Appendix A

Electromagnet analysis

A.1 Electromagnet steady-state flux circuit analysis

In order to determine the static lift force characteristic of the electromagnet, it is necessary to determine the relationship between applied coil mmf and the resultant mmf across each suspension air gap. This can be achieved by analysing a model of the electromagnet flux circuit. Figure A.1 shows a model of the electromagnet flux circuit which incorporates three flux quantities, namely air gap flux, leakage flux and electromagnet core flux.

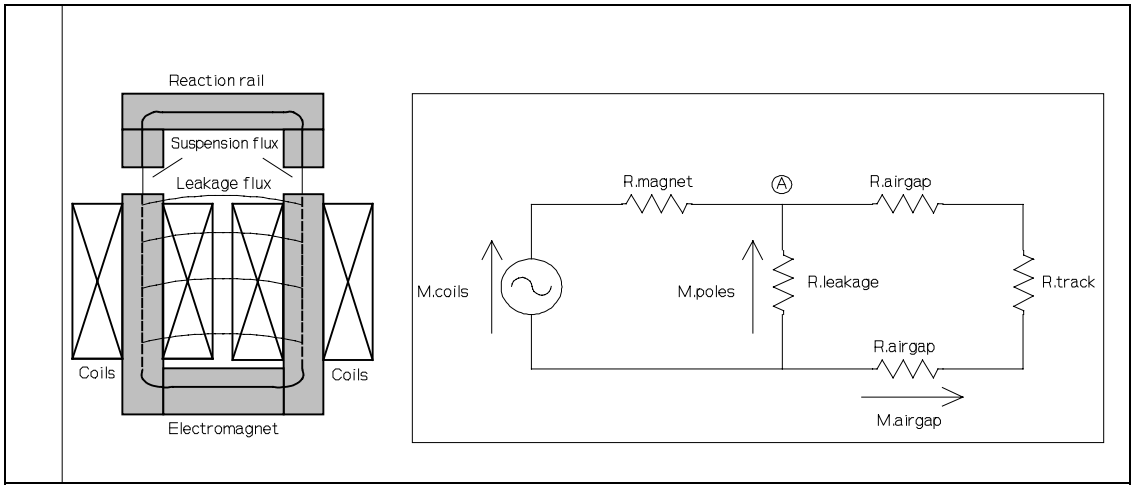


Figure A.1 Electromagnet flux paths and flux model circuit diagram

Network analysis and the application of Kirchhoff's Current Law is now used to determine the relationship between the applied coil mmf, M_{coils}, and the resulting air gap mmf, M_{airgap}. First, the currents into node A (see Figure 1) must be summed to zero, giving:

$$\frac{(M_{coils} - M_{poles})}{R_{magnet}} + \frac{(0 - M_{poles})}{R_{leakage}} + \frac{(0 - M_{poles})}{(R_{track} + 2R_{airgap})} = 0 \qquad \textbf{A.1}$$

This can be simplified by multiplying by the electromagnet and leakage reluctances,

$$(M_{coils} - M_{poles})R_{leakage} - M_{poles}R_{magnet} - \frac{M_{poles}R_{magnet}R_{leakage}}{(R_{track} + 2R_{airgap})} = 0 \qquad \textbf{A.2}$$

and collecting terms and rearranging thus,

$$M_{coils}R_{leakage} = M_{poles}\left(R_{leakage} + R_{magnet} + \frac{R_{magnet}R_{leakage}}{(R_{track} + 2R_{airgap})}\right) \qquad \textbf{A.3}$$

The mmf across each gap is given by the simple potential divider,

$$M_{airgap} = M_{poles}\left(\frac{R_{airgap}}{R_{track} + 2R_{airgap}}\right) \qquad \textbf{A.4}$$

and hence the pole piece mmf, in terms of the air gap mmf is given by:

$$M_{poles} = M_{airgap}\left(\frac{R_{track} + 2R_{airgap}}{R_{airgap}}\right) \qquad \textbf{A.5}$$

The expression for M_{poles} can now be substituted into Equation 3, giving:

$$M_{coils}R_{leakage} = M_{airgap}\left(\frac{R_{track} + 2R_{airgap}}{R_{airgap}}\right)\left(R_{leakage} + R_{magnet} + \frac{R_{magnet}R_{leakage}}{(R_{track} + 2R_{airgap})}\right) \qquad \textbf{A.6}$$

This can be rearranged to give the required relationship between coil mmf and airgap mmf,

$$\frac{M_{airgap}}{M_{coils}} = \frac{R_{leakage}R_{airgap}}{(R_{track} + 2R_{airgap})(R_{leakage} + R_{magnet}) + R_{magnet}R_{leakage}} \qquad \textbf{A.7}$$

A.2 Eddy current time constant analysis

The flux lag time constant due to eddy-currents circulating within the electromagnet and track cores must be determined before control system synthesis can be performed. A novel time domain analysis is proposed which considers elemental circuits within the core as depicted in Figure A.2. To simplify the analysis, the ferromagnetic core is assumed to have infinite permeability. The analysis is performed in 5 stages, involving the calculation of the following:

- inductance of the elemental circuit within the core.
- inductance of an external coil (ie. outside the core) with a flux coupling equivalent to the internal elemental circuit.
- resistance of the elemental coil.
- time constant of the equivalent external coil circuit.
- total flux lag time constant is obtained by integrating the elemental time constants.

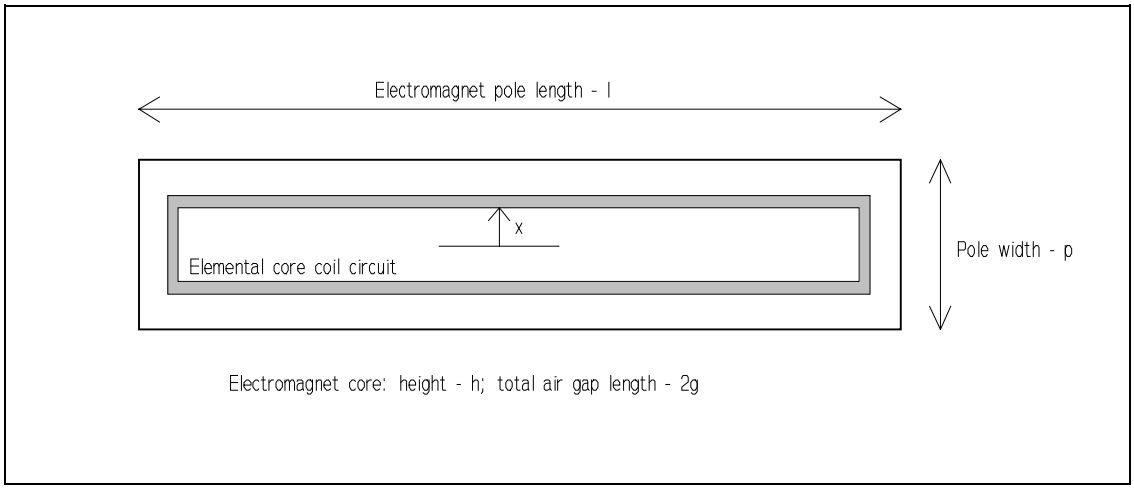


Figure A.2 Eddy current elemental coil circuit analysis

By assuming infinite core permeability, the self inductance of a cored coil of cross sectional area A, with N turns, and a core air gap g, is given by:

$$L_{coil} = \frac{\mu_o A N^2}{g} \qquad \textbf{A.8}$$

where μ_o is the permeability of free space.

The self inductance of the elemental coil circuit within the electromagnet core (with two air gaps) as depicted in Figure A.2 can therefore be approximated by:

$$L_{elem} = \frac{\mu_o 2x\,(l - p + 2x)}{2g} \approx \frac{\mu_o x\, l}{g} \qquad for\ l \gg p,x \qquad \textbf{A.9}$$

The elemental coil inductance must now be translated to the inductance of an external coil coupled to the entire core flux, this is given by:

$$L'_{elem} = L_{elem}\left(\frac{2x}{p}\right) = \frac{2\mu_o x^2 l}{pg} \qquad \textbf{A.10}$$

The resistance of the elemental coil circuit is given by:

$$R_{elem} = \frac{\rho\,(2l - 2p + 8x)}{h\delta x} \approx \frac{2\rho l}{h\delta x} \qquad for\ l \gg p,x \qquad \textbf{A.11}$$

where ρ is the resistivity of the core material, and δx is the width of the elemental coil.

The time constant for the equivalent external coil circuit is thus given by,

$$T'_{elem} = \frac{L'_{elem}}{R_{elem}} = \frac{2\mu_o x^2 l h \delta x}{2\rho l p g} = \frac{\mu_o h x^2 \delta x}{\rho p g} \qquad \textbf{A.12}$$

Since the equivalent external coil circuit is effectively coupled to the full core flux, the total time flux lag time constant due to eddy currents for all elemental coils is given by summing the time constant for each coil (see next section),

$$T_{eddy} = \sum T'_{elem} = \sum_x \frac{\mu_o h x^2 \delta x}{\rho p g} \qquad \textbf{A.13}$$

This summation can be most accurately and conveniently achieved by integrating the time constant of elemental eddy current coil circuits, giving,

$$T_{eddy} = \int_0^{p/2} \frac{\mu_o h x^2}{\rho p g}\, dx = \frac{\mu_o h}{\rho p g}\left[\frac{x^3}{3}\right]_0^{p/2} = \frac{\mu_o h p^2}{24\rho g} \qquad \textbf{A.14}$$

A.3 Summation of coil and eddy current time constants

The eddy current circuits analysed in the previous section give rise to a flux lag characteristic which augments the flux lag due to the electromagnet coil circuit.

The eddy current effect has been modelled using equivalent external coils. The electromagnet, therefore, can be modelled as a transformer with two windings consisting of the excitation coil turns and equivalent eddy current circuit turns. By neglecting any leakage inductance, the two windings can be assumed to be perfectly coupled and hence modelled by the first circuit shown in Figure A.3. The second circuit in Figure A.3 has a secondary winding circuit which has been referred with respect to the primary and is therefore equivalent to the first circuit. The second circuit is now used to analyse the combined behaviour of the coil and eddy current circuits.

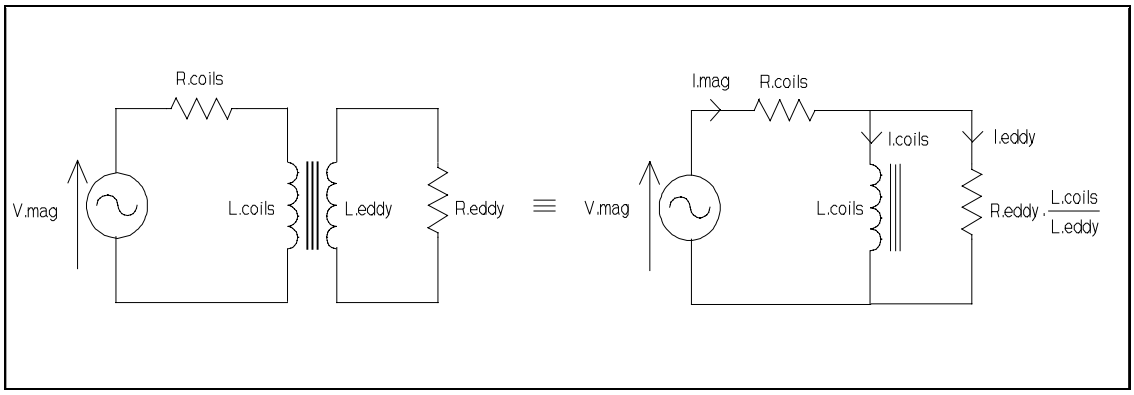


Figure A.3 Schematic models for the coil and eddy current circuits

For convenience the referred eddy current circuit resistance can be expressed more simply by:

$$R'_{eddy} = \frac{L_{coils}}{T_{eddy}} \qquad where \quad T_{eddy} = \frac{L_{eddy}}{R_{eddy}} \qquad \textbf{A.15}$$

The parallel impedance of the coil inductance and the normalised eddy current circuit resistance is then given by:

$$Z(L_{coils}) \parallel Z(R'_{eddy}) = \frac{sL_{coils}\dfrac{L_{coils}}{T_{eddy}}}{sL_{coils} + \dfrac{L_{coils}}{T_{eddy}}} = \frac{sL_{coils}}{(1+sT_{eddy})} \qquad \textbf{A.16}$$

where *Z(x)* represents the impedance of *x*, and *s* is the Laplace operator.

The voltage across the coil inductance is given by the potential divider:

$$\frac{V_{coils}}{V_{mag}} = \frac{\dfrac{sL_{coils}}{(1 + sT_{eddy})}}{R_{coils} + \dfrac{sL_{coils}}{(1 + sT_{eddy})}} = \frac{s\dfrac{L_{coils}}{R_{coils}}}{\left(1 + sT_{eddy} + s\dfrac{L_{coils}}{R_{coils}}\right)} \qquad \textbf{A.17}$$

Finally, this can be rearranged to express the coil current, I_{coils}, in terms of the applied electromagnet voltage, this gives:

$$I_{coils} = \frac{V_{coils}}{sL_{coils}} = \frac{1}{1 + s(T_{coils}+T_{eddy})}\frac{V_{mag}}{R_{coils}} \qquad where \quad T_{coils} = \frac{L_{coils}}{R_{coils}} \qquad \textbf{A.18}$$

The overall flux actuation characteristic is therefore a first-order lag with a time constant equal to the sum of the coil and eddy current time constants.

This result can be expanded in an iterative fashion to prove that any number of perfectly coupled shorted windings will give rise to a first-order flux lag with a time constant equal to the sum of the winding time constants. This fact is used in the previous section to combine the effect of elemental eddy current circuits.

Finally, the transfer function for the referred eddy current, and the total electromagnet current, in terms of the applied electromagnet voltage, are given by the following:

$$I_{eddy} = \frac{V_{coils}}{L_{coils}/T_{eddy}} = \frac{sT_{eddy}}{1 + s(T_{coils}+T_{eddy})}\frac{V_{mag}}{R_{coils}} \qquad \textbf{A.19}$$

$$I_{mag} = I_{coils} + I_{eddy} = \frac{1 + sT_{eddy}}{1 + s(T_{coils}+T_{eddy})}\frac{V_{mag}}{R_{coils}} \qquad \textbf{A.20}$$

A.4 Computer program to calculate electromagnet model parameter values

```
Program Magnet_Model();

{ Calculates parameter values and forces for the electromagnet model developed in Chapter 2}
{ Pascal Program;  Author: N. S. McLagan; 1-9-90; all variables in elementary units }


{ Electromagnet dimensions }
Const
  length = 0.200;
  pole   = 0.0095;
  offset = 0.0015;
  height = 0.063;
  width  = 0.033;
  num_turns = 274;

  mu_o = 1.2566e-6; { 4e-7.pi }


Function Gap_area( z : Real ) : Real;
  Begin    {Air gap normal plus fringe flux area - from Equation 2.11}
  Gap_area := length * (pole + (2*z / pi))
  End;


Function Lift_force_ratio( z : Real ) : Real;
  Begin    {Electromagnet lift/gross force ratio - Equation 2.20}
  Lift_force_ratio := 1 - (offset/z)*arctan(offset/z) / (1+(pi*pole)/(2*z))
  End;


Function R_mag( mu_m : real ) : Real;
  Begin    {Electromagnet core reluctance - Equation 2.13}
  R_mag := (2*height + width + 2*pole) / (mu_m * mu_o * length * pole)
  End;


Function Mu_mag( core_flux, mu_max, mu_break, mu_span : real ) : Real;

  { mu_max:    Plateau value for mu before roll-off. /1 }
  { mu_break:  Flux density break point for mu roll-off. /Tesla }
  { mu_span:   Span of fall from break point to zero. /Tesla }

  Var
    core_flux_density, mu : Real;
  Begin    {Electromagnet core permeability - Table 2.2}
  mu := mu_max;
  core_flux_density := core_flux / (pole * length);
  IF (core_flux_density > mu_break) Then
    mu := mu * (1 - (core_flux_density - mu_break)/mu_span);
  If (mu < 1) Then
    mu := 1;
  Mu_mag := mu
  End;  { of Mu_mag }


Function R_track( mu_t : Real ) : Real;
  Begin    {Track reluctance - Equation 2.12}
  R_track := (width + 4*pole) / (mu_t * mu_o * length * pole )
  End;


Function Mu_track : Real;
  Begin    {Relative track permeability}
  Mu_track := 2000;
  End;


Function R_leak : Real;
  Begin    {Leakage reluctance - Equation 2.15}
  R_leak := 2*width /( mu_o * (length + 2*width/pi) * (height + 2*width/pi) )
  End;
```

```
Function R_gap( z : real ) : Real;
  Begin    {Air gap reluctance - from Equation 2.11}
  R_gap := z / ( mu_o * Gap_area(z) )
  End;


Function L_mag( z, mu_m, mu_t : Real ) : Real;
  Begin    {Electromagnet inductance - Equation 2.32}
  L_mag := num_turns * num_turns * (R_track(mu_t) + 2*R_gap(z) + R_leak) /
       ((R_track(mu_t)+2*R_gap(z))*(R_leak+R_mag(mu_m))+(R_mag(mu_m)*R_leak))
  End;


Procedure Calculate( Var current, airgap_flux, leakage_flux, core_flux : Real;
               { Using } airgap, force, mu, mu_break, mu_span : Real );
  Var
    gross_force_per_pole : Real;
    pole_mmf, iron_mmf, coil_mmf : Real;

  Begin
  gross_force_per_pole := force / (2 * Lift_force_ratio(airgap));
  airgap_flux  := SQRT( 2*gross_force_per_pole * Gap_area(airgap) * mu_o );
  pole_mmf := airgap_flux * (2 * R_gap(airgap) + R_track( Mu_track ) );
  leakage_flux := pole_mmf / R_leak;
  core_flux  := airgap_flux + leakage_flux;
  iron_mmf := core_flux * R_mag( Mu_mag( core_flux, mu, mu_break, mu_span ) );
  coil_mmf := pole_mmf + iron_mmf;
  current := coil_mmf / num_turns;
  End;  { of Calculate }


Procedure Force;

  Var
    airgap_index : Integer;
    force, airgap : Real;
    airgap_flux, leakage_flux, core_flux : Real;
    current, k : Real;

  Begin
    writeln;
    write( 'Enter required lift force in Newtons: ');
    readln( force );
    writeln;
    For airgap_index := 1 To 9 Do
      Begin
      airgap := airgap_index / 1000;
      Calculate( current, airgap_flux, leakage_flux, core_flux,
                 { Using } airgap, force, 2000, 1.0, 0.6 );
      k := force * airgap * airgap * 1E6 / (current * current);
      write( 'Airgap =', airgap_index:2 );
      write( '  I =',current:7:2 );
      write( '  k =', k:6:2 );
      write( '  track B =', airgap_flux/pole/length:5:2 );
      write( '  mag B =', core_flux/pole/length:5:2 );
      write( '  mu_m =', Mu_mag( core_flux, 2000, 1.0, 0.6 ):5:0 );
      writeln
      End; { of gap loop }
    End;  { of Force }


Procedure Parameters;
  Var
    airgap_index, mu : Integer;
    gap : Real;

  Begin
  mu := 2000;
  writeln;  writeln('All reluctances are kA/Wb, Inductances are in mH' );
  For airgap_index := 0 To 9 Do
    Begin
    gap := airgap_index / 1000;
    writeln;  write( 'Gap = ', airgap_index );
    write( '  R_mag = ',R_mag(mu)/1000:1:0 );
    write( '  R_track = ',R_track(mu)/1000:1:0 );
    write( '  R_leak = ', R_leak/1000:1:0 );
    write( '  2*R_gap = ', 2*R_gap(gap)/1000:4:0 );
    write( '  L_mag =', 1000*L_mag(gap,mu,mu):5:1 );
    write( '   A_gap =', Gap_area(gap):3:3 ); }
    End
  End;  { of Parameters }
```

```
Procedure Spreadsheet_plots;
  Var
    datafile : Text;
    airgap_index, force_index : Integer;
    airgap, force : Real;
    current_fo, current_imu, current_fmu, current_vmu : Real;
    airgap_flux, leakage_flux, core_flux : Real;

  Begin
  writeln;
  writeln( 'Writing spreadsheet data to file: magmodel.dat ' );
  write( 'Airgaps: ');
  Assign( datafile, 'magmodel.dat' );
  Rewrite( datafile );
  For airgap_index := 1 To 7 Do
    Begin
    write( airgap_index, ',' );
    For force_index := 0 To 100 Do
      Begin
      airgap := airgap_index / 1000;
      force := force_index * 20;
      current_fo := SQRT(4*force/(mu_o*pole*length))*airgap/num_turns;
      Calculate( current_imu, airgap_flux, leakage_flux, core_flux,
                 { Using } airgap, force, 1E6, 1E6, 1E6 );
      Calculate( current_fmu, airgap_flux, leakage_flux, core_flux,
                 { Using } airgap, force, 2000, 1E6, 1E6 );
      Calculate( current_vmu, airgap_flux, leakage_flux, core_flux,
                 { Using } airgap, force, 2000, 1.0, 0.6 );
      writeln( datafile, force:10:1, current_fo:8:2, current_imu:8:2,
                                     current_fmu:8:2, current_vmu:8:2  );
      End;  { of force loop }
      writeln( datafile )
    End;  { of airgap loop }
    Close( datafile )
  End;  { of Spreadsheet_plots }


Procedure Menu;
  Var
    response : Char;
  Begin
    Repeat
      writeln;
      writeln;
      writeln('Force and flux characteristic');
      writeln('Parameters');
      writeln('Spreadsheet plot file');
      writeln('Quit');
      readln(response);
      Case response Of
        'f','F': Force;
        'p','P': Parameters;
        's','S': Spreadsheet_plots;
        End; { of Case }
    Until (response = 'Q') Or (response = 'q')
  End;  { of Menu }


Begin
Menu
End.
```

A.5 Electromagnet and rail design parameters

The analysis of the experimental electromagnet described in Chapter 2 provides a good grounding in the fundamental electromagnetic principles and practical issues that are central to the operation of a suspension electromagnet. This section first examines the impact of electromagnet and rail design parameters on the steady-state force and the force dynamics, and then two distinct electromagnet configurations that have evolved are discussed.

A.5.1 Steady-state force

The air gap flux coupling the electromagnet and its reaction rail generates a force of attraction between the electromagnet and rail. To assist in the understanding of the concepts involved, it is helpful to make two simplifying assumptions. The first assumption is that the electromagnet and rail cores have negligible reluctance relative to the air gaps, and the second is that the air gap flux is uniformly distributed over an area equal to the electromagnet pole face area. Using these approximations, the lift force is proportional to the square power of the air gap flux density multiplied by the total air gap flux area. To get a satisfactory core lift/weight ratio, the core must be operated with a high flux density. Unit magnetic flux density produces a lift force per unit area of about 4×10^5 N/m^2. This is a 'magnetic pressure' of 4 bar (60 lb/in^2) which is comparable with a typical truck tyre pressure. The flux density used and hence the magnetic pressure determines the pole face area required to support a given load. For example, a 1 t lift capacity requires a total electromagnet pole face area of about 250 cm^2 at unit flux density.

