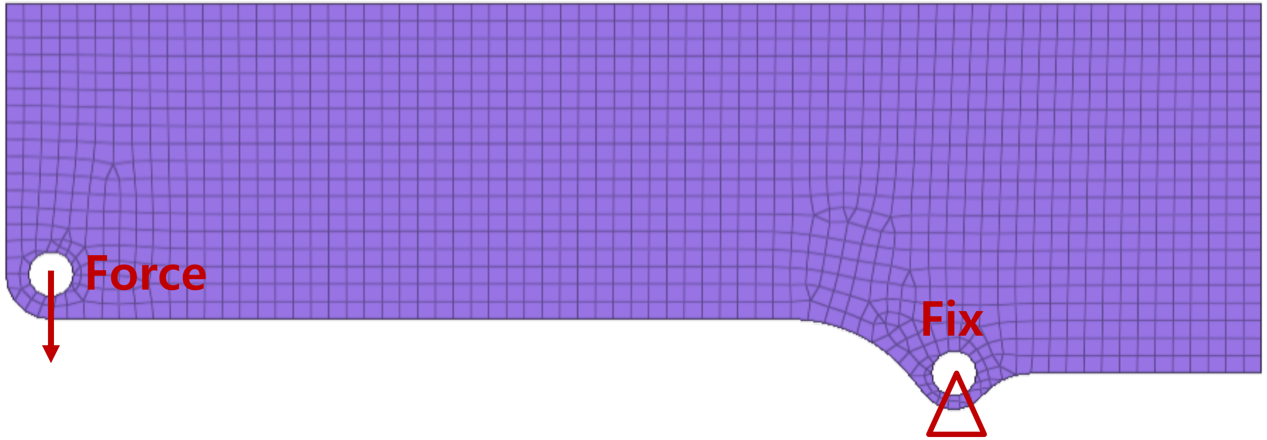
$$where \int_{\Omega} \gamma_e d\Omega \leq V_m$$

$$0 \leq \gamma_e \leq 1$$

$$e \in \Omega$$

v_e : volume of element
γ_e : density of element
n: number of element
Ω : design domain

Model Info: C:\Users\Hyoseok Byun\Desktop\Real Arm\Arm optimization HM.hm



- Material: AISI 1035 steel

$$E = 210GPa, v = 0.3, \rho = 7{,}900kg/m^3, \sigma_y = 380MPa, S_e = 228MPa$$

