Introduction to Advanced LIGO Suspension Design and Development

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Part I

Advanced LIGO Suspensions Workshop, Caltech
14th October 2003

Suspension Team

- GEO (Glasgow and Hannover) : G Cagnoli, C. Cantley, D. Crooks, E Elliffe, S. Gossler, A. Grant, A Heptonstall, R. Jones, J. Hough, H. Lueck, M. Perreur-Lloyd, M. Plissi, P. Sneddon, K. Strain, S. Rowan, D. Robertson, H. Ward
- Caltech: H. Armandula, M. Barton, D. Coyne, L. Jones, J. Romie, C. Torrie, P. Willems
- Stanford: N. Robertson
- MIT: R. Mittleman, P Fritschel, D Shoemaker

Now joined by Rutherford Appleton Lab: J. Greenhalgh, I Wilmut

Suspension Design for GW Detectors

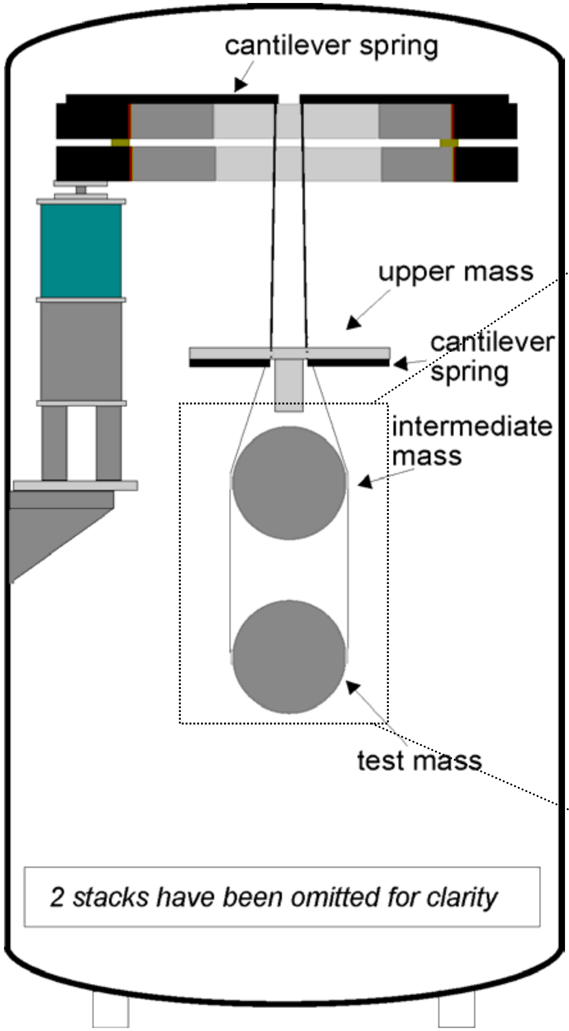
- **Requirements of suspension system**:
  - support the mirrors so as to minimise the effects of
    - thermal noise in the suspensions
    - seismic noise acting at the support point
  - allow a means to damp the low frequency suspension resonances (local control)
  - allow a means to maintain arm lengths as required in the interferometer (global control)

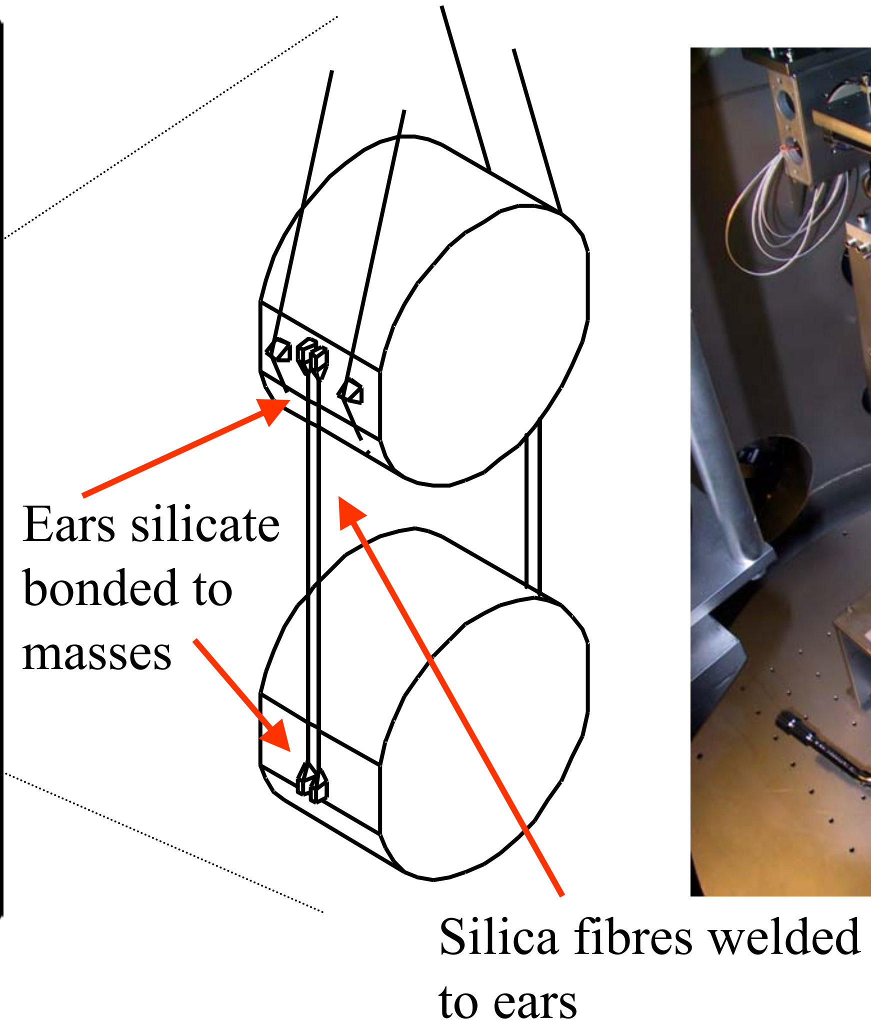
    while at the same time
  - not compromise the low thermal noise of the mirror
  - not introduce/reintroduce noise through control loops

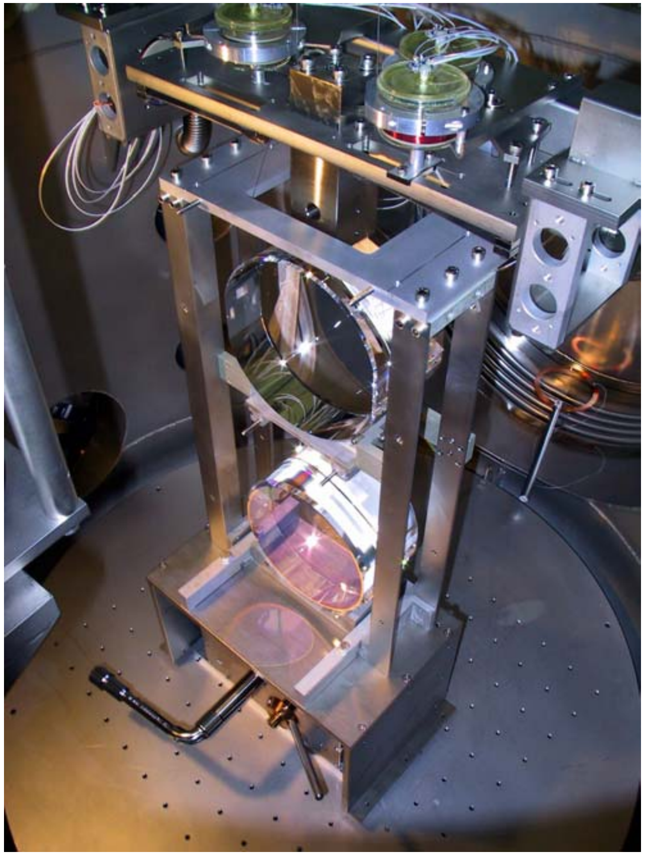
Suspension Design for Advanced LIGO

- Based on GEO triple pendulum design - key features:
  - *Monolithic fused silica suspension* as final stage for low pendulum thermal noise and preservation of high quality factor of mirror
  - *Triple* pendulum for horizontal isolation *+ 2 stages of maraging steel blades* for vertical isolation
  - *Local control* for damping of all low frequency pendulum modes by 6 co-located sensors and actuators *on topmost mass* for sufficient noise isolation: requires all low frequency modes observable at topmost mass
  - *Global control* at penultimate mass and at mirror (electrostatic at mirror) using adjacent “identical” *reaction pendulum as quiet reference*

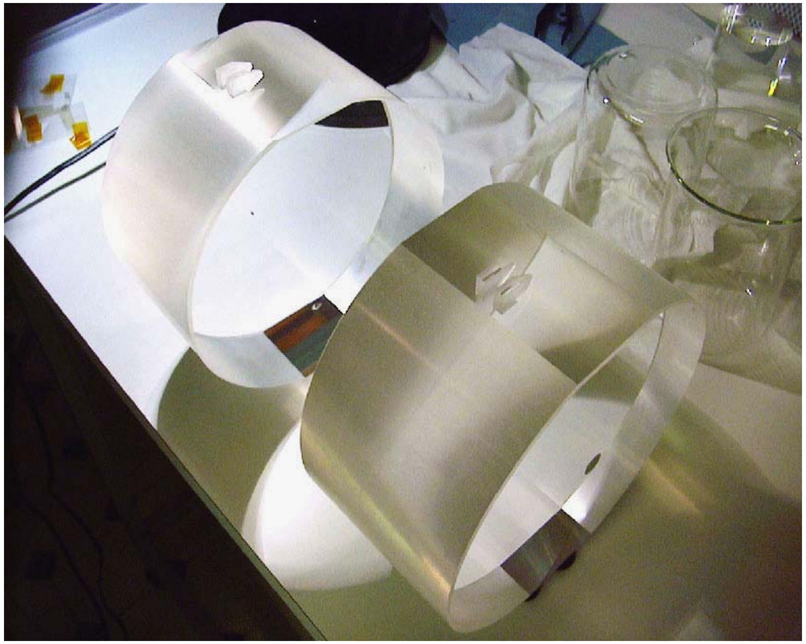
GEO Triple Pendulum Suspension



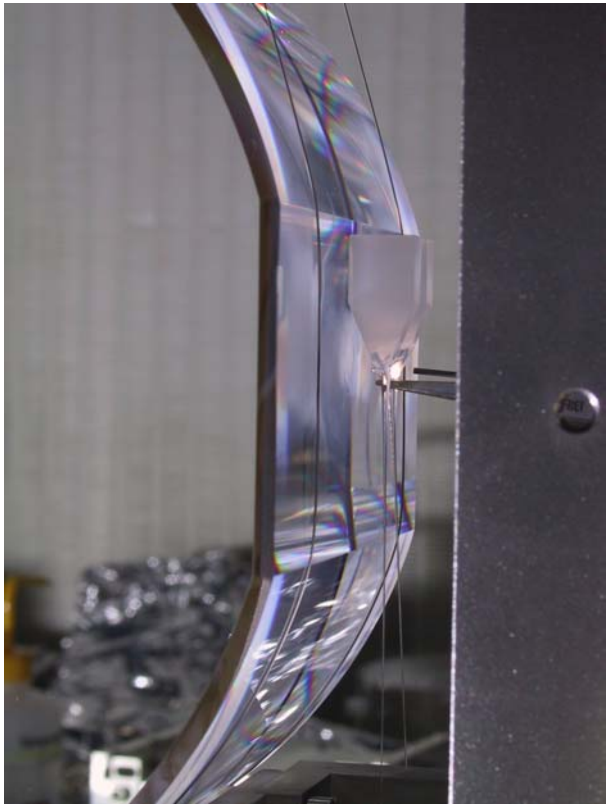




Monolithic Suspension - Assembly

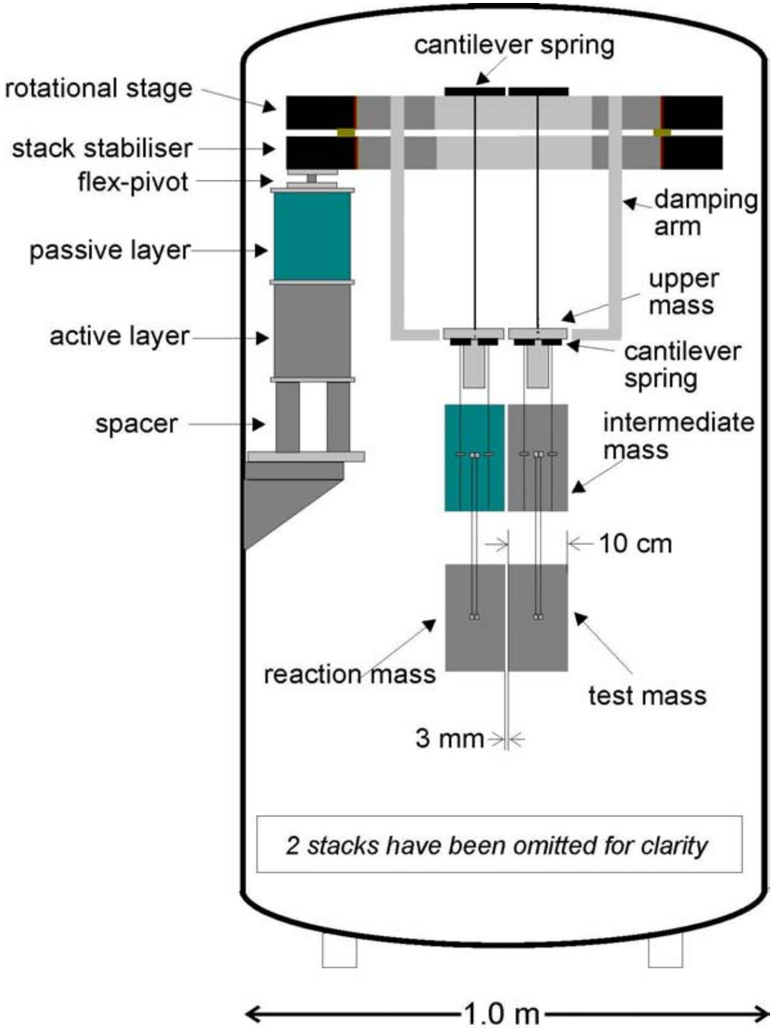


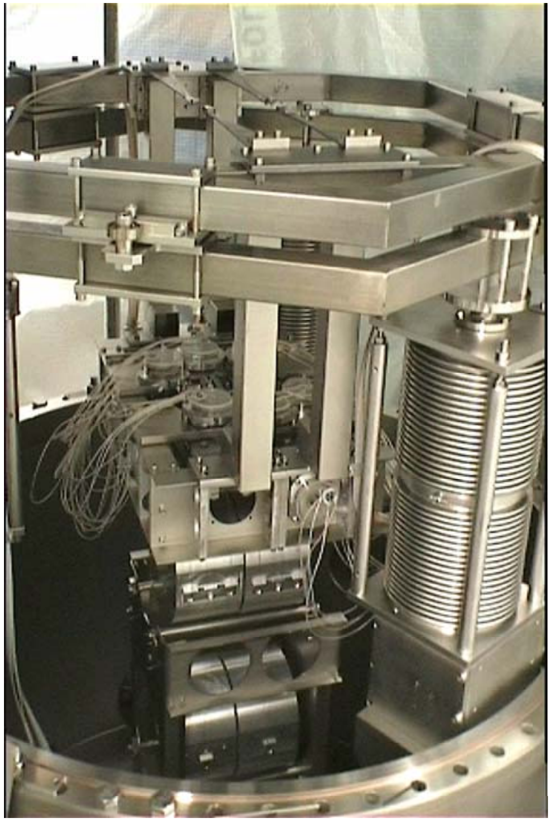
Bonding of ears



Welding of fibres

GEO 600 Suspension (side view)





Triple pendulum + reaction pendulum in situ (all metal)

Reaction mass with gold plated grid for electrostatic control

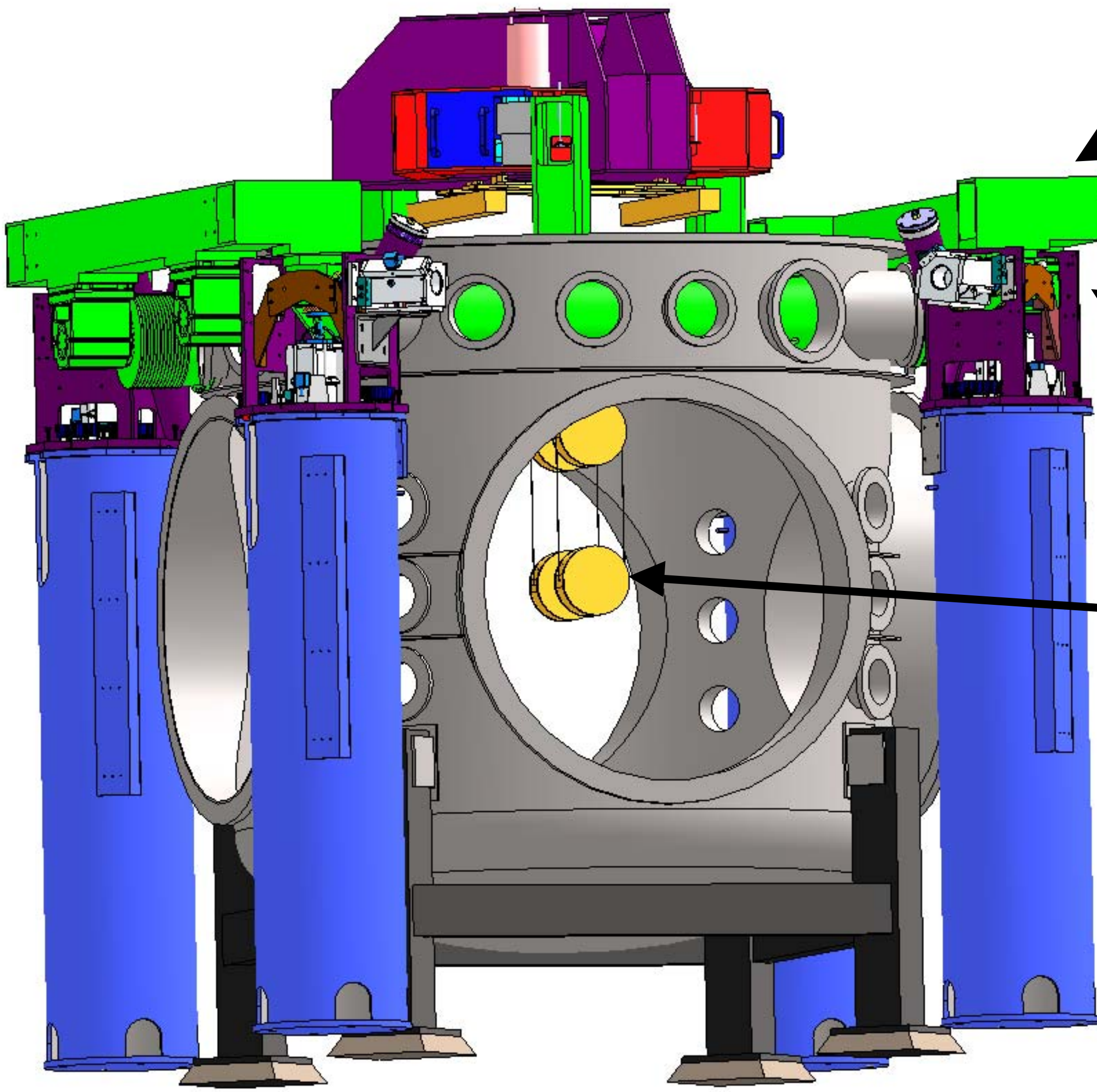
Extension of GEO Design to Advanced LIGO

