Assembly Fine Motions

- Goals of this class
  - outline the basic issues of assembly in the small
  - how to look at and take apart a product
  - characterize assembly motions
  - model motions in 3 dimensions
  - relate motions and forces using vector-matrix models

Basic Issues in Assembly in the Small

- The steps are:
  - understand each assembly step in detail
  - do conventional Design for Assembly
  - identify high risk areas
  - identify necessary experiments
  - recommend local design improvements

Greg Blonder Video (17 min of 1:45)

- Talk given at Bell Labs Jan 16, 1990
- Has been analyzing precision consumer products for about 5 years
- Takes about a day to analyze each one
- Takes apart and analyzes a $100 Canon camera
- Classifies ~ 400 parts including 60 screws (!)
- Tells what it means to get high assembly yield
- Tries to explain it to a high level executive
- Discusses shutter and flash subassemblies
- He later became a VP of Lucent

Understand Each Step

- Take the product apart (or use drawings if that's all you have)
- Get really familiar with every part and its role in the assembly (story: Yes, Alex)
- Make a structured bill of materials
- Draw a picture (2D is OK) of each part
- Make an exploded view drawing
- Choose any convenient assembly sequence
- Study each part mate and draw it, noting each place on each feature where the parts touch during assembly
- Note where the part can be gripped
- Note how the part can be fixtured before assembly
- Note any problems that could occur

Do Conventional DFA

- The issues are: (Boothroyd except where noted)
  - assembling each part -
    - feeding/presenting
    - handling/carrying/getting into position
    - inserting without damage, collisions, fumbling
  - reducing part count (driven by local economic analysis)
    - two adjacent parts of same material?
    - do they move wrt each other after assembly
    - is disassembly needed later (use, repair, inspection, upgrade...)
    - the part is a main function carrier?(Fujitsu)
    - if not, consider combining them (but see DFA class)
    - are there too many fasteners? (but see DFA class)
  - identifying cost drivers (Denso)

Identify High Risk Areas

- Showstoppers, safety, regulatory issues
- Do we understand the process?
  - Vague instructions: “use a small amount,” “wipe off excess,” “check for defects,” “clean” fiber
  - Tasks only one person can do
- Person can do it but can a machine??
  - Look for part damage, find a part that works better
- Unavailability of an otherwise attractive sequence
  - story: disassembly after balancing
- Inability to guarantee a constant task time
  - Calibration
- Typical errors: wrong part, incorrect assembly of a good part, correct assembly of a bad part

Identify Necessary Experiments

- Usually address high risk areas
- Determine physical feasibility
- Determine economic feasibility
- Generate metrics for successful assembly and means for detecting failures on the fly
  - cycle time
  - checks for part correctness/presence/placement
  - avoidance of parts damage
  - awareness of potential undocumented sources of trouble

Recommend Local Design Improvements

- These address the high risk areas as well as physical and economic feasibility
- There usually is no strategic or system content in these kinds of improvements
- “Assembly in the large” addresses such issues

Keep an Eye Out for Mysteries

- Parts or features that don’t seem to do anything
- Parts that look greatly over- or under-designed
- “Pay attention to what the fool says”