At the required high operational flux levels, the reluctance of the cores is not negligible relative to the air gap reluctance. Also, for air gap dimensions comparable to the pole width, significant flux fringing occurs giving an effective air gap flux area larger than the pole face area. For accurate modelling, the simplifying assumptions used above are untenable and a more detailed analysis is required.

The coil excitation required to produce unit flux density in the air gap is dominantly determined by the permeability of free space. Thus, approximately 1600 ampere-turns are required per mm of electromagnet air gap (this figure allows for both air gaps). The desired operating air gap range and lift force range thus determine the required coil excitation range. The coil must be able to dissipate the waste heat generated at the

required excitation and also provide an acceptable power/lift ratio so that excessive power controller weight is avoided. Two critical factors are the conductor resistivity and the method of cooling the coils. These factors dictate a nominal operational current density for the windings based on thermal considerations. The coil cross-section and hence the slot area between the pole pieces can be calculated directly from the current density and the ampere-turns. Coils are usually made from copper or aluminium wire or foil. Aluminium is less dense than copper, but it has a higher resistivity, thus requiring a lower current density than copper for a given power dissipation. The lower current density for aluminium is achieved at the expense of a larger coil cross-sectional area which also needs a longer and hence heavier core. A detailed optimisation analysis is therefore required to design for best power/lift and lift/weight ratios.

In addition to the air gap flux linking the electromagnet and rail, flux also flows across the slot between the pole pieces, increasing the flux through the cores. If the slot is too narrow, this leakage flux requires a larger, heavier core, whereas if it is too wide, the extra yoke length also increases the core weight. The amount of leakage flux is also affected by the location of the coils which can be wound either around the pole pieces or around the yoke. With the coils on the pole pieces, the m.m.f. rises up the pole pieces from 0% at the yoke to 100% at the pole faces. However, with a yoke wound coil, the full m.m.f. is present all the way up the pole pieces. The first arrangement benefits from a smaller leakage flux, thus requiring a smaller and lighter core, whilst the latter arrangement allows a modest increase in the pole face length and area without increasing the yoke and coil size and weight. The optimum slot width/height ratio and the coil location clearly depends on the detailed electromagnet configuration and dimensions.

The partitioning of the coil cross-section into a particular number of turns depends largely on a practical consideration of available power semiconductor technology. From a heat transfer viewpoint, a solid coil consisting of one turn would be ideal. However, such a high current and low voltage coil would obviously require rather a heavy and inefficient power controller and interconnecting cables ! To enable the use of light and economical power controllers, the voltage and current rating of the coil must be matched for use with available power semiconductor technology. The slot space occupied by insulation, and the thermal insulation attendant with electrical insulation must be factored into the allowable coil current density discussed above.

The lift force characteristic outlined above assumes the electromagnet and its rail are vertically aligned. If the electromagnet is displaced laterally so that there is some

overlap of the poles, then the shear flux near the pole edges produces a lateral force component in addition to a reduced lift force component. By using an inverted U-shaped rail core, shear flux occurs at both electromagnet pole faces when the electromagnet and rail are laterally displaced. This rail core shape gives approximately double the lateral force, but at the expense of a reduced lift force because of the increased air gap reluctance. For small lateral displacements (relative to the pole width), the lateral force is approximately proportional to the displacement, thus giving a reasonably constant lateral stiffness. The lateral force and hence stiffness do however decrease as the air gap increases. Accurate modelling of the lateral force for a given pole face geometry, lateral displacement and electromagnet air gap requires a detailed analysis of the air gap flux distribution.

Having considered the design parameters which affect the steady-state force characteristics of suspension electromagnets, the parameters affecting the rate of change of flux must now be considered to determine the dynamic force characteristics.

A.5.2 Force dynamics

Electromagnet flux changes from one steady-state value to a new steady-state value whenever the air gap or the applied coil terminal voltage changes. The variation in the electromagnet core flux generates an e.m.f. across any conducting circuits that enclose the flux. For a suspension electromagnet, there are two such circuits. The first is the excitation coil circuit, whilst the second circuit occurs within the core material in which circulating eddy currents are distributed. The coil inductance and resistance impose a first order lag characteristic on the core flux with the time constant given by the inductance / resistance ratio. The flux lag due to eddy currents in the core can be approximated by integrating the effect of elemental circuits within the core. This produces a first order flux lag with a time constant proportional to the square power of the smallest pole face dimension divided by the resistivity of the core material. The combined effect of the flux coupled circuits is a first order flux lag characteristic, with a time constant equal to the sum of the coil and core lag time constants. Both the coil inductance and the effective eddy current circuit inductance are a function of the magnetic reluctance of the flux path and hence the air gap length. The flux lag time constant is therefore inversely proportional the air gap length.

The dynamic requirements and structure of the closed-loop suspension controller determine acceptable flux lag time constants for the electromagnet coil and core. There

is little design flexibility with the coil time constant since the coil inductance is fundamentally determined by the air gap reluctance and the coil resistance is generally designed on the basis of coil weight and steady-state power dissipation. The number of coil turns offers no help since doubling the number of turns doubles both the inductance and resistance (assuming a constant coil cross section) leaving the time constant unchanged.

The flux lag time constant due to eddy currents in electromagnet/rail cores depends critically on the shape and size of the pole faces. The time constant can be reduced using a suitable feedback strategy, but if necessary, it is usually more cost effective to modify the core. This can be achieved through the use of high silicon steel (which has a larger resistivity than mild steel) or by using a laminated core construction to reduce the dimensions of the eddy current circuits within the core.

Eddy currents also affect the motion of an electromagnet along its rail. This is because eddy currents in the rail cause a lag in the magnetisation and subsequent demagnetisation of the rail as an electromagnet progresses along the guideway. These spatial flux lags reduce the lift force and generate a drag force. The time a moving electromagnet takes to pass a point on its rail is given by the electromagnet length divided by its speed. As this passing time decreases towards the flux lag time constant of the rail core, the problem becomes more severe. This problem thus increases with higher speeds, shorter magnets and longer rail core time constants. It can therefore be alleviated by using longer electromagnets, higher resistivity steel or a laminated track core. Rather than use a very long electromagnet, a series of shorter electromagnets that maintain the rail magnetism over a number of electromagnets often carries practical advantages.

In addition to controlled d.c. excitation of the electromagnet coil, controlled a.c. excitation provides a similar characteristic lift force behaviour. However, by suitably configuring a number of multi-phase a.c. windings, a moving magnetic field can be produced which generates a propulsion force component in addition to the lift force component. Unfortunately, a.c. excitation produces a lower lift force compared with d.c. excitation. This is because the mean amplitude of a sinusoidal flux is $1/\sqrt{2}$ of the d.c. flux level. Since the force is proportional to the square power of the flux, a 50% loss of force results from the use of a.c. rather than d.c. excitation, assuming a given maximum core flux level. A.c. excited cores also suffer from higher leakage flux due to the larger number of narrower slots which are required to accommodate the multi-phase windings. The overall effect is that a.c. excitation requires approximately

double the core size and weight compared with d.c. excitation. The coil must also be larger and heavier since it must encircle the larger core. The rapid cycling of flux associated with typical a.c. excitation means that laminated magnetic steel or iron cores are mandatory. The merits of using an a.c. excited suspension/propulsion electromagnet/motor clearly depend on whether the additional weight and complexity of the combined scheme is less than that required for a separate linear induction/synchronous motor.

The last dynamic effect to be considered is that due to the magnetic hysteresis of the core materials. Hysteresis can be viewed as an effect which modifies the permeability of the core material. It is very difficult to model accurately because it is a nonlinear function of the flux history of the core. Fortunately, the impact of the core hysteresis on the total flux path reluctance can be largely neglected due to the dominance of the air gap reluctance. However, at small air gaps the effect of hysteresis on the lift force is significant and a qualitative consideration must be made when designing the electromagnet suspension control system.

A detailed analysis of an electromagnetic suspension system in terms of the required closed loop bandwidth, vehicle speed and electromagnet deployment is required to determine suitable pole face dimensions, mode of excitation (a.c. or d.c.), and electromagnet and rail core constructions.

A.5.3 Practical suspension electromagnets

The overview given above of the influence of electromagnet design parameters on both the steady-state and dynamic performance shows the highly interactive nature of suspension electromagnet design. A successful design clearly requires a constrained optimisation, involving all of the critical design factors, and the use of a structured design procedure[1] is a prerequisite. Out of the multitude of possible electromagnet designs, practical and economic considerations have led to the emergence of two distinct configurations. The base configurations both use U-shaped electromagnets with a flat rail to provide a balance between the critical electromagnet parameters listed in Table A.1.

The two configurations which have emerged are characterised by the orientation with which the magnetic flux passes through the rail. This being either perpendicular (transverse flux) or in-line (axial flux) to the rail direction of travel.

Table A.1 Critical performance parameters for an electromagnetic suspension

• Lift force range	• Weight
• Operational air gap range	• Power consumption
• Lateral force stiffness	• Electromagnet cost
• Track velocity range	• Track cost
• Flux time constant	

Achieving an acceptable rail core size for transverse flux electromagnets requires the use of long, narrow electromagnet poles (with a typical pole length/width ratio of about 100). Such pole faces are sufficiently narrow to permit the use of solid steel cores for the electromagnet and rail with an acceptable eddy current flux lag, even at high speeds. The alternative axial flux electromagnet configuration can use a relatively square pole face without incurring a rail size penalty. However, the square pole cross-section causes a large flux lag time constant due to eddy currents circulating within the cores. This necessitates the use of either a high resistivity or laminated core for the axial flux electromagnet and a laminated core for its rail,[2] thus incurring a significant additional cost over a solid steel rail core.

The are two main performance advantages that accrue from the use of relatively square pole faces rather than long, narrow pole faces. Firstly, they have a much smaller perimeter which results in shorter, lighter coils, with the additional benefit of lower power consumption. A shorter pole length also leads to significantly reduced leakage flux between the pole pieces. This enables the electromagnet core size and weight to be reduced. An additional refinement is possible when two or more adjacent axial flux electromagnets are required, since they can be combined to share common inner pole coils. This configuration (referred to as an E-core when two U-cores are combined) reduces the coil weight relative to independent electromagnets.

The axial flux configuration is thus capable of providing a performance improvement over the transverse flux configuration in terms of the electromagnet lift/weight and power/lift ratios. This performance improvement is achieved at the expense of the requirement for a laminated rail core and either a high resistivity or laminated electromagnet core.

In order to provide a feel for practical electromagnet configurations, the parameters of the axial flux electromagnets used on the PMG vehicle[3] at Birmingham, and the transverse flux electromagnets used on the University of Sussex experimental vehicle[4]

are listed in Table A.2. Both vehicles use electromagnets with anodised aluminium foil coils wound around the pole pieces. The superior performance of the axial flux electromagnet is illustrated by its lift/weight ratio which is almost double that of the transverse flux electromagnet.

Table A.2 Parameters of typical axial flux and transverse flux electromagnets

Electromagnet Parameters	Axial Flux	Transverse Flux
Vehicle	PMG Birmingham 8t	Sussex University 1t
Lift capacity	1 t	¼ t
Nominal air gap	15 mm	10 mm
Pole face (length × width)	100 × 50 mm	1000 × 12 mm
Number of flux circuits	2	1
Slot width	100 mm	100 mm
Electromagnet core	E-shaped Magnetic steel	U-shaped Mild steel
Rail core	Laminated Magnetic steel	U-shaped Mild steel
Lift / Weight ratio	11	6
Power / Lift ratio	3 kW/t	2.8 kW/t

The final configuration to be considered is the a.c. excited axial flux electromagnet/motor employed by the combined suspension/propulsion schemes. The induction motor design uses a slotted, laminated electromagnet/motor core excited by multi-phase a.c. windings. The laminated rail incorporates shorted conduction bar coils as found in conventional induction motor rotors. The active track synchronous motor based scheme uses a slotted, laminated rail core, with powered multi-phase a.c. stator coils to provide propulsion and suspension excitation. The matching 'rotor' cores also carry coils which are used to control the suspension lift force. These combined systems have the obvious advantage of not requiring a separate and heavy propulsion motor and aluminium guideway reaction rail. However, a.c. excitation requires double the electromagnet and rail core size and weight plus a much heavier coil compared to d.c. excitation. An additional drawback for the linear induction motor scheme is that the rail cost is higher than a normal laminated rail due to the conduction bars. The extreme expense of the rail core and coils and the associated power controllers for the active

track linear synchronous motor scheme are justified only for very high speed systems. The active track overcomes the problem of trying to supply many megawatts of propulsion power in a non-contacting fashion to a vehicle travelling at speeds of up to 500 km/h. It is interesting to note that the force of attraction between the stator and 'rotor' of the linear synchronous motor would in most other applications probably be regarded as an undesirable parasitic effect.

A.6 References

1 Sinha, P. K.: 'Electromagnetic suspension: Dynamics & control', Peter Peregrinus, London, Chapter 6, 1987.

2 Yamamura, S. and Yamaguchi, H.: 'Electromagnetic Levitation System by means of salient pole type magnets coupled with laminated slotless rails', *IEEE Trans. on Veh. Tech.*, **VT-39**, 1990, pp 83-7.

3 Nenadovic, V. and Riches, E.E.: 'Maglev at Birmingham Airport: from system concept to successful operation', *GEC Review*, **1**, 1985, pp 3-17.

4 Jayawant, B.V., Sinha, P.K., Wheeler, A.R., Whorlow, R.J. and Willsher, J.: 'Development of a 1-ton magnetically suspended vehicle using controlled d.c. electromagnets', *Proc. IEE, Pt. A*, **123**, 1976, pp 941-8.

Appendix B

Electromagnet force control

B.1 Open-loop electromagnet force/voltage transfer function

The air gap flux, Φ, of the electromagnet is approximately proportional to the coil current, I, divided by the air gap, C, (see Equation 2.27). This nonlinear flux behaviour can be linearised for small perturbations and represented in the frequency domain by the Laplace transfer function given by:

$$\Delta\Phi(s) = k_{\phi i}\,\Delta I(s) - k_{\phi c}\,\Delta C(s) \quad \textit{where} \quad k_{\phi i} = \frac{\partial\phi(i_o,c_o)}{\partial i}, \quad k_{\phi c} = -\frac{\partial\phi(i_o,c_o)}{\partial c} \qquad \textbf{B.1}$$

The same treatment applied to the electromagnet force, F, (see Equation 2.25), which is approximately proportional to the square power of the air gap flux, gives:

$$\Delta F(s) = k_{f\phi}\,\Delta\Phi(s) \quad \textit{where} \quad k_{f\phi} = \frac{\partial f(i_o,c_o)}{\partial\phi} \qquad \textbf{B.2}$$

The dynamic relationship between electromagnet coil voltage, V, coil current, and air gap flux, (see Equation 2.26), is given by:

$$\Delta V(s) = sN\,\Delta\Phi(s) + R_{coils}\,\Delta I(s) \qquad \textbf{B.3}$$

where N is the number of coil turns, and R_{coils} is the coil resistance. Finally, the acceleration of the suspended load due to the electromagnet force is given by:

$$s^2\,\Delta C(s) = -\frac{\Delta F(s)}{m} \qquad \textbf{B.4}$$

where m is the total load mass. Equation B.1 is now rearranged to form an expression for the current in terms of the flux and air gap, this gives:

$$\Delta I(s) = \frac{1}{k_{\phi i}}\Delta\Phi(s) + \frac{k_{\phi c}}{k_{\phi i}}\Delta C(s) \qquad \textbf{B.5}$$

This current expression is substituted into Equation B.3, giving:

$$\Delta V(s) = sN\Delta\Phi(s) + \frac{R_{coils}}{k_{\phi i}}\Delta\Phi(s) + \frac{R_{coils}k_{\phi c}}{k_{\phi i}}\Delta C(s) \qquad \textbf{B.6}$$

Equation B.2 is now rearranged to form an expression for flux in terms of force, this gives:

$$\Delta\Phi(s) = \frac{\Delta F(s)}{k_{f\phi}} \qquad \textbf{B.7}$$

This flux expression is substituted into Equation B.6, giving:

$$\Delta V(s) = \frac{\Delta F(s)}{k_{f\phi}}\left(sN + \frac{R_{coils}}{k_{\phi i}}\right) + \frac{k_{\phi c}R_{coils}}{k_{\phi i}}\Delta C(s) \qquad \textbf{B.8}$$

Equation B.4 is now rearranged to give an expression for air gap in terms of forces by:

$$\Delta C(s) = -\frac{\Delta F(s)}{ms^2} \qquad \textbf{B.9}$$

This air gap expression is substituted into Equation B.8, giving:

$$\Delta V(s) = \frac{\Delta F(s)}{k_{f\phi}}\left(sN + \frac{R_{coils}}{k_{\phi i}} - \frac{k_{f\phi}k_{\phi c}R_{coils}}{k_{\phi i}ms^2}\right) \qquad \textbf{B.10}$$

This can now be rearranged to give the electromagnet force/voltage transfer function:

$$\frac{\Delta F(s)}{\Delta V(s)} = \frac{k_{f\phi}k_{\phi i}}{R_{coils}}\frac{s^2}{\left(s^3Nk_{\phi i}/R_{coils} + s^2 - k_{f\phi}k_{\phi c}/m\right)} \qquad \textbf{B.11}$$

For convenience, it is noted that (see Equations 2.27 and 2.29):

$$k_{\phi i} = \frac{\partial\phi}{\partial i} = \frac{\partial}{\partial i}\left(\frac{L_{coils}\,i}{N}\right) = \frac{L_{coils}}{N}, \qquad \textbf{B.12}$$

$$\therefore \quad L_{coils} = Nk_{\phi i}, \qquad T_{coil} = \frac{L_{coils}}{R} = \frac{Nk_{\phi i}}{R}$$

B.2 Closed-loop current feedback transfer function

The transfer function for the electromagnet current feedback loop is now analysed. Figure B.1 shows the configuration of the current feedback controller, where k_{amp} is the current loop gain, V_{mag} is the applied electromagnet coil voltage, I_{mag} is the electromagnet current, and I_{coils} is the component of the electromagnet current which produces the suspension force. The open-loop electromagnet transfer functions $I_{coils}/V_{mag}(s)$ and $I_{mag}/V_{mag}(s)$ are derived in Appendix A, Section 3.

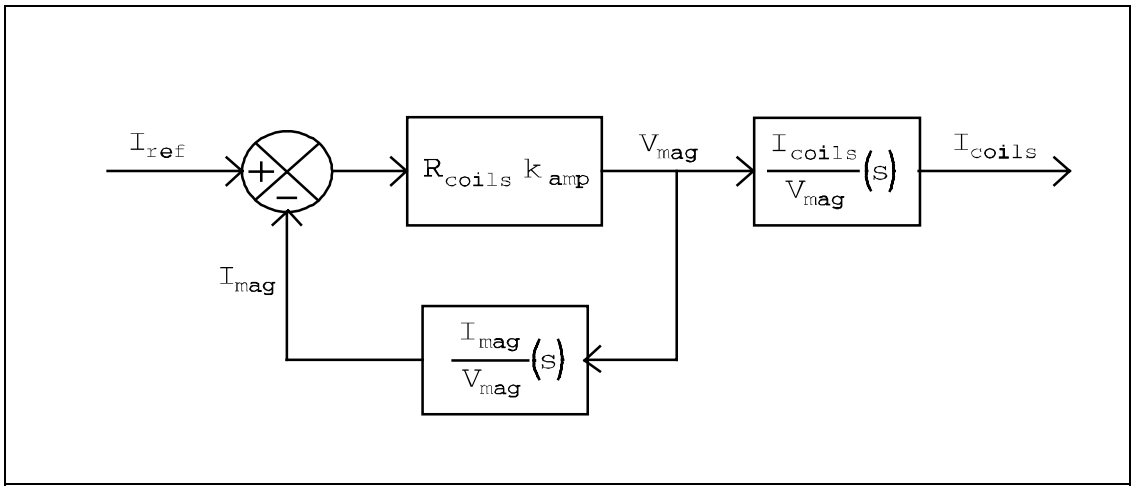


Figure B.1 Configuration of the closed-loop current feedback control

The closed-loop transfer function in terms of the Laplace operator s, is given by:

$$\frac{I_{coils}(s)}{I_{ref}(s)} = \frac{R_{coils}\, k_{amp}\, \dfrac{I_{coils}}{V_{mag}}(s)}{1 + R_{coils}\, k_{amp}\, \dfrac{I_{mag}}{V_{mag}}(s)} \qquad \textbf{B.13}$$

Expanding the two open-loop transfers functions gives:

$$\frac{I_{coils}(s)}{I_{ref}(s)} = \frac{R_{coils}\, k_{amp} \left(\dfrac{1}{R_{coils}} \dfrac{1}{1 + s\left(T_{coils} + T_{eddy}\right)} \right)}{1 + R_{coils}\, k_{amp} \left(\dfrac{1}{R_{coils}} \dfrac{1 + s\,T_{eddy}}{1 + s\left(T_{coils} + T_{eddy}\right)} \right)} \qquad \textbf{B.14}$$

This can be simplified to give:

$$\frac{I_{coils}(s)}{I_{ref}(s)} = \frac{k_{amp}}{1 + s\left(T_{coils} + T_{eddy}\right) + k_{amp}\left(1 + sT_{eddy}\right)} \qquad \textbf{B.15}$$

For large values of feedback gain k_{amp}, this can be approximated by:

$$\frac{I_{coils}(s)}{I_{ref}(s)} \approx \frac{1}{1 + s\left(\frac{T_{coils}}{k_{amp}} + T_{eddy}\right)} \qquad where \quad k_{amp} \gg 1 \qquad \textbf{B.16}$$

Equation B.16 shows that the use of current feedback reduces the time constant due to the electromagnet coil, but not the time constant due to the eddy currents circulating within the cores.