- For the most sensitive optics - the test masses (ETM, ITM) - requirements on thermal, seismic and technical noise lead to baseline design:
  - 40 kg *sapphire* mass
  - use of *ribbons* or *dumbbell fibres* rather than simple cylindrical fibres
  - *quadruple* suspension
- Other main optics (beamsplitter (BS), modecleaner (MC), recycling mirrors (PRM, SRM), folding mirror (FM) , compensation plate (CP)): designs depend on particular requirements – some will be quads, some triples, some will have reaction chains, some not

References:

- Advanced LIGO Suspension System Conceptual Design T010103-02-D
- Cavity Optics Suspension Subsystem Design Requirements Document T010007-01 (currently being updated)

Advanced LIGO Suspension+ Isolation



Corwin Hardham

Plan of Action

- 3 *controls prototypes* for testing at LASTI: MC triple, RM triple, ETM quad
  - All metal assemblies for testing mechanical and control features
- 7 *noise prototypes* for LASTI: ETM, ITM, 3 MCs, 1 SRM, 1 PRM
  - These should be close to final design, incorporating sapphire/silica optics and silica suspensions where required
- Production and installation of 47 *final suspensions* in Adv LIGO (23 BSC, 24 HAM, not incl. spares)
  - Several different types of suspensions: ETM, ITM, BS, CP, FM, MC, RM + reaction chains as required.
  - All need individual designs

Initial Design Information

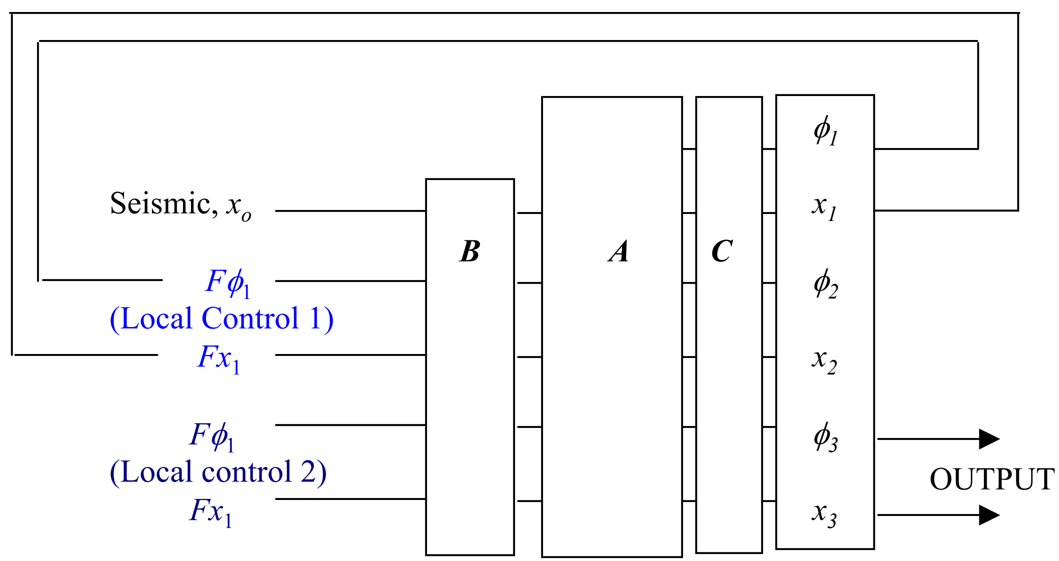
- Mass, dimensions and material of optic
- Requirements on thermal noise, seismic isolation, technical noise and control – leads to choice of:
  - number of stages
  - choice of silica or wire final stage suspension + X-section of fibre/wire
  - length of final stage
  - necessity or otherwise of reaction chain, and length of reaction chain
- Overall footprint available in tanks – leads to:
  - limit on overall length of suspension
  - limits on sizes of blades

Initial Design Rules

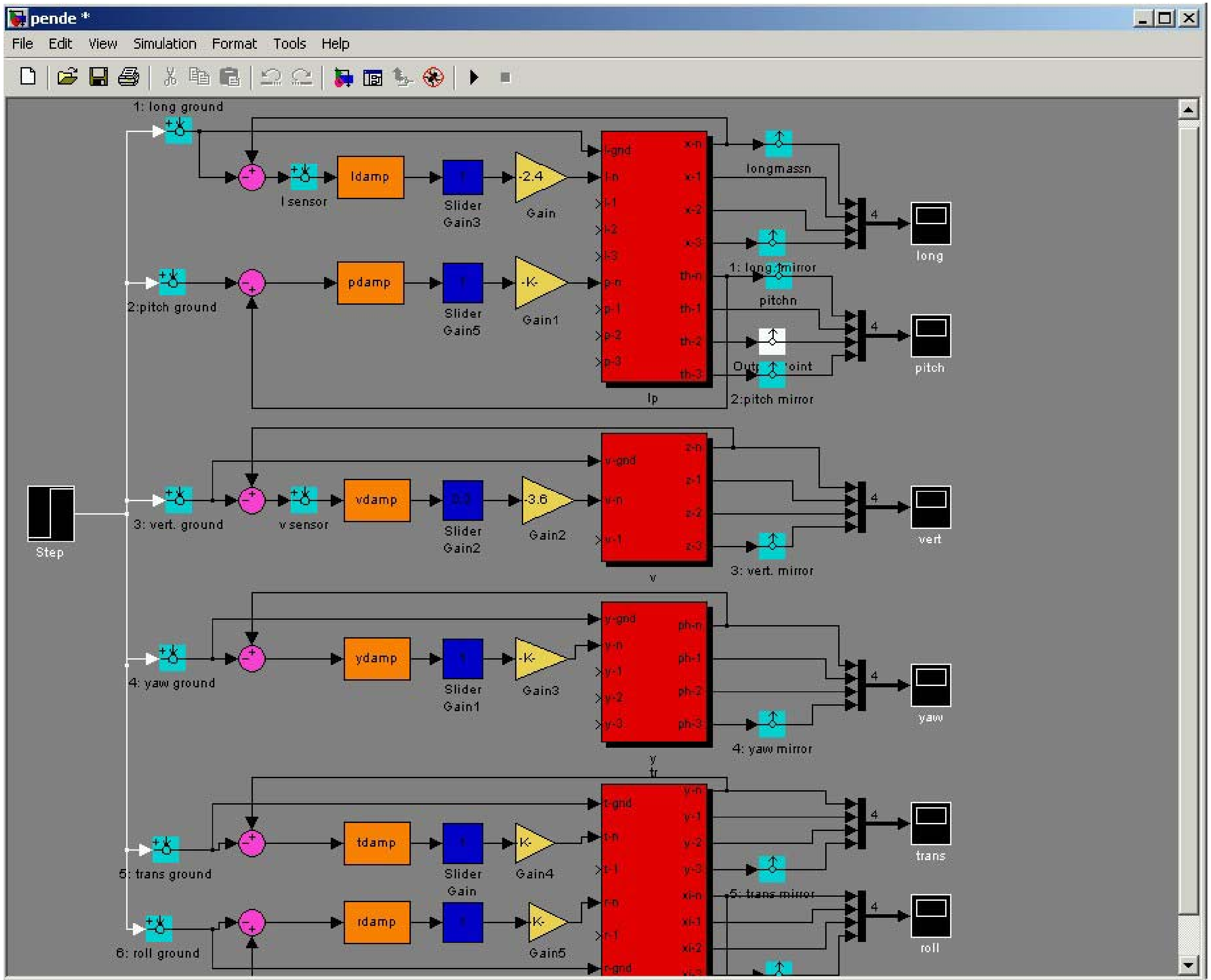
- Basic starting place:
  - where possible take previous “working” example and extend
  - ~ equal masses for each stage
  - ~ equal moment of inertia about the equivalent axis
  - ~ equal lengths
  - break off points +/-1mm w.r.t. line through the centre of mass
  - appropriate choice of spacing and angle of the wires
    - physically reasonable
    - coupling good in all dimensions

Design Tool – MATLAB/SIMULINK model

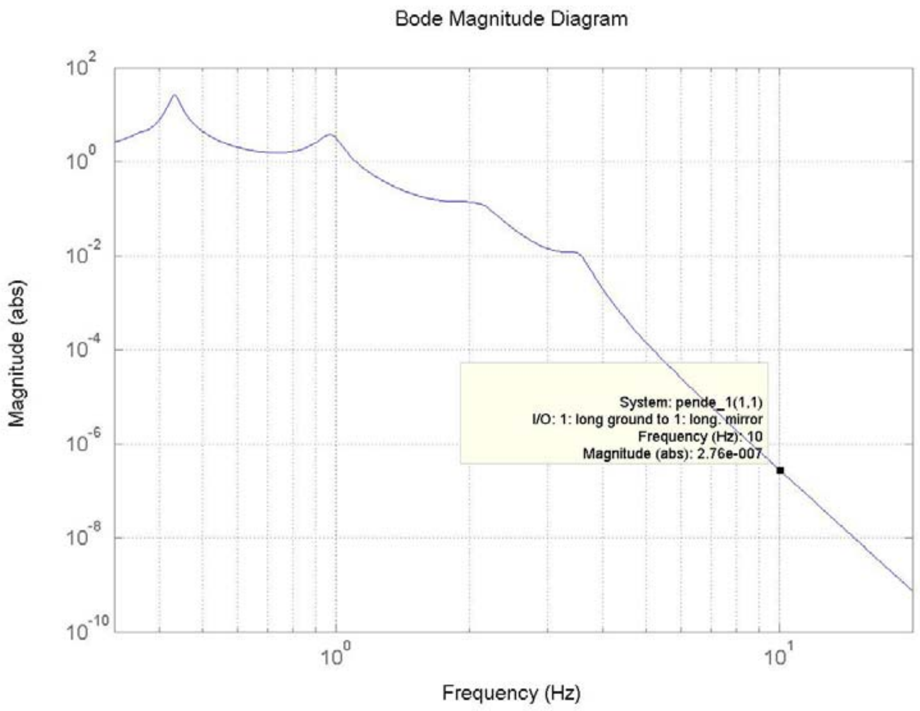
- State space representation of dynamics +control
- 6 degree of freedom with symmetry assumed
  - longitudinal+pitch
  - vertical
  - transverse+roll
  - yaw
- Input: trial parameter set
- Output: mode frequencies, transfer functions, impulse responses……
- Iterative process to arrive at "working" model with parameter set from which to start engineering design

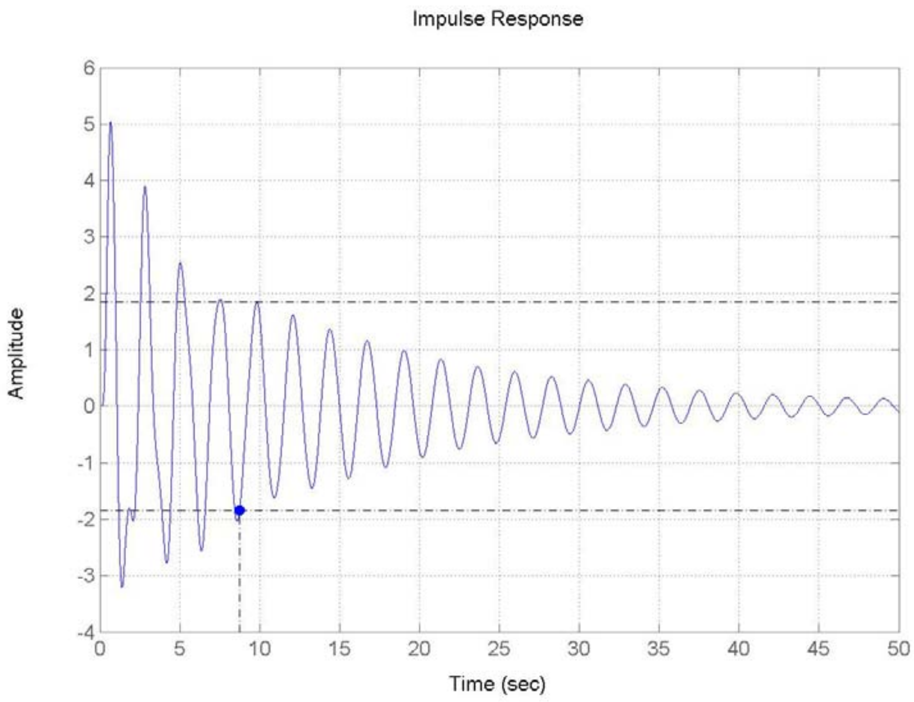


Design Tool – MATLAB/SIMULINK model

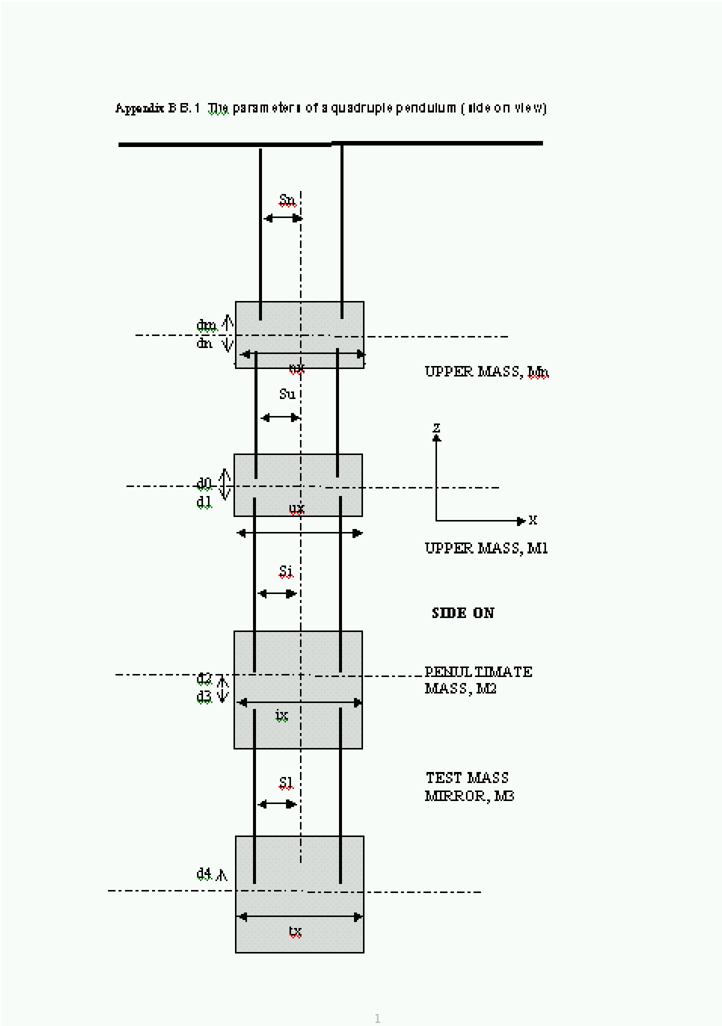


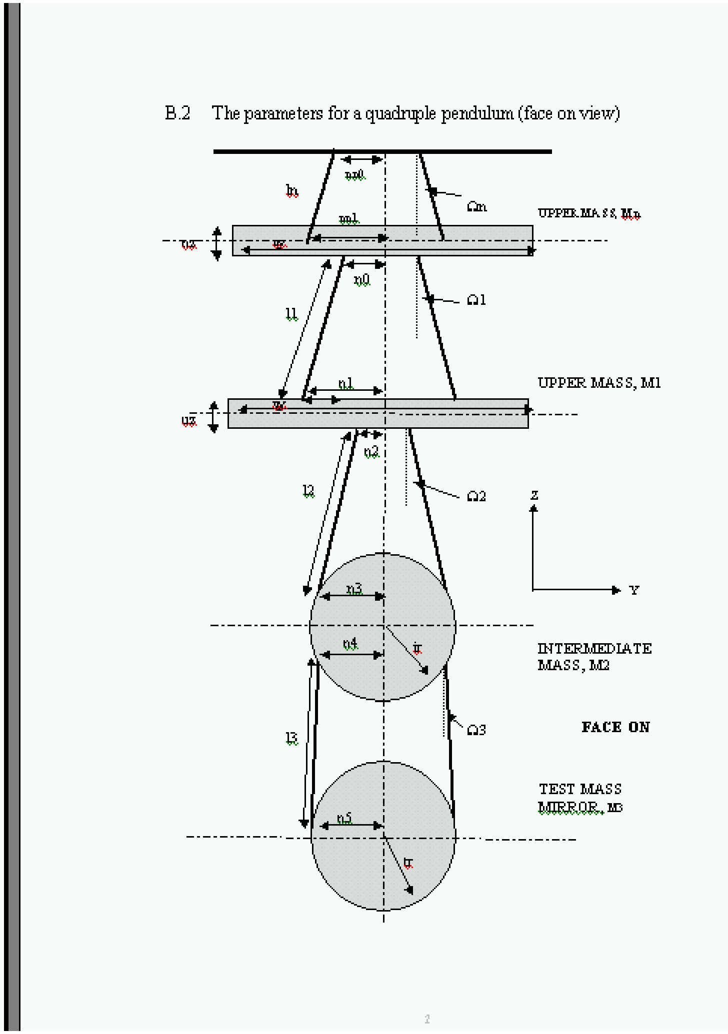
Examples of output: transfer function and impulse response for longitudinal direction





Pendulum Parameters





Typical output of parameters for a quad

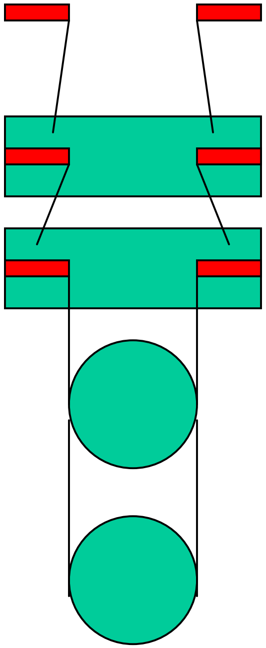
```
pend =  nx: 0.1300
        ny: 0.5000
        nz: 0.0840
      denn: 4000
        mn: 21.9000
       Inx: 0.4740
       Iny: 0.0713
       Inz: 0.4900
        ux: 0.1300
        uy: 0.5000
        uz: 0.0840
      den1: 4000
        m1: 21.8400
       I1x: 0.4678
       I1y: 0.0436
       I1z: 0.4858
        ix: 0.1300
        ir: 0.1570
      den2: 3980
        m2: 40.0660
       I2x: 0.4938
       I2y: 0.3033
       I2z: 0.3033
        tx: 0.1300
        tr: 0.1570
      den3: 3980
        m3: 40.0660
       I3x: 0.4938
       I3y: 0.3033
       I3z: 0.3033
        ln: 0.5400
        l1: 0.3040
        l2: 0.3020
        l3: 0.6000
       nwn: 2
       nw1: 4
       nw2: 4
       nw3: 4
        rn: 7.0000e-004
        r1: 4.0000e-004
        r2: 3.5000e-004
        r3: 2.0000e-004
        Yn: 2.2000e+011
        Y1: 2.2000e+011
        Y2: 2.2000e+011
        Y3: 7.0000e+010
       lnb: 0.4800
       anb: 0.0961
       hnb: 0.0045
      ufcn: 2.3596
       stn: 8.9910e+008
 intmode_n: 73.5303
       l1b: 0.4200
       a1b: 0.0583
       h1b: 0.0049
      ufc1: 2.5555
       st1: 8.9994e+008
 intmode_1: 104.5764
       l2b: 0.3400
       a2b: 0.0500
       h2b: 0.0045
      ufc2: 2.1106
       st2: 7.9192e+008
 intmode_2: 146.5517
        dm: 0.0010
        dn: 0.0010
        d0: 0.0010
        d1: 0.0010
        d2: 0.0010
        d3: 0.0010
        d4: 0.0010
twistlength: 0
      d3tr: 0.0010
      d4tr: 0.0010
        sn: 0
        su: 0.0030
        si: 0.0030
        sl: 0.0080
       nn0: 0.2500
       nn1: 0.0900
        n0: 0.2000
        n1: 0.0700
        n2: 0.1200
        n3: 0.1635
        n4: 0.1585
        n5: 0.1585
       tln: 0.5168
       tl1: 0.2768
       tl2: 0.3009
       tl3: 0.6020
     l_com: 1.6964
        bd: 0
```