* L.R.Jackson, *Fatigue of Metals and Structures*, Bureau of Naval Weapons Document NAVWEPS 00-25-534, 1960.

3. Topology optimization - Optistruct

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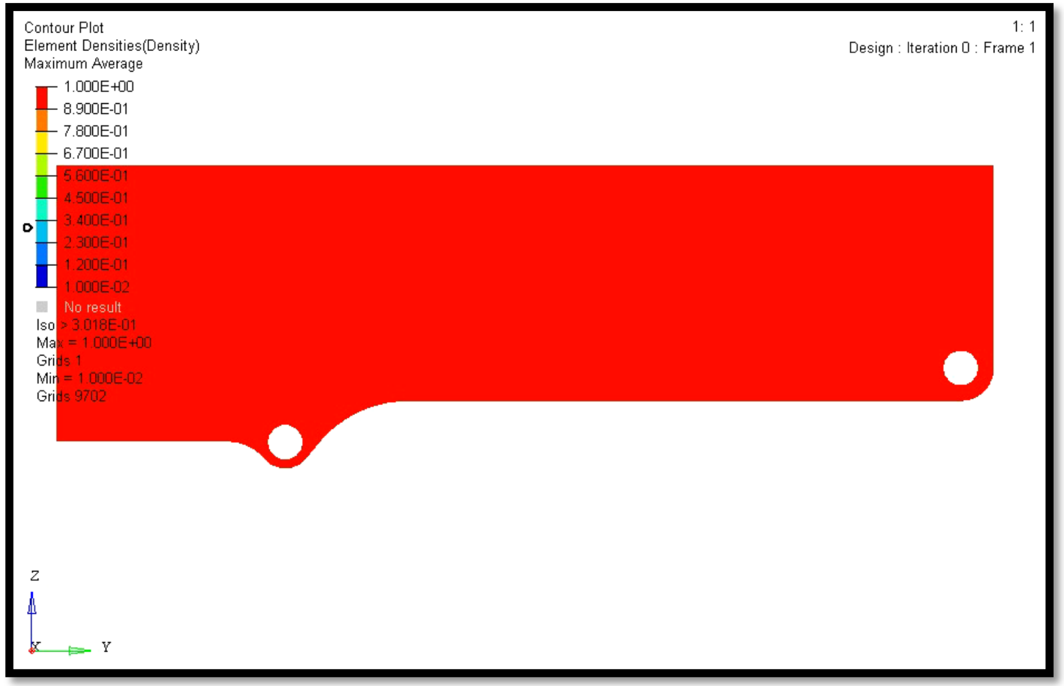
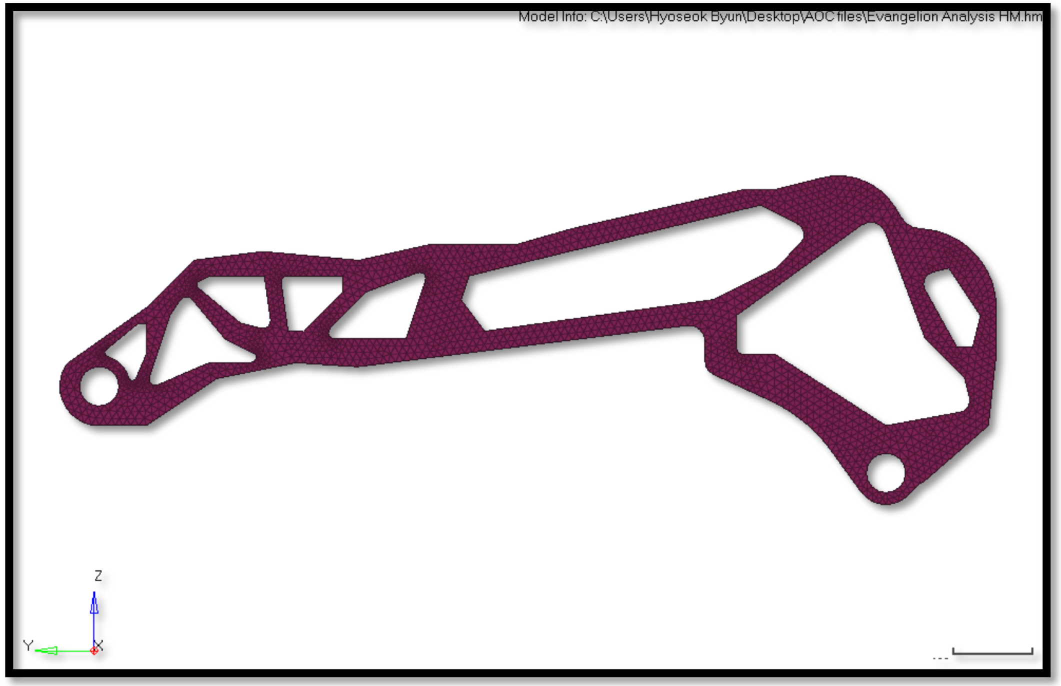
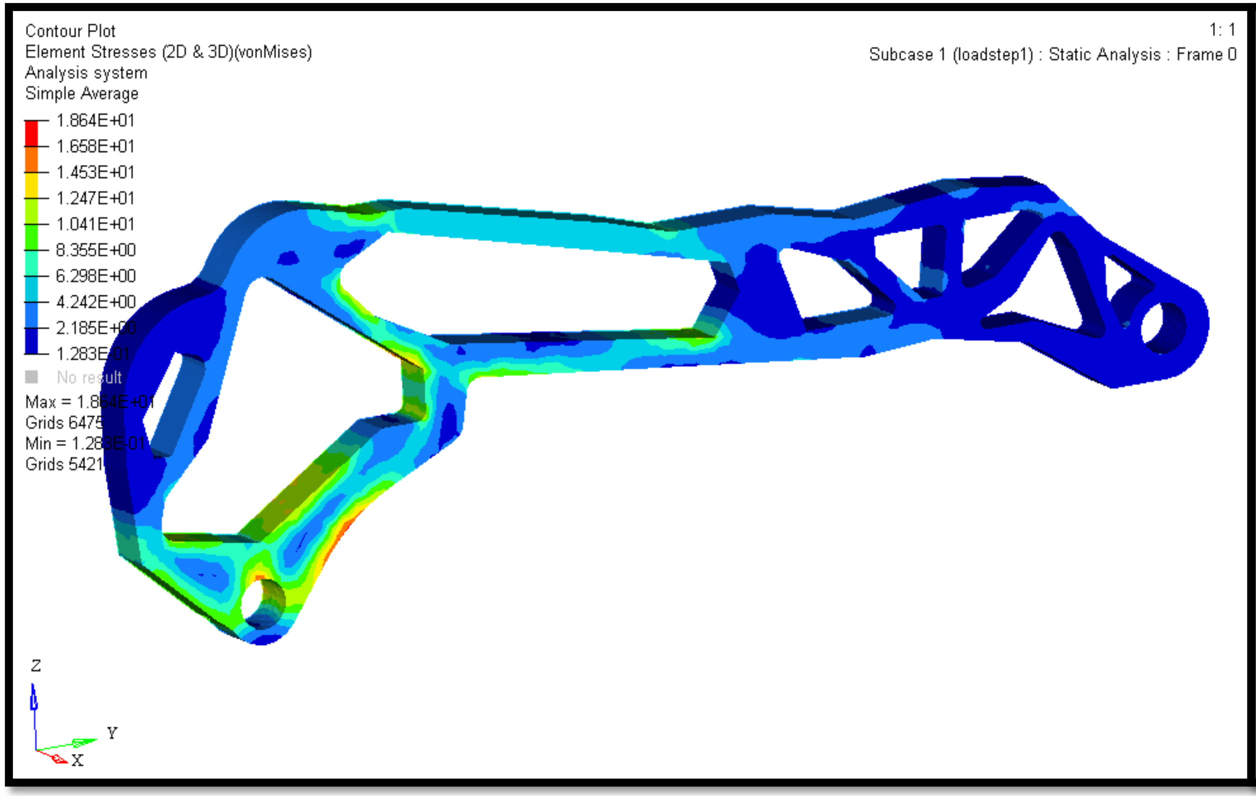
- Topology optimization result & remodeling