B.3 Matlab models for root loci generation

```
%  MatLab Script  f_locus.m
%
%  This script produces a root locus plot for force feedback
%
%         Author:  N. S. McLagan
%  Last modified:  11th December, 1990
%

% Electromagnet/amplifier parameters
Tflux = 0.116
kc = 950000
mass = 15

% Gain factor range
kmax = 120
k = [ 0:0.005:0.135, 0.1409811442, 0.141, 1 ];

% H(s) numerator & denominator
num = [ kmax, 0, 0 ]
den = [ Tflux, 1, 0, -kc/mass ]

p = rlocus( num, den, [0] )
r = rlocus( num, den, k );
a = rlocus( num, den, [1] );
axis([-200, +100, -100, +100])
plot( real(r), imag(r), '-' )
text( real(p)-1.5, imag(p)-2.4, 'X')
text( real(a(2))-1.5, imag(a(2))-2.4, '>' )
text( real(a(3))-1.5, imag(a(3))-2.4, '<' )
grid

!del f_locus.met
meta f_locus.met              % Put current plot into temporary metafile
!gpp f_locus /dhpgl           % Invoke GPP to convert to HPGL
```

```
%  MatLab Script  c_locus.m
%
%  This script produces a root locus plot for air gap feedback
%
%         Author:  N. S. McLagan
%  Last modified:  12th December, 1990
%

% Electromagnet/amplifier parameters
Tflux = 0.0057
kc = 950000
mass = 15

% Gain factor range
kmin = 0
kmax = 2
k = [ kmin:0.05:0.9, 0.92800303825, 1.000001, 1.05:0.05:kmax ];

% H(s) numerator & denominator
num = [ 0 0 kc/mass ]
den = [ Tflux 1 0 -kc/mass ]

p = rlocus( num, den, [kmin] )
r = rlocus( num, den, k );
a = rlocus( num, den, [kmax] );
axis([-400, +200, -200, +200])
plot( real(r), imag(r), '-' )
text( real(p)-3, imag(p)-4.8, 'X')
text( real(a(1))-3, imag(a(1))-4.8, '<' )
grid

!del c_locus.met
meta c_locus.met              % Put current plot into temporary metafile
!gpp c_locus /dhpgl           % Invoke GPP to convert to HPGL
```

Appendix C

Suspension mode control

C.1 Position control system transfer function

This section details the derivation of the Laplace transfer function of the suspension position control system illustrated in Figure 4.4. The Laplace transform of the control law for the position controller is given by:

$$F_{demand}(s) = -\left(k_{pos} + \frac{k_{pos}}{sT_{err}}\right)\left(\frac{s^2 Z(s)}{\left(s+\omega_{int}\right)^2} - Z_{ref}(s)\right) - k_{vel}\frac{s^2 Z(s)}{\left(s+\omega_{int}\right)} - k_{acc} s^2 Z(s) \quad \textbf{C.1}$$

where Z is the position, Z_{ref} is the position reference, and the feedback gains are denoted by: k_{pos} - position error (stiffness), T_{err} - error integral (time constant), k_{vel} - velocity (damping), k_{acc} - acceleration (virtual mass), and ω_{int} is the low frequency cutoff point for the state integrators. This equation is rearranged for later convenience, giving:

$$F_{demand}(s) = -\frac{Z(s)}{\left(s+\omega_{int}\right)^2}\left[s\frac{k_{pos}}{T_{err}} + s^2 k_{pos} + s^2\left(s+\omega_{int}\right)k_{vel} + s^2\left(s+\omega_{int}\right)^2 k_{acc}\right] + \frac{Z_{ref}(s)}{s}\left[\frac{k_{pos}}{T_{err}} + s k_{pos}\right] \quad \textbf{C.2}$$

The acceleration of the suspended load due to the control force demand and a disturbance force is given by:

$$s^2 Z(s) = \frac{F_{demand}(s)}{m\left(1+sT_{force}\right)} + \frac{F_{disturb}(s)}{m} \quad \textbf{C.3}$$

where $F_{disturb}$ is the disturbance force, T_{force} is the force actuation time constant, and m is the suspended mass. This is also rearranged for convenience, giving:

$$F_{demand}(s) \quad = \quad s^2\left(1+sT_{force}\right)m\ Z(s) \quad - \quad \left(1+sT_{force}\right)\ F_{disturb}(s) \qquad \textbf{C.4}$$

The Laplace transform of the closed-loop position/disturbance force transfer function can now be determined by equating the control force demand of Equation C.2 and Equation C.4, this gives:

$$\frac{Z(s)}{\left(s+\omega_{int}\right)^2}\left[s\frac{k_{pos}}{T_{err}} + s^2k_{pos} + s^2\left(s+\omega_{int}\right)k_{vel} + s^2\left(s+\omega_{int}\right)^2k_{acc} + s^2\left(1+sT_{force}\right)\left(s+\omega_{int}\right)^2m\right]$$

$$= \quad \frac{Z_{ref}(s)}{s}\left[\frac{k_{pos}}{T_{err}} + sk_{pos}\right] + F_{disturb}(s)\ \left(1+sT_{force}\right) \qquad \textbf{C.5}$$

As an intermediate step, it is useful to expand the terms which comprise the characteristic polynomial of the closed-loop transfer function. The characteristic polynomial is thus given by:

$$CharPoly(s) \quad = \quad s\frac{k_{pos}}{T_{err}} + s^2k_{pos} + s^3k_{vel} + s^2\omega_{int}k_{vel} + s^4k_{acc} + 2s^3\omega_{int}k_{acc} + s^2\omega_{int}^2k_{acc}$$

$$+ \quad s^4m + 2s^3\omega_{int}m + s^2\omega_{int}^2m + s^5mT_{force} + 2s^4\omega_{int}mT_{force} + s^3\omega_{int}^2mT_{force} \qquad \textbf{C.6}$$

Equation C.5 can now be rearranged with the help of Equation C.6 to obtain the closed-loop transfer function of the position control system in terms of the position reference input and the disturbance force input. This yields:

$$\frac{Z(s)}{Z_{ref}(s)} = \frac{k_{pos}\left(s+1/T_{err}\right)\left(s+\omega_{int}\right)^2}{s^6\left(mT_{force}\right) + s^5\left(k_{acc}+m+2\omega_{int}mT_{force}\right) + s^4\left(k_{vel}+2\omega_{int}(k_{acc}+m)+\omega_{int}^2mT_{force}\right) + s^3\left(k_{pos}+\omega_{int}^2(k_{acc}+m)+\omega_{int}k_{vel}\right) + s^2\left(k_{pos}/T_{err}\right)} \qquad \textbf{C.7}$$

$$\frac{Z(s)}{F_{disturb}(s)} = \frac{\left(1+sT_{force}\right)\left(s+\omega_{int}\right)^2}{s^5\left(mT_{force}\right) + s^4\left(k_{acc}+m+2\omega_{int}mT_{force}\right) + s^3\left(k_{vel}+2\omega_{int}(k_{acc}+m)+\omega_{int}^2mT_{force}\right) + s^2\left(k_{pos}+\omega_{int}^2(k_{acc}+m)+\omega_{int}k_{vel}\right) + s\left(k_{pos}/T_{err}\right)} \qquad \textbf{C.8}$$

C.2 ACSL model of electromagnet suspension control system

```
Program Maglev
"---- Single Electromagnet Suspension System Simulation"

"---- Features: - Nonlinear electromagnet model"
"----           - Nonlinear force controller"
"----           - Absolute position controller (P+I+D+DD)"
"----           - Guideway following filter (2 pole)"

"---- Author: Neil McLagan"
"---- Last modified: 4-2-91"

"---- All variables are in elementary units (eg. secs, metres, newtons)"
"---- unless the variable name suggests otherwise, eg. gap.mm"

Initial
    "---- Electromagnet characteristics"
    Constant  Rcoil = 0.79
    Table  Lcoil, 1, 3 / 0.001, 0.003, 0.005,   0.088, 0.067, 0.059 /
    Table  Teddy, 1, 3 / 0.001, 0.003, 0.005,   0.005, 0.003, 0.002 /
    "---- Electromagnet force = kForce * I^2 / G^2"
    Constant  kForce = 44.8E-6
    Constant  Fmin = 1.0, Fmax = 1000.0
    Constant  Mass = 15.0

    "---- Current Amplifier characteristics"
    Constant  kIerr = 100.0    $ "Closed-loop gain"
    Constant  Vmax = 30.0      $ "Supply voltage"
    Constant  Imin = 0.0,  Imax = 20.0
    Constant  DeltaI = 0.005    $ "DAC resolution"

    "---- Disturbance characteristics"
    Constant  Ride = 1.5E-3, Tstart = 0.1, Ts = 0.0
    Constant  StpSiz = 1.0E-3, StpWid = 2.5
    Constant  MinGap = 0.5E-3, MaxGap = 10.0E-3

    "---- Feedback sensor time constants and quantization"
    Constant  TgapS = 0.80E-3, deltaG = 5.0E-6
    Constant  TaccS = 0.45E-3, deltaA = 5.0E-3

    "---- Acceleration signal high-pass filter (H/W) time constant"
    Constant  TaccF = 1.5

    "---- Absolute position controller feedback gains"
    Constant  Steady =      1.0  $ "-- s"
    Constant  Stiff  = 250000.0  $ "-- N/m"
    Constant  Damp   =   6500.0  $ "-- N/(m/s)"
    Constant  Vmass  =     15.0  $ "-- kg (virtual mass)"

    "---- Other time constants"
    Constant  Tfollo = 0.04  $ "Guideway following cutoff freq: 4 Hz"
    Constant  Tinteg = 1.6   $ "State integration cutoff freq: 0.1 Hz"
    Constant  Tforce = 0.0015 $ "Required force actuation time constant"

    "---- Initialise feedback signals"
    Idem = 0.0
    Gap = MinGap
    Gapmm = Gap * 1000.0
    Pi = 3.1415926
```

```
    "---- Simulation control"
    Constant  Tstop = 8.0
    Tdisp = Tstop - 2.0 * StpWid

End $ " of Initial"


Dynamic
    Termt(t .ge. Tstop)
    Td = t - Ts
    Tdisp = Tstop - 2.0 * StpWid

    Cinterval Tcomm = 10.0E-3  $  "Communication interval"
    Algorithm Ialg=3  $ "Euler integration"


    Derivative  Magnet  $  "Electromagnet and Current Amplifier"

      Maxterval Tmagss = 0.1E-3  $ "Integration step size"
      Nsteps Msteps = 1

      Procedural

        "---- Closed loop magnet current controller"
        Vmag = Bound( -Vmax, Vmax, kIerr * (Idem - Imag) )

        "---- Apply coil flux lag to electromagnet "
        Imag = RealPl( Lcoil(Gap)/Rcoil, Vmag/(Rcoil*Gap) ) * Gap

        "---- Apply eddy current flux lag to electromagnet"
        Flux = RealPl( Teddy(Gap), Imag/Gap )

        "---- Limits for magnet movement (clamped initially)"
        LowLim = FcnSw( t-Tstart, ride, MinGap, MinGap)
        UprLim = FcnSw( t-Tstart, ride, MaxGap, MaxGap)

        "---- Static electromagnet force characteristic"
        Fmag = Bound(Fmin, Fmax, kForce * (Flux*Flux) )

        "---- Magnet acceleration, velocity & position"
        Acc = 9.81 - (Fmag / Mass)
        DblInt(Pos, Vel =  0.0, Acc, 0.0, LowLim, UprLim)
        Gap = Bound( MinGap, MaxGap, Pos )
        Gapmm = Gap * 1000.0

        "---- Air gap and acceleration feedback sensors"
        GapFB = RealPl( TgapS, Gap, MinGap )
        AccFB2 = RealPl( TaccS, Acc )
        AccFB1 = RealPl( TaccS, AccFB2 )

        "---- Acceleration high-pass filter (analogue)"
        AccFB = AccFB1 - RealPl( TaccF, AccFB1 )

      End $ " of Procedural"
    End $ " of Derivative Electromagnet & Current Amplifier Model"
```

```
    Discrete  Contro  $  "Discrete time digital controller"

      Interval  Tsampl = 0.8E-3  $  "Controller sampling interval"
      Procedural

        "---- Position step input reference"
        GapRef = Ride + Bound(0.0, StpSiz, -1.0E6 * SIN(Pi*t/StpWid) )

        "---- Feedback sensor Quantization"
        AccQ = Bound( -9.81, +9.81, Qntzr(deltaA, AccFB) )
        GapQ = Bound( 0.0, 10.0E-3, Qntzr(deltaG, GapFB) )

        "---- Calculate Magnet acc, vel, pos & Track pos"
        AccHP  = AccQ - RealPl( Tinteg, AccQ )
        VelHP = RealPl( Tinteg, AccHP * Tinteg )
        PosHP = RealPl( Tinteg, VelHP * Tinteg )
        TrkHP = (GapRef + PosHP) - GapQ

        "---- Apply Guideway following filter"
        TrkF1  = RealPl( Tfollo, TrkHP )
        PosRef = RealPl( Tfollo, TrkF1 )

        "---- Absolute position controller"
        PosErr = PosHP - PosRef
        AccDem = Vmass * AccHP
        VelDem = Damp * VelHP
        PosDem = Stiff * PosErr
        SseDem = (Stiff/Steady) * LimInt(PosErr,0.0,-0.02,+0.02)

        "---- Steady-state, position, velocity, acceleration demand"
        Fdem = (9.81 * Mass) + AccDem + VelDem + PosDem + SseDem

        "---- Determine required magnet current"
        Fsqrt = SQRT( Bound( Fmin, Fmax, Fdem ) / kForce )
        Idem = Qntzr( deltaI, LedLag(Teddy(0.001), Tforce, Fsqrt*gapQ))

      End $ " of Procedural"
    End $ " of Discrete Controller"
End $ " of Dynamic "
End $ " of Maglev Simulation "
```

Appendix D

Control system hardware

This Appendix lists the specifications of the industrial accelerometer and air gap sensor, and the schematic diagrams for all of the control system hardware. The various system components are listed below:

D.1 Accelerometer

The Model 3110 is a general purpose, solid-state, piezo-resistive accelerometer with built-in amplification and temperature compensation. The module consists of a silicon micro-machined accelerometer.

ICSensors, accelerometer, model 3110-002, specifications.
(Supply voltage = 10 Vdc, Ambient temperature = 25 °C)

PARAMETERS	Min	Typ	Max	Units	Notes
Range		±2		g	
Frequency Response		0-350		Hz	
Mounted Resonant Frequency		600		Hz	
Full Scale Output (- Acc)		0.5		Volts	1
Full Scale Output (+ Acc)		4.5		Volts	1
Full Scale Output Span	3.96	4.00	4.04	Volts	1
Zero Acceleration Output	2.48	2.5	2.52	Volts	1
Damping Factor		0.7			2
Accuracy		0.2	1.0	±%Span	3
Transverse Sensitivity		1.0	3.0	±%Span	
Temperature Coefficient - Span		1.0	2.0	±%Span	4
Temperature Coefficient - Zero		1.0	2.0	±%Span	4
Supply Voltage	8.0	10.0	30.0	Volts	
Supply Current		5.0		mA	
Output Resistance		0.1		Ω	
Output Noise		0.5		mV p-p	
Output Load Resistance	2			kΩ	
Acceleration Limits		20x		Rated	
Operating Temperature	-20		+85	°C	
Storage Temperature	-40		+125	°C	
Weight (Excluding Cable)		23		Grams	

Notes

1. The output voltage increases from the Zero Acceleration Output for positive acceleration and decreases for negative acceleration. The sensitivity is then 2V/Range.

2. The 0.7 damping factor represents critical damping. The damping factor is controlled to within ±10% over the entire operating temperature range. Alternate damping factors are available on a special order basis.

3. Includes repeatability, hysteresis and linearity (best straight line fit).

4. Compensated temperature range: 0 to 50 °C in reference to 25 °C.

5. See Model 3021 for an accelerometer without amplification and compensation.

6. Pin 2 provides an optional 2.5 V reference which may be used, if desired, to provide a stable zero-g reference. Thus, the full scale differential output between Pin 2 and Pin 4 would be ±2 Vdc. If a single-ended output signal is preferred (0.5-4.5 Vdc), make no connection to Pin 2.

ICSensors, Model 3110, Pin connections.

Pin:	1	2	3	4	5
Function:	Ground	Zero-g ref.	Supply (+)	Output	Test point

D.2 Air gap sensor

The non-contacting air gap sensor used is a general purpose device, which uses the power loss due to eddy currents in the target to determine the air gap or material properties. For accurate measurement of air gap, the resistivity of the target must remain constant, ie. known material and constant temperature.

Pepperl+Fuchs, Inductive displacement sensor, model IA8-M1K-I3, specifications.

PARAMETERS	VALUES
Sensing Range	3mm - 8 mm
Nominal Values:	
Damping plate, 1mm St 37	35 mm x 35 mm
Linearity (rel. to FSD)	± 3%
Zero Tolerance	± 2%
Working Voltage	15 to 30 V dc
Cut-off Frequency (3 dB)	≈ 190 Hz
Repeatability Accuracy	≤ 15 µm
Hysteresis Error	≤ 30 µm
Electrical Data:	
Output Signal	0 - 20 mA
Load Resistance R_L	0..500 Ω
Quiescent Current Consumption	< 8 mA
Ripple Current (measured @ R_L=100Ω)	≈ ±1.5% FSD
Temperature Drift (target & transducer at same temperature)	≈ ±1 %/K FSD
Current Consumption max.	≤ 35 mA
Mechanical Data:	
Ambient Temperature	-10 to +70 °C
Protection class to DIN 40 050	IP 67
Permissable shock and vibration stresses	b ≤ 30 g, T ≤ 11 ms f ≤ 55 Hz, a ≤ 1 mm
Type of connection	Wire, $\phi \leq 2.5mm^2$

The useable sensing range with the MAGLEV track as target is about 3 mm - 10 mm, with distances above 8 mm being outside the rated specification (see full data sheet).

D.3 Equipment chassis configurations

All equipment chassis are 3U high and 84E wide, ie. for single height, short eurocards (160 x 100 mm). The single electromagnet suspension contains all cards and modules in one chassis, whilst the multi-magnet vehicle uses 2 chassis: one with the DAC and the power controllers, and the other with the ADCs, processors and PSUs.