Frequencies of modes (Hz)

longpitch1: [0.3698 0.4327 0.8520 0.9600]
longpitch2: [1.6768 1.9957 3.4073 3.9375]
yaw: [0.6457 1.3642 2.3789 3.1399]
transroll1: [0.4407 0.8199 0.9760 2.0311]
transroll2: [2.7208 3.5610 3.9241 12.4805]
vertical: [0.6867 2.7317 4.4000 8.7578]

Initial Parameter Set

- Build up initial parameter set:
  - dummy blocks for the masses incorporating blades
  - first cut at blade properties (frequencies, dimensions)



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PART 2

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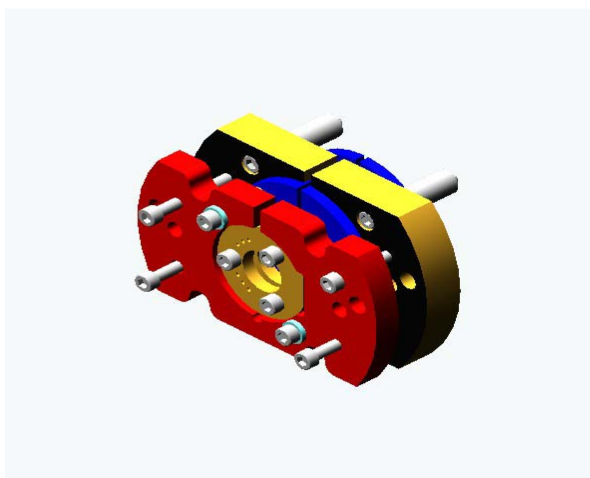
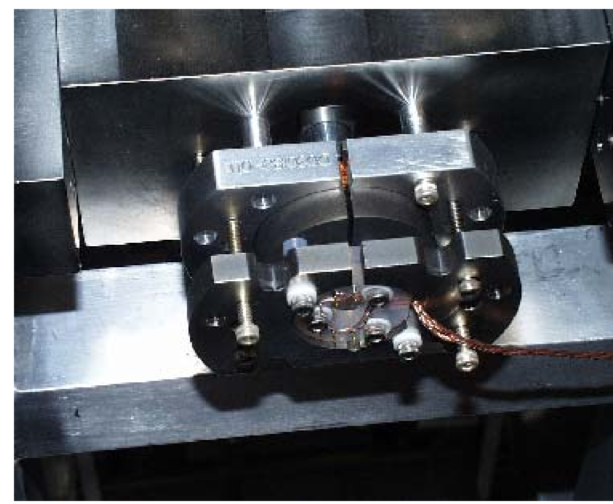
Design: From Start to End

```
% overall length calculation added by CIT and PAW 12/2001
pend.tl1        = sqrt(pend.l1^2 - (pend.n0-pend.n1)^2);
pend.tl2        = sqrt(pend.l2^2 - (pend.n2-pend.n3)^2);
pend.tl3        = sqrt(pend.l3^2 - (pend.n4-pend.n5)^2);
%overall length to the centre of mass of the test mass
pend.l_cofm     = pend.tl1+pend.tl2+pend.tl3+pend.d0+pend.d1+pend.d2+pend.d3+pend.d4;
%overall length including the radius of the test mass
pend.l_total    = pend.tl1+pend.tl2+pend.tl3+pend.d0+pend.d1+pend.d2+pend.d3+pend.d4+pend.tr;
```





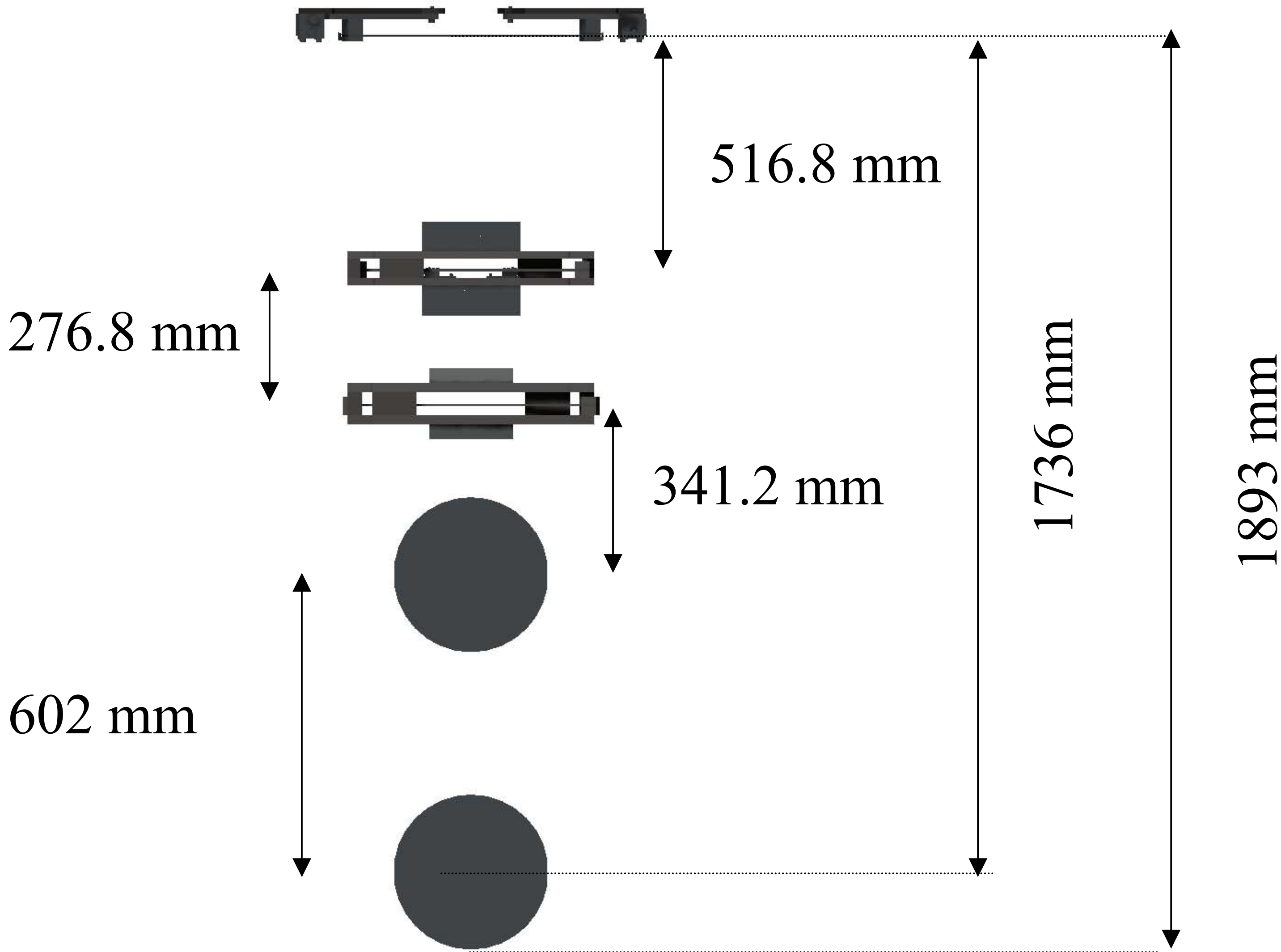
CALUM

2-D and 3-D Layout

- CONSIDER
  - 2-D Layout of masses with respect to footprint

```
% 2nd Attempt - CONTROLS PROTOTYPE
% Aluminium "dummy" test mass
tx              = 0.10;
tr              = 0.265/2;
m3 =    12.181;     %Actual shape calculated from SWorks 01/09/02
I3x =   1.051e-1;   % dimensions 100mm thick x 265mm diam
I3y =   6.277e-2;
I3z =   6.259e-2;
m3_parameters = 'Controls P-tpye: Calculated from SWorks Assembly';
material3 = 'alum with holes, flats + s/stl clamps';


 pend.m3_parameters = m3_parameters;
 pend.material3 = material3;
 pend.tx = tx;
 pend.tr = tr;
 pend.m3 = m3;
 pend.I3x = I3x;
 pend.I3y = I3y;
 pend.I3z = I3z;

%*********************************************************************************************


 l1             = 0.20;                 %upper wire length, changed from .25 by PAW 12/2001
 %l2            = 0.234;                %intermediate wire length
 %l2            = 0.25;                 %increased to give good clearance between masses w/ T top mass NAR Apr02


 l2             = 0.201;                %intermediate wire length changed from 0.234 by PAW 7/2002
                                        %incorporated by CAC 01/2003
 %l3            = 0.30;                 %lower wire length, changed from .20 by PAW 12/2001

 l3             = 0.253;                %lower wire length, changed from 0.30 by PAW 7/2002
                                        %incorporated by CAC 01/2003
pend.l1         = l1;
pend.l2         = l2;
pend.l3         = l3;
%**************************************************************************************
```

```
% overall length calculation added by CIT and PAW 12/2001
pend.tl1        = sqrt(pend.l1^2 - (pend.n0-pend.n1)^2);
pend.tl2        = sqrt(pend.l2^2 - (pend.n2-pend.n3)^2);
pend.tl3        = sqrt(pend.l3^2 - (pend.n4-pend.n5)^2);
%overall length to the centre of mass of the test mass
pend.l_cofm     = pend.tl1+pend.tl2+pend.tl3+pend.d0+pend.d1+pend.d2+pend.d3+pend.d4;
%overall length including the radius of the test mass
pend.l_total    = pend.tl1+pend.tl2+pend.tl3+pend.d0+pend.d1+pend.d2+pend.d3+pend.d4+pend.tr;
```

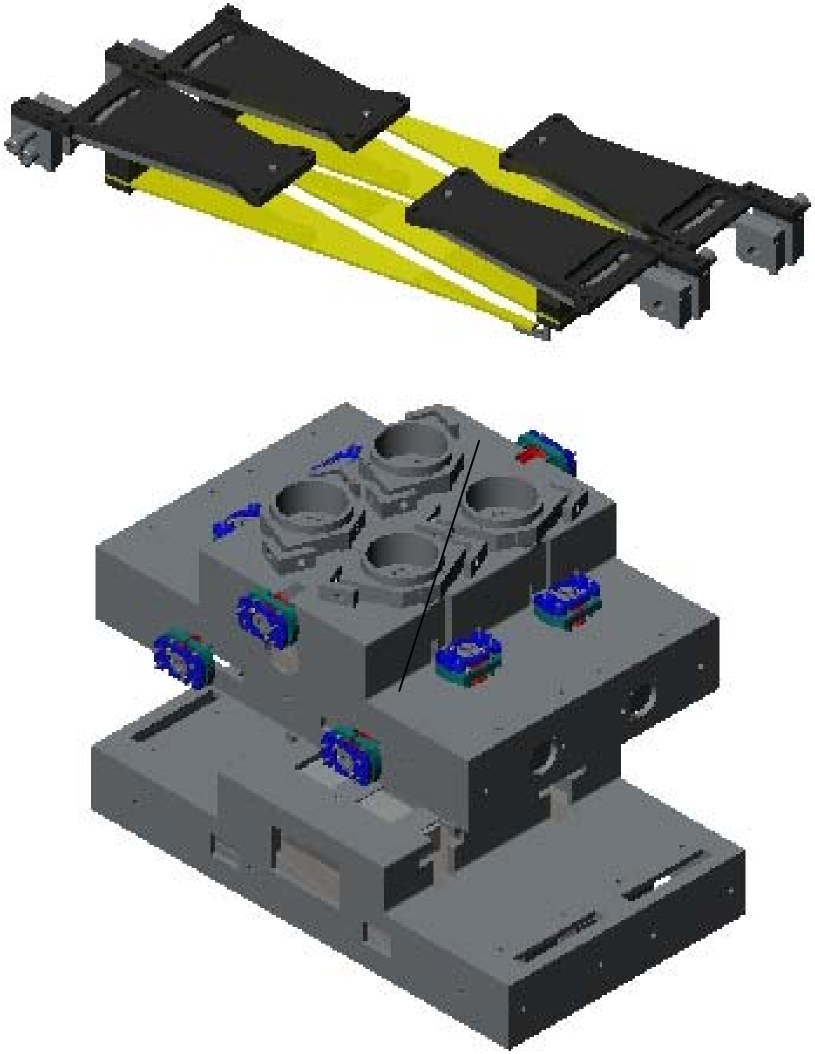

516.8 mm
276.8 mm
341.2 mm
602 mm
1736 mm
1893 mm

2-D and 3-D Layout

- CONSIDER
  - 2-D Layout of masses with respect to footprint
  - WIRES w.r.t. LOCAL CONTROL Coil Assemblies

```
% Y direction separation


%n0            = 0.06;                 % 1/2 separation of upper wires at suspension point
 n0             = 0.077;                % changed by NAR for similar footprint to MC
 nl             = 0.13;                 % 1/2 separation of upper wires at upper mass

                                        % incorporated by CAC 01/2003
%n2             = 0.03;                 % 1/2 separation of intermediate wires at upper mass - TO BE CONFIRMED
                                        % incorporated by CAC 01/2003
 n2             = 0.06;                 % CIT 02/04/03 CIT IN ORDER TO FIT WITH CLEARANCE OF THE 'T'-PIECE
 n2             = 0.07;                  %increased to accommodate wider T piece NAR 4MAr03

 %n3            = ir+0.0065;            % 1/2 separation of intermediate wires at intermediate mass
 %n3            = ir+0.0095;            % increased to give clearance of wire from edge of penultimate mass

 n3             = iy/2+0.0139;          % 1/2 separation of intermediate wires at intermediate mass
                                        % incorporated by CAC 01/2003
 n3 = 0.1275+0.01;                            % new number from CIT

 n4             = tr+0.0015;            % 1/2 separation of lower wires at intermediate mass
 n4 = 0.1275+0.01;                           % new number from CIT

 n5             = tr+0.0015;            % 1/2 separation of lower wires at test mass
 n5 = tr-0.0024+0.0074;                 % new number from CIT

 pend.n0        = n0;
 pend.nl        = nl;
 pend.n2        = n2;
 pend.n3        = n3;
 pend.n4        = n4;
 pend.n5        = n5;
```

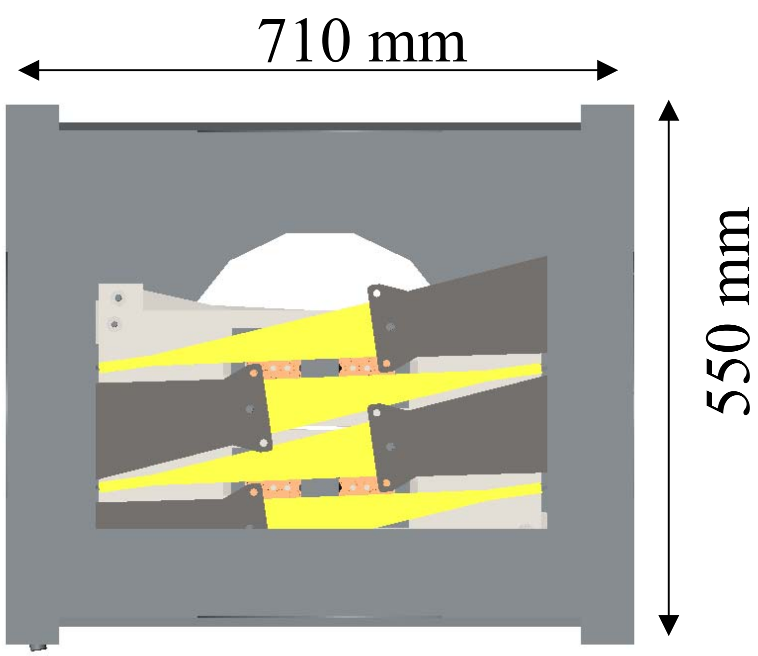
```
%*****************************************************************************
%IMPORTANT FOR REFERENCE ONLY!!!
% THE FOLLOWING IS USED TO EXPLAIN THE CALCULATION OF THE NUMBER USED IN THE GAIN TRIANGLE
%Gain triangles in pendn.m

% lever_pitch    = 0.04;                %PW DEC 02
% lever_yaw      = 0.1;                 %PW DEC 02
% lever_roll     = 0.1;                 %PW DEC 02    %UPDATED 10th FEB 2003 CIT

%% lever_pitch    = 0.03;               %changed by NAR to be same as MC
%% lever_yaw      = 0.08;               %changed by NAR to be same as MC
%% lever_roll     = 0.06;               %changed by NAR to be same as MC

% pend.lever_pitch = lever_pitch;
% pend.lever_yaw = lever_yaw;
% pend.lever_roll = lever_roll;

%gain   = -0.2;                          %PW DEC 02

%% gain = -0.4;                          %changed by NAR to be same as MC

```

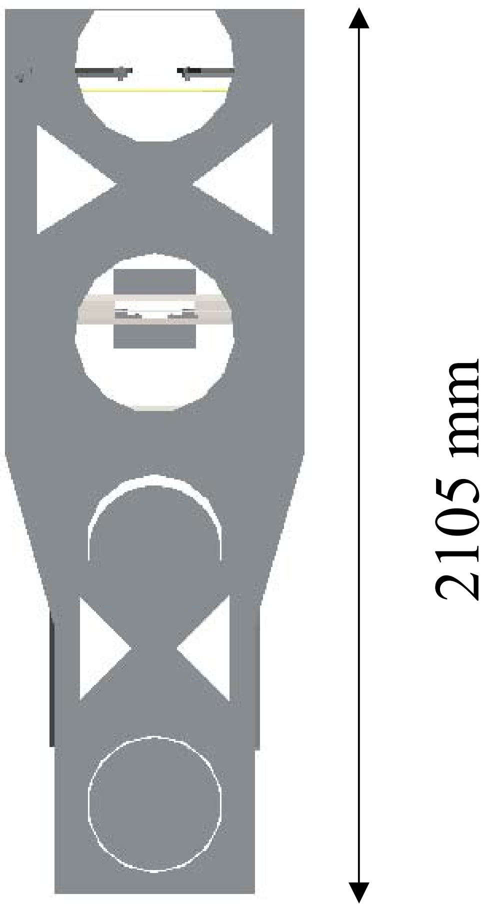


2-D and 3-D Layout

- CONSIDER
  - 2-D Layout of masses with respect to footprint
  - WIRES w.r.t. LOCAL CONTROL Coil Assemblies
  - Cantilever Blades w.r.t. Footprint

```
%**********************************************************************************************************

% THE opt.m function is used to estimate a cantilever blade in order to get started.
% In order to take the design of a Cantilever blade forward it is necessary to used the EXCEL and ANSYS model.
% It is then necessary to override opt.m with the calculated numbers (an example is shown below on line 196


%blade design - upper blades
 mntb           = (m1 +m2 +m3)/2;        %total per blade
 mnb            = m1/2;                  %uncoupled mass

 %[uf,lnb,anb,hnb,stn] = opt(mnb,mntb,8e8,0.28,0.07);
  [uf,lnb,anb,hnb,stn] = opt(mnb,mntb,8e8,0.25,0.065);      %changed by NAR, same length as MC

 ufcl           = uf;
 pend.llb       = lnb;
 pend.alb       = anb;
 pend.hlb       = hnb;
 pend.ufcl      = uf;
 pend.stl       = stn;
 pend.intmode_l = 55*hnb*0.37^2/(0.002*lnb^2); %scaled from GEO blade


 %*****************************
 %NAR override
 %Upper blades:length: 25 cm, width: 6.5 cm, thickness: 2.3 mm, max. defl.: 104.8 mm, ufcl: 2.6 Hz (shape factor of 1.36).
 %masses from top to bottom of 12.6, 12.2, and 12.15 kg.

 ufcl=2.6;          % MIKE PLISSI JAN/29/2003
 pend.ufcl = ufcl;
 %*******************************************
```