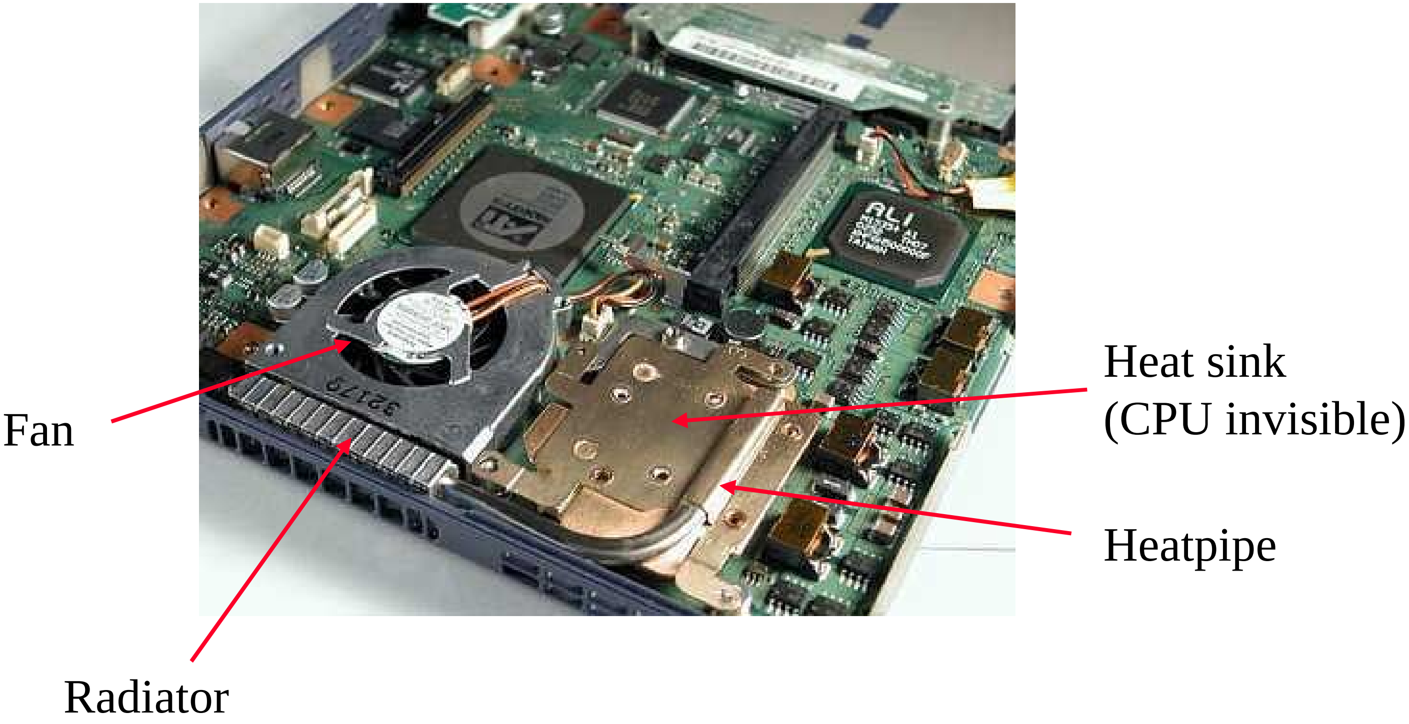
Hole in Battery-Operated Vac Housing

Images removed for copyright reasons.

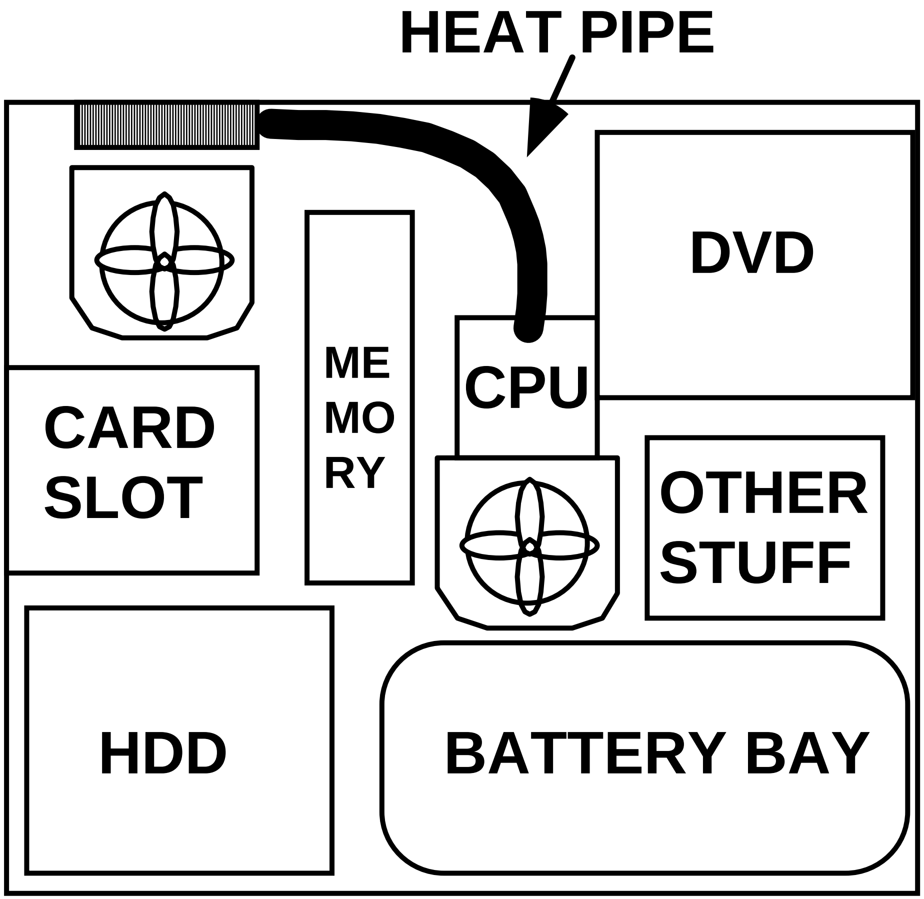
Source:

Figure 13-13 in [Whitney 2004] Whitney, D. E. *Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development*. New York, NY: Oxford University Press, 2004. ISBN: 0195157826.