D.3.1 Single electromagnet suspension system

Logic & Power Control Chassis

Card:	EMCA	PSU	-	DAC	-	TMB	TMB	IPIF	ADC	SAP	CONN
Width:	20	10	4	4	4	10	10	4	4	4	10

D.3.2 Vehicle suspension system

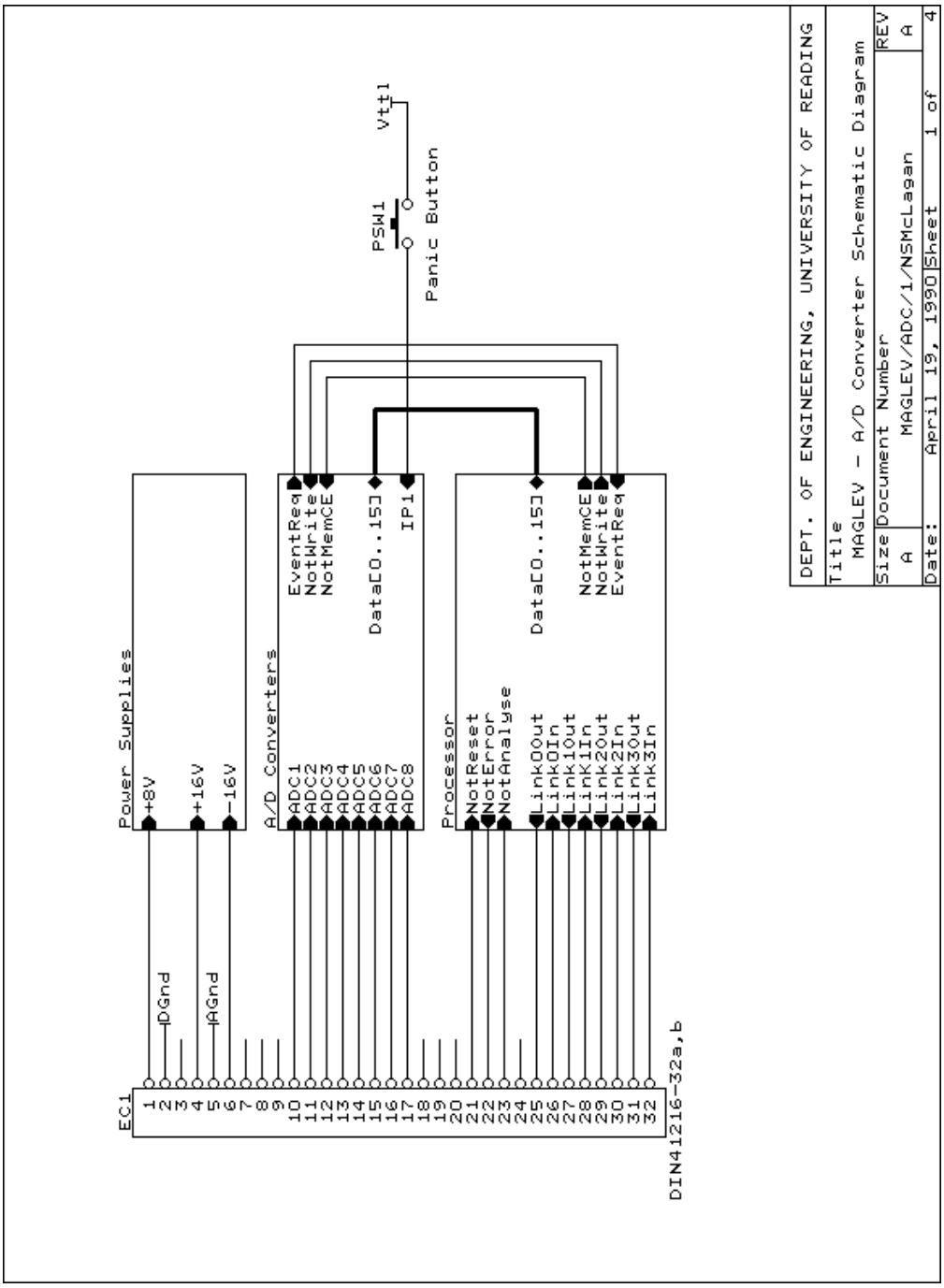
Logic Control Chassis

Card:	PSU	PSU	-	OPIF	TMB	TMB	TMB	IPIF	-	ADC	SAP	CONN
Width:	10	10	4	4	10	10	10	4	4	4	4	10

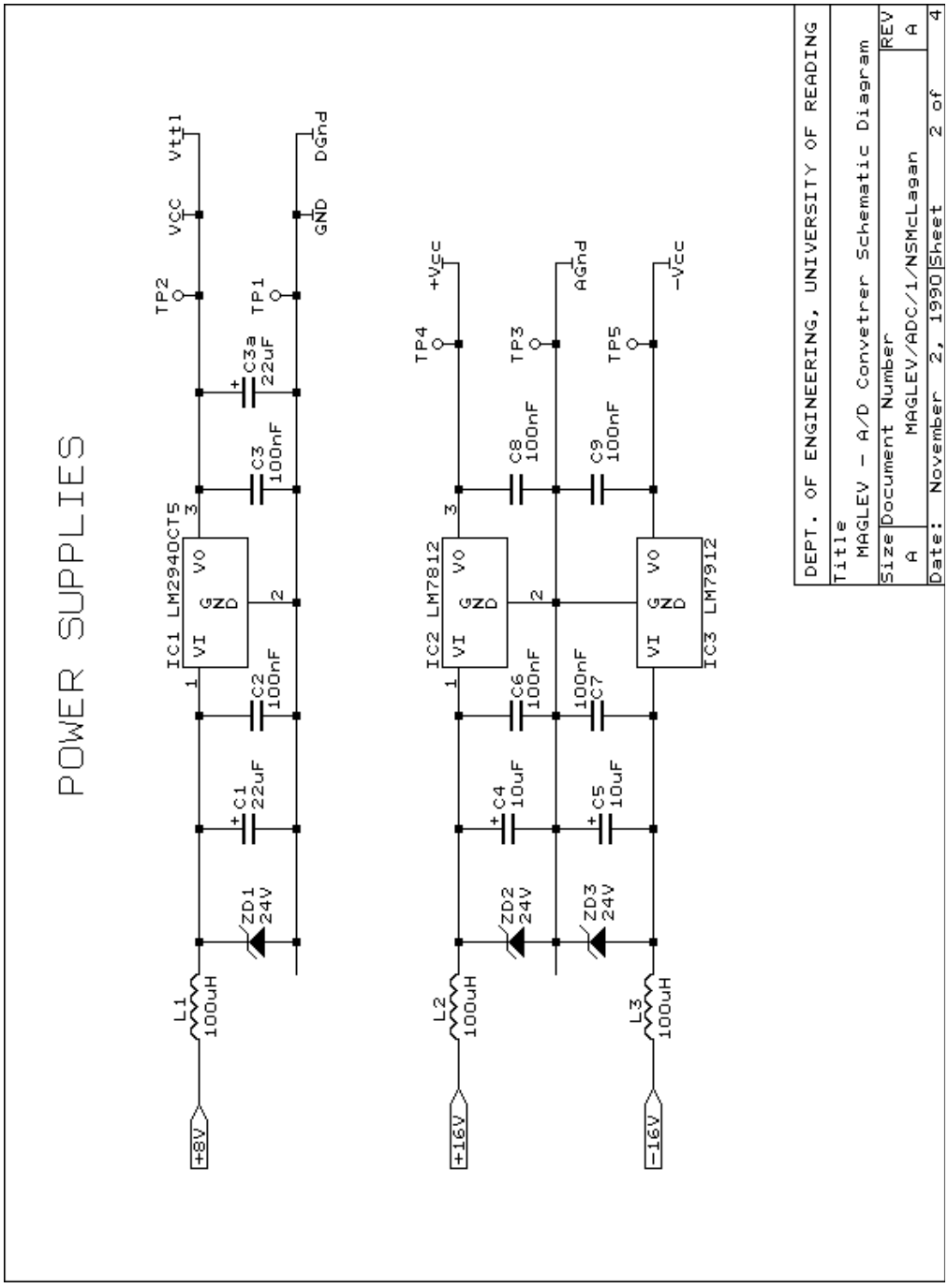
Power Control Chassis

Card:	EMCA	EMCA	EMCA	EMCA	DAC
Width:	20	20	20	20	4

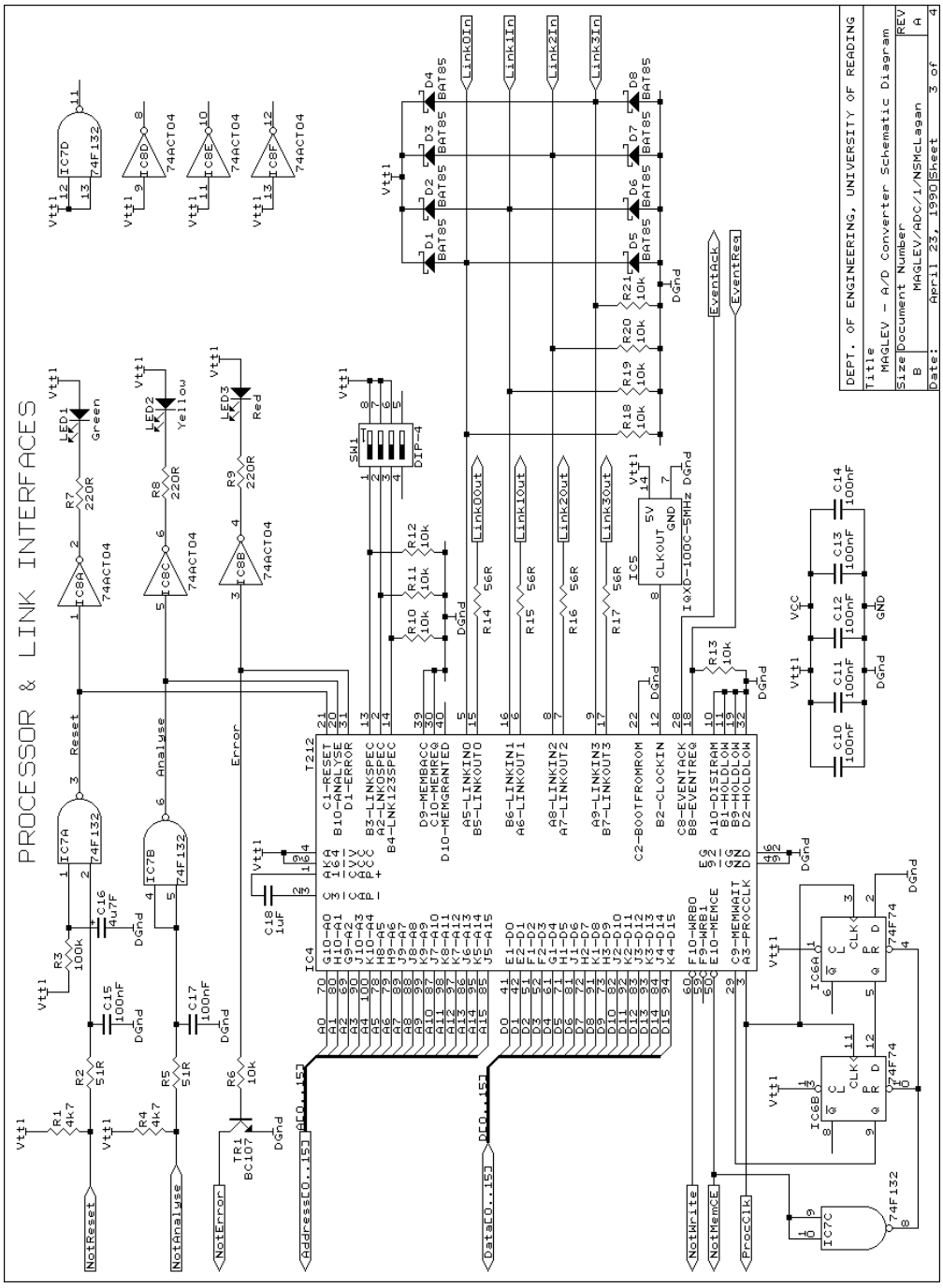
D.4 Analogue-to-digital converter (8 channel) card



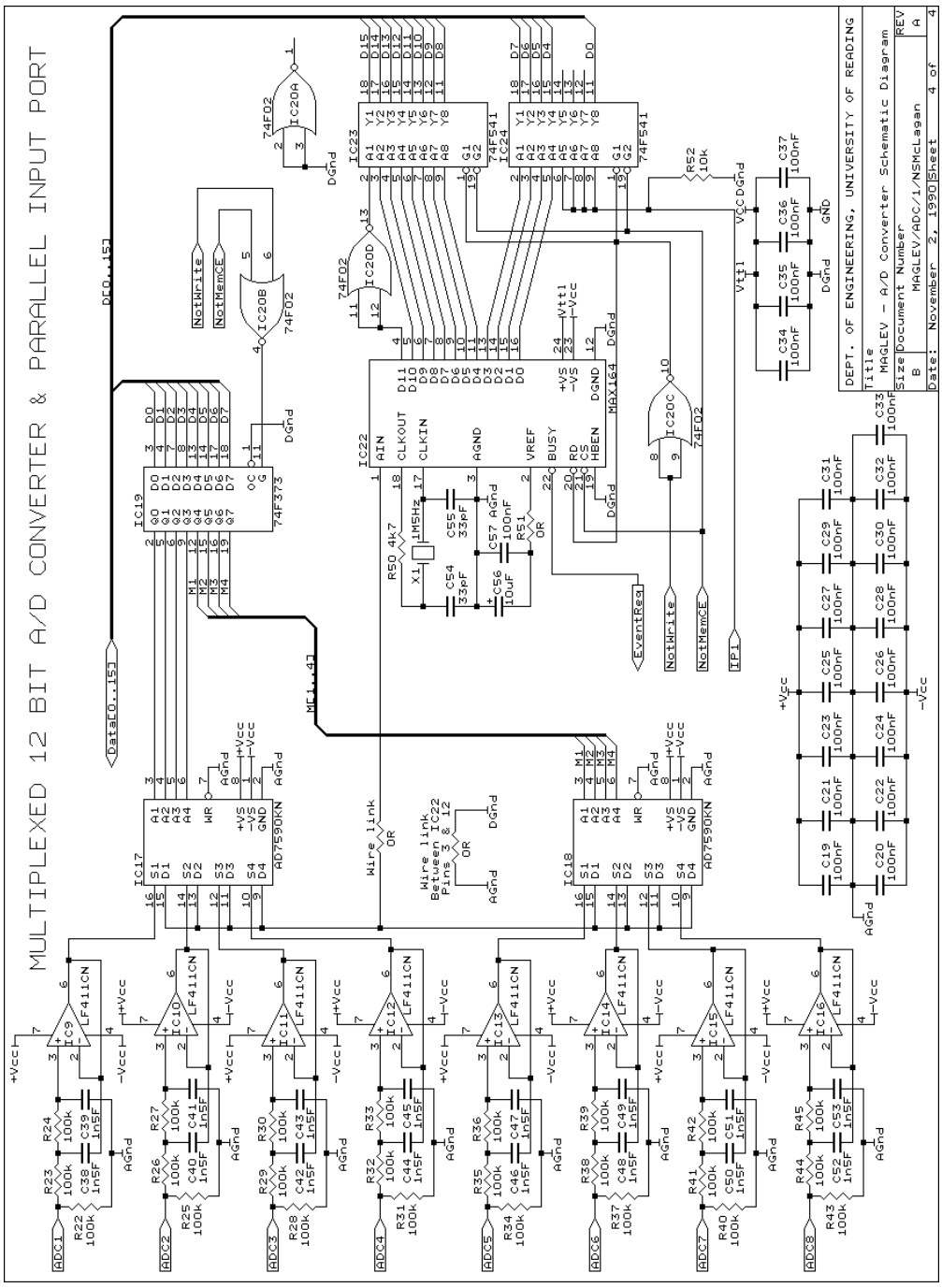
D.4.1 ADC card power supplies



D.4.2 ADC processor & link interfaces



D.4.3 ADC anti-alias filters, multiplexer & converter



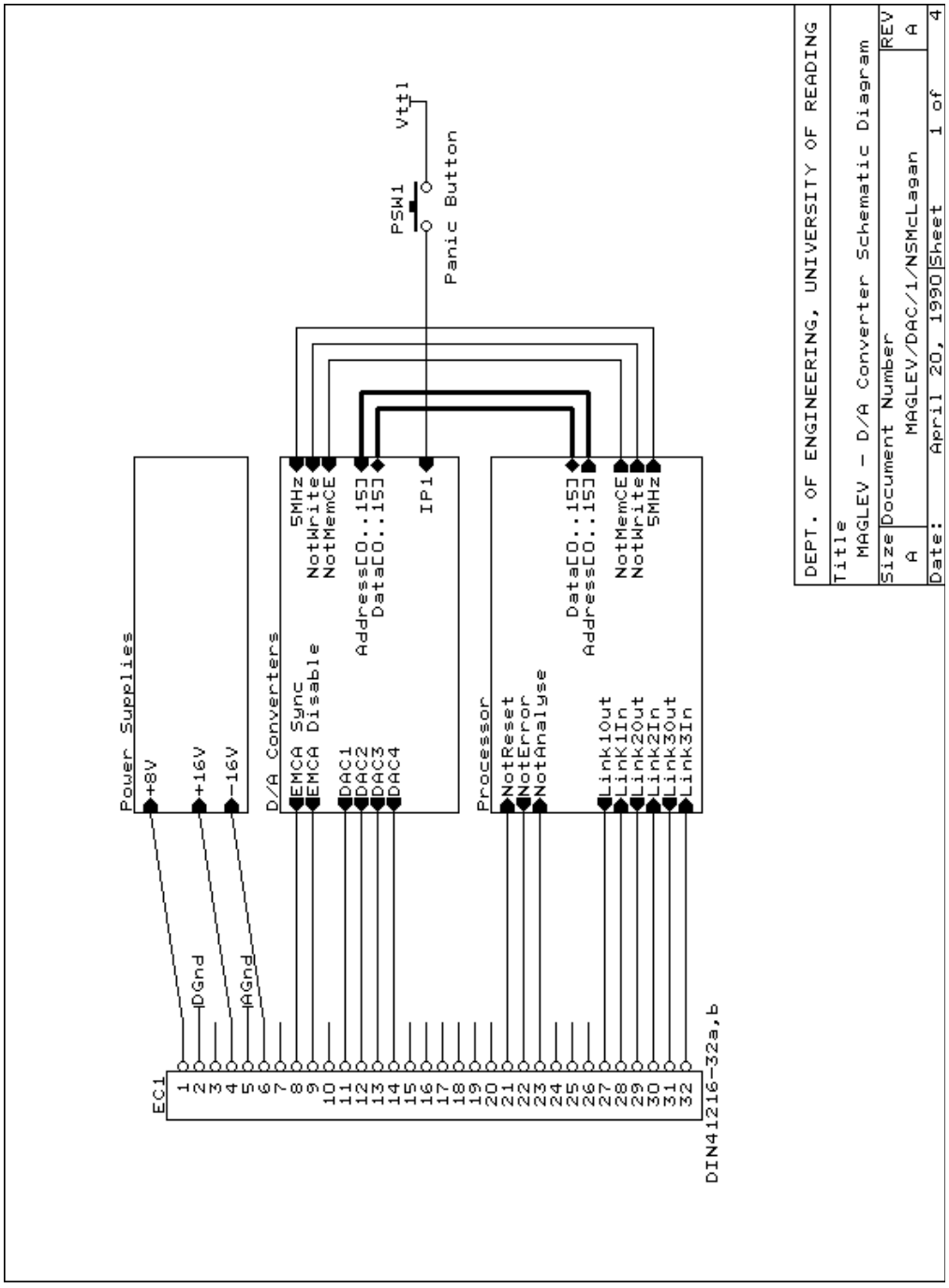
D.4.4 ADC card component parts list

MAGLEV - A/D Converter Schematic Diagram Revised: November 2, 1990
MAGLEV/ADC/1/N.S.McLagan Revision: A

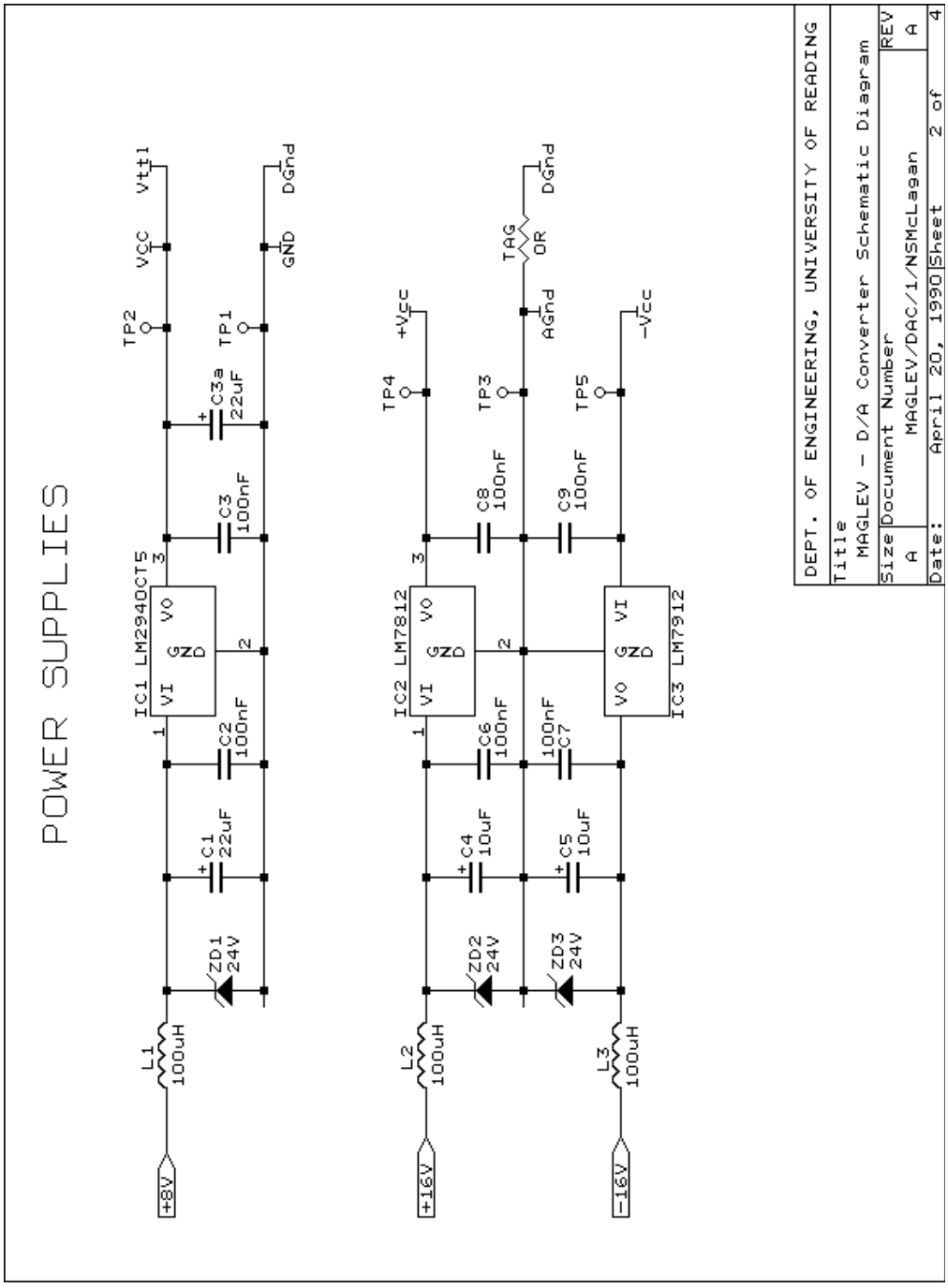
Bill Of Materials November 2, 1990 16:09:26 Page 1

Quantity	Reference	Part
1	C1	22uF
1	C16	4u7F
1	C18	1uF
34	C2,C3,C6,C7,C8,C9,C10, C11,C12,C13,C14,C15,C17, C19,C20,C21,C22,C23,C24, C25,C26,C27,C28,C29,C30, C31,C32,C33,C34,C35,C36, C37,C57,C58	100nF
16	C38,C39,C40,C41,C42,C43, C44,C45,C46,C47,C48,C49, C50,C51,C52,C53	1n5F
3	C4,C5,C56	10uF
2	C54,C55	33pF
8	D5,D1,D2,D3,D4,D6,D7,D8	BAT85
1	EC1	DIN41216-32a,b
1	IC1	LM2940CT5
8	IC16,IC9,IC10,IC11,IC12, IC13,IC14,IC15	LF411CN
2	IC17,IC18	AD7590KN
1	IC19	74F373
1	IC2	LM7812
1	IC20	74F02
1	IC22	MAX164BCNG
2	IC23,IC24	74F541
1	IC3	LM7912
1	IC4	T212
1	IC5	IQXD-100C-5MHz
1	IC6	74F74
1	IC7	74F132
1	IC8	74ACT04
3	L2,L1,L3	100uH
1	LED1	Green
1	LED2	Yellow
1	LED3	Red
1	PSW1	Push Switch
3	R1,R4,R50	4k7
4	R15,R14,R16,R17	56R
2	R2,R5	51R
25	R3, R22,R23,R24,R25,R26, R27,R28,R29,R30,R31,R32, R33,R34,R35,R36,R37,R38, R39,R40,R41,R42,R43,R44, R45	100k
1	R51	Wire link
10	R6,R10,R11,R12,R13,R18, R19,R20,R21,R52	10k
3	R7,R8,R9	220R
1	SW1	DIP-4 way SPST
5	TP2,TP1,TP3,TP4,TP5	Test pins
1	TR1	BC107
1	X1	1.5 MHz crystal
3	ZD1,ZD2,ZD3	24V

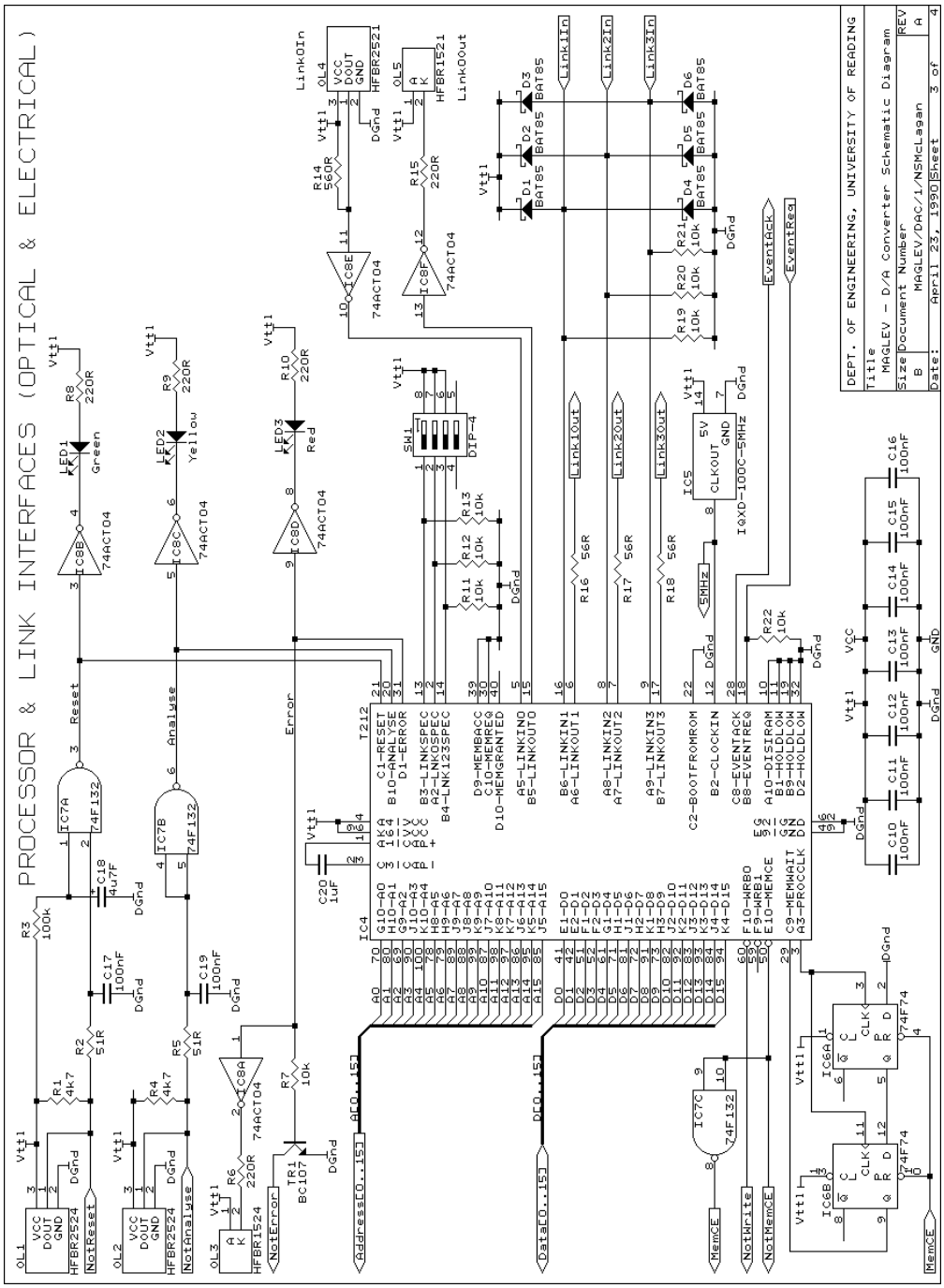
D.5 Digital-to-analogue converter (4 channel) card