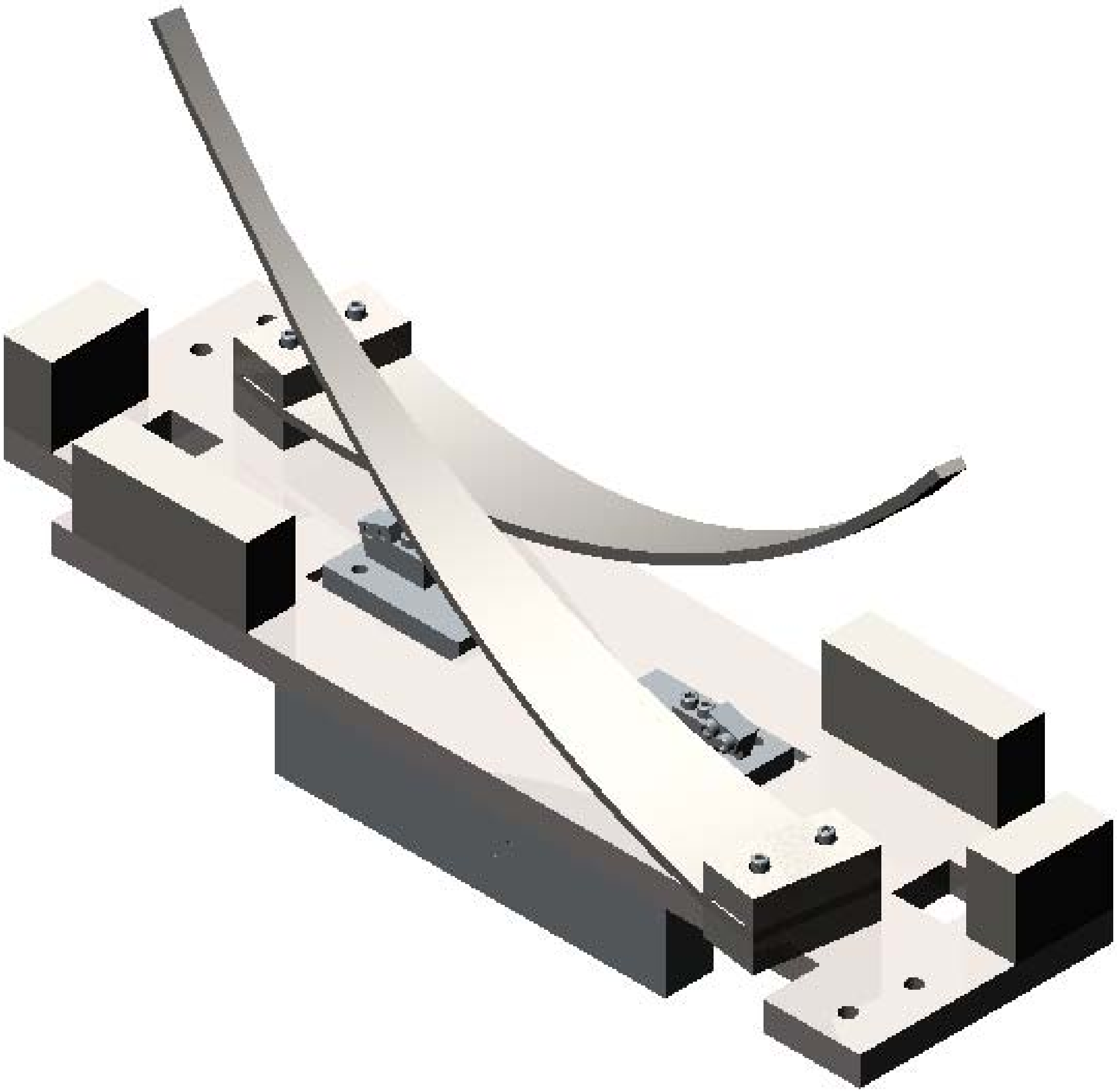


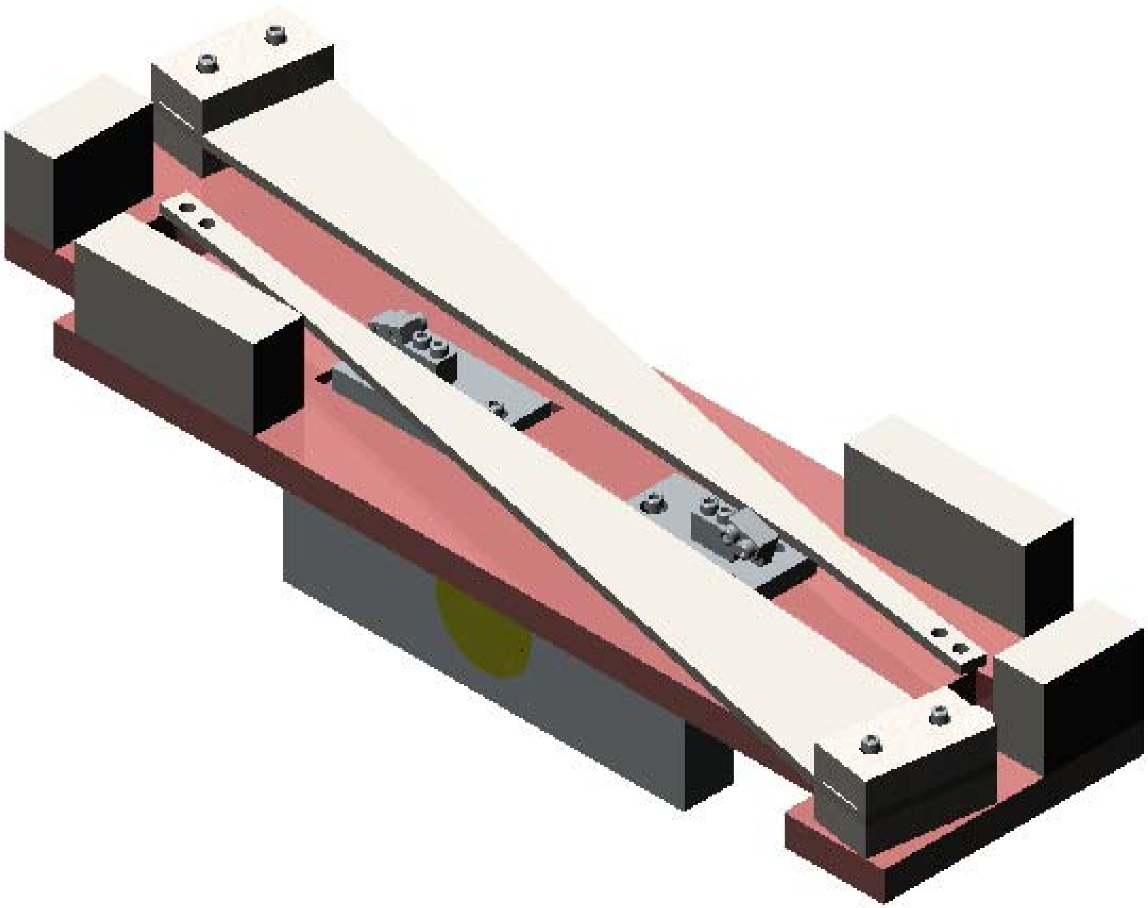
ETM

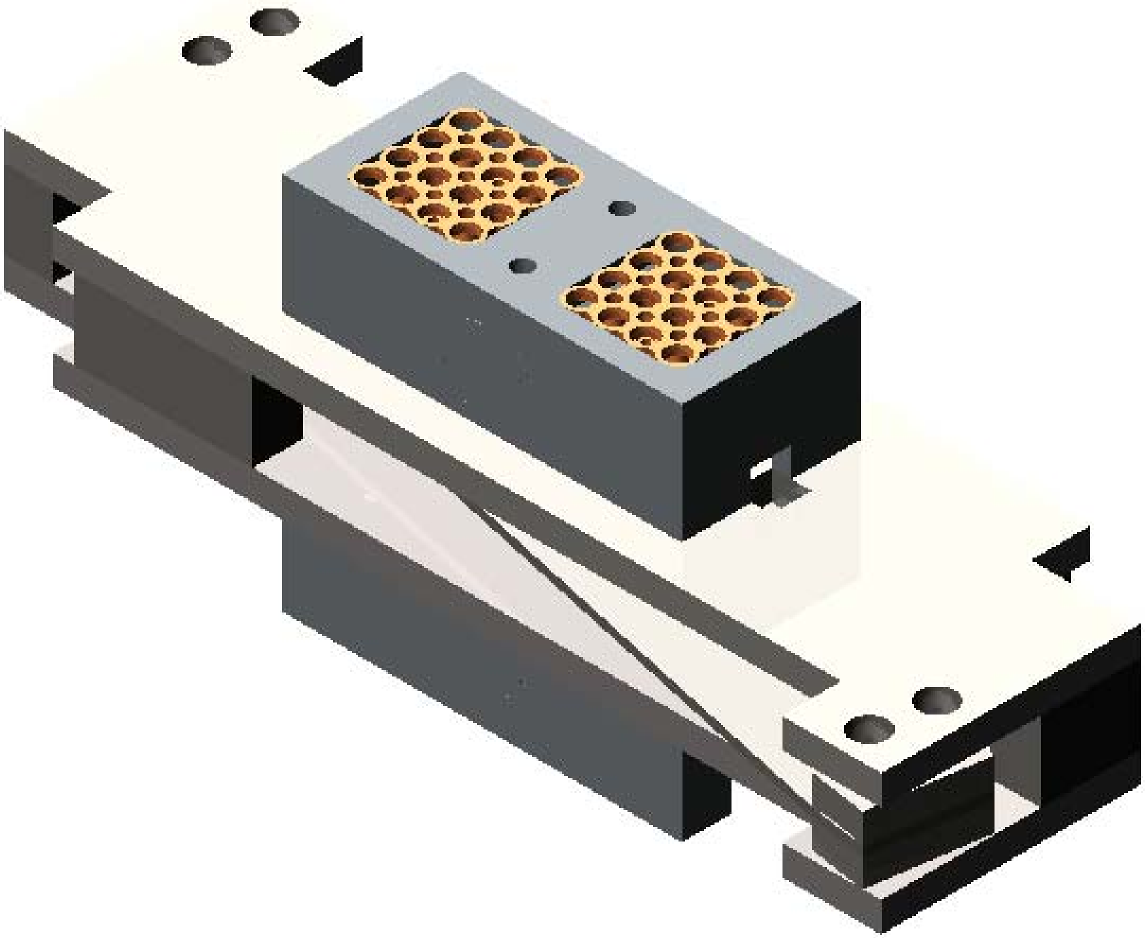
2-D and 3-D Layout

- CONSIDER
  - 2-D Layout of masses with respect to footprint
  - WIRES w.r.t. LOCAL CONTROL Coil Assemblies
  - Cantilever Blades w.r.t. Footprint
  - Actual UPPER MASS, weight and Moment of Inertia's

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%% UPPER MASS %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%*****1st ATTEMPT*****
%% top mass is REPRESENTED by a rectangular BLOCK
%% in reality it will be larger and less dense.
 %ux     = 0.10;         %dimensions of UPPER MASS (square)
 %uy  =  0.30;
 %uz     = 0.06;
 %denl  = 7000;     %density (steel with holes)
 %ml     = denl* uy* uz* ux; %mass
 %Ilx    =  ml*( uy^2+ uz^2)/12; %moment of inertia (transverse roll)
 %Ily    =  ml*( uz^2+ ux^2)/12; %moment of inertia (longitudinal pitch)
 %Ilz    =  ml*( uy^2+ ux^2)/12; %moment of inertia (yaw)
 %ml_parameters = 'represented by a regtangular block';
 %materiall = 'steel'
%%%%%%%%%%%%%%%%%%%%%%%%
```



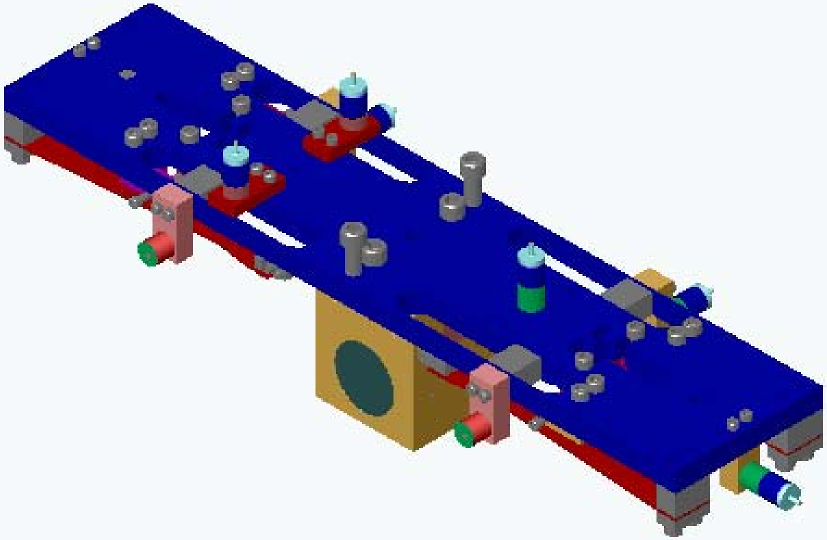




Mass properties of D020535

Assembly_uppermass+tablecloth

Output coordinate System : Coordinate System1



Mass = 3085.3668 grams

Center of mass: (millimeters)

X = 25.6710

Y = -22.7546

Z = -9.2266

Moments of inertia: (grams * square millimeters)

Taken at the center of mass and aligned with the\

output coordinate system.

Lxx = 23883291.1368

Lyy = 2451004.189

Lzz = 23879032.0909

Modeling Variations to Parameter Set

- **The following is done in MATLAB to facilitate the design**
  - **+/- 500 g in mass**
  - **+/- mm in length**

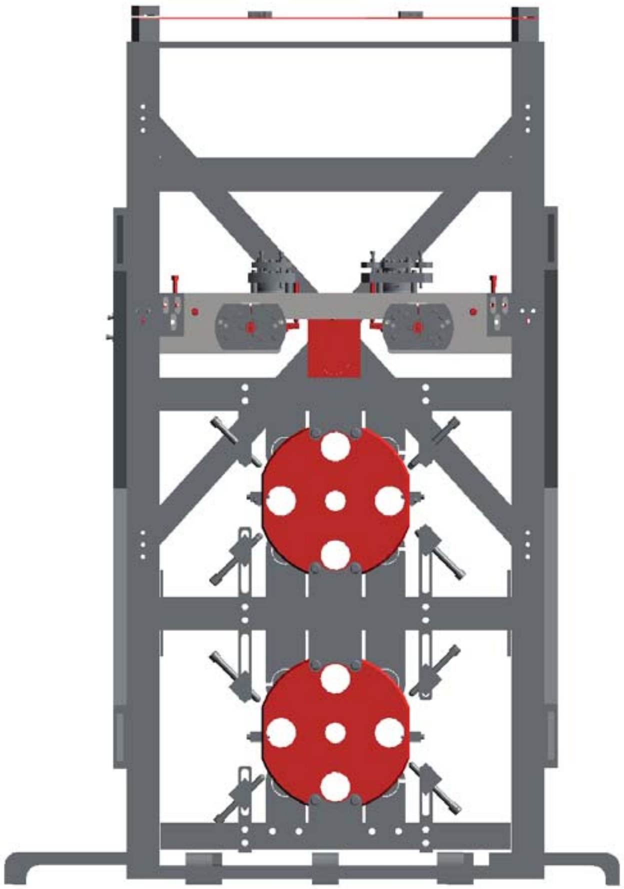
- **Asymmetries**

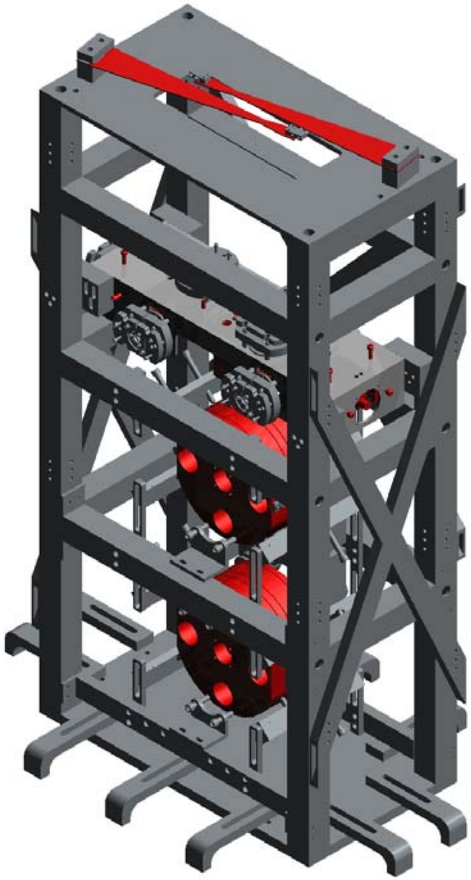
  - **(REF: Mark Barton's MATHMATICA Model**

2-D and 3-D Layout

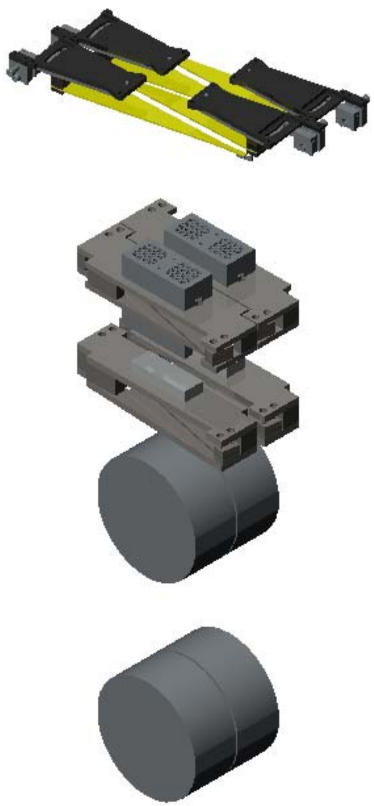
- CONSIDER
  - 2-D Layout of masses with respect to footprint
  - WIRES w.r.t. LOCAL CONTROL Coil Assemblies
  - Cantilever Blades w.r.t. Footprint
  - Actual UPPER MASS, weight and Moment of Inertia's
  - Full layout of MASSES, w.r.t. structure, reaction chain etc …

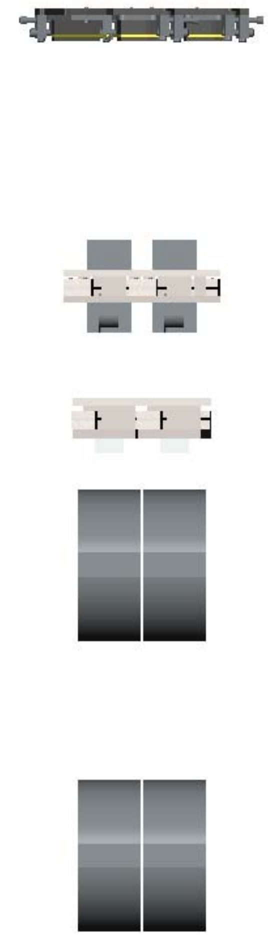
Mode Cleaner Suspension





ETM Suspension





Interaction between Designers and Modellers

- The Mode Cleaner Upper Blade design required interaction between
  - CIT + JHR at Caltech NAR, MVP, MPL + KAS at Stanford and Glasgow
- Upper Mass Assembly Configurations
  - Information passes back and forth until all avenues are covered
    - blades, clamps, upper wire clamp, magnet assembly, lever-arms, mass, moments of inertia, reaction chain, stiffness, centre of mass
    - a prototype is usually made, suspended and tested

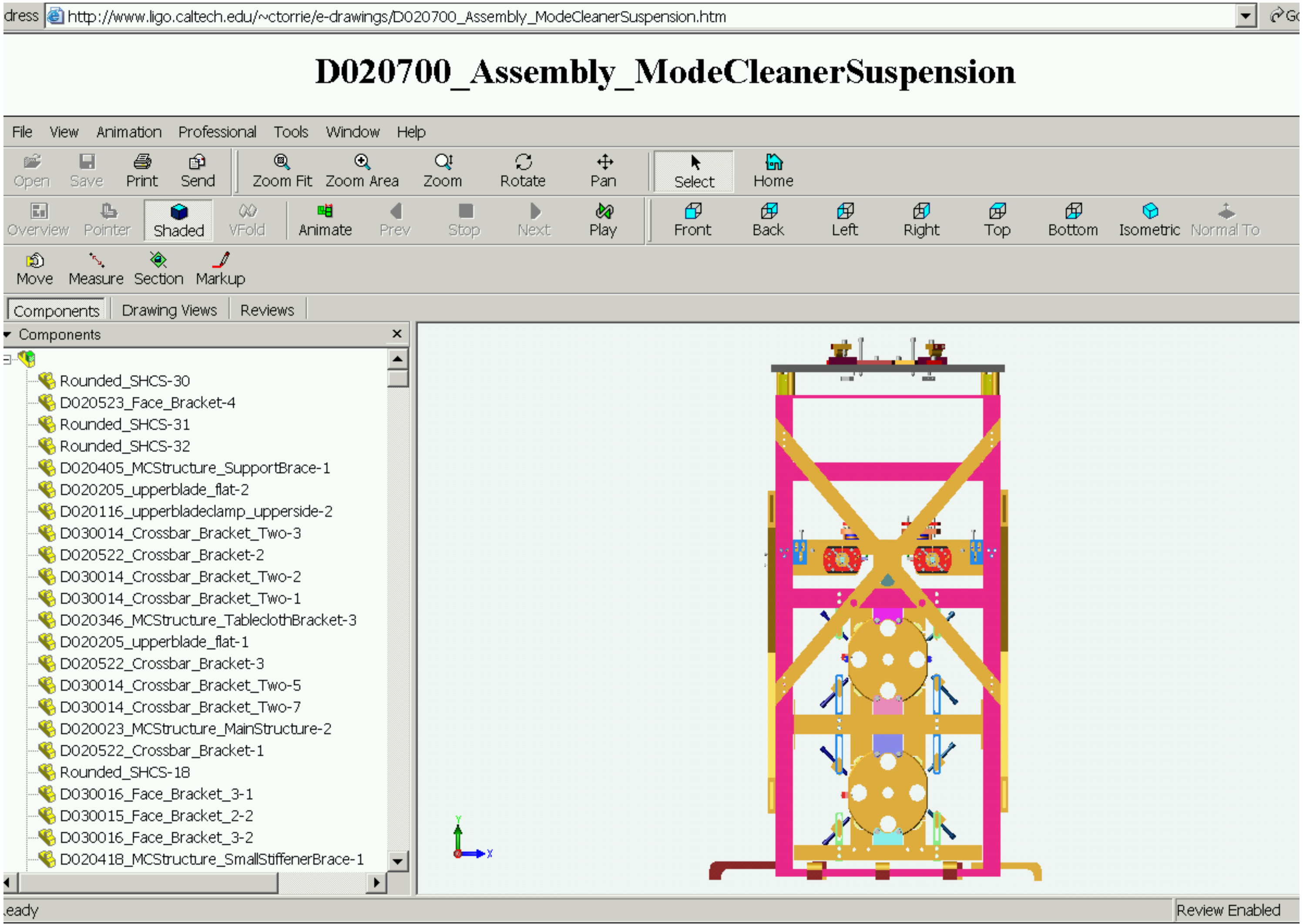
MATLAB Parameters