Laptop Heat Removal



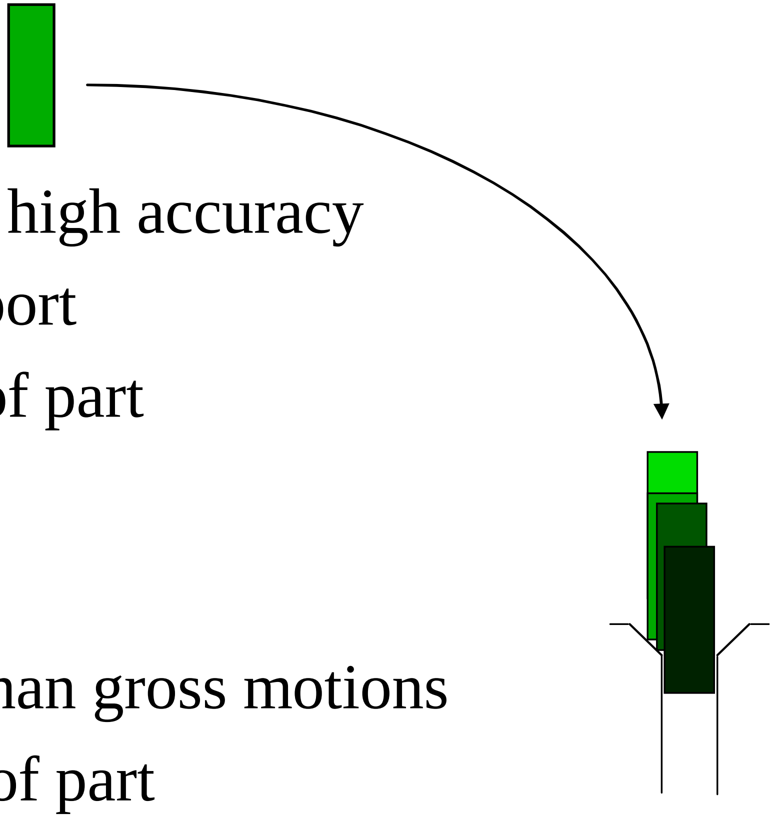
Gateway Laptop, 2002



Over-designed Part

Images removed due to copyright restrictions. (Photos of hinge mounts and heat pipe laptop parts.)

Gross and Fine Motions



- Assembly alternates between two kinds of motions:
- Gross motions
  - are fast and do not need high accuracy
  - basically used for transport
  - large compared to size of part
- Fine motions
  - need high accuracy
  - are likely to be slower than gross motions
  - small compared to size of part

Characteristics of Gross and Fine Motions

- Parts do not (should not) contact during gross motion
- Parts normally contact during fine motion
- Fine motion is basically a series of controlled contacts

Nature of Gross Motions

- Errors:
  - could happen
  - they can be seen but not felt *until too late*
  - people use sensors
  - machines use preplanning

- Preplanning:
  - is rewarded
  - errors can be catastrophic
  - low cost to avoid them
  - savings are reaped many times
  - characterized by “structure” - an open loop approach

Nature of Fine Motions

- Errors:
  - are unavoidable for reasonable cost
  - they can be felt but not seen
  - they generate signals that can be used to correct them

- Preplanning:
  - is not rewarded
  - even tiny errors can stop some tasks
  - cost of avoiding them grows too fast as their size shrinks
  - a closed loop approach is suitable

Essence of Force Feedback Fine Motions

- Make a model of the process, giving forces that result from various classes of geometric errors
- Invert the model so that sensed forces can be used to estimate the errors
- Make up a strategy that generates corrective motions in response to specific errors
- Design a controller that will execute the response motions without going unstable
  - motion → force → motion → force → etc!

Multi-axis Force-Fine Motion Models

Images removed for copyright reasons.
Source:
Figure 9-2 in [Whitney 2004] Whitney, D. E.
Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development .
New York, NY: Oxford University Press, 2004. ISBN: 0195157826.