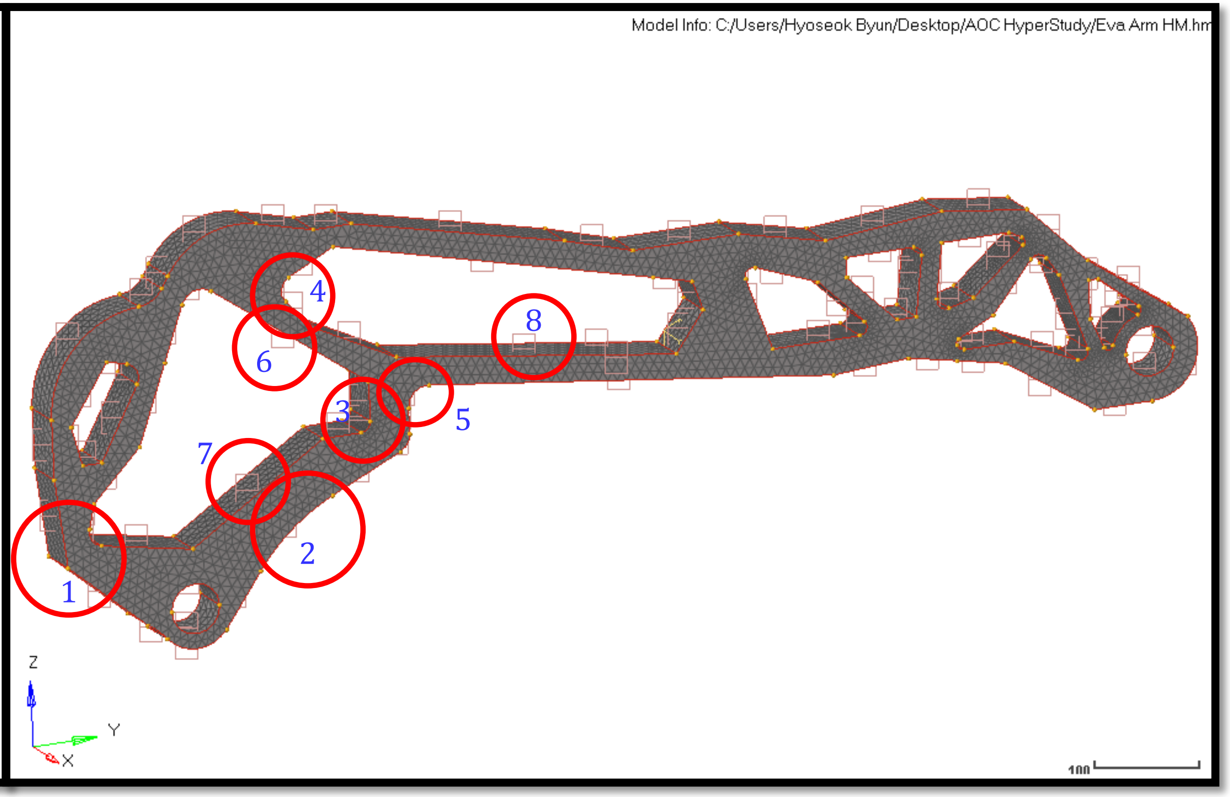


Define arm design through topology optimization result

3. Size Optimization - HyperMorph



Analysis Model



Define shapes model

Define 8 shape variable from analysis result

3. Size Optimization - HyperMorph

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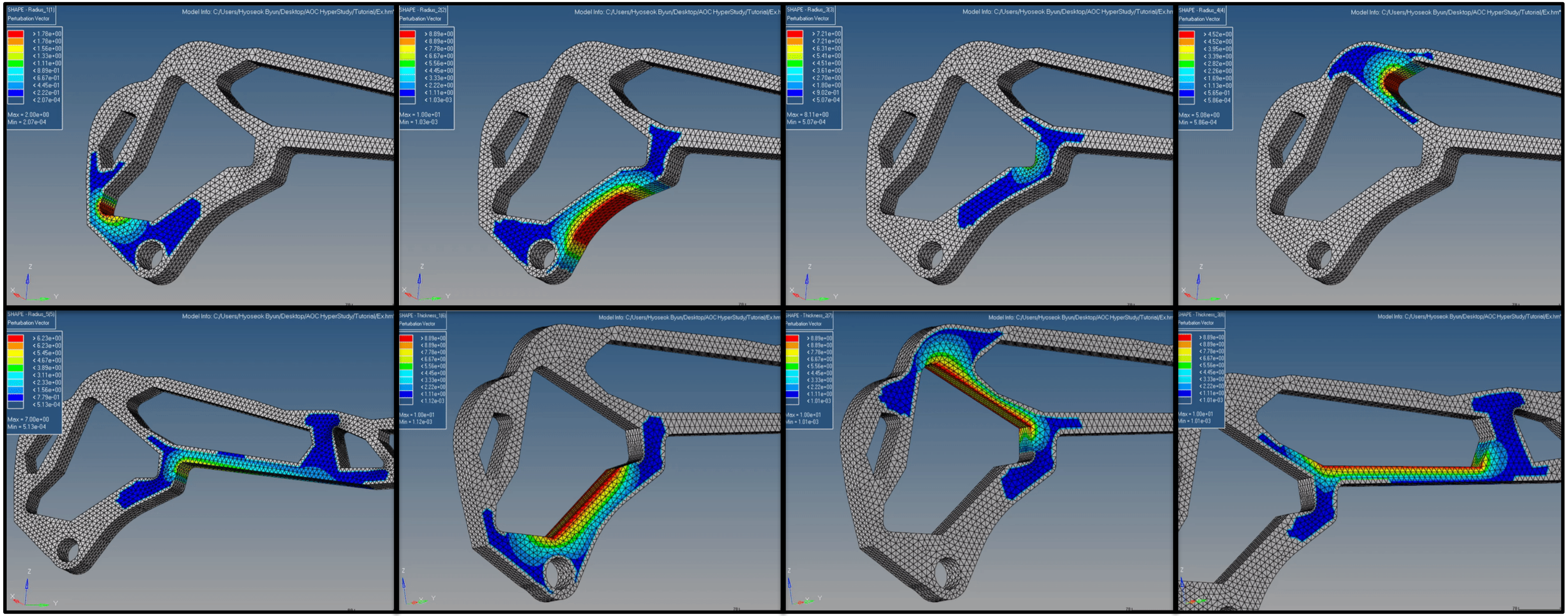

Define 8 shape variable from analysis result by HyperMorph

3. Size Optimization – HyperStudy

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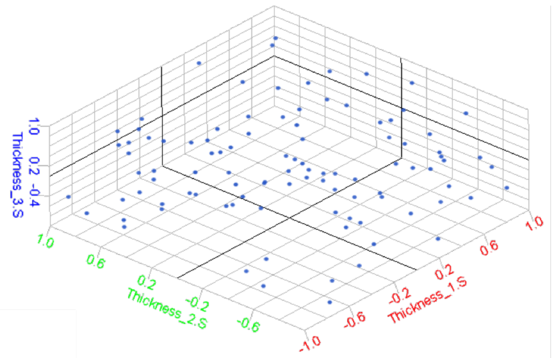
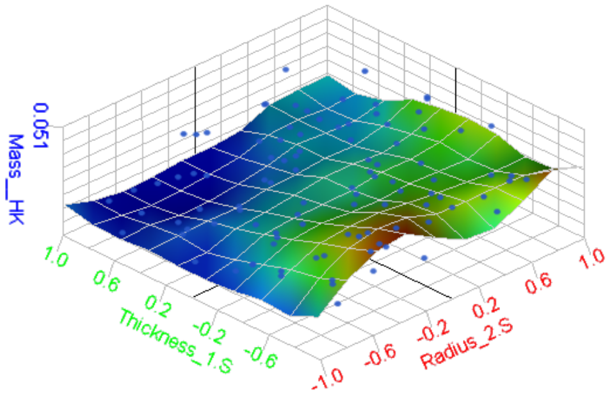


Latin Hypercube Sampling
Screening

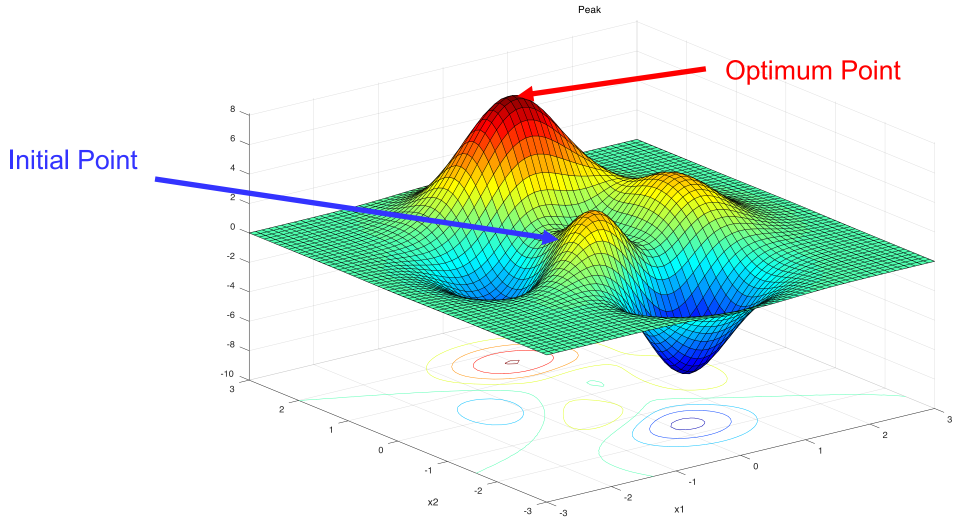
Design of Experiment

Fit

Optimization



Hyper Kriging
Validate Model



Surrogate Model-based
Design Optimization

Formulation	
Minimize	*Mass*
s.t	$Von\ Mises\ Stress \leq 228MPa$ $Displacement \leq 0.5mm$ $-1 \leq Design\ Variables \leq 1$