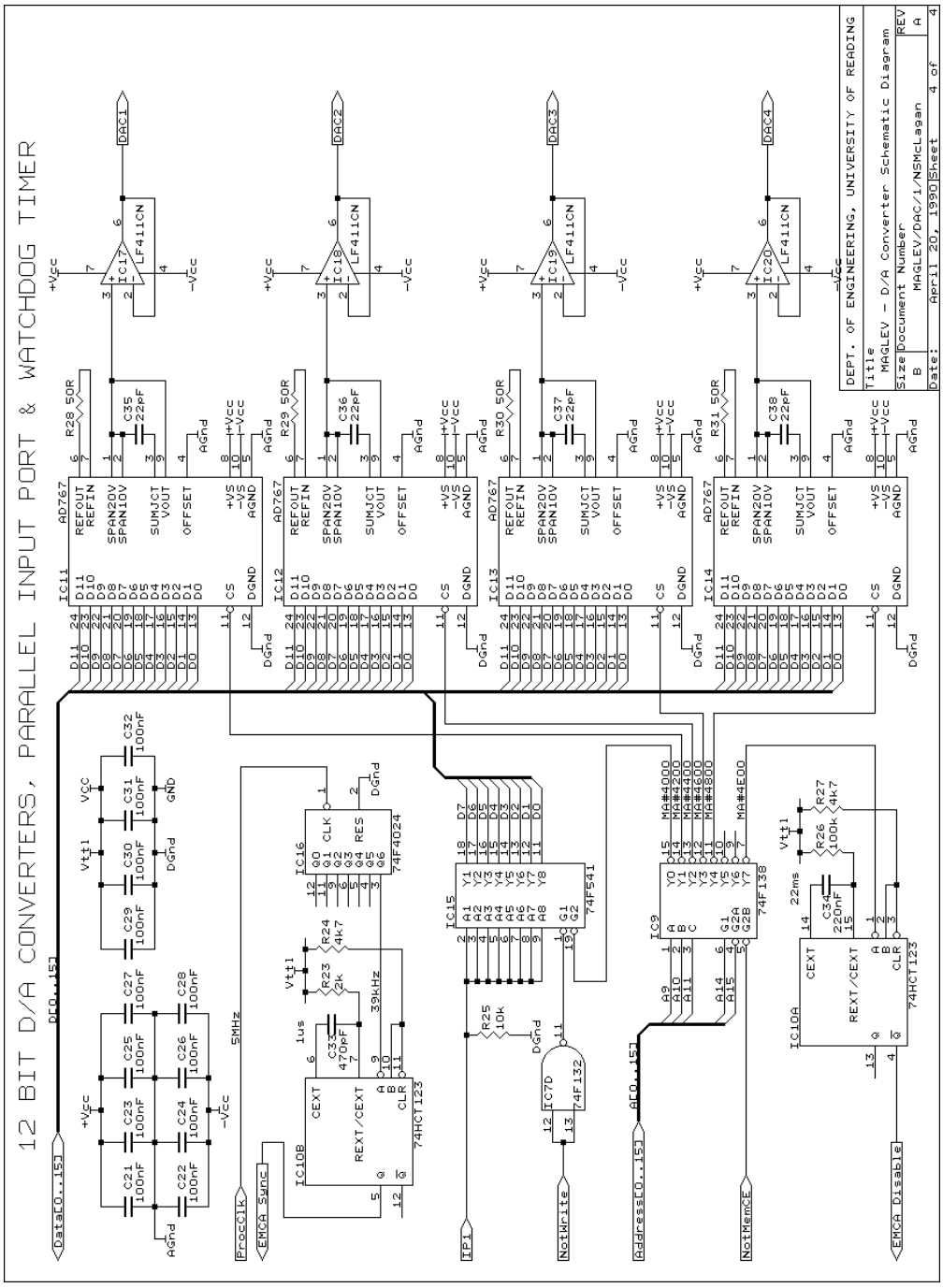
D.5.1 DAC card power supplies



D.5.2 DAC processor & link interfaces (optical & electrical)



D.5.3 DAC converters & watchdog timer



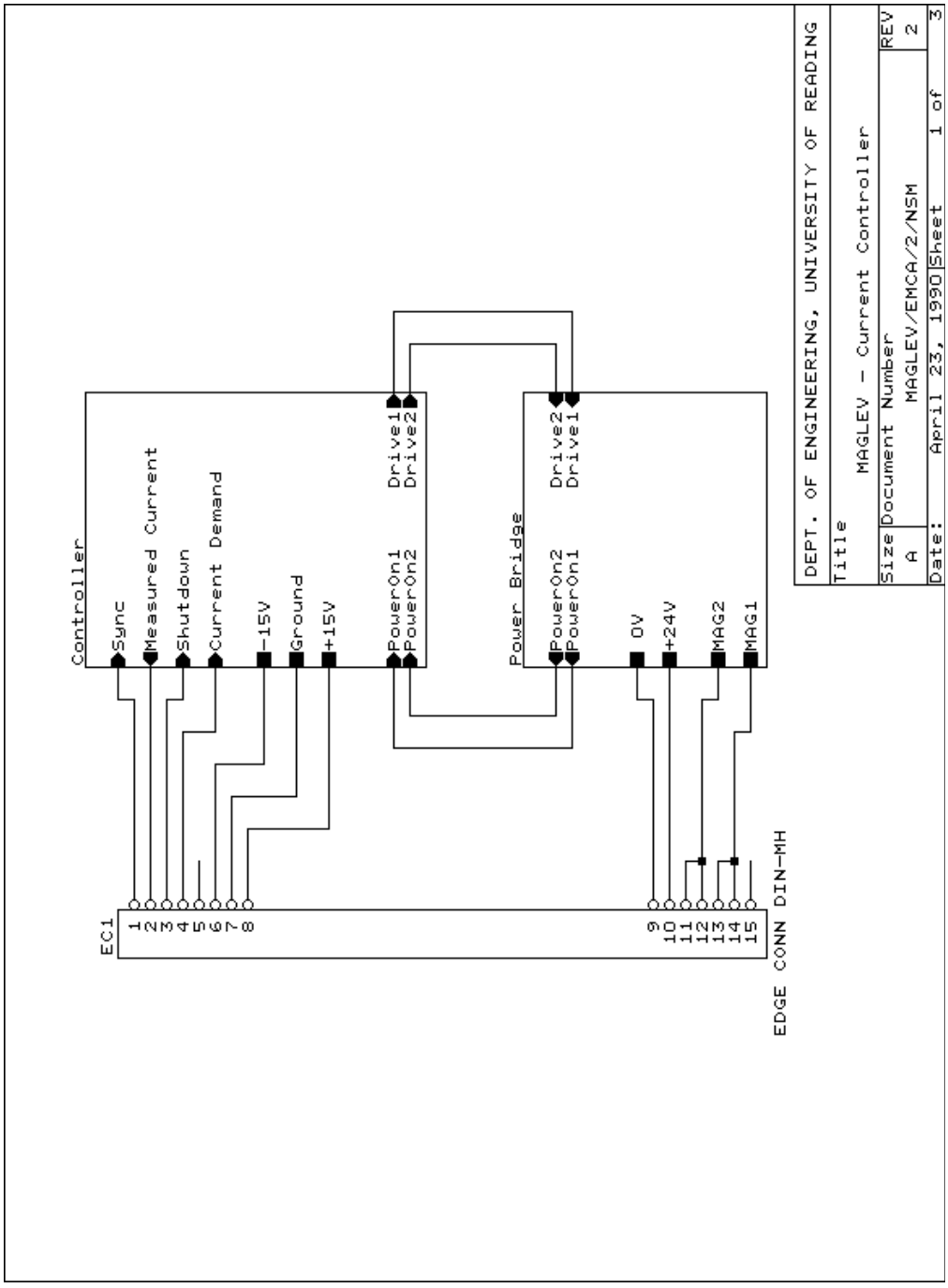
D.5.4 DAC card component parts list

MAGLEV - D/A Converter Schematic Diagram Revised: January 24, 1990
MAGLEV/DAC/1/N.S.McLagan Revision: A

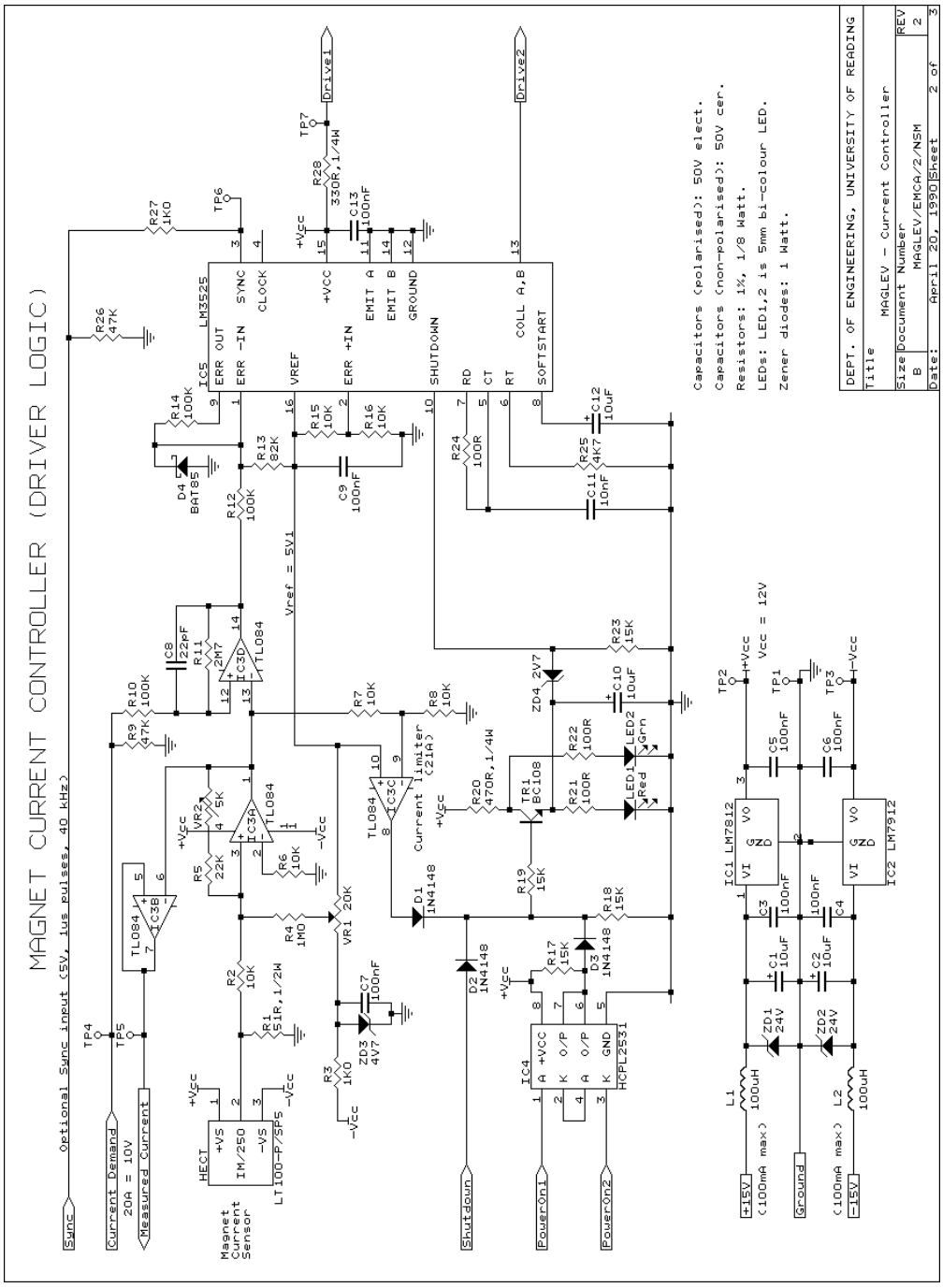
Bill Of Materials January 25, 1990 16:09:15 Page 1

Quantity	Reference	Part
1	C1	22uF
1	C18	4u7F
27	C2,C3,C6,C7,C8,C9,C10, C11,C12,C13,C14,C15,C16, C17,C19,C21,C22,C23,C24, C25,C26,C27,C28,C29,C30, C31,C32	100nF
1	C20	1uF
1	C33	470pF
1	C34	220nF
4	C35,C36,C37,C38	22pF
2	C4,C5	10uF
6	D6,D2,D3,D4,D7,D8	BAT85
1	EC1	DIN41216-32a,b
1	IC1	LM2940CT5
1	IC10	74HCT123
4	IC11,IC12,IC13,IC14	AD767
1	IC15	74F541
1	IC16	74ACT4024
4	IC17,IC18,IC19,IC20	LF411CN
1	IC2	LM7812
1	IC3	LM7912
1	IC4	T212
1	IC5	IQXD-100C-5MHz crystal
1	IC6	74F74
1	IC7	74F132
1	IC8	74ACT04
1	IC9	74F138
3	L2,L1,L3	100uH
1	LED1	Green
1	LED2	Yellow
1	LED3	Red
2	OL1,OL2	HFBR2524
1	OL3	HFBR1524
1	OL4	HFBR2521
1	OL5	HFBR1521
1	PSW1	Push switch
4	R1,R4,R24,R27	4k7
2	R15,R6	100R
3	R16,R17,R18	56R
2	R2,R5	51R
1	R23	2k
4	R28,R29,R30,R31	50R
2	R3,R26	100k
1	R14	560R
9	R7,R11,R12,R13,R19,R20, R21,R22,R25	10k
3	R8,R9,R10	220R
1	SW1	DIP-4 way SPST
1	TAG	Earth tag
5	TP2,TP1,TP3,TP4,TP5	Test pins
1	TR1	BC107
3	ZD1,ZD2,ZD3	24V

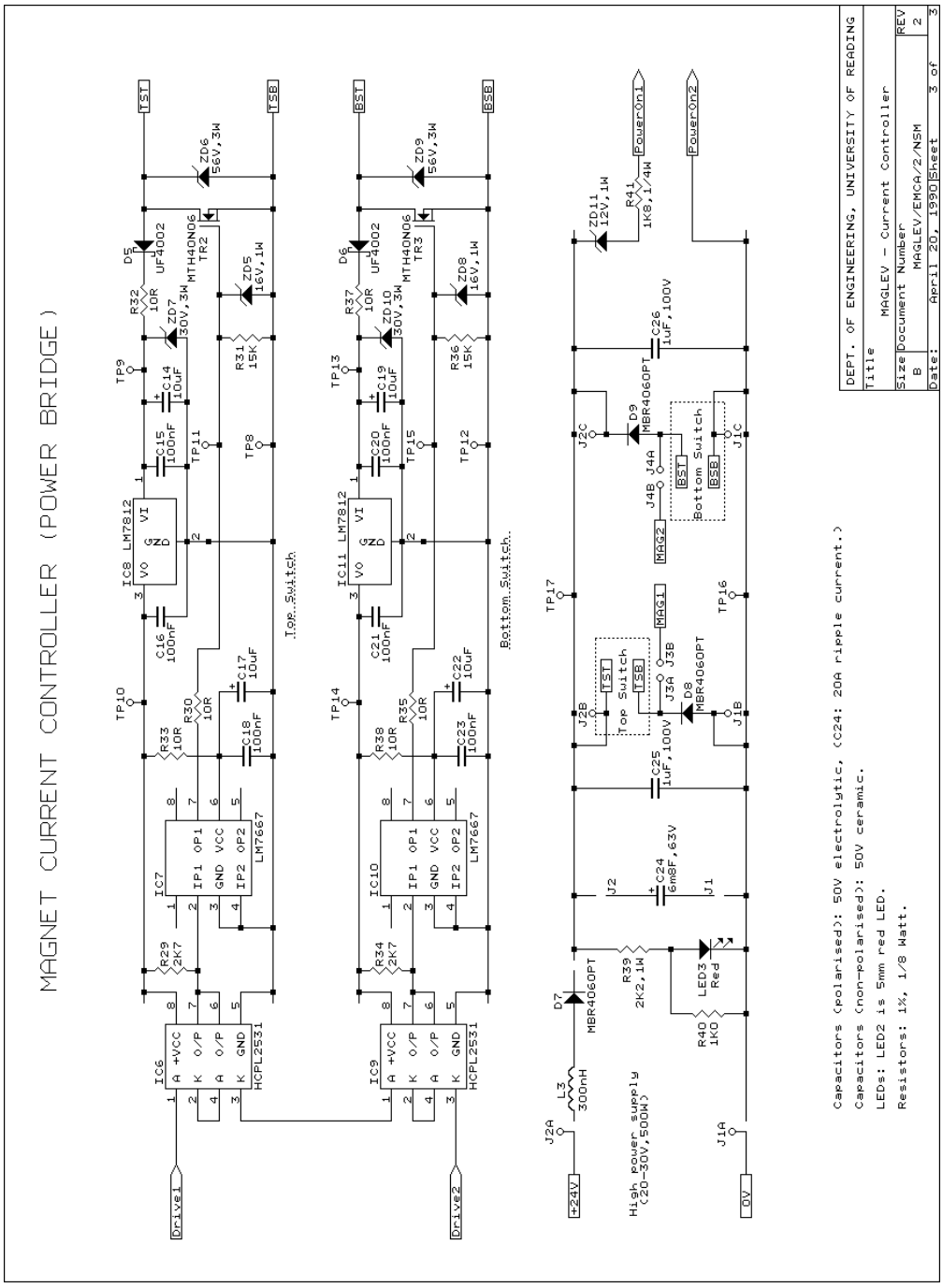
D.6 Electromagnet current controller module