Typically requires a matrix relation between task coordinates X and command coordinates θ

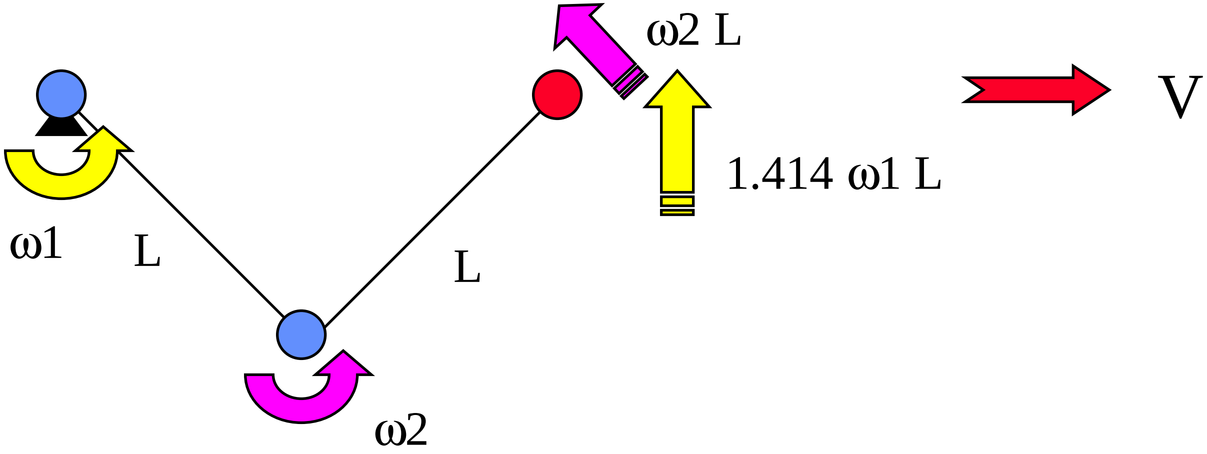
$$\dot{x} = J\,\dot{\theta}$$

$$\dot{\theta} = J^{-1}\,\dot{x}$$

Typically requires a matrix relation between sensed parameters and responses

$$\dot{x} = -K_f F$$

Differential Motion Analysis



X direction: = - 0.707 ω2 L

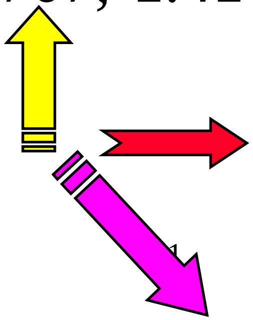
Y direction: = 1.414 ω1 L + 0.707 ω2 L

$$J = \begin{bmatrix} 0 & -0.707\ L \\ 1.414\ L & 0.707\ L \end{bmatrix}$$

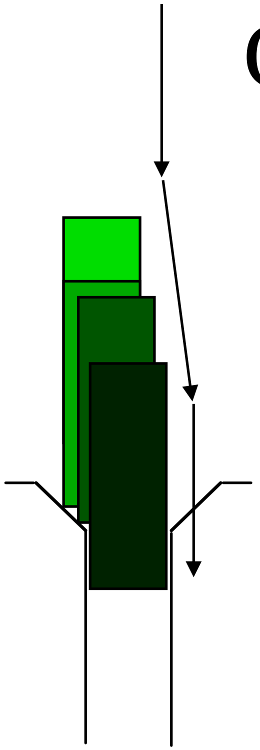
If $V=[1,0]^T$, then $\omega=[.707,-1.414]^T$