3. Size Optimization – HyperStudy

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- Design of Experiments for Space Filling – Latin Hypercube Design

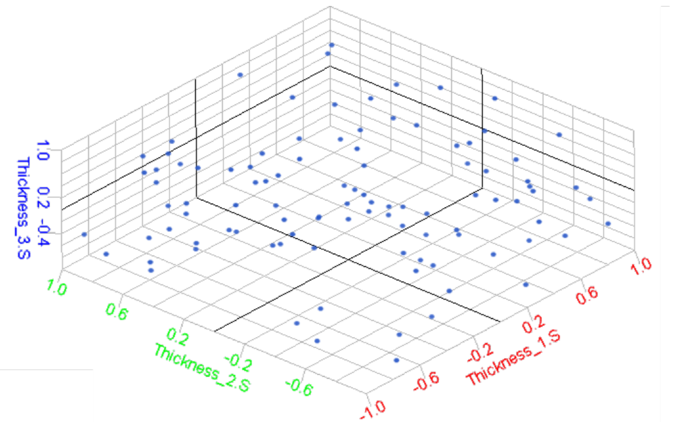
  Objective

  - Fewer factors
  - Model of relationships
  - Accurate prediction
  - Optimization

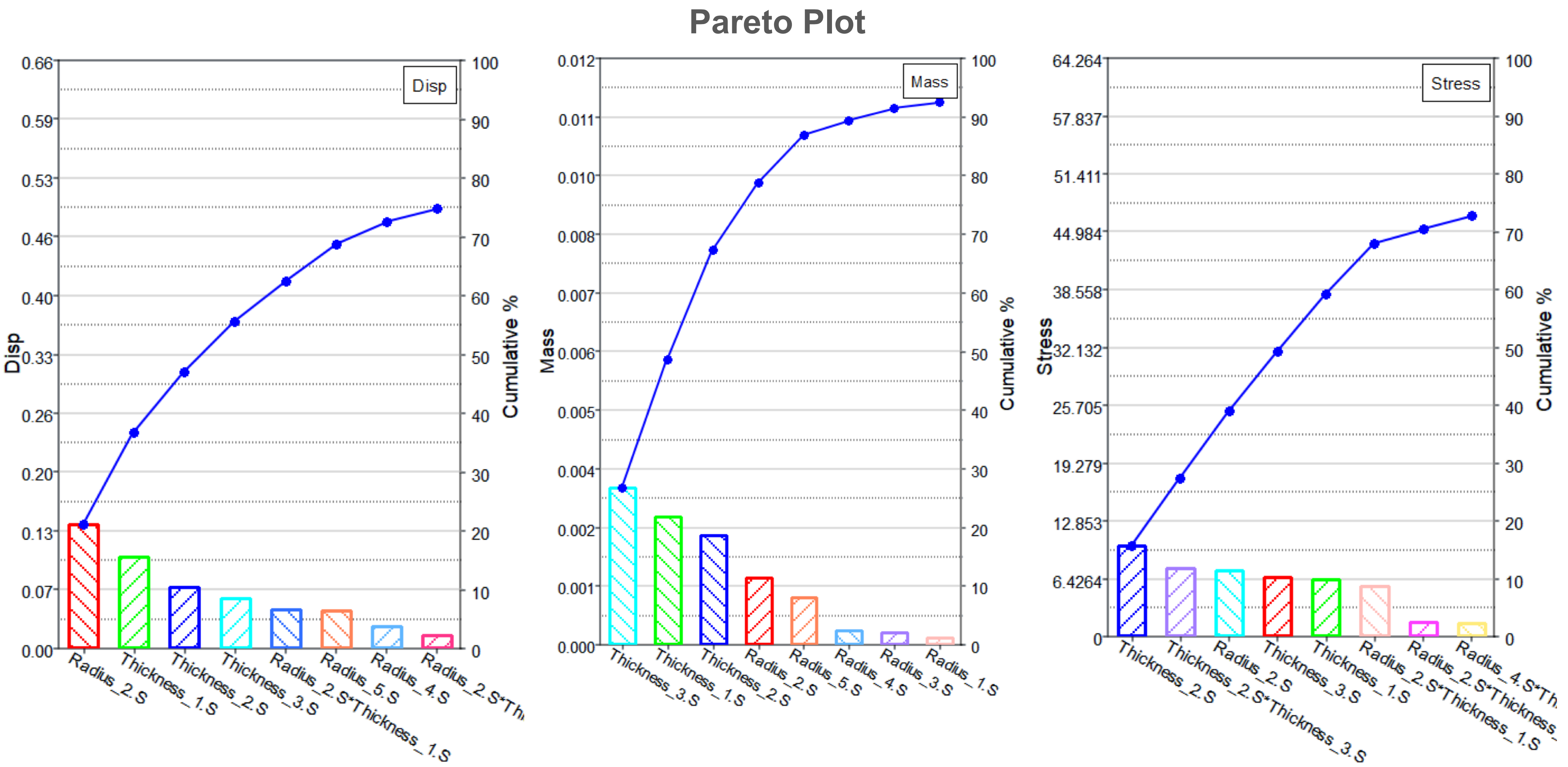
- Saturated Number – $\mathrm{nSAT} = \frac{(\mathrm{NDV}+1)(\mathrm{NDV}+2)}{2} = \frac{(8+1)(8+2)}{2} = 45$

  $\mathrm{NDV} : \mathit{Number\ of\ Design\ Variable}$

- Recommended sample points $\geq\ 2\times\mathrm{nSAT}$
- Set LHD sample points to $3\times\mathrm{nSAT} = 135$



3. Size Optimization – HyperStudy



3. Size Optimization – HyperStudy

Linear Effects

	Label	Varname	Disp	Mass	Stress
1	Radius_1.S	var_1	-0.0617628	0.0013611	-2.9473327
2	Radius_2.S	var_2	-0.1381821	0.0010573	-6.1109146
3	Radius_3.S	var_3	-0.0411535	7.63e-04	-1.0116503
4	Radius_4.S	var_4	0.0508906	-0.0010207	2.7931991
5	Radius_5.S	var_5	-0.0612039	0.0010263	-1.3187996
6	Thickness_1.S	var_6	0.1065944	-0.0028846	6.5367821
7	Thickness_2.S	var_7	0.0571644	-0.0022952	9.0335708
8	Thickness_3.S	var_8	0.0473969	-0.0032399	6.0765664

- From analysis the Pareto plot & Linear Effects, Radius_2(R2) , Thickness_1(T1), Thickness_2(T2), Thickness_3(T3) was governing the responses.
- So with 4 design variables, optimization progressed.