```
g               = 9.81;

%%%%%%%%%%%%%%%%%%%%%%%%%%% UPPER MASS %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%*****1st ATTEMPT*****
%% top mass is REPRESENTED by a rectangular BLOCK
%% in reality it will be larger and less dense.
 %ux    = 0.10;         %dimensions of UPPER MASS (square)
 %uy  =  0.30;
 %uz    = 0.06;
 %denl  = 7000;     %density (steel with holes)
 %ml    = denl* uy* uz* ux; %mass
 %Ilx   =  ml*( uy^2+ uz^2)/12; %moment of inertia (transverse roll)
 %Ily   =  ml*( uz^2+ ux^2)/12; %moment of inertia (longitudinal pitch)
 %Ilz   =  ml*( uy^2+ ux^2)/12; %moment of inertia (yaw)
 %ml_parameters = 'represented by a regtangular block';
 %materiall = 'steel'
%%%%%%%%%%%%%%%%%%%%%%%

%%*****2nd ATTEMPT*****
%% T-shaped calculated from mofi2.m
% ml              = 12.65;
% Ilx             = 8.96e-2;
% Ily             = 2.76e-2;
% Ilz             = 8.30e-2;

% ml              = 12.168; %top piece 0.1x0.44x0.017m, bottom piece 0.1x0.116x0.07m NAR 4 Mar 2003
% Ilx             = 10.97e-2;
% Ily             = 1.8613e-2;
% Ilz             = 11.137e-2;

% ml_parameters = 'T-shaped calculated from mofi2.m';
% materiall = 'steel';
%%%%%%%%%%%%%%%%%%%%%%%

%%*****3rd ATTEMPT*****
%% FROM SOLIDWORKS ASSEMBLY OR ACTUAL MASS
 ml =     12.07;      %Actual shape calculated from SWorks 01/09/02
 Ilx =    1.263e-1;   %top plate 100X440X20mm / T-section 96X116X64mm
 Ily =    1.857e-2;
 Ilz =    1.274e-1;
 ml_parameters = 'Calculated from SWorks Assem 2003Mar26';
 materiall = 'combination steel+alum';
%%%%%%%%%%%%%%%%%%%%%%%

