Precision Machine Deterministic Design Process for a New Machine

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Precision Machine Deterministic Design Process

1. Based on customer degrees of freedom needed, determine number of coordinate systems needed to model the machine
2. Initially apportion (budget) allowable errors (i.e., how accurate each axis and its components) will need to be so when assembled the machine has a good chance of meeting requirements
3. Investigate potential strategies wrt considerations of ergonomics, cost and potential to meet accuracy goals
    1. Use preliminary analysis of structure and bearings for each strategy
4. For the "best" strategy, create concept ideas
    1. FUNdaMENTAL Principles will be key to rationally creating potentially workable designs
5. Use preliminary analysis of structure and bearings for each concept
    1. Select "best" concept(s)
6. Create detailed error budget where machine structure and elements are sized based on the preliminary analysis
    1. Evolve machine structure and elements (using of course FUNdaMENTAL Principles such as Reciprocity, Abbe Errors, Preload, Centers of Action, Self Help, Parallel Axis Theorem…)
7. Detail design, build, test, compare to prediction (close the design loop)

Step 1: Number of Coordinate Systems

- Verify degrees of freedom (dof) required
- Nominally the number of Coordinate Systems (CS) required to model the machine to be designed equals degrees of freedom required
- Sometimes a complex structure (e.g., an Γ shape) may warrant an extra CS to make modeling the structure more manageable
- To be conservative for the initial model, make #CS = dof + 1

Example: Customer requires…

- 1.5 meter reach arm
- Three degrees of freedom
  - Very open work environment needed
  - System must retract and get out of the way when not in use
- 0.1 mm endpoint accuracy

Steps 1 & 2

- #CS required = 3 dof + 1 = 4

Axis_error_apportionment_estimator.xls								
To apportion errors between types and axes. By Alex Slocum, last modified AHS 2017.03.15								
Enter numbers in **BOLD,** Results in **BLUE**								
# coordinate systems in model, N	**4**							
Total allowable error, dtot (mm)	**0.1**	what the customer wants from their machine						
				Apportion of error within each axis (amount allocated to each of X, Y, Z directions) to be determined by sensitive directions				
				Bearings (fb)	Structure (fs)	Actuator (fa)	Sensor (fs)	Cables (fc)
				Relative importance factor				
Source of error	Importance Factor (f)	Apportion of error (dtot/f)	Apportion of error per axis	1	0.5	0.2	0.2	0.2
Based on linear sum of errors								
Geometric, fg	1.0	0.050	0.013	0.006	0.003	0.001	0.001	0.001
Thermal, ft	0.5	0.025	0.006	0.003	0.001	0.001	0.001	0.001
Load-induced (deflection), fl	0.5	0.025	0.006	0.003	0.001	0.001	0.001	0.001
Process, fp	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Based on root square sum of errors								
Geometric, fg	1.0	0.082	0.041	0.035	0.017	0.007	0.007	0.007
Thermal, ft	0.5	0.041	0.020	0.017	0.009	0.003	0.003	0.003
Load-induced (deflection), fl	0.5	0.041	0.020	0.017	0.009	0.003	0.003	0.003
Process, fp	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Average (expected case) of linear and RSS							
Geometric, fg	1.0	0.066	0.027	0.020	0.010	0.004	0.004	0.004
Thermal, ft	0.5	0.033	0.013	0.010	0.005	0.002	0.002	0.002
Load-induced (deflection), fl	0.5	0.033	0.013	0.010	0.005	0.002	0.002	0.002
Process, fp	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Step 3

- The bearing requirements are not too severe
  - ABEC 5 bearings can easily achieve 0.02 mm (10 micron) geometric accuracy, and be sized so <0.01 mm deflection under load
- Structure:
  - A 1.5 m reach structure can easily be made accurate to 0.01 mm

Step 3 (cont'd)

- Not feasible to have cantilever structure <0.01 mm deflection under load of its own weight:

Cantilever arm structure loaded under its own weight	
length (mm)	1500
Section	round
Outside diameter (mm)	100
wall thickness (mm)	6
2nd moment area I (mm^4)	1964991
Cross section area (mm^2)	1772
Material	aluminum
Young's Modulus (N/mm^2)	66667
Density (g/cm^3)	2.7
Deflection	
assume N X own weight to account for other components	2
Uniform loading (N/mm)	0
Deflection cantilever beam unifirmly loaded (mm)	0.453

- Gravity is very repeatable, so the deflection as a function of position of the arm can be calculated (or mapped) and countered by the control system
  - Reference: This is commonly done in commercial robots