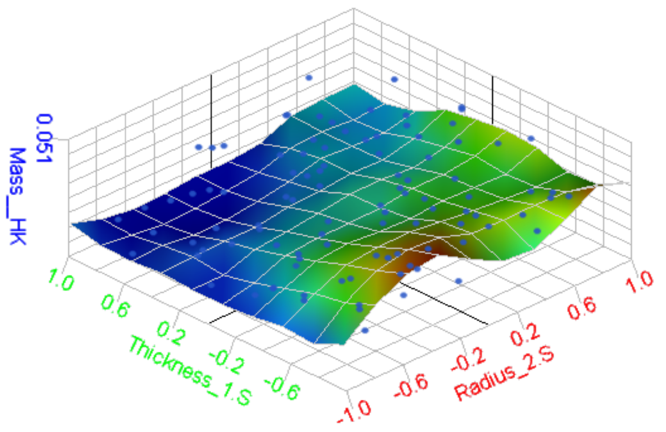
4 Design Variables(R2 T1 T2 T3) Selected

3. Size Optimization – HyperStudy

- Validation Methods – Interpolation model
  - R-square
    - Needs additional sample points
    - Impractical in practical application
    - A quantitative measure

$$R^2 = 1 - \frac{\sum_{i=1}^{n_v}\left(Y_i - \hat{Y}_i\right)^2}{\sum_{i=1}^{n_v}\left(Y_i - \bar{Y}\right)^2}$$

n_v : number of additional validation points



  - Cross – Validation approach
    - Uses the existing sample points
    - Refit models n- times
    - A qualitative measures
    - A measure to quantify insensitivity of surrogate model when a sample point is left out
    - Root Mean Square Error (RMSE)
      - A high quality fit will have a lower value

$$CV = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\hat{Y}_i(\mathbf{X_i}) - Y(\mathbf{X_i})\right)^2}$$

3. Size Optimization – HyperStudy

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Mass Hyper Kriging Diagnostics

	Criterion	Input Matrix	Cross-Validation Matrix
1	R-Square	0.9999974	0.9481137
2	Relative Average Absol…	7.84e-04	0.1896537
3	Maximum Absolute Err…	1.41e-05	7.50e-04
4	Root Mean Square Error	2.41e-06	3.39e-04
5	Number of Samples	134	134

Stress Hyper Kriging Diagnostics

	Criterion	Input Matrix	Cross-Validation Matrix
1	R-Square	0.9999993	0.9328972
2	Relative Average Absol…	3.91e-04	0.2078640
3	Maximum Absolute Err…	0.0222170	3.8403885
4	Root Mean Square Error	0.0040414	1.2540422
5	Number of Samples	134	134

Displacement Hyper Kriging Diagnostics

	Criterion	Input Matrix	Cross-Validation Matrix
1	R-Square	0.9999966	0.9308392
2	Relative Average Absol…	8.11e-04	0.2154982
3	Maximum Absolute Err…	7.96e-04	0.0383313
4	Root Mean Square Error	1.11e-04	0.0157300
5	Number of Samples	134	134

- From Cross-Validation results, conclude all kriging models are proper to use.
- Expected Accuracy of kriging model

$$\text{Mass} > \text{Displacement} > \text{Stress}$$

3. Size Optimization – HyperStudy

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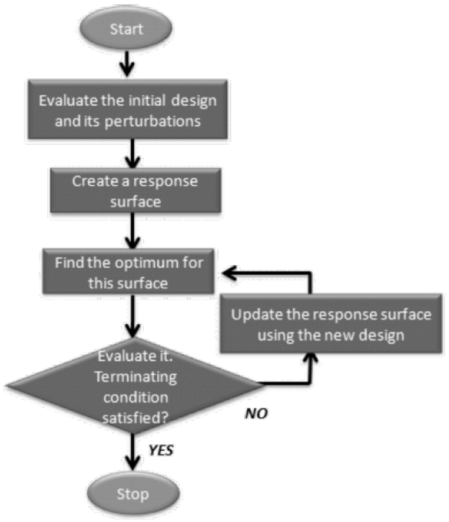
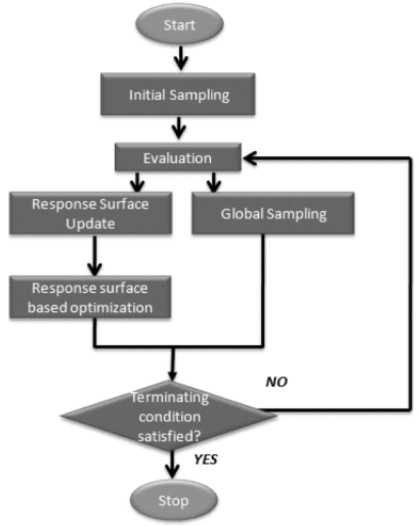
ARSM

Number of Evaluations	24
Absolute convergence	0.0010000
Relative convergence (%)	1.0000000
Constraint violation tol. (%)	0.5000000
Design variable convergence	0.0010000
On failed evaluation	Ignore failed evaluations



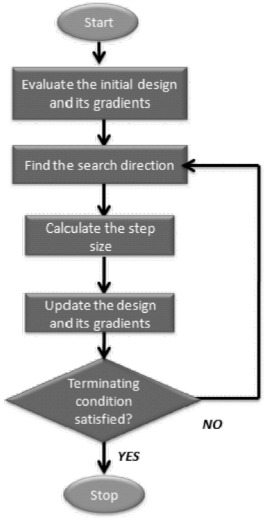
GRSM

Number of Evaluations	50
On failed evaluation	Ignore failed evaluations



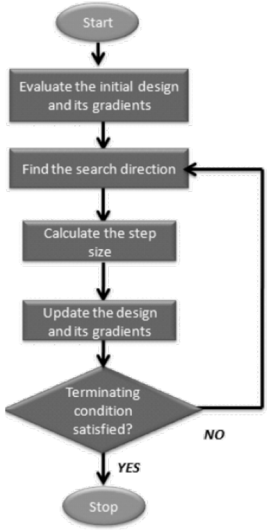
SQP

Maximum Iterations	25
Constraint violation tol. (%)	0.1000000
Design variable convergence	0.0000000
On failed evaluation	Ignore failed evaluations