$$J^{-1} = \begin{bmatrix} 0.707/L & 0.707/L \\ -1.414/L & 0 \end{bmatrix}$$

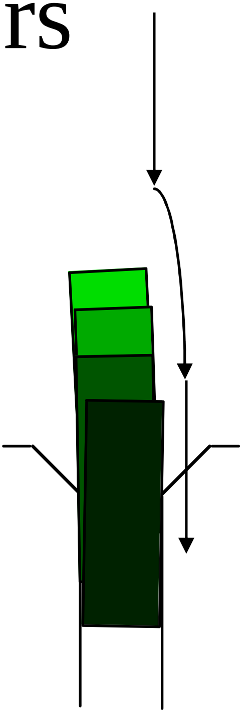
ω2=-2 ω1 for all joint angles



Typical Motion-Force Process with Geometric Errors



Lateral error requires lateral motion to correct it

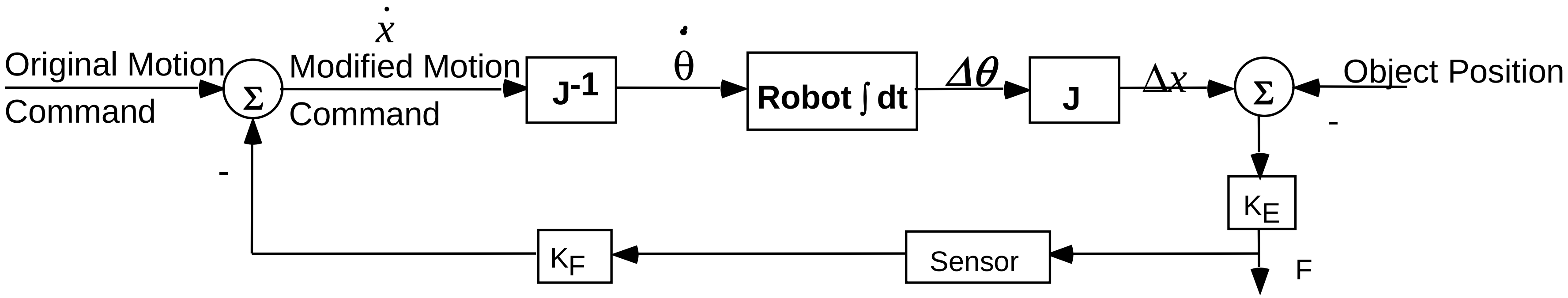


Angular error requires angular motion to correct it

Active Force-Motion Strategy

Image removed for copyright reasons.
Source:
Figure 9-3 in [Whitney 2004] Whitney, D. E. *Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development*. New York, NY: Oxford University Press, 2004. ISBN: 0195157826.

Closed Loop Force-Motion System



Actually modeled and analyzed as a sampled time system. This allows us to “single step” through history, observing the dynamics as carefully as we want.

Force-Motion Stability

- Stability Criterion:
  - $K_F\ K_E\ \Delta T < 1$
- Essentially means that not all the accumulated contact force can be removed during the next ΔT
  - see next slide
- Problem is made worse by stiff coupling to environment
- Problem is made better by faster sampling, up to a point

The Stability Criterion in Words

$$K_F K_E \Delta T < 1 \quad (1)$$

$$\Delta X_{i+1} = V_i \Delta T$$

$$\Delta F_{i+1} = K_E \Delta X_{i+1}$$

$$V_i = K_F F_i$$

$$multiply\ both\ sides\ of\ (1)\ by\ V:$$

$$K_F (K_E V_i \Delta T) < V_i$$

$$K_F \Delta F_{i+1} < K_F F_i$$

$$\Delta F_{i+1} < F_i$$

Motions Made by Choice of K_F

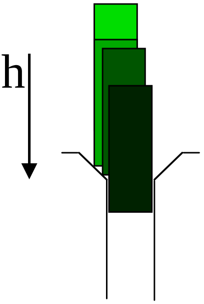
Diagonal K_F creates damping, nulling feedback

Cross terms in K_F turn sensed force into rotation or sensed torque into translation

Box packing, putting records on turntables, crank-turning

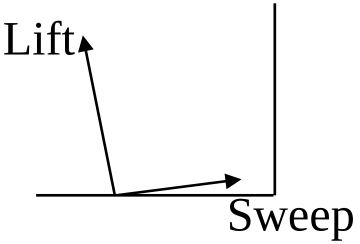
Some Force Feedback Matrices

Command Reach

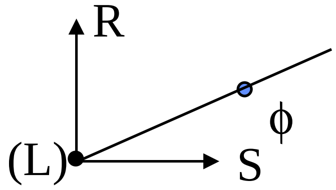


$$\begin{array}{l} R \\ S \\ L \\ Tw \\ Tn \\ Tl \end{array}\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & -100 & 0 & 0 & 0 & 0 \\ 0 & 0 & -100 & 0 & 0 & 0 \\ 0 & 0 & 0 & -100 & 0 & 0 \\ 0 & 0 & 0 & 0 & -100 & 0 \\ 0 & 0 & 0 & 0 & 0 & -100 \end{bmatrix}$$

Command -Lift



$$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -100 & 0 & 0 & 0 \\ 0 & 200 & -100 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$



Command -Lift

moment about reach =
$-F_{lift} R \sin \phi$
moment about sweep =
$F_{lift} R \cos \phi$

$$\begin{bmatrix} 0 & 0 & 0 & -V_R & 0 & 0 \\ 0 & 0 & 0 & 0 & V_R & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Lateral Error Can Become Angular Error with Disastrous Results