D.6.1 EMCA controller logic



D.6.2 EMCA power switching bridge

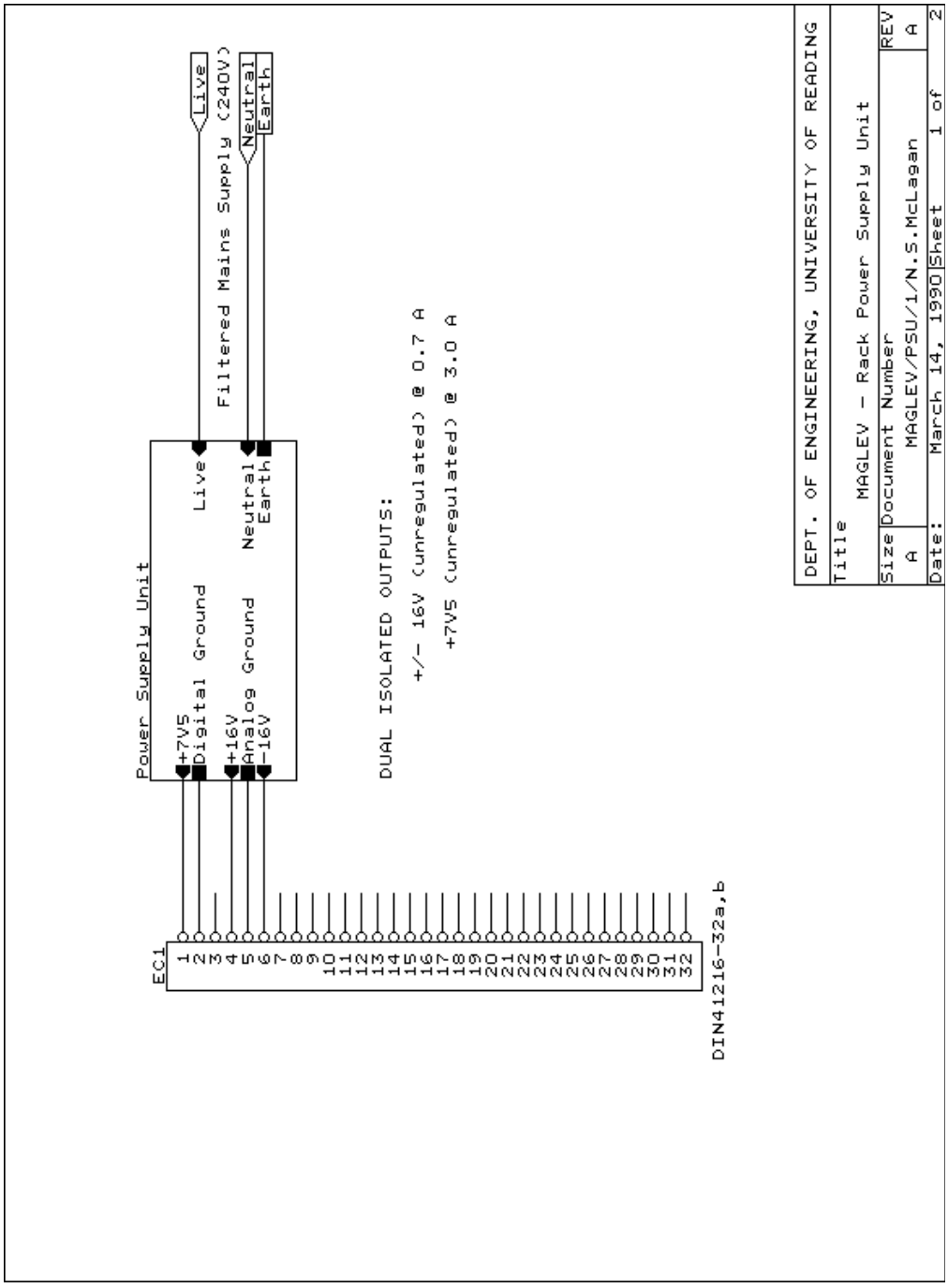


D.6.3 EMCA card component parts list

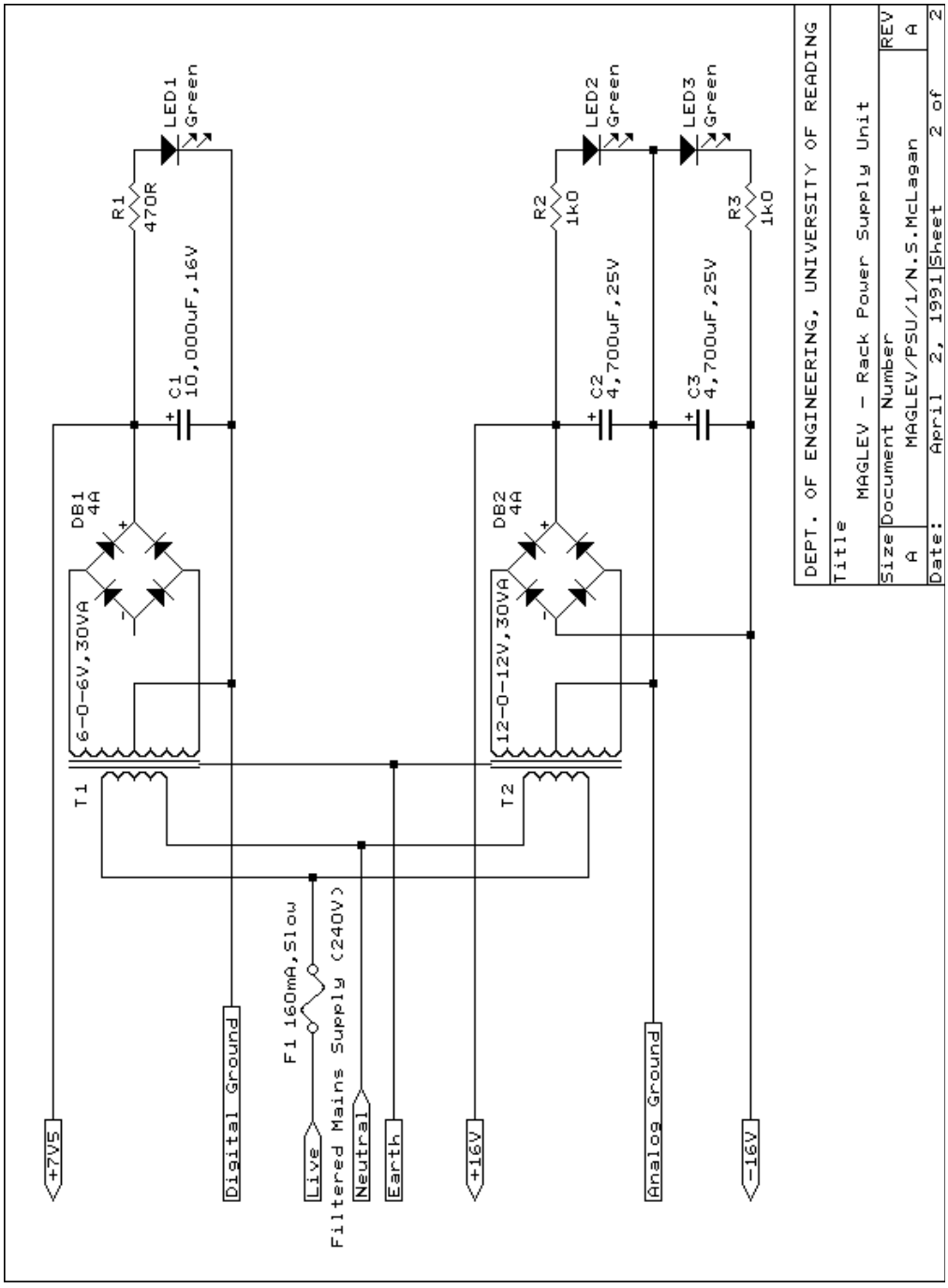
ELECTROMAGNET CURRENT AMPLIFIER **Revised: November 8, 1989**
MAGLEV/EMCA/2/N.S.McLagan **Revision: A**

Quantity	Reference	Part
1	C11	10nF
8	C14,C1,C2,C17,C19,C22 C10,C12	10uF
13	C15,C3,C4,C5,C6,C7,C9, C13,C16,C18,C20,C21,C23	100nF
1	C24	6m8F,63V
2	C25,C26	1uF,63V
1	C8	22pF
3	D2,D1,D3	1N4148
1	D4	BAT85
2	D5,D6	UF4002
3	D7,D8,D9	MBR4060PT
1	EC1	DIN41216 'MH'
1	HECT	LT100-P/SP5
1	IC2	LM7912
1	IC3	TL084
1	IC5	LM3525
3	IC6,IC4,IC9	HCPL2531
2	IC7,IC10	LM7667
3	IC8,IC1,IC11	LM7812
10	J1A,J1B,J1C,J2A,J2B,J2C, J3A,J3B,J4A,J4B	20A Jumpers
2	L1,L2	100uH
1	L3	300nH
1	LED2	Green LED
2	LED3,LED1	Red LED
1	R1	51R,1/2W
3	R10,R12,R14	100K
1	R11	2M7
1	R13	82K
6	R2,R6,R7,R8,R15,R16	10K
1	R20	470R,1/4W
3	R21,R22,R24	100R
1	R25	4K7
1	R28	330R,1/4W
2	R29,R34	2K7
6	R31,R17,R18,R19,R23,R36	15K
6	R33,R30,R32,R35,R37,R38	10R
1	R39	2K2,1W
1	R4	1M0
3	R40,R3,R27	1K0
1	R41	1K8,1/4W
1	R5	22K
2	R9,R26	47K
17	TP8,TP1,TP2,TP3,TP4,TP5, TP6,TP7,TP9,TP10,TP11, TP12,TP13,TP14,TP15,TP16,TP17	Test pins
1	TR1	BC108
2	TR2,TR3	MTH40N06
1	VR1	20K
1	VR2	5K
2	ZD1,ZD2	24V
1	ZD11	12V,1W
1	ZD3	4V7
1	ZD4	2V7
2	ZD6,ZD9	56V,3W
2	ZD7,ZD10	30V,3W
2	ZD8,ZD5	16V,1W

D.7 Chassis power supply module



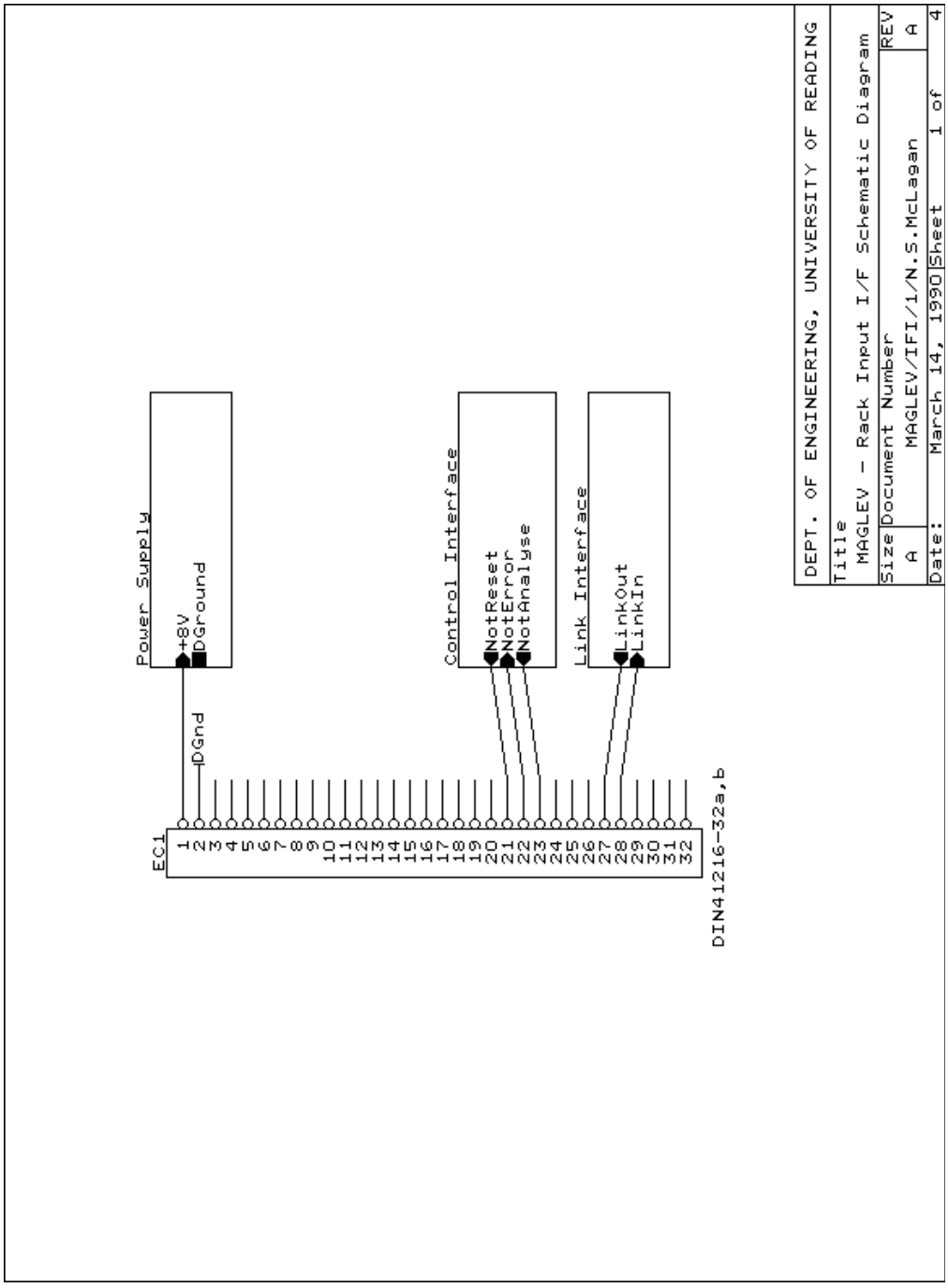
D.7.1 PSU supply conditioning



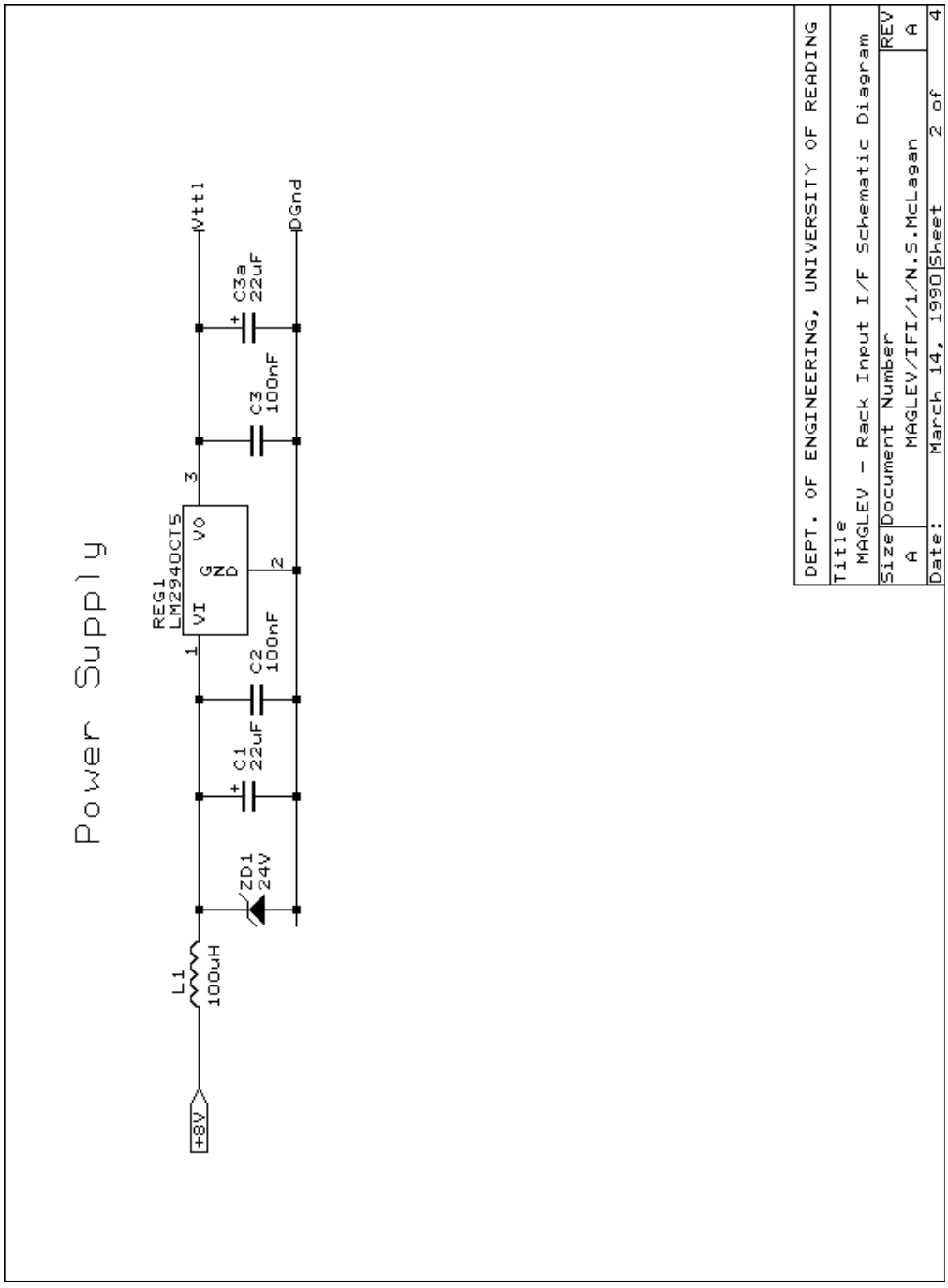
D.7.2 PSU card component parts list

```
MAGLEV - Rack Power Supply Unit                  Revised:     March 14, 1990
MAGLEV/PSU/1/N.S.McLagan                         Revision: A

Bill Of Materials              April  2, 1991     17:45:25          Page    1

Quantity  Reference                Part

    1     C1                       10,000uF,16V
    2     C2,C3                    4,700uF,25V

    2     DB1,DB2                  4A

    1     EC1                      DIN41216-32a,b

    1     F1                       160mA,Slow

    3     LED1,LED2,LED3           Green

    1     R1                       470R
    2     R2,R3                    1k0

    1     T1                       6-0-6V,30VA
    1     T2                       12-0-12V,30VA
```

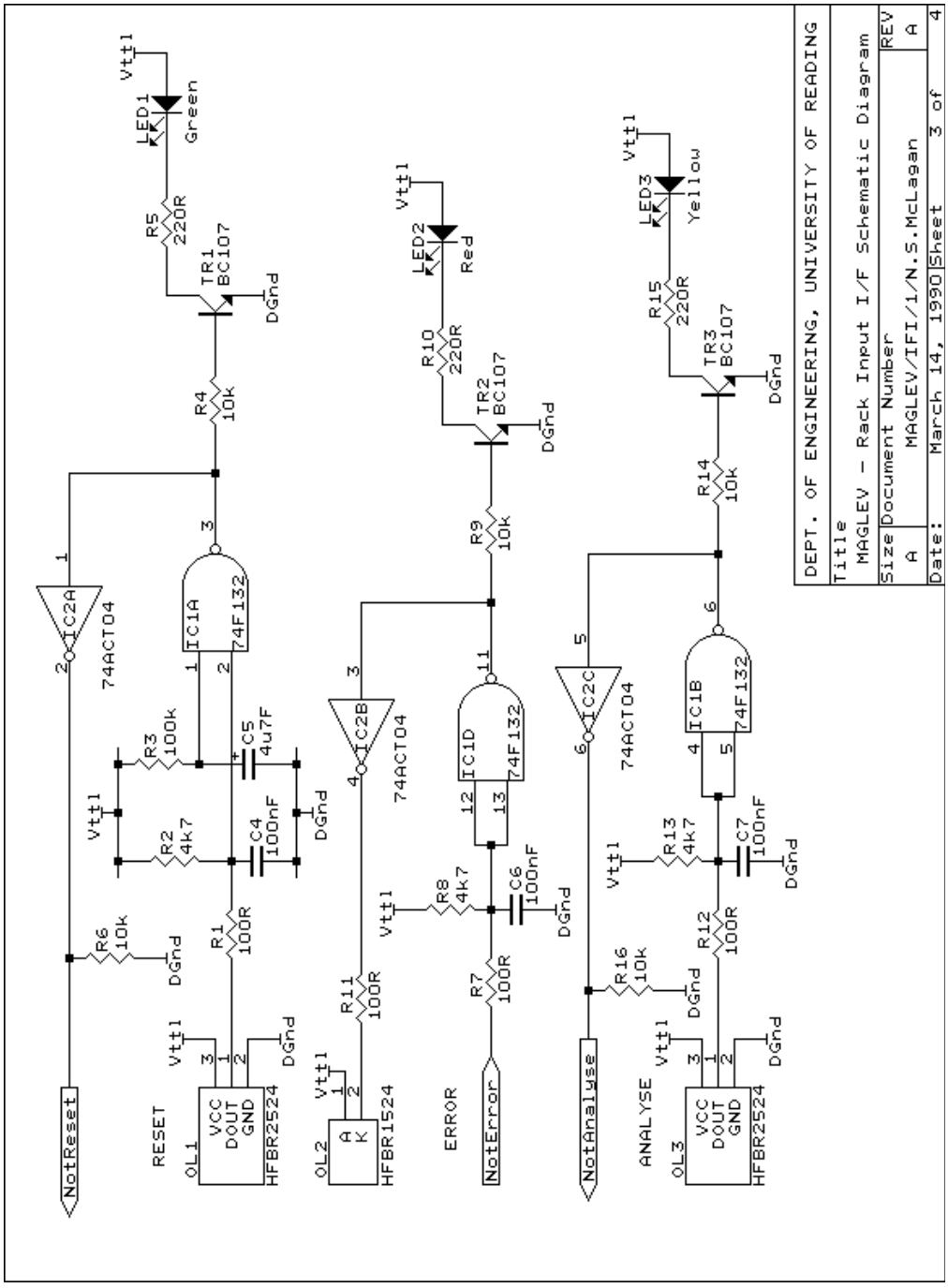
D.8 Chassis optical input interface card



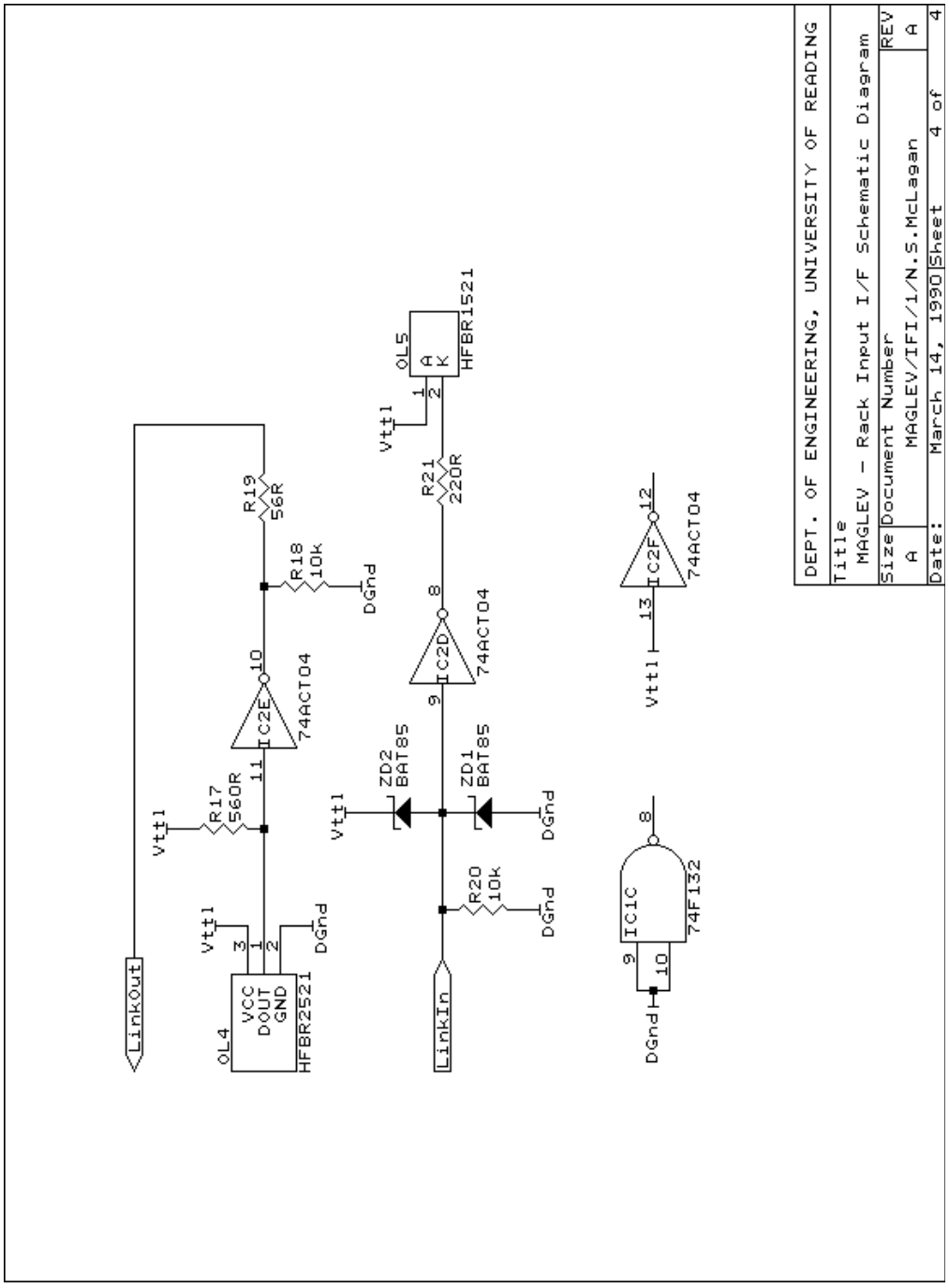
D.8.1 Chassis input interface power supply