 pend.ml_parameters = ml_parameters;
 pend.materiall = materiall;
 pend.ml = ml;
 pend.Ilx = Ilx;
 pend.Ily = Ily;
 pend.Ilz = Ilz;
```

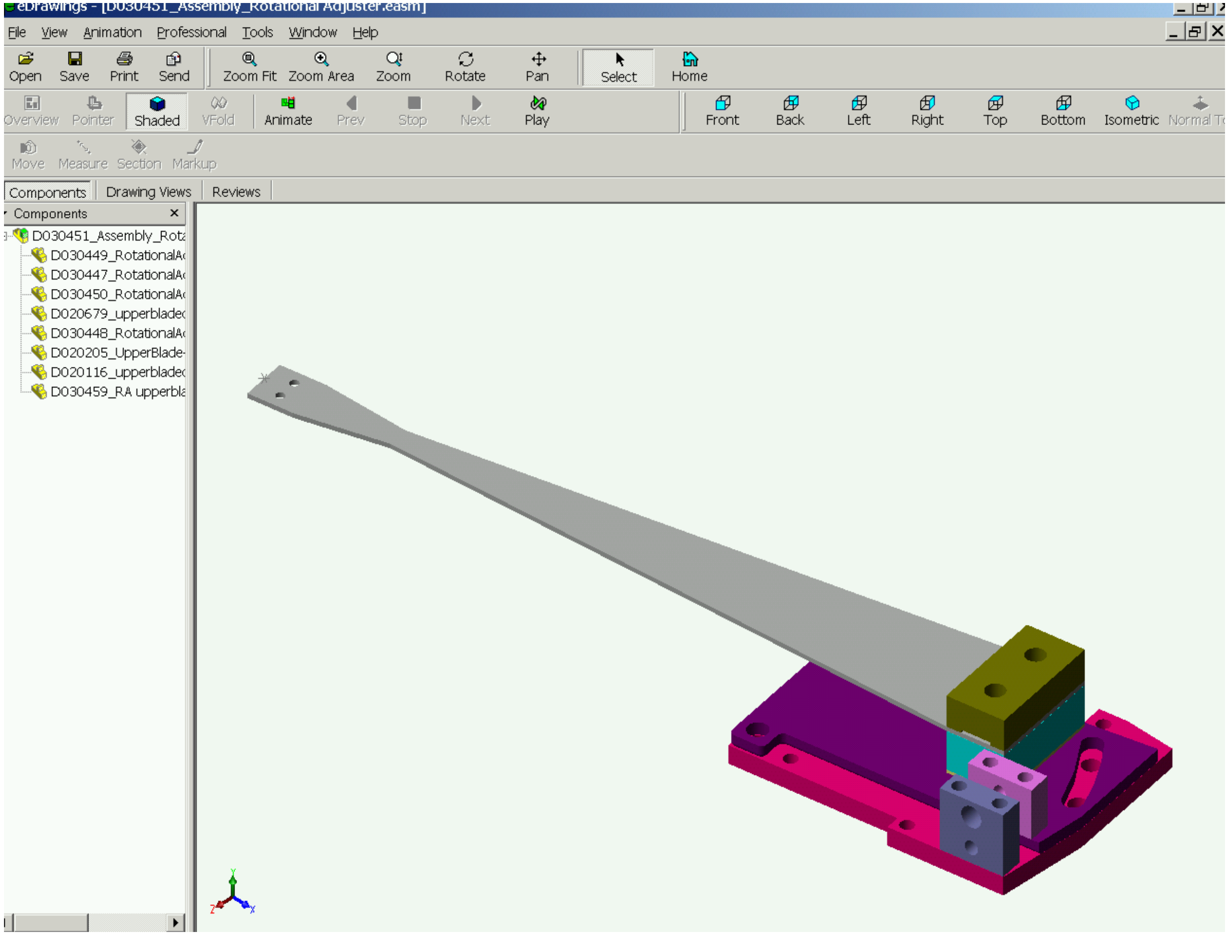
C.A.D. Related

- SOLIDWORKS 2003
  - E-drawings + 3-D INSTANT WEBSITE
  - Compatibility with PRO-E?
  - Feature Works
  - PushButton pdf

3-D Instant Web Page of D020700



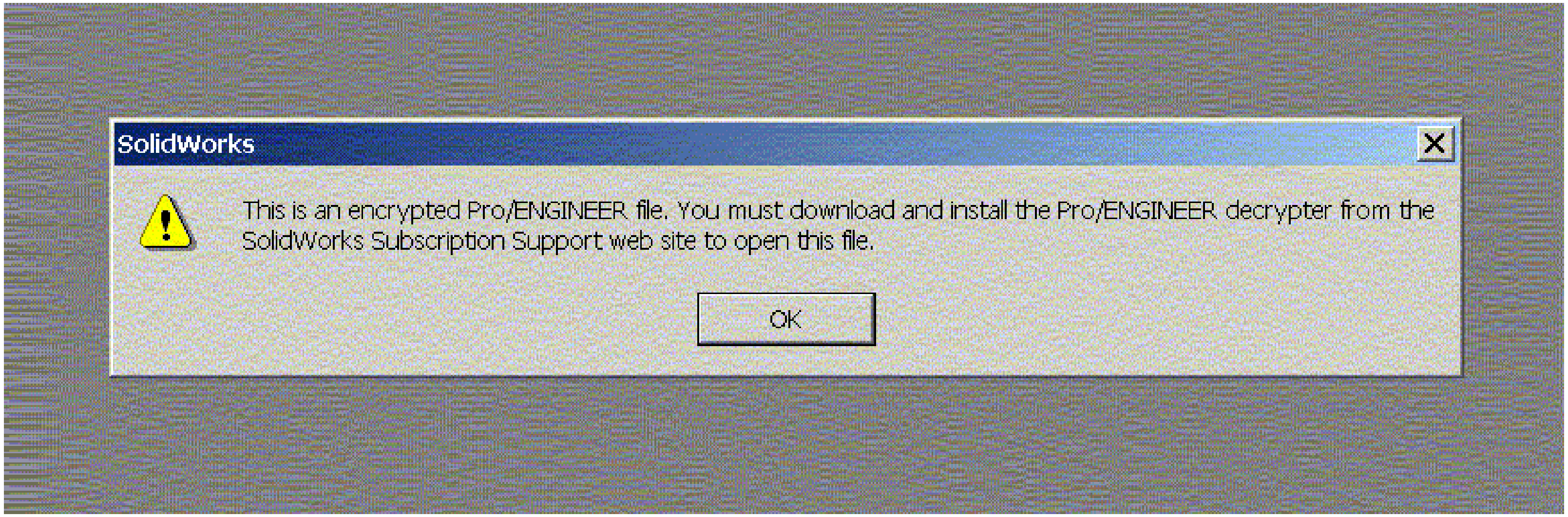
E - Drawings



eDrawings - [D030451_Assembly_Rotational Adjuster.easm]
File View Animation Professional Tools Window Help
Open Save Print Send Zoom Fit Zoom Area Zoom Rotate Pan Select Home
Overview Pointer Shaded VFold Animate Prev Stop Next Play Front Back Left Right Top Bottom Isometric
Move Measure Section Markup
Components Drawing Views Reviews
Components
D030451_Assembly_Rot
D030449_RotationalA
D030447_RotationalA
D030450_RotationalA
D020679_upperblade
D030448_RotationalA
D020205_UpperBlade-
D020116_upperblade
D030459_RA upperbl

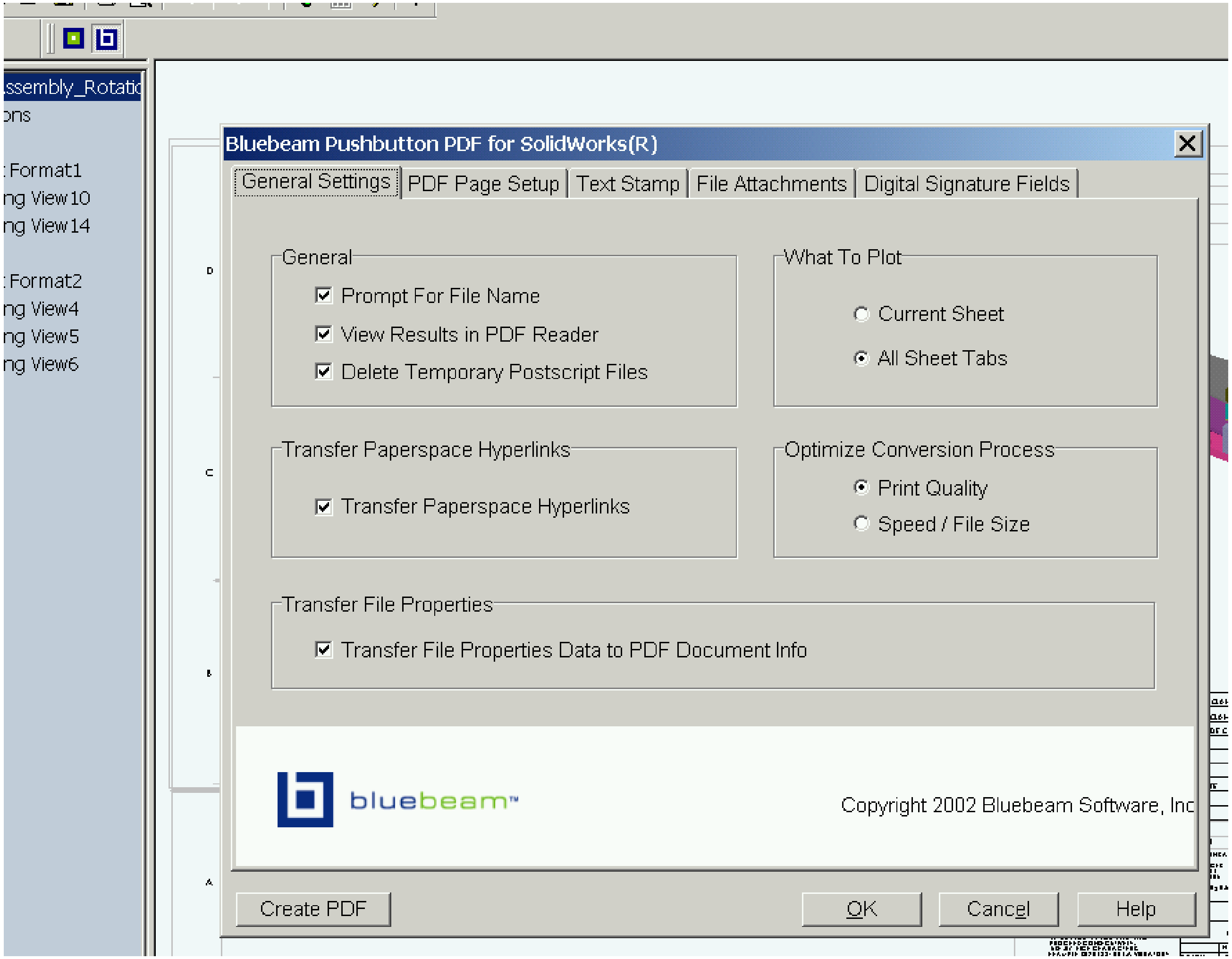
Pro Engineer to SolidWorks

- Pro E Files direct to SolidWorks?

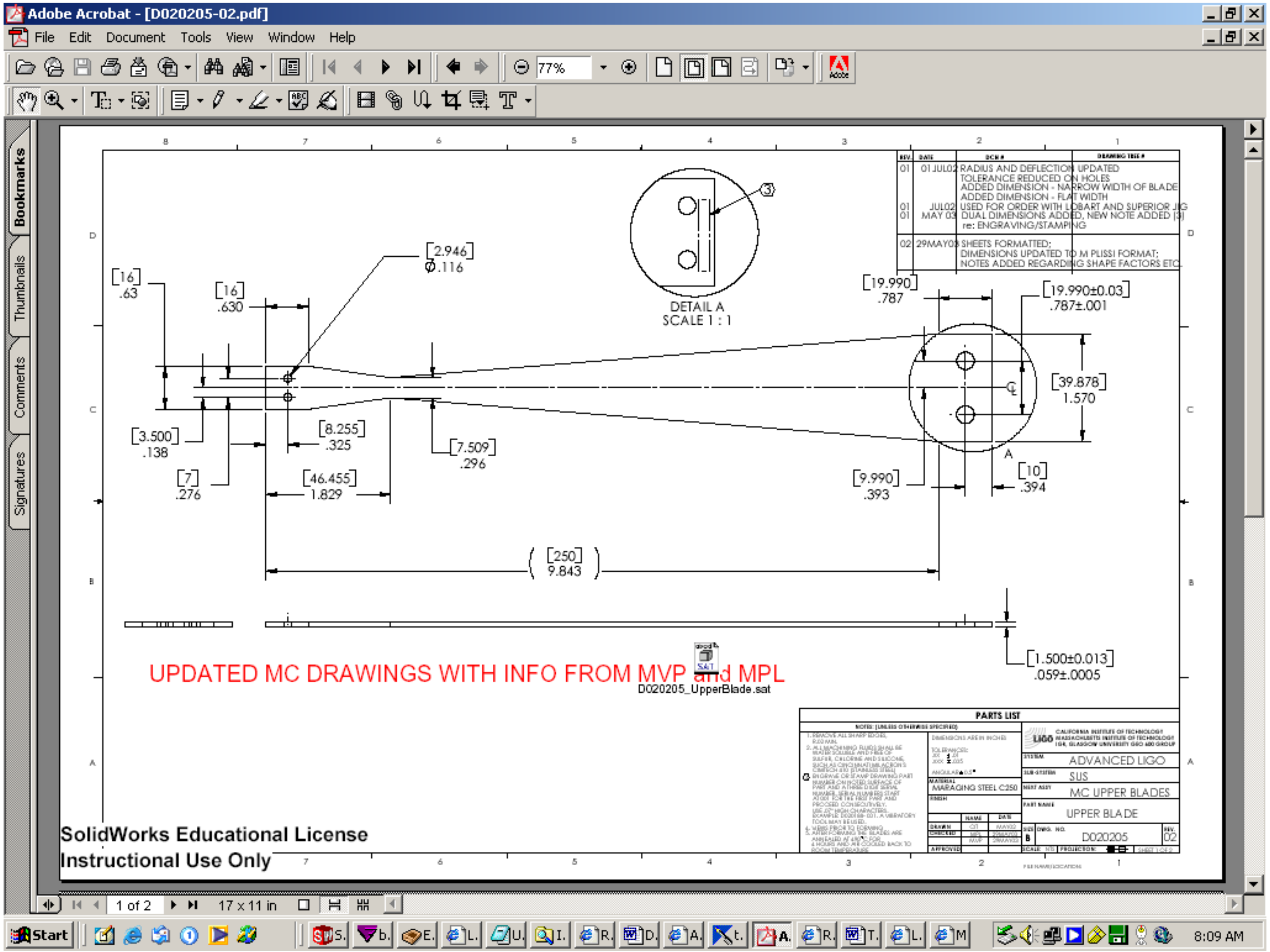


- FeatureWorks loads .SAT files or equiv while recognising features

Bluebeam Pushbutton PDF



Bluebeam Pushbutton PDF



C.A.D. Related

- SolidWorks 2003
  - Feature Works
  - E-drawings + 3-D INSTANT WEBSITE
  - Compatibility with PRO-E?
  - PushButton pdf

- **Designing in SolidWorks**

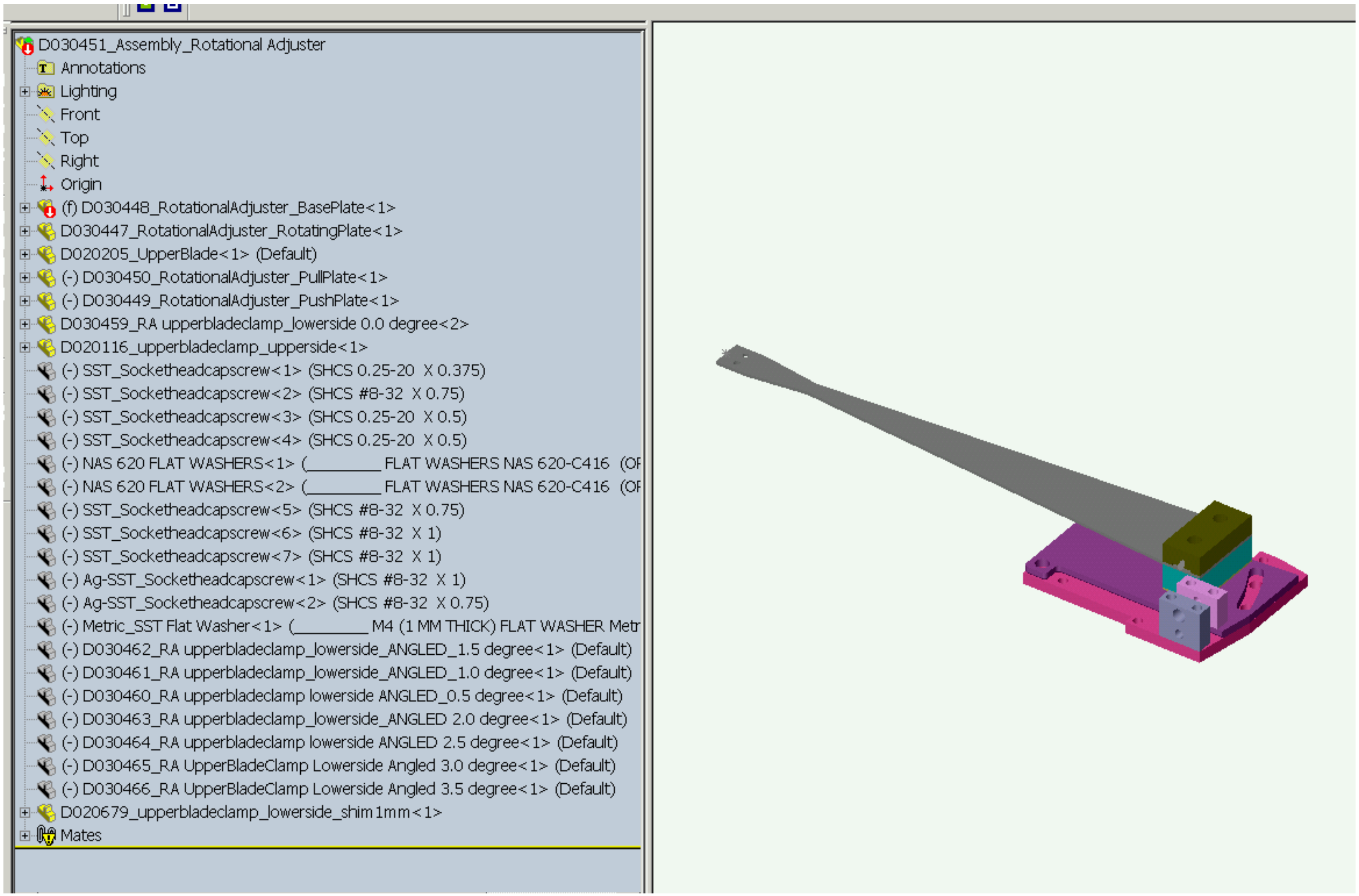
Designing in SolidWorks

- Customized Tools for Design and Documentation of LIGO Parts, Assemblies and Drawings
  - (Mike Lloyd)
  - T030143
  - http://www.ligo.caltech.edu/docs/T/T030143-02.pdf

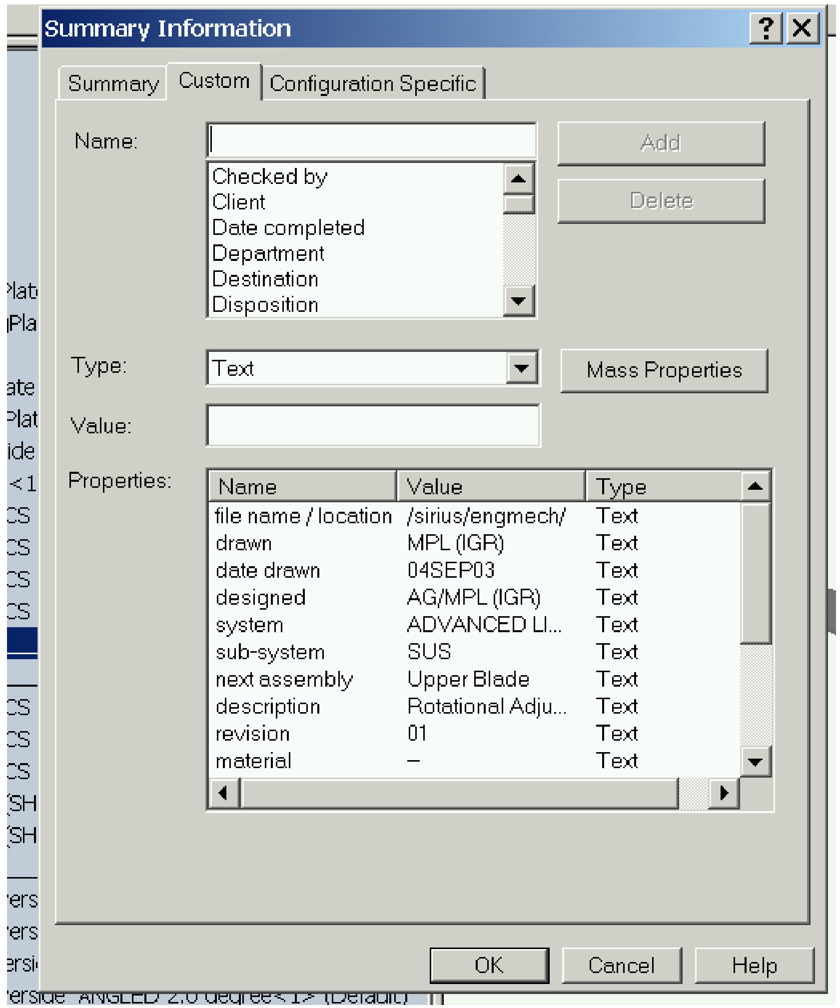
Customised Tools

- Smart CAD and Data Templates for Advanced LIGO
  - (Mike Lloyd, Calum I.Torrie)
  - D030382
- Bill of Materials (BOM)
  - (Mike Lloyd, Calum I. Torrie)
  - D030384
- Toolbox Library
  - (Mike Lloyd and Calum Torrie)
  - D0300383

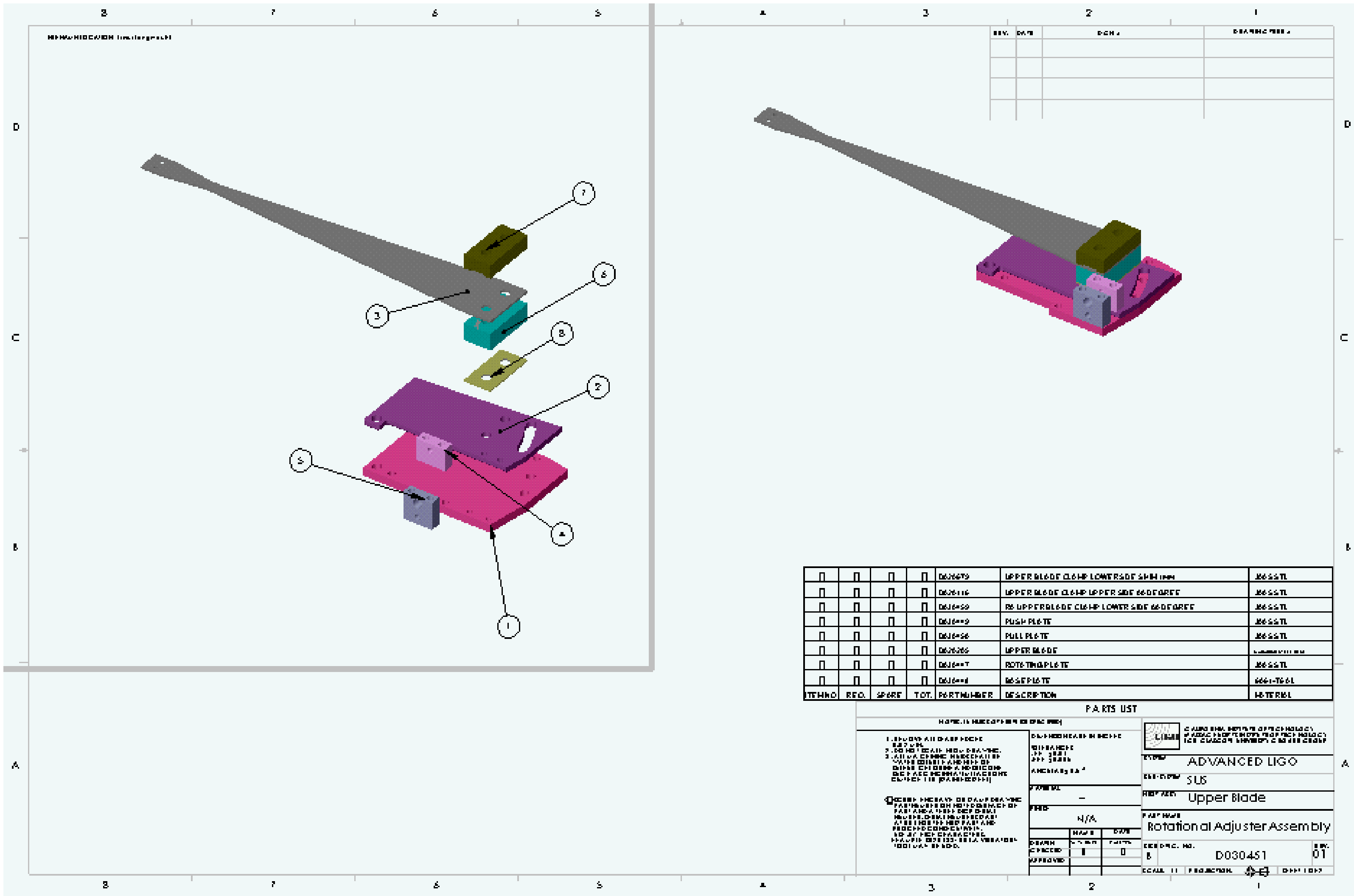
SolidWorks Assembly



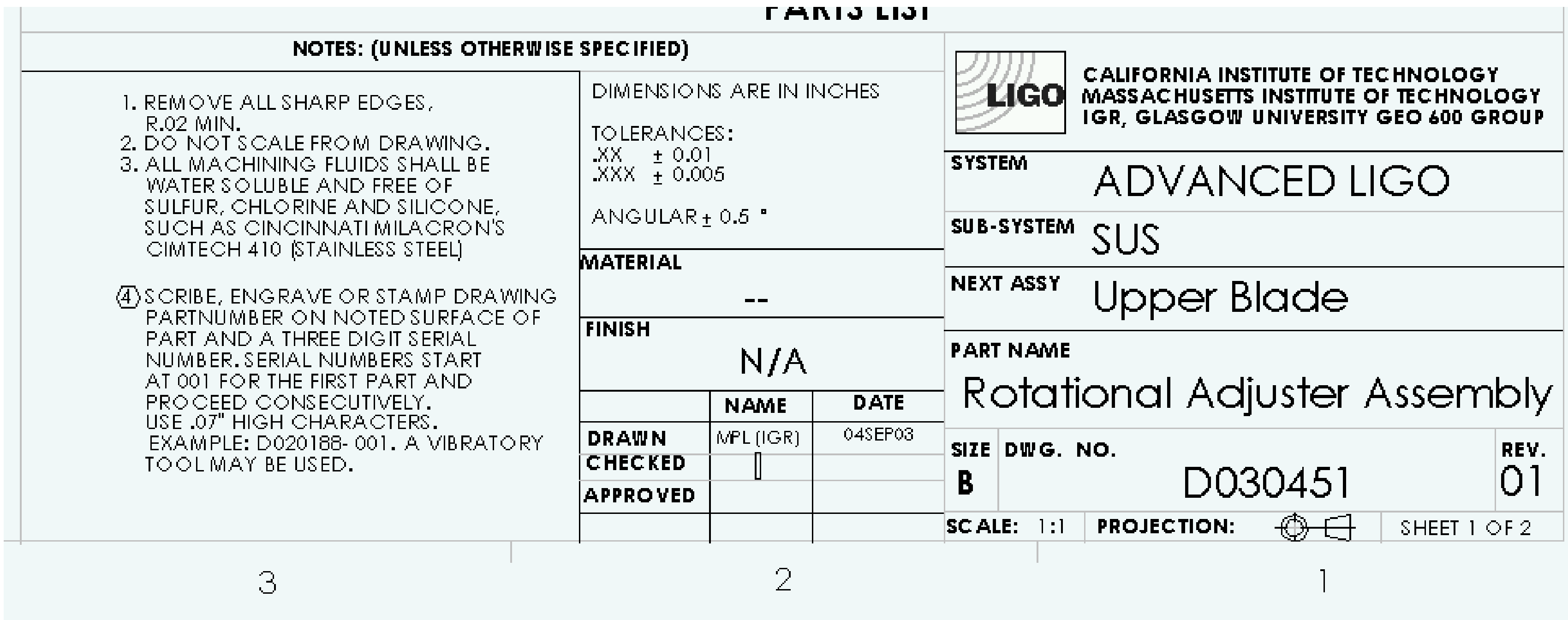
Custom Properties



SolidWorks Drawing



Custom Template – One for all



SolidWorks Custom Bill of Materials

ITEM NO	REQ.	SPARE	TOT.	PART NUMBER	DESCRIPTION	MATERIAL
8	8	1	9	D020679	UPPER BLADE CLAMP LOWERSIDE SHIM 1mm	300 SSTL
7	1	1	2	D020116	UPPER BLADE CLAMP UPPER SIDE 0.0 DEGREE	300 SSTL
6	1	1	2	D030459	RA UPPER BLADE CLAMP LOWER SIDE 0.0 DEGREE	300 SSTL
5	4	2	6	D030449	PUSH PLATE	300 SSTL
4	4	2	6	D030450	PULL PLATE	300 SSTL
3	1	1	2	D020205	UPPER BLADE	MARAGING STEEL C250
2	4	2	6	D030447	ROTATING PLATE	300 SSTL
1	4	2	6	D030448	BASE PLATE	6061-T6 AL

PARTS LIST

NOTES: (UNLESS OTHERWISE SPECIFIED)

1. REMOVE ALL SHARP EDGES, R.02 MIN.
2. DO NOT SCALE FROM DRAWING.
3. ALL MACHINING FLUIDS SHALL BE WATER SOLUBLE AND FREE OF SULFUR, CHLORINE AND SILICONE, SUCH AS CINCINNATI MILACRON'S CIMTECH 410 (STAINLESS STEEL)
4. SCRIBE, ENGRAVE OR STAMP DRAWING PARTNUMBER ON NOTED SURFACE OF PART AND A THREE DIGIT SERIAL NUMBER. SERIAL NUMBERS START AT 001 FOR THE FIRST PART AND PROCEED CONSECUTIVELY. USE .07" HIGH CHARACTERS. EXAMPLE: D020188-001. A VIBRATORY TOOL MAY BE USED.