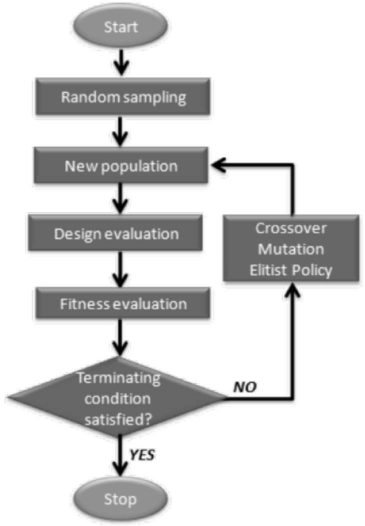
MFD

Maximum Iterations	25
Absolute convergence	0.0010000
Relative convergence (%)	1.0000000
Constraint violation tol. (%)	0.5000000
On failed evaluation	Ignore failed evaluations



GA

Maximum Iterations	50
Minimum Iterations	25
Population size	84
Global search	2
Constraint violation tol. (%)	0.5000000
Type	Real
On failed evaluation	Ignore failed evaluations



Set options default value and used all algorithms and compared the results

3. Size Optimization – HyperStudy

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First Trial

Algorithm	Radius_2	Thick_1	Thick_2	Thick_3	Dis	Mass	Stress	Condition
Initial	0	0	0	0	0.4521356	0.0465194	21.012781	Feasible
GA	0.4947566	0.7516936	0.9999919	0.9999729	0.5024877	0.043717	35.44546	Acceptable

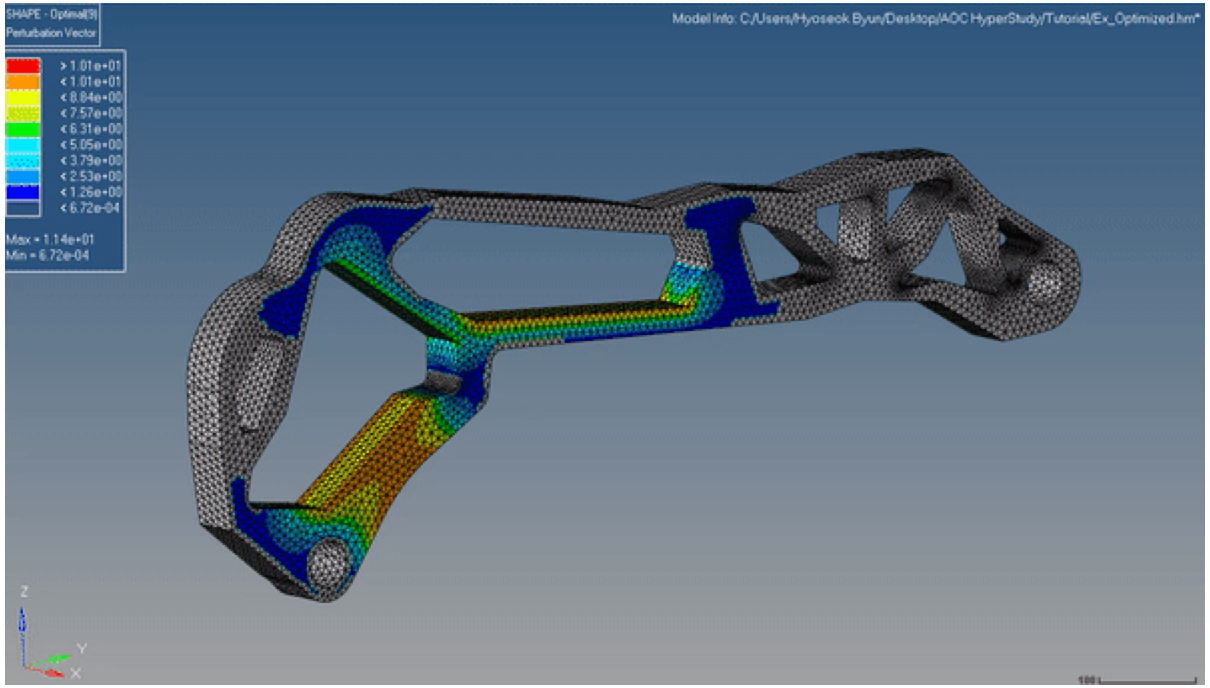
- Because other algorithms are affected by initial value, first used Genetic Algorithm and then use the result to initial value

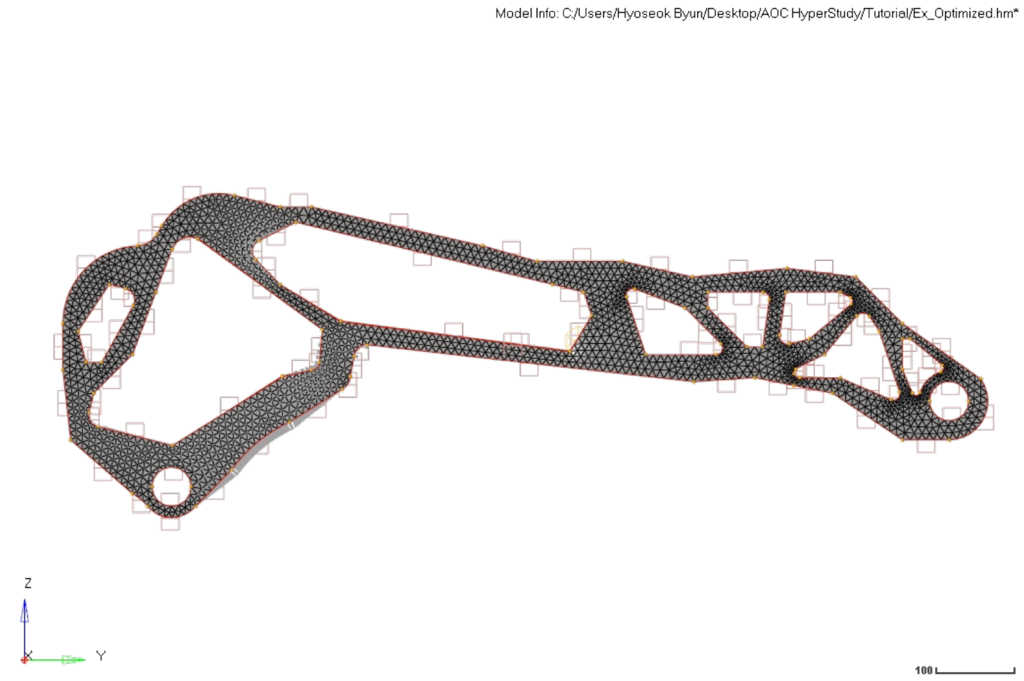
Second Trial

Algorithm	Radius_2	Thick_1	Thick_2	Thick_3	Dis	Mass	Stress	Condition
Initial	0.4947566	0.7516936	0.9999919	0.9999729	0.5024877	0.043717	35.44546	Acceptable
ARSM	0.4583464	0.819414	1	1	0.5007391	0.043733	35.96158	Acceptable
GRSM	0.7814154	0.9974211	0.8725204	0.9981926	0.5022103	0.043552	33.7651	Acceptable
SQP	0.438694	0.8460709	1	1	0.4999803	0.04374	36.16379	Feasible
MFD	0.4902443	0.7607944	1	1	0.5024021	0.043716	35.51739	Acceptable