D.8.2 Chassis input interface control signals



D.8.3 Chassis input interface data signals

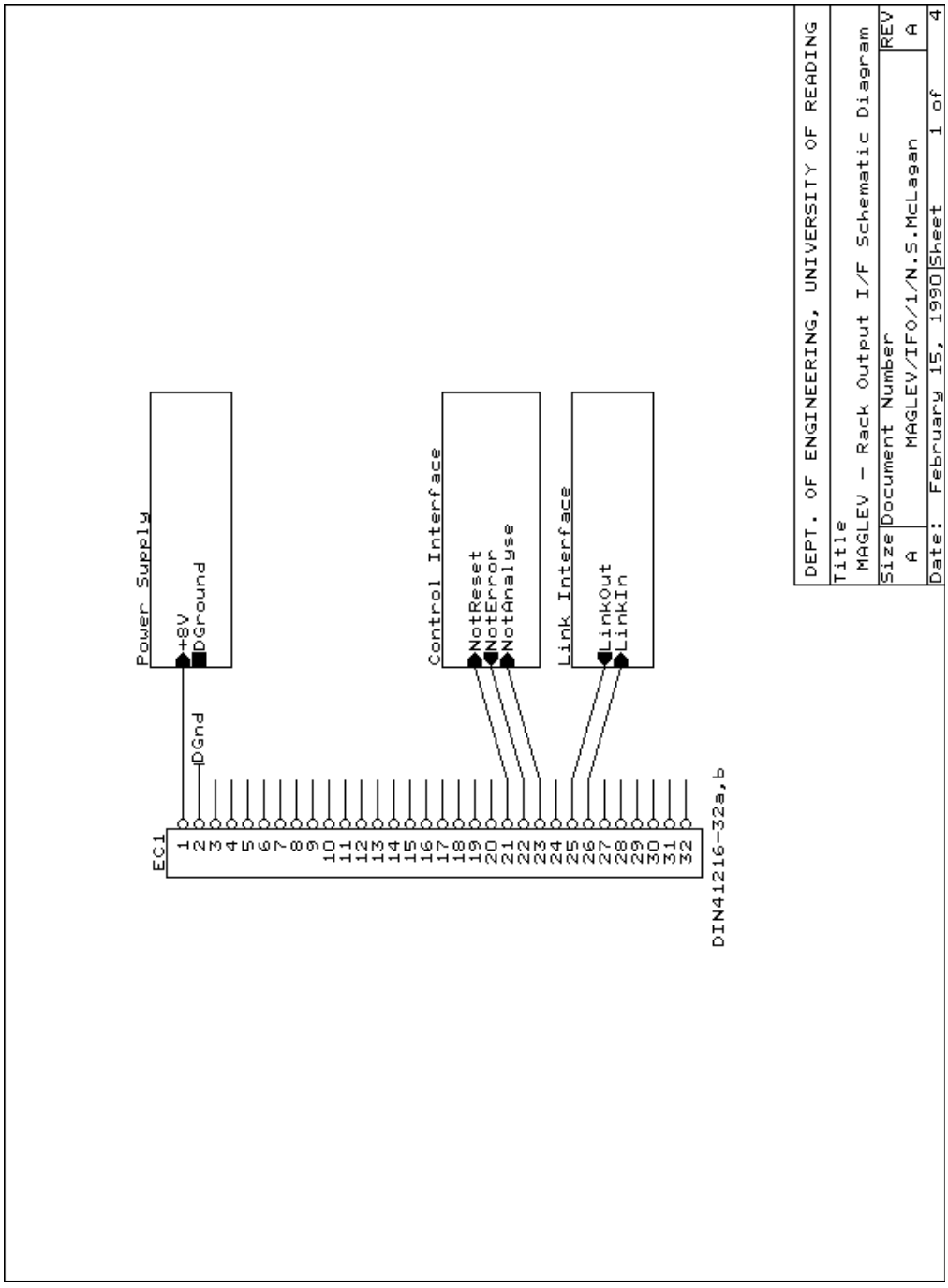


D.8.4 Chassis input interface card component parts list

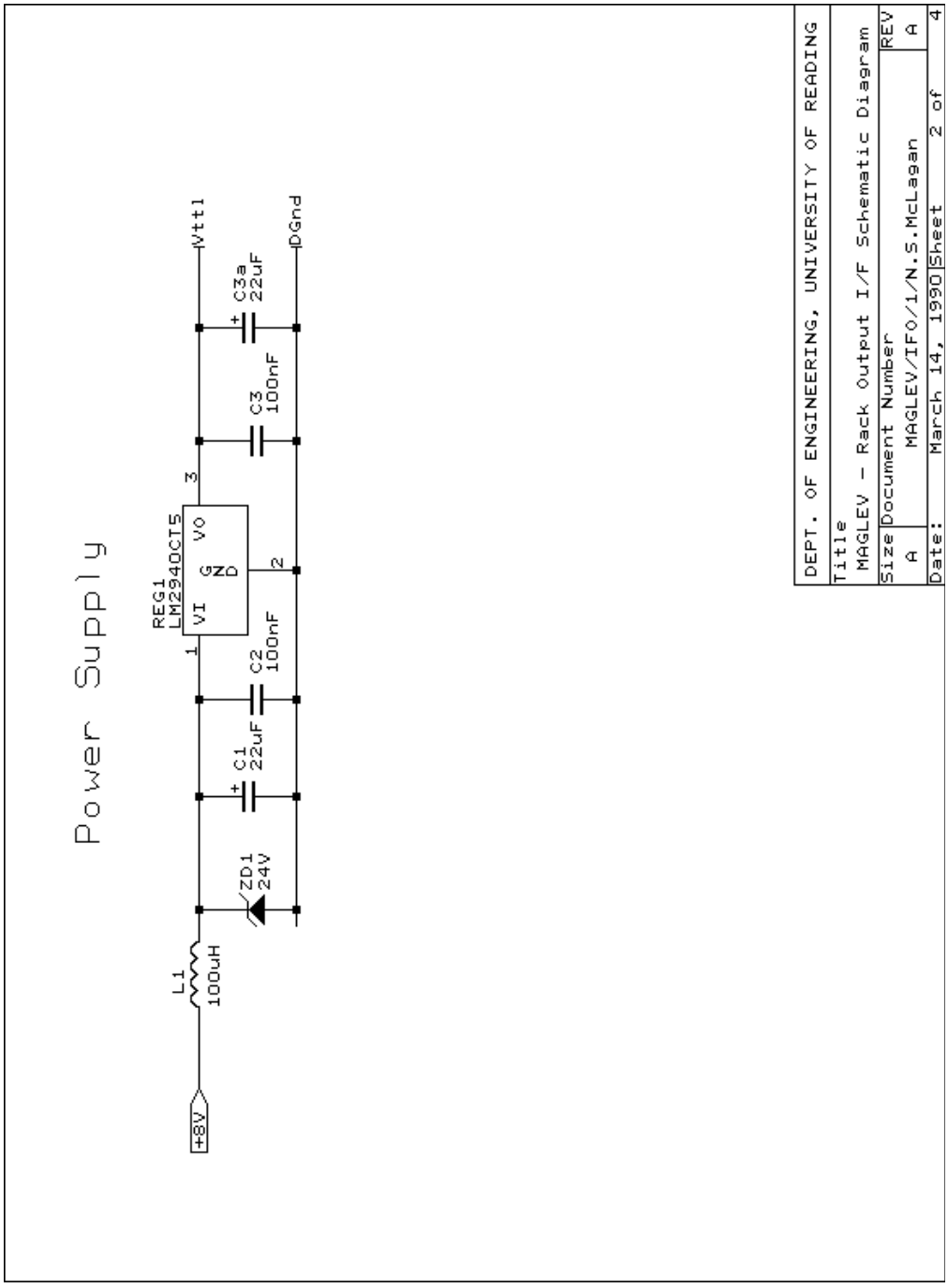
```
MAGLEV - Rack Input I/F Schematic Diagram         Revised:     March 14, 1990
MAGLEV/IFI/1/N.S.McLagan                          Revision: A

Bill Of Materials              April  2, 1991     17:27:12          Page    1
```

Quantity	Reference	Part
2	C1,C3a	22uF
5	C2,C3,C4,C6,C7	100nF
1	C5	4u7F
1	EC1	DIN41216-32a,b
1	IC1	74F132
1	IC2	74ACT04
1	L1	100uH
1	LED1	Green
1	LED2	Red
1	LED3	Yellow
2	OL1,OL3	HFBR2524
1	OL2	HFBR1524
1	OL4	HFBR2521
1	OL5	HFBR1521
3	R2,R8,R13	4k7
1	R3	100k
7	R4,R6,R9,R14,R16,R18,R20	10k
4	R1,R7,R11,R12	100R
4	R5,R10,R15,R21	220R
1	R17	560R
1	R19	56R
1	REG1	LM2940CT5
3	TR1,TR2,TR3	BC107
1	ZD1	24V
2	ZD1,ZD2	BAT85

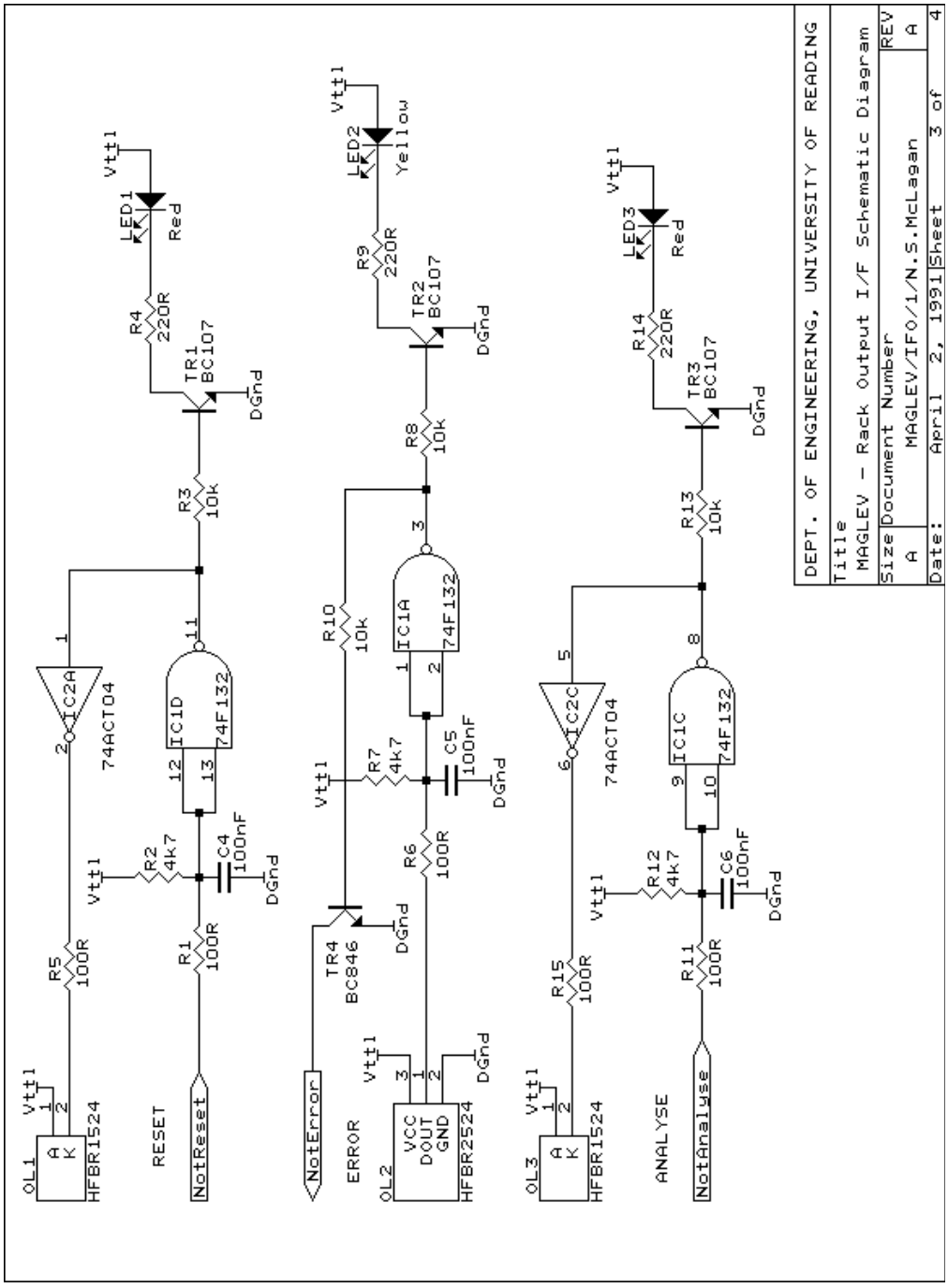
D.9 Chassis optical output interface card



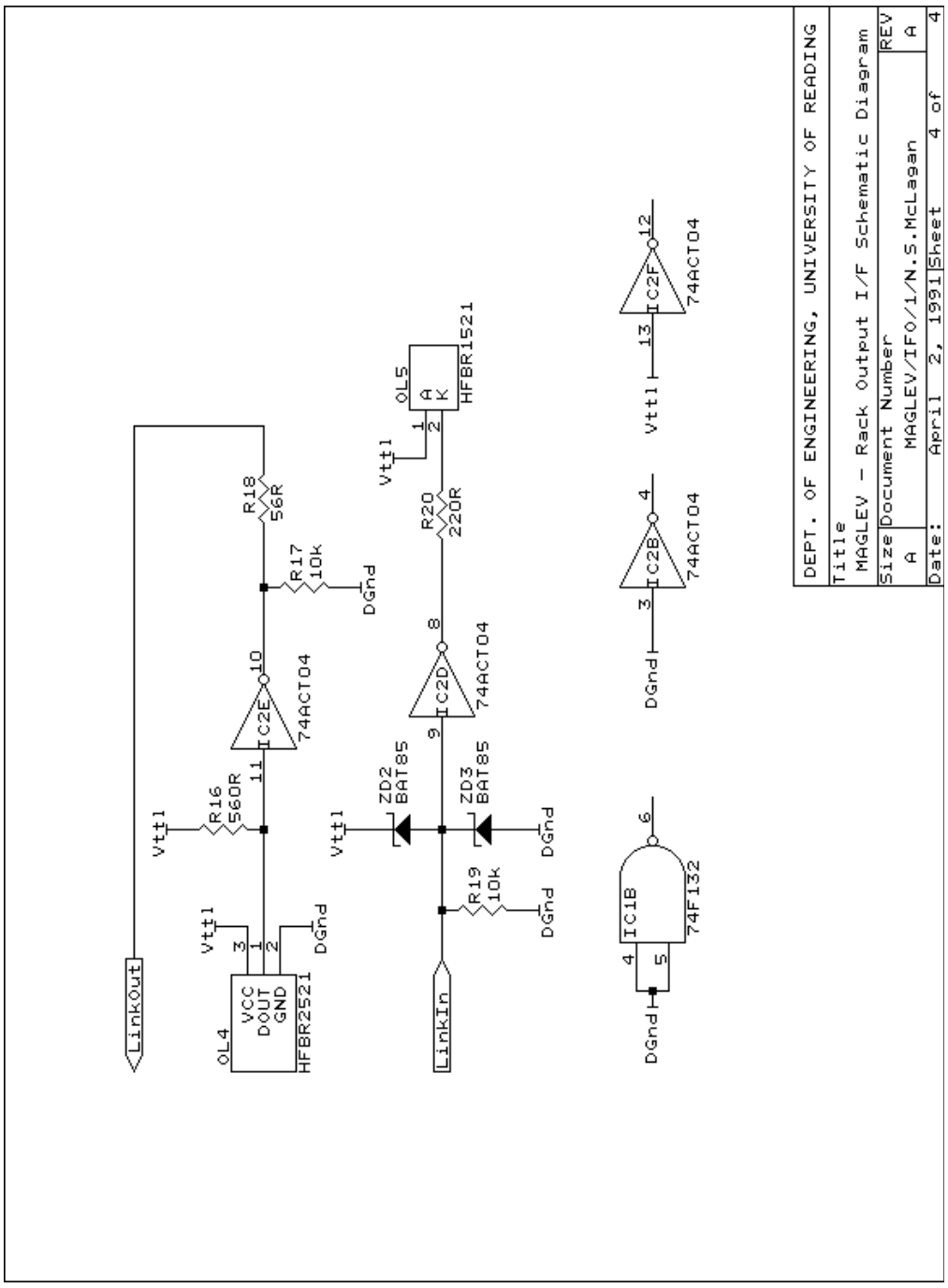
D.9.1 Chassis output interface power supply



D.9.2 Chassis output interface control signals



D.9.3 Chassis output interface data signals



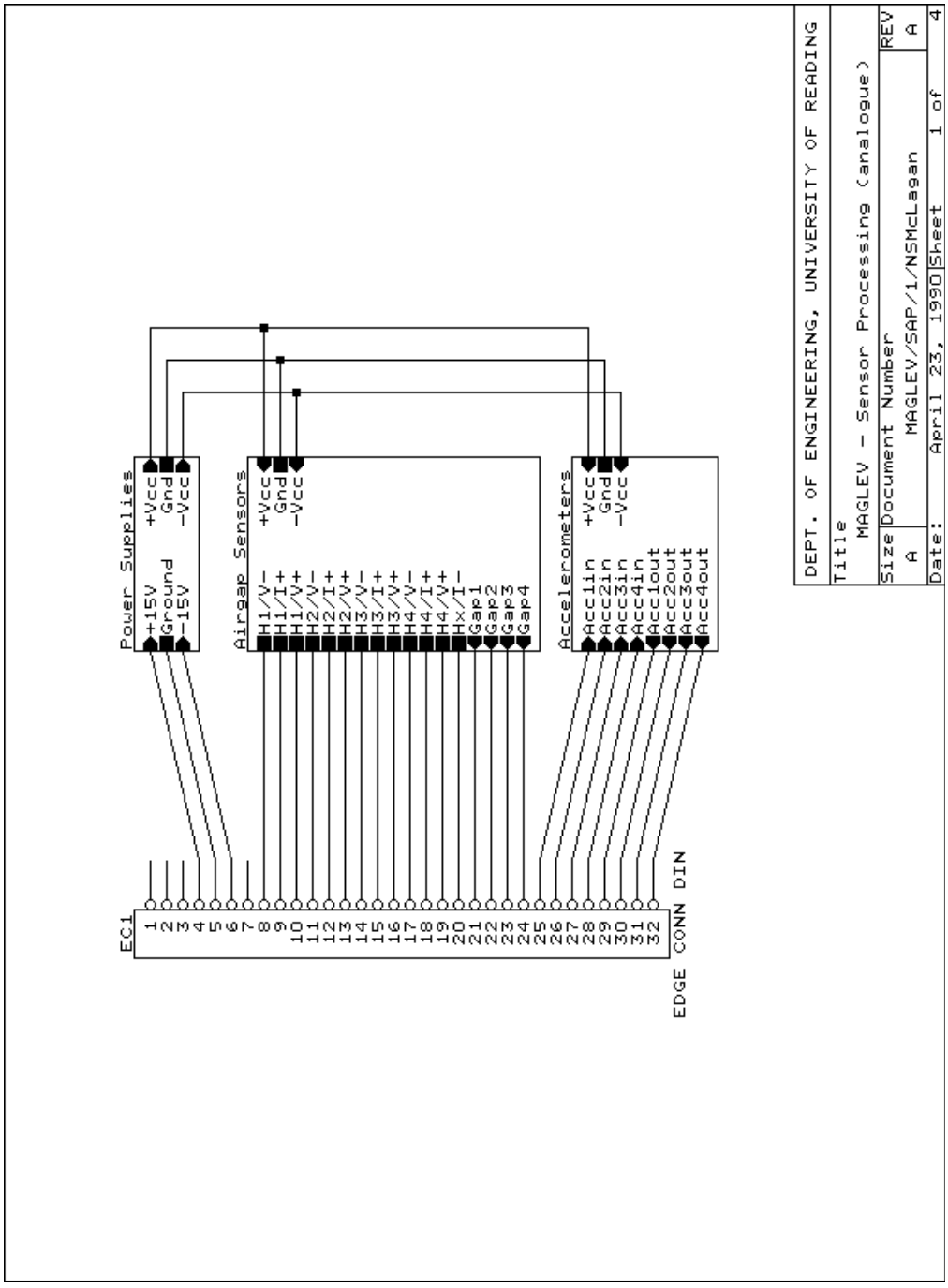
D.9.4 Chassis output interface card component parts list

MAGLEV - Rack Output I/F Schematic Diagram Revised: February 15, 1990
MAGLEV/IFO/1/N.S.McLagan Revision: A

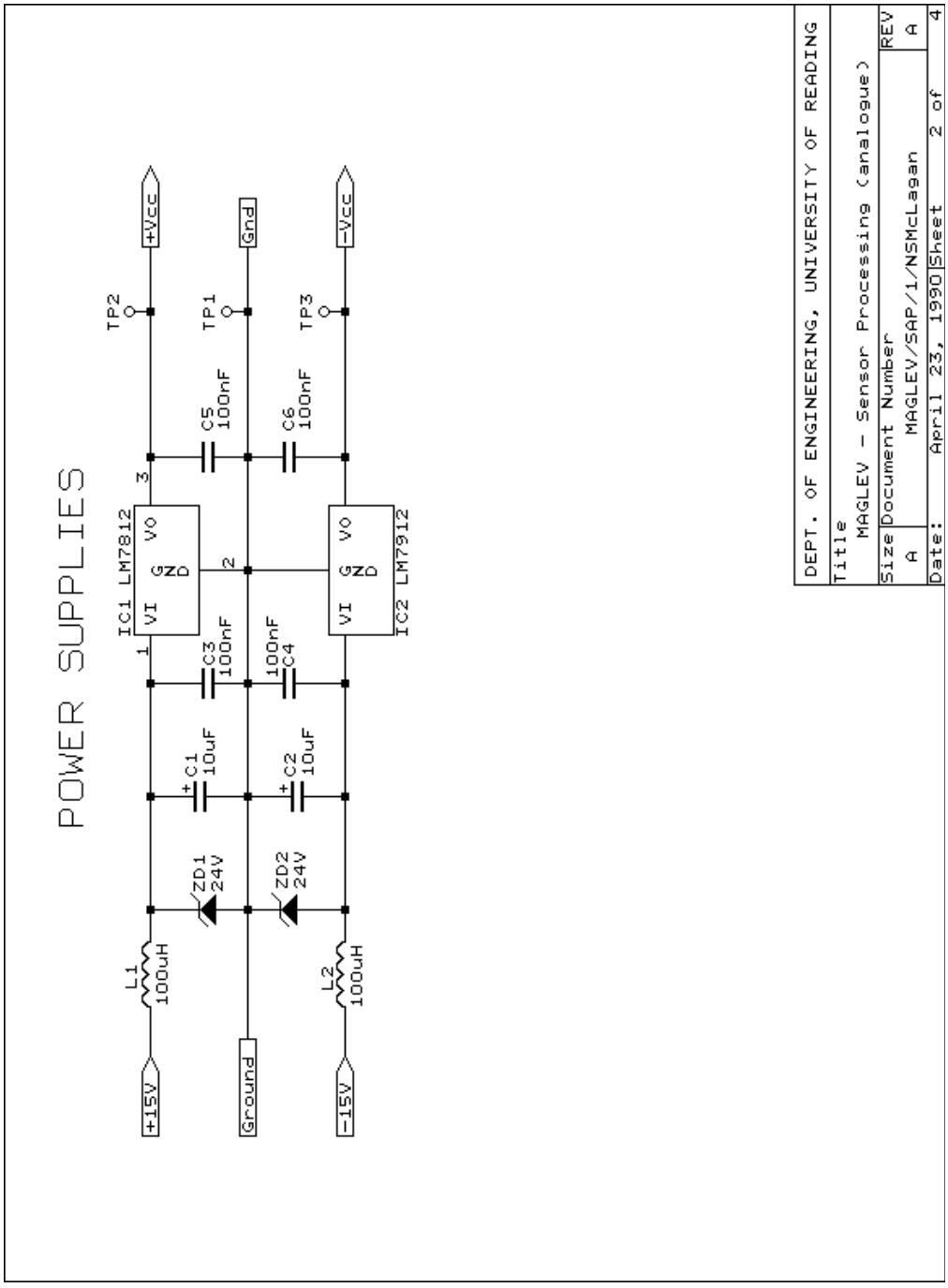
Bill Of Materials April 2, 1991 17:45:09 Page 1