DIMENSIONS ARE IN INCHES

TOLERANCES:
.XX ± 0.01
.XXX ± 0.005

ANGULAR ± 0.5 °

MATERIAL --

FINISH N/A

	NAME	DATE
DRAWN	MPL (IGR)	04SEP03
CHECKED		
APPROVED		

LIGO — CALIFORNIA INSTITUTE OF TECHNOLOGY, MASSACHUSETTS INSTITUTE OF TECHNOLOGY, IGR, GLASGOW UNIVERSITY GEO 600 GROUP

SYSTEM ADVANCED LIGO

SUB-SYSTEM SUS

NEXT ASSY Upper Blade

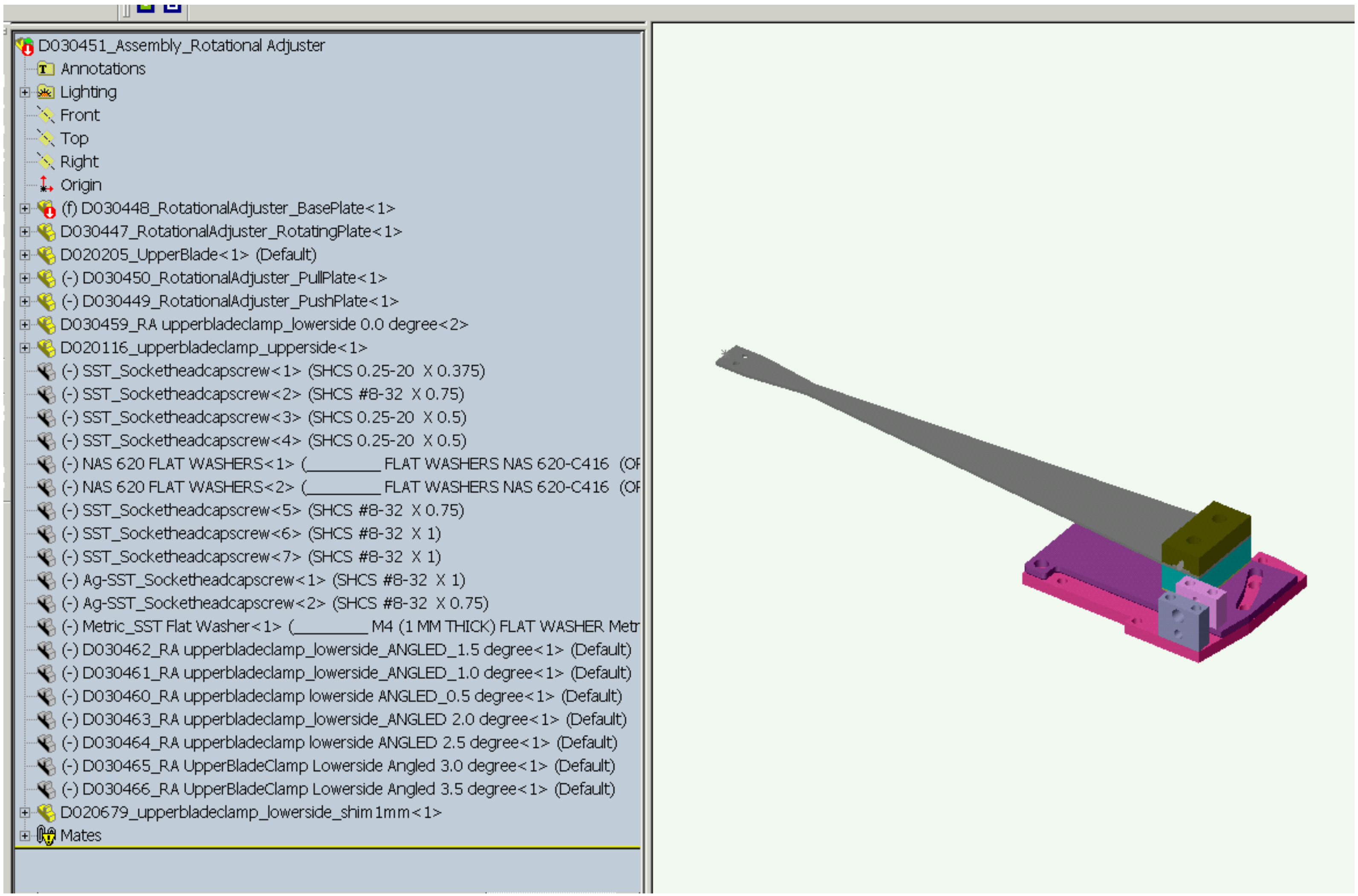
PART NAME Rotational Adjuster Assembly

SIZE B **DWG. NO.** D030451 **REV.** 01

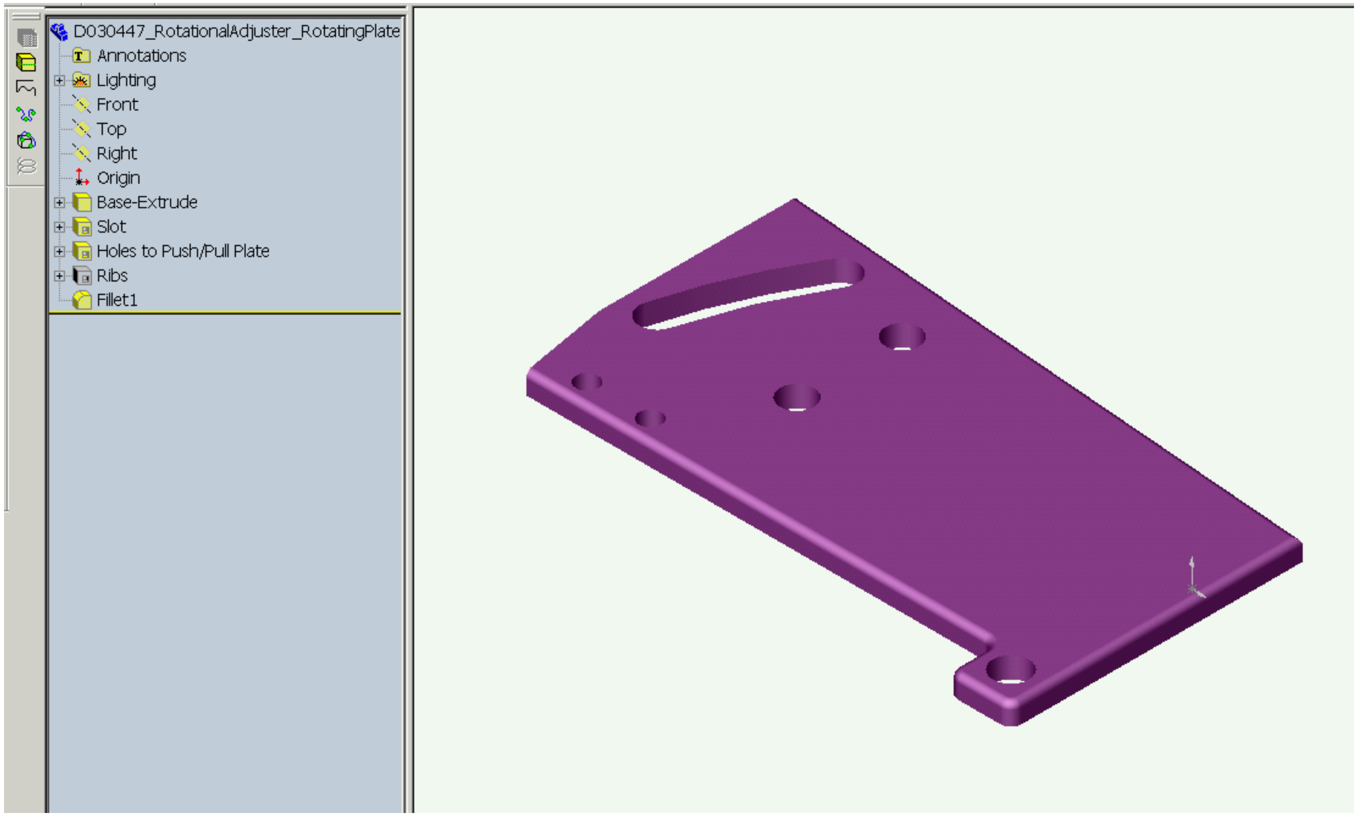
SCALE: 1:1 **PROJECTION:** SHEET 1 OF 2

3 2 1

SolidWorks Assembly



SolidWorks Part



C.A.D. Related

- SolidWorks 2003
  - Feature Works
  - E-drawings + 3-D INSTANT WEBSITE
  - Compatibility with PRO-E?
  - PushButton pdf

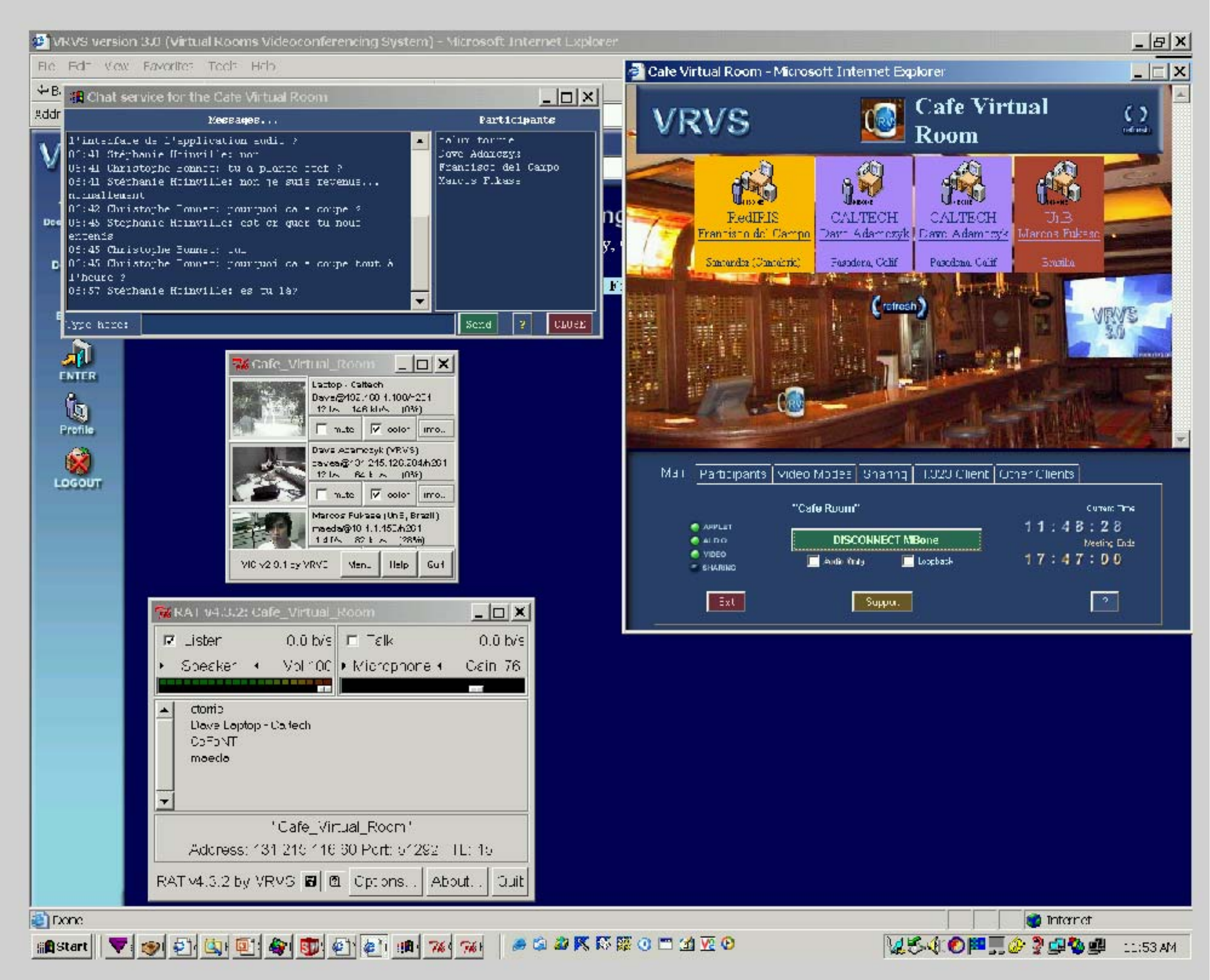
- Designing in SolidWorks

- **Storage / Other**
  - **Drawings to DCC**
  - **V.R.V.S.**
  - **SUS WEB PAGE, http://www.ligo.caltech.edu/~ctorrie/**
  - **Back up to Tape**
  - **PDM Works (Data Storage Software)**

C.A.D. Related

- Files stored on the DCC
- http://www.ligo.caltech.edu/docs/D/
- email files to turner_l@ligo.caltech.edu or in /DCC/Out

V.R.V.S.



VRVS version 3.0 (Virtual Rooms Videoconferencing System) - Microsoft Internet Explorer
Chat service for the Cafe Virtual Room
Messages...
Participants
Cafe Virtual Room - Microsoft Internet Explorer
VRVS
Cafe Virtual Room
RedIRIS
CALTECH
CALTECH
UnB
ENTER
Profile
LOGOUT
Cafe_Virtual_Room
Participants
Video Modes
"Cafe Room"
DISCONNECT MBone
11:48:28
17:47:00
Listen
Talk
Speaker
Microphone
Dave Laptop - Caltech
maeda
'Cafe_Virtual_Room'
RAT v4.3.2 by VRVS
Options...
About...
Quit
Internet
Start

Suspension Web Pages

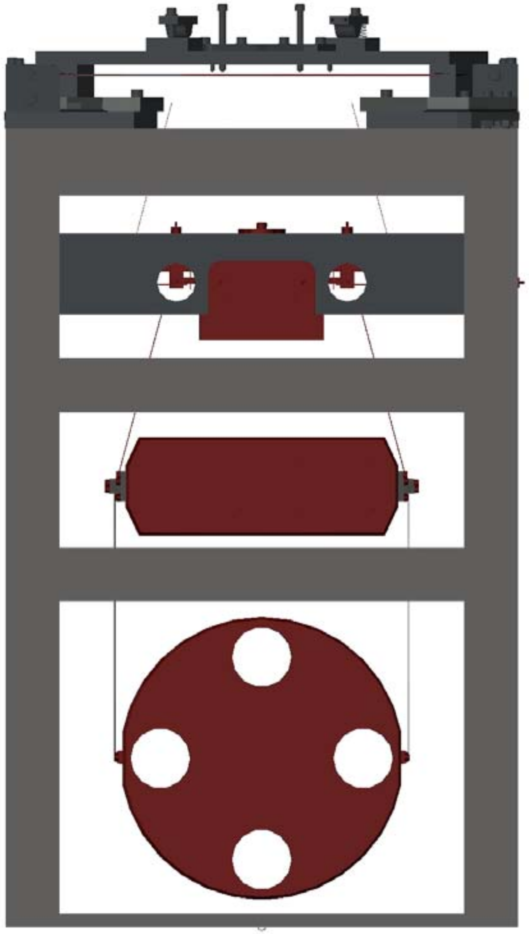
- **Calum Torrie**
  - **http://www.ligo.caltech.edu/~ctorrie/**
- **Suspension Weekly Telecon**
  - http://www.ligo.caltech.edu/SUS.html
- Workshop
  - http://www.ligo.caltech.edu/~ctorrie/

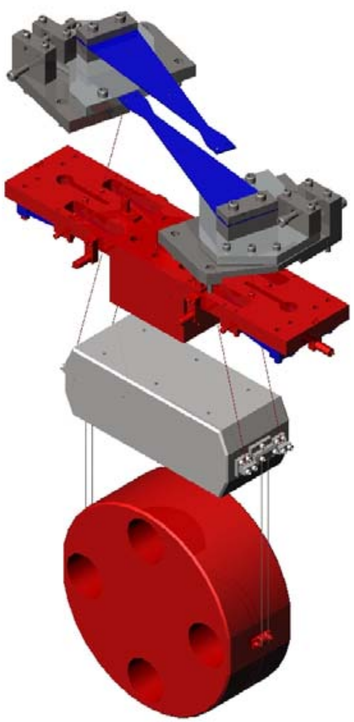
    (And click on +SUS WORKSHOP+)

Revision Control

- Currently 1 Person is the librarian for all of the CAD files
- All CAD files located and stored on server
  - updated each night onto tape
- Starting to implement PDM Works (Data Management Software)

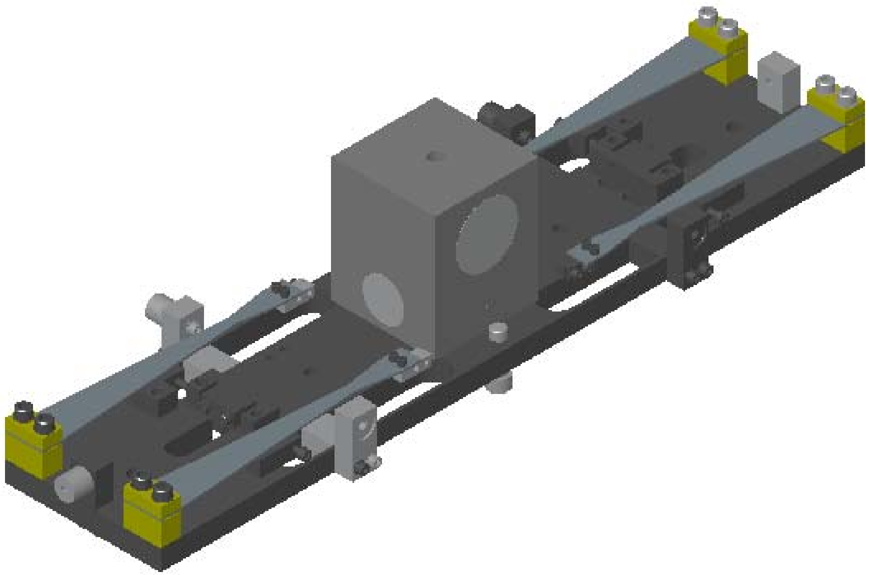
Recycling Mirror Suspension



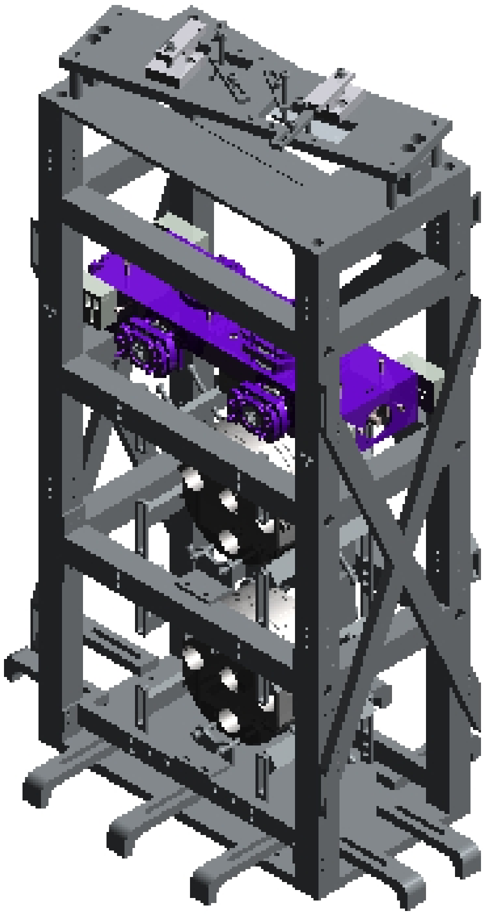


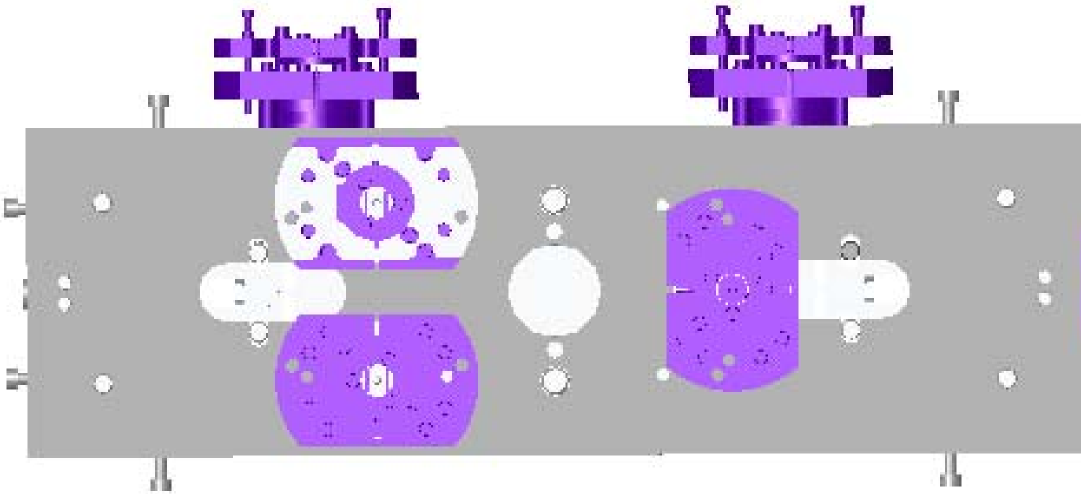
RECYCLING MIRROR

MC: Upper Mass Assembly



MC: 6 Co - Located Voice Coil Actuators

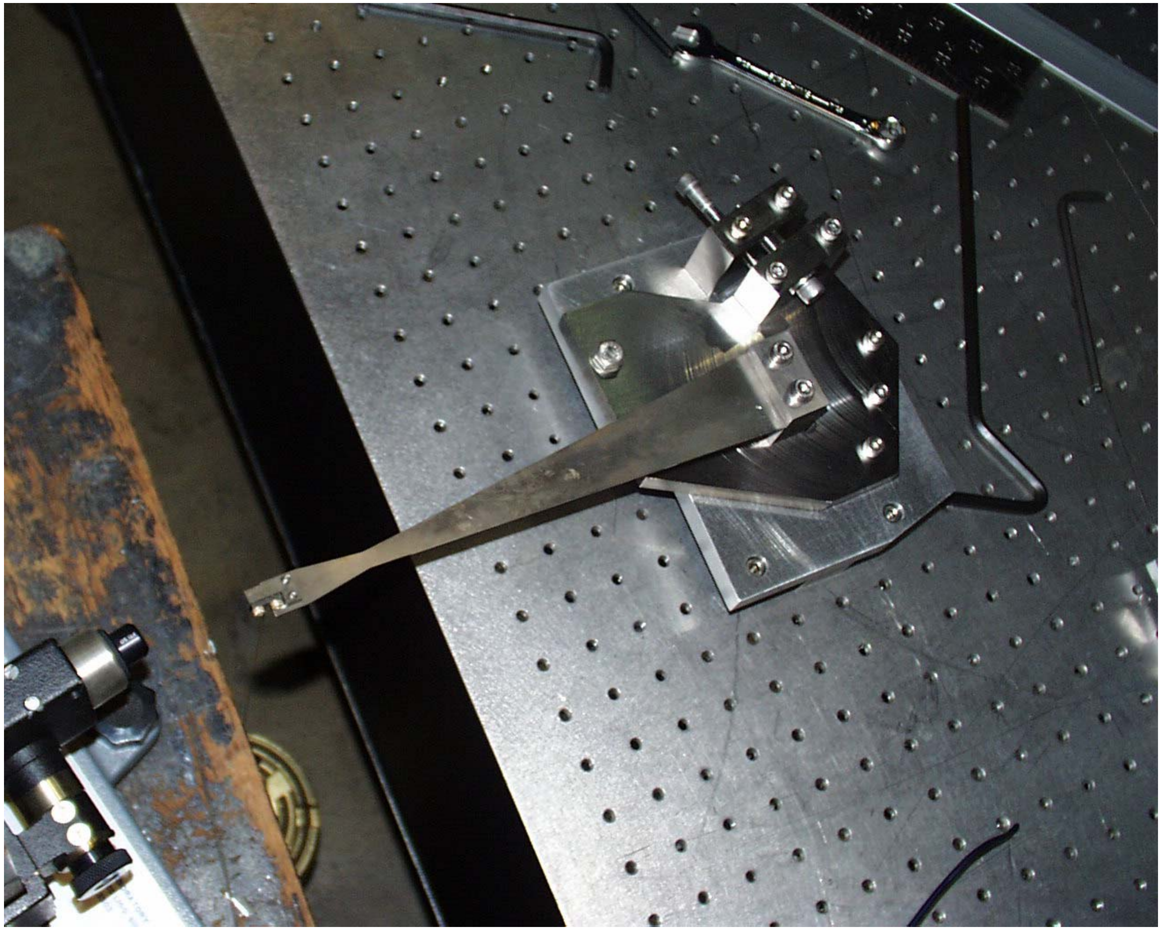




Pre - Prototypes

- For the Recycling Mirror prototypes have been made for several of the sub-assemblies including: -
  - Upper mass assembly
  - Yaw adjuster for the upper blades

Pre – Prototypes: RM Yaw Adjuster



Pre – Prototypes: RM Upper Mass

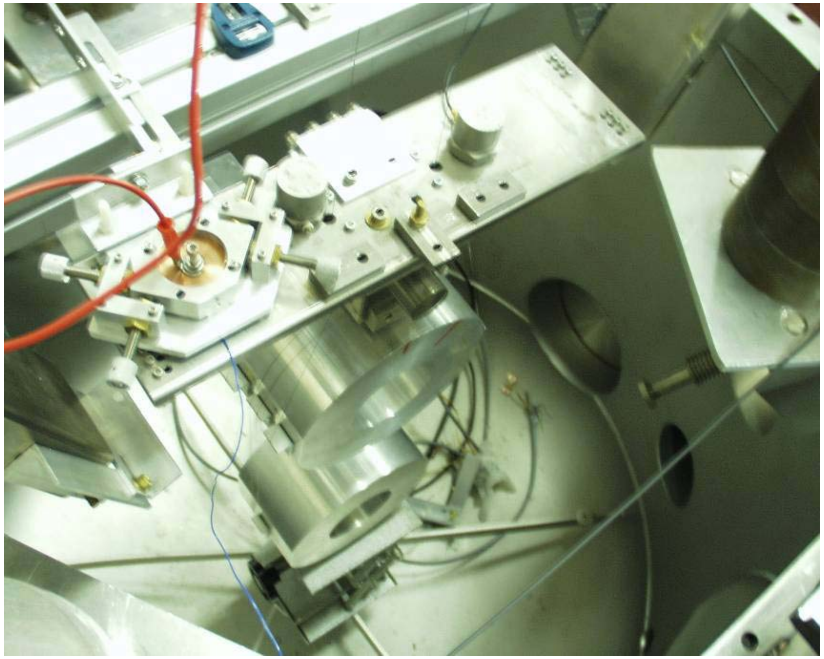
Pre – Prototypes

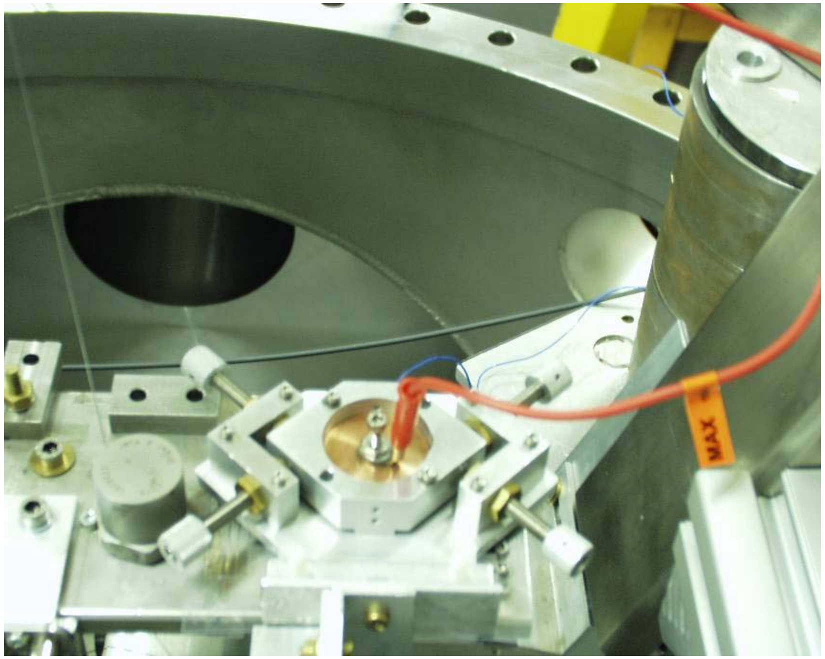
- For the Recycling Mirror prototypes have been made for several of the sub-assemblies including: -