MFD's result selected

3. Size Optimization – HyperMorph





	Mass	Stress	Displacement
Initial	46.5194kg	21.012781MPa	0.4521356mm
Optimized	43.716kg	35.51739MPa	0.5024021mm
Conclusion	**6.026%↓**	**Feasible**	**Acceptable**

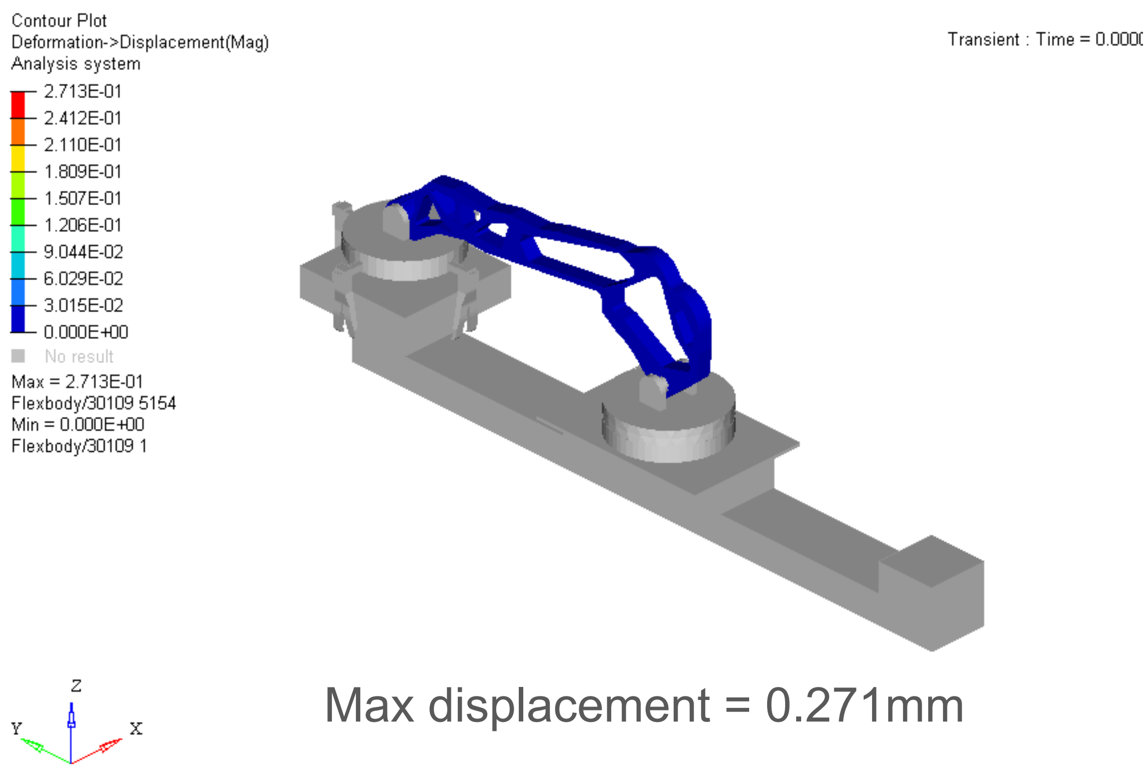
3. Productivity Check – Click2Cast

Material	Elastic Modulus [GPa]	Elongation at Break [%]	Fatigue Strength [MPa]	Poisson's Ratio	Reduction in Area [%]	Shear Modulus [GPa]	Tensile Strength [MPa]	Ultimate Strength [MPa]
ASTM A216 cast steel	190	25 to 27	200 to 230	0.3	39	72	500 to 570	230 to 310
SAE-AISI 1035 steel	190	13 to 21	210 to 340	0.3	40 to 45	73	570 to 620	300 to 530

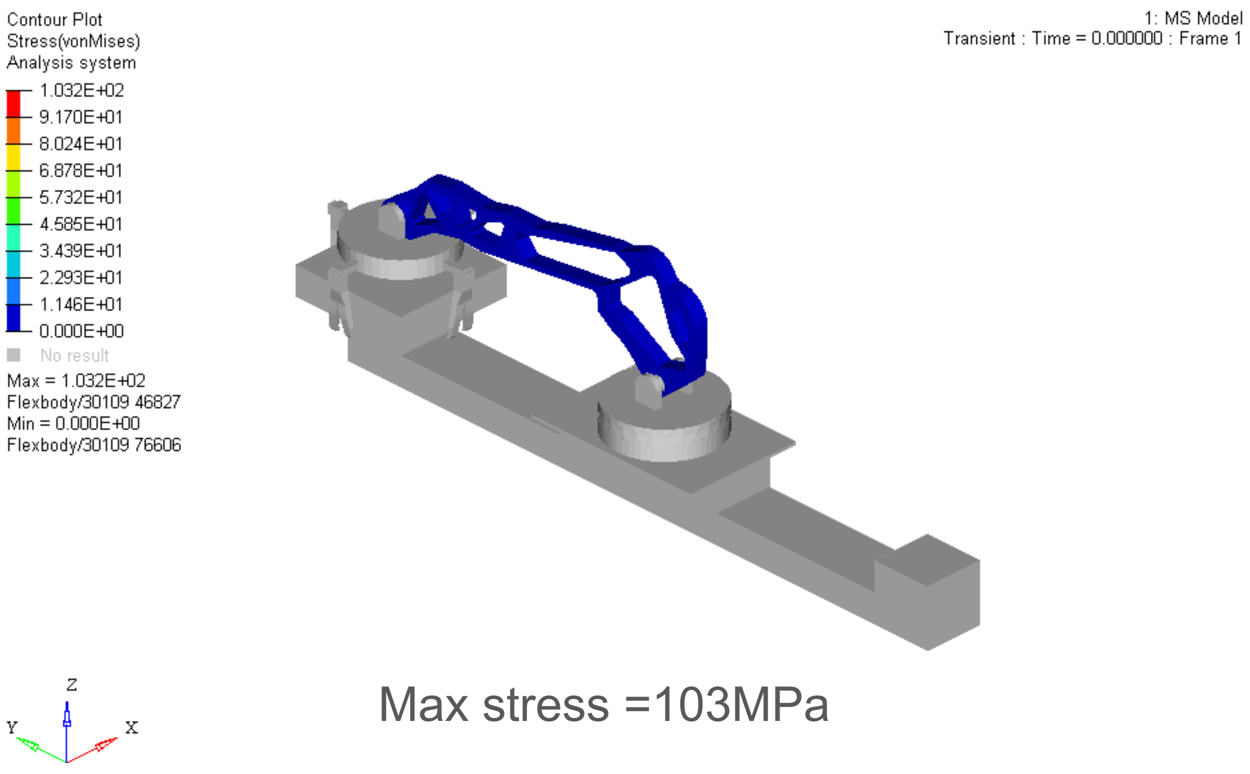
- Both ASTM A216 cast steel and SAE-AISI 1035 steel are iron alloys
- Including mechanical properties, 29 material properties value for both materials are similar
- **To produce robot arm by casting method, SAE-AISI 1035 steel can be replaced with ASTM A216 cast steel**