Quantity	Reference	Part
2	C1,C3a	22uF
5	C2,C3,C4,C5,C6	100nF
1	EC1	DIN41216-32a,b
1	IC1	74F132
1	IC2	74ACT04
1	L1	100uH
2	LED1,LED3	Red
1	LED2	Yellow
2	OL1,OL3	HFBR1524
1	OL2	HFBR2524
1	OL4	HFBR2521
1	OL5	HFBR1521
3	R2,R7,R12	4k7
6	R3,R8,R10,R13,R17,R19	10k
5	R1,R5,R6,R11,R15	100R
4	R4,R9,R14,R20	220R
1	R16	560R
1	R18	56R
1	REG1	LM2940CT5
3	TR1,TR2,TR3	BC107
1	TR4	BC846
1	ZD1	24V
2	ZD2,ZD3	BAT85

D.10 Sensor analogue preprocessor (4 channel) card

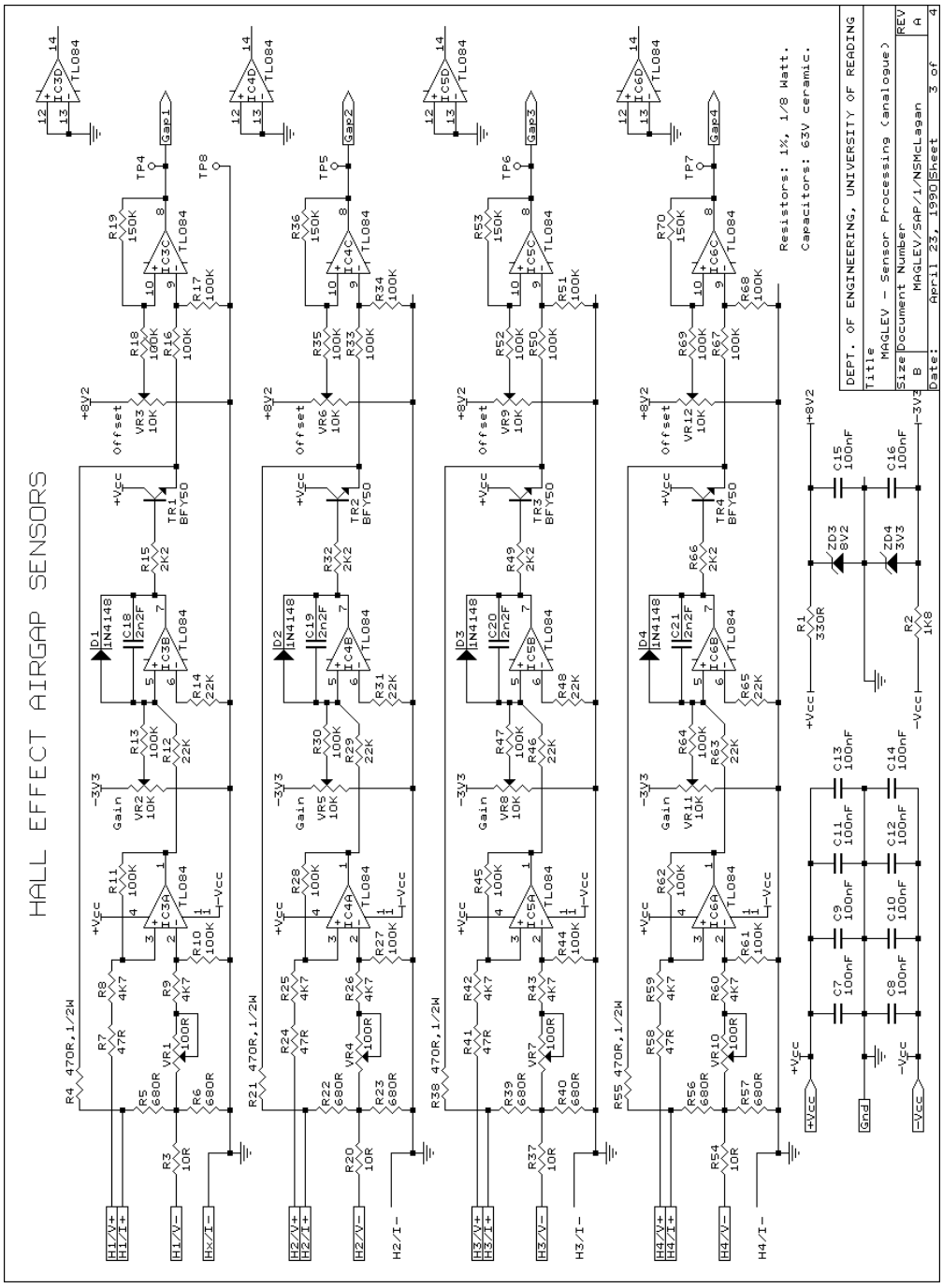


D.10.1 SAP card power supplies

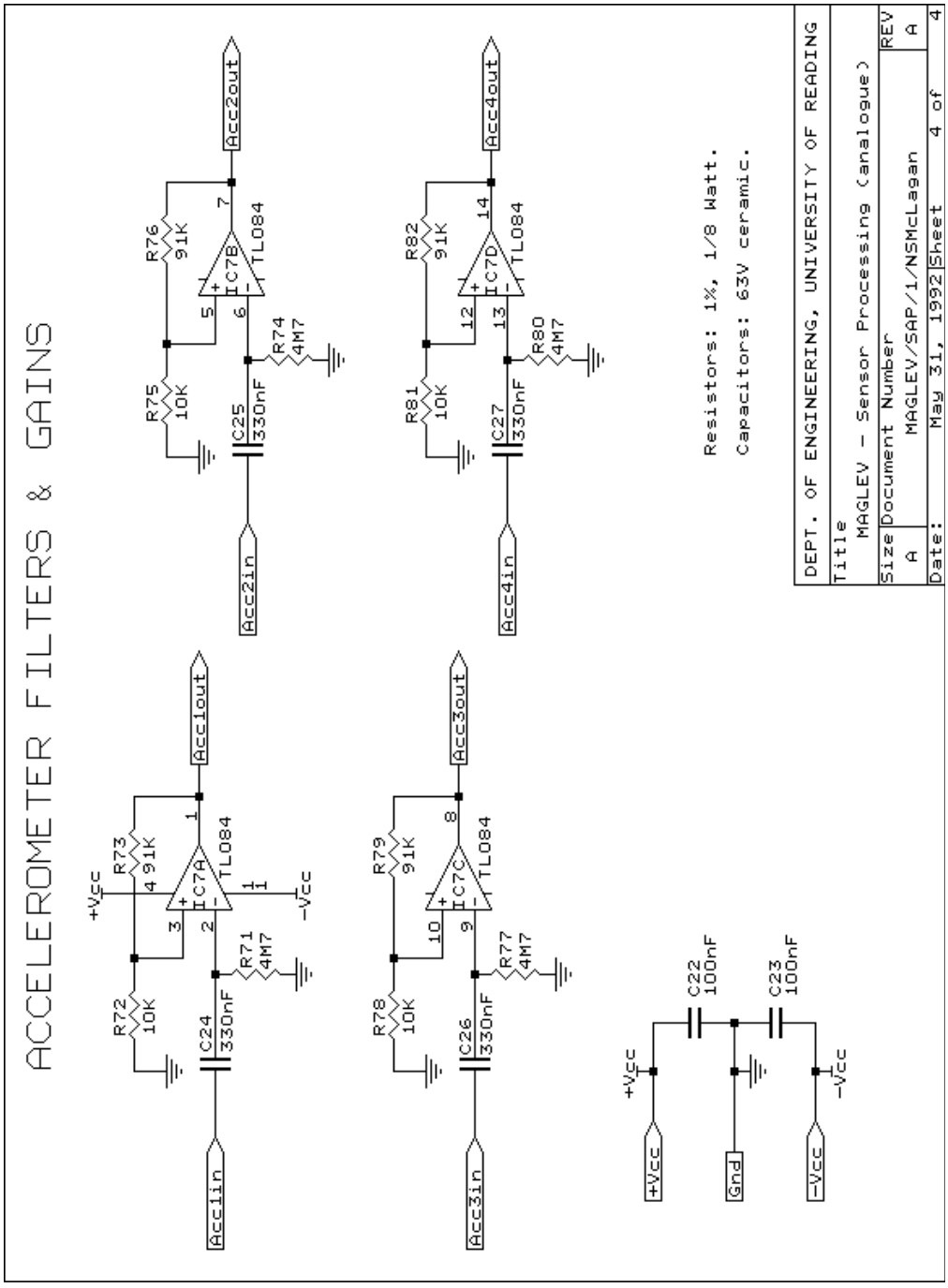


D.10.2 SAP Hall-effect air gap sensor controllers

Note: This circuitry is not implemented because commercial air gap sensors have been used instead. It is included here in case it is used in future systems.



D.10.3 SAP sensor filters and amplifiers

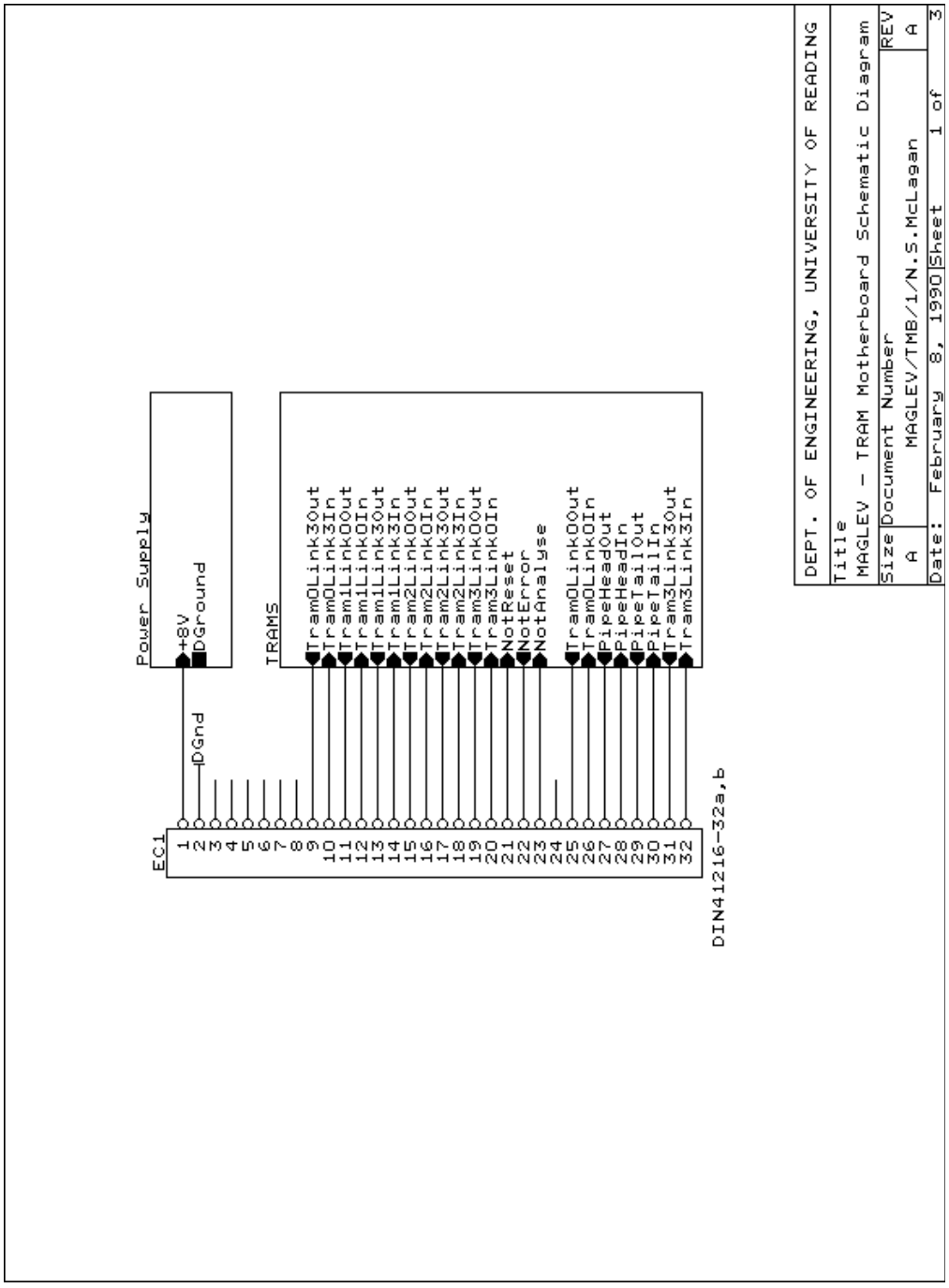


D.10.4 SAP card component parts list

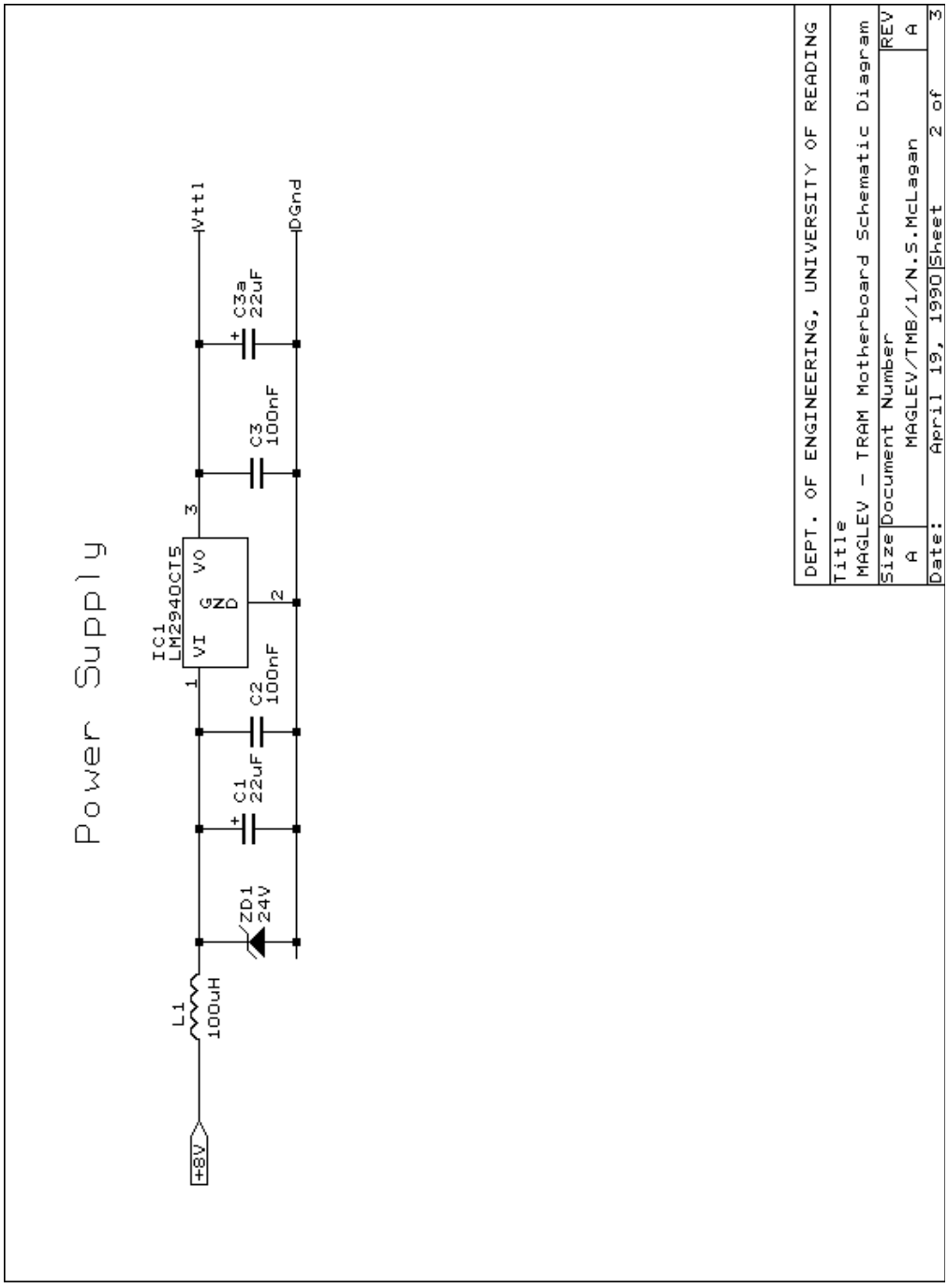
```
MAGLEV - Sensor Processing (analogue)            Revised:  November  2, 1989
MAGLEV/SAP/1/N.S.McLagan                         Revision: A

Bill Of Materials          November  3, 1989     18:08:46          Page   1
```

Quantity	Reference	Part
2	C1,C2	10uF
16	C15,C3,C4,C5,C6,C7,C8,C9, C10,C11,C12,C13,C14,C16, C22,C23	100nF
4	C18,C19,C20,C21	2n2F
4	C24,C25,C26,C27	330nF
4	D1,D2,D3,D4	1N4148
1	EC1	DIN41216-32a,c
1	IC1	LM7812
1	IC2	LM7912
5	IC3,IC4,IC5,IC6,IC7	TL084
2	L1,L2	100uH
1	R1	330R
24	R10,R11,R13,R16,R17,R18, R27,R28,R30,R33,R34,R35, R44,R45,R47,R50,R51,R52, R61,R62,R64,R67,R68,R69	100k
8	R12,R14,R29,R31,R46,R48, R63,R65	22k
4	R15,R32,R49,R66	2K2
4	R19,R36,R53,R70	150K
1	R2	1K8
4	R3,R20,R37,R54	10R
4	R4,R21,R38,R55	470R,1/2W
8	R6,R5,R22,R23,R39,R40, R56,R57	680R
4	R7,R24,R41,R58	47R
4	R71,R74,R77,R80	4M7
4	R72,R75,R78,R81	10K
4	R73,R76,R79,R82	91K
8	R9,R8,R25,R26,R42,R43, R59,R60	4k7
8	TP4,TP1,TP2,TP3,TP5,TP6, TP7,TP8	Test pins
4	TR1,TR2,TR3,TR4	BFY50
4	VR1,VR4,VR7,VR10	100R
9	VR3,VR2,VR5,VR6,VR8,VR9, VR11,VR12	10k
2	ZD1,ZD2	24V
1	ZD3	8V2
1	ZD4	3V3

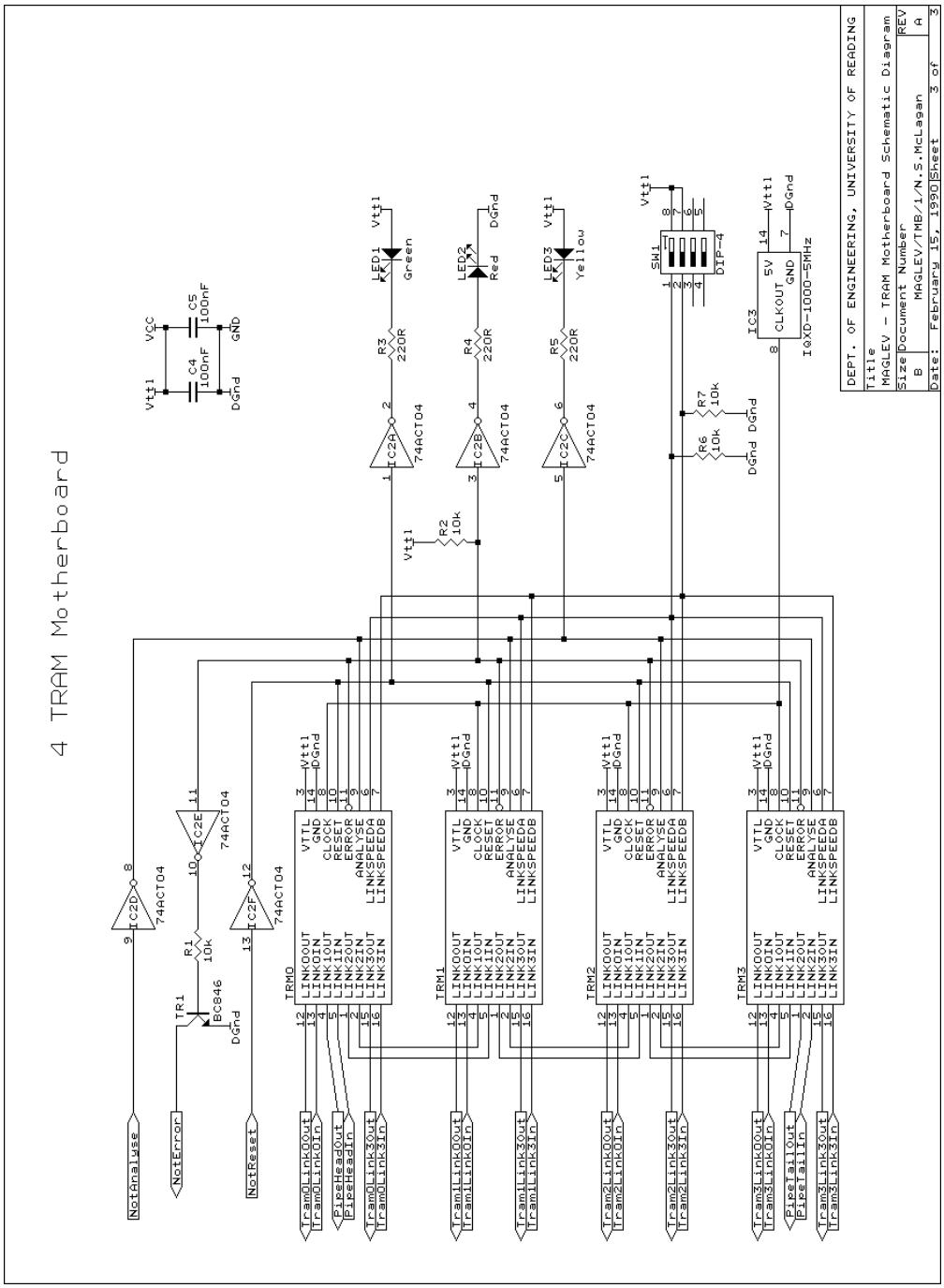
D.11 Transputer motherboard (4 tram) card



D.11.1 TMB card power supply



D.11.2 TMB TRAM connectivity



D.11.3 TMB card component parts list

```
MAGLEV - TRAM Motherboard Schematic Diagram   Revised:  February  7, 1990
MAGLEV/TMB/1/N.S.McLagan                      Revision: A

Bill Of Materials           February  8, 1990     14:08:10         Page 1

Quantity  