  - Upper mass assembly
  - Yaw adjuster for the upper blades

- Mode Cleaner
  - Blade wire clamp
  - Eddy current damper

Pre – Prototypes: Work at the I.G.R.

Pre – Prototypes: Work at the I.G.R.





Mode Cleaner Controls Prototype

- 2 triple pendulum suspensions
  - One for LASTI and the other for Caltech
- Machined parts
  - Caltech Physics Shop
  - Central Engineering at Caltech (including structure)
  - University of Glasgow (coils + associated parts)
- Cantilever Blades
  - Outside machine shops in Los Angeles Area
- Hardware
  - Imperial bolts etc … (Unbrako or UC-Components)

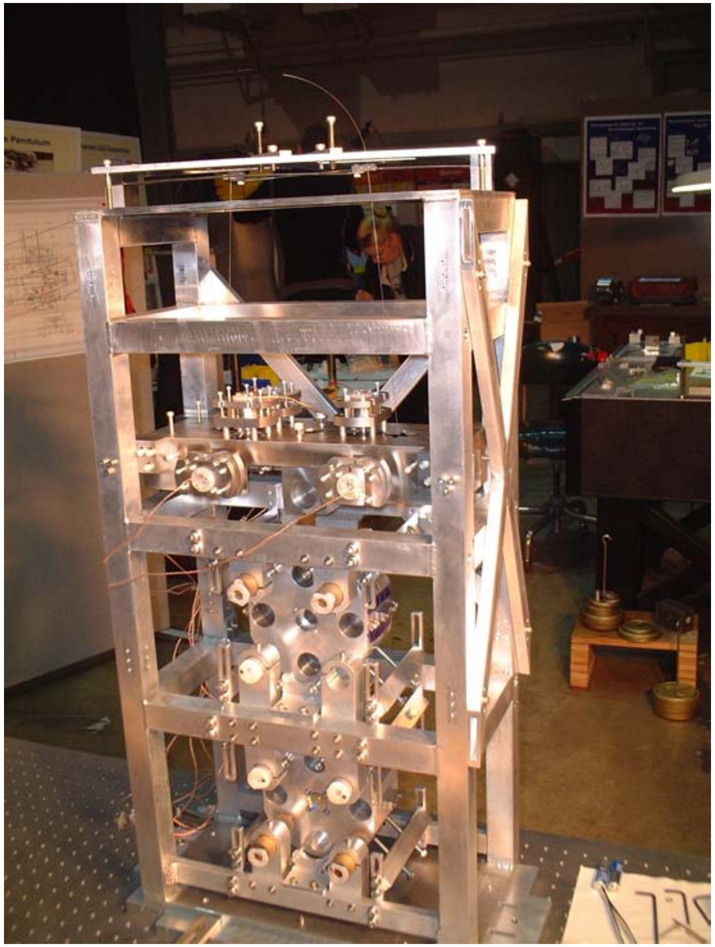
Final Assembly

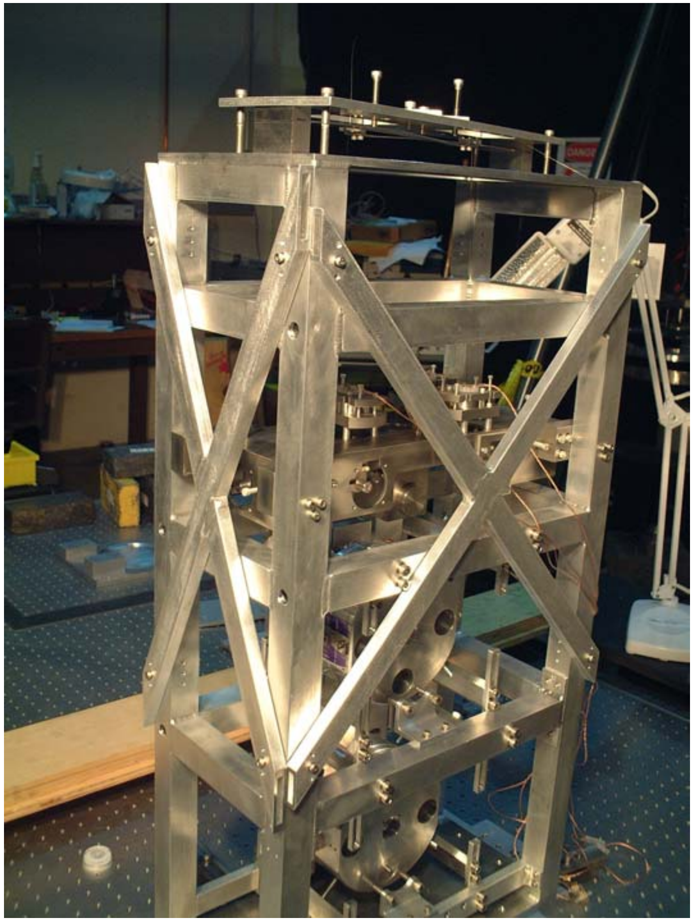
REF: -

HAM Overview - One Possible method of Assembly for the Advanced LIGO Mode Cleaner Controls Prototype Triple Pendulum Suspension

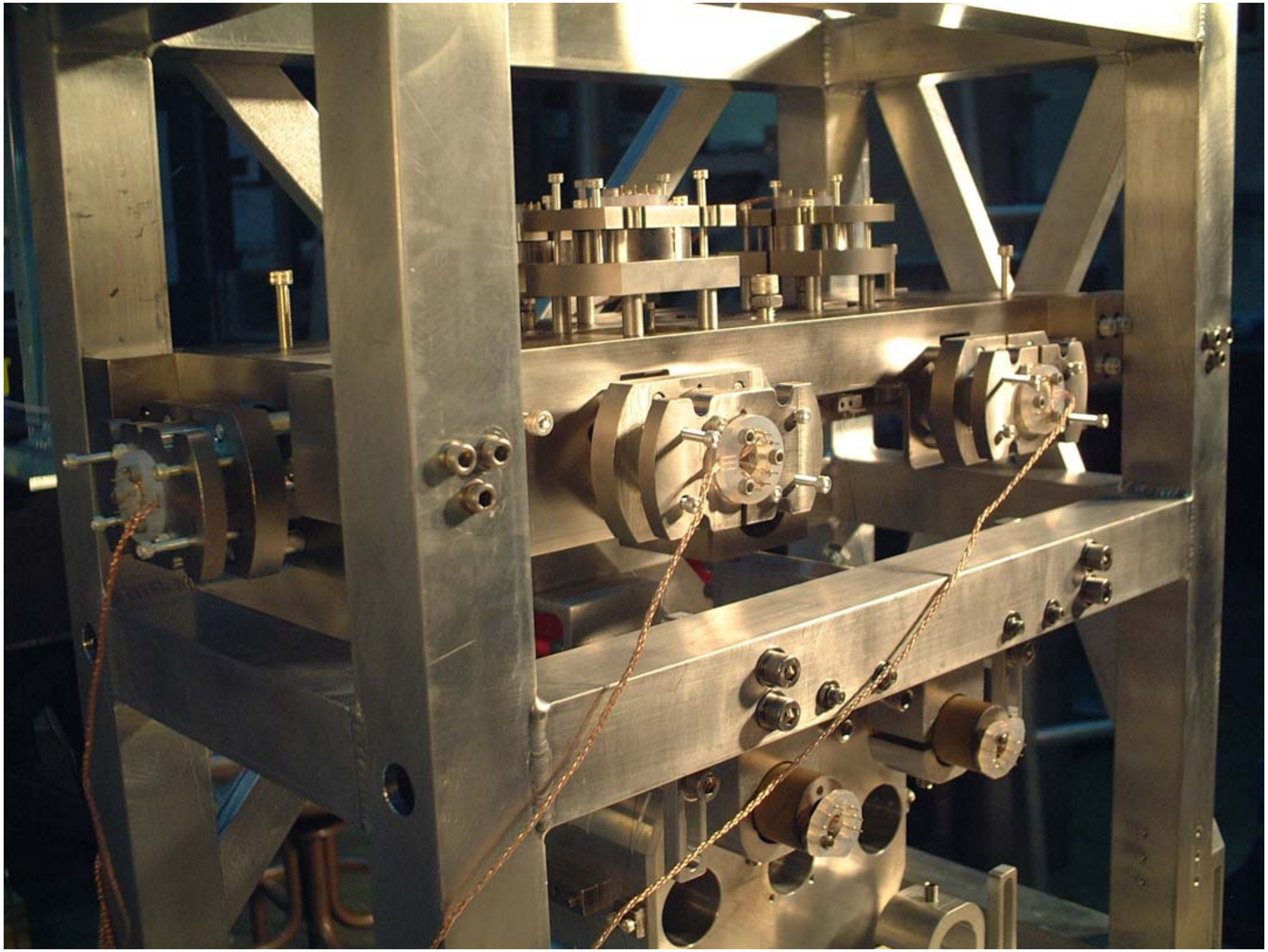
CALUM I. TORRIE and colleagues
California Institute of Technology
LSC MEETIING, HANNOVER
AUGUST 2003

Mode Cleaner Suspension





Mode Cleaner Suspension



References

- Quadruple suspension design for Advanced LIGON A Robertson, G Cagnoli, D R M Crooks, E Elliffe, J E Faller, P Fritschel, S Gosler, A Grant, A Heptonstall, J Hough, H Luck, R Mittleman, M Perreur-Lloyd, M V Plissi, S Rowan, D H Shoemaker, P H Sneddon, K A Strain, C I Torrie, H Ward and P Willems **Class. Quantum Grav. 19 4043-4058, 2002**

- Torrie CI 1999 PhD Thesis University Of Glasgow

- Husman M E, 2000 PhD Thesis University Of Glasgow

- Plissi MV, Torrie CI, Husman ME, Robertson NA, Strain KA and Hough J **2000 Rev. Sci. Instrum 71 2539-45**

- Husman ME, Torrie CI, Plissi MV, Robertson NA, Strain KA and Hough J **2000 Rev. Sci. Instrum 71 2546-51**

- Plissi MV, Strain KA, Torrie CI, Robertson NA, Rowan, S, Twyford S, Ward, H, Skeldon K and Hough J **1998 Rev. Sci. Instrum 69 3055-61**

- Fused Silica Suspensions for Advanced GW Detectors S. Rowan et al, **Proc. 2nd TAMA Workshop, Tokyo 1999, Gravitational Wave Detection II, Frontiers Science Series No. 32, UAP Inc Tokyo, 2000, 203 215,**

- Very high Q measurements of a fused silica monolithic pendulum for use in enhanced gravity wave detectors **G Cagnoli et al, Phys. Rev. Lett. 85, 2442-2445, 2000**

Schedule

- **Online + Handout**
  - MODE CLEANER ASSEMBLY
    - See before
  - WORK WITH RAL
    - Package of work sent to RAL + aligo_sus
  - ALIGNMENT
    - Doug, Betsy, Ken, Mike on Thursday

Suspension Workshop

- **YELLOW BOOK**
  - **DRAWING TREE, E030507** — I
  - **MATLAB PARAMETERS, E030508** — II
  - **OVERALL BILL OF MATERIALS, E030258** — III
  - **SUMMARY OF ASSEMBLIES + ASSEMBLY DRAWINGS** — IV
  - **NOT CURRENTLY CALLED IN THE OVERALL ASSEMBLY** — V
  - **COSTINGS, E030509** — VI
  - **HARDWARE COSTS e.g WIRE etc …** — VII
  - **HAM OVERVIEW, G030386** — VIII

- **BLUE FOLDERS** — REF
- **ASSSEMBLY PROCEDURE** — REF
- **D - SPACE and CONTROLLER INSTRUCTION MANUAL** — REF
- LIGO CLEANING PROCEDURE, E960022 — REF
- **WORKSHOP WEB PAGE** — REF