https://www.makeitfrom.com/compare/ASTM-A216-Cast-Carbon-Steel/SAE-AISI-1035-G10350-Carbon-Steel

3. Design Validation - MotionSolve



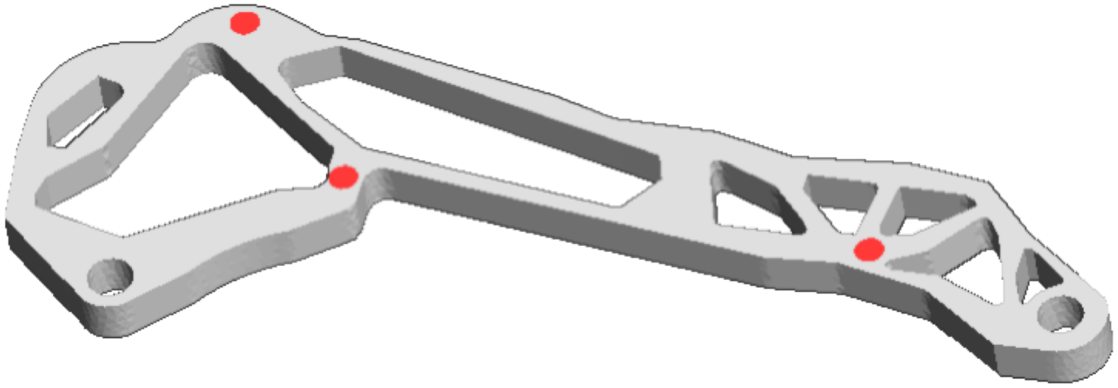
Max displacement = 0.271mm



Max stress =103MPa

- As a result of the dynamic analysis, displacement and stress do not exceed the constraint
- In particular, displacement which was an active constraint, was included the feasible region with enough margin

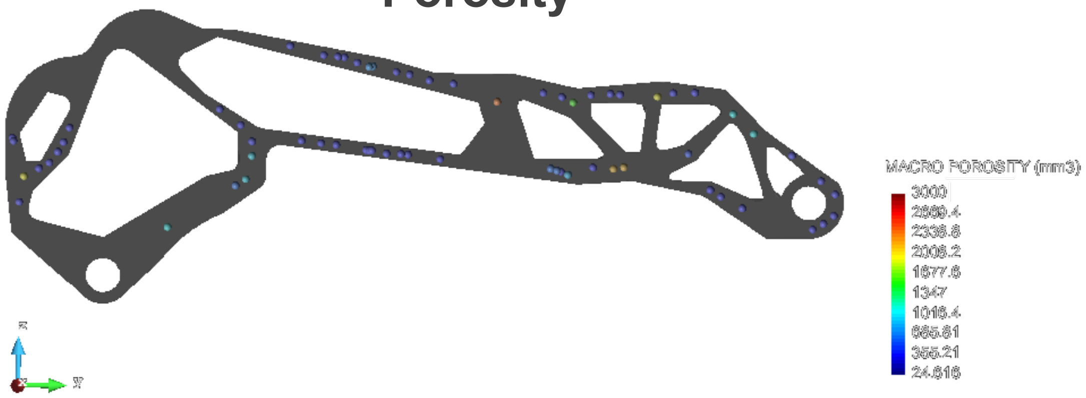
3. Productivity Check – Click2Cast



: Inlet

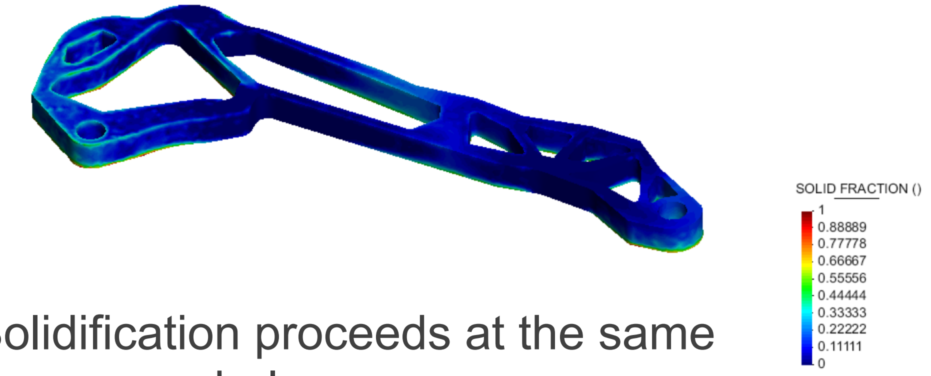
Flow Front

Porosity



Porosities are enough to small

Solid Fraction



Solidification proceeds at the same time as a whole

- **No problem to product robot arm**

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4. Conclusion

4. Conclusion

Design goal decision

↓

Conceptual robot design

↓

Dynamic analysis

↓

Topology & Size optimization

↓

Final model validation

↓

Robot arm design that meets all target performance

4. Conclusion

- Find critical moment by dynamic analysis and analysis that moment
- There may be moments that are not the most critical, but can be influential to robot arm enough
- Displacement constraint is too tight compared to stress constraint
- It is expected that smaller mass robot arm can be design if optimization process performed in dynamic condition with weak displacement constraint

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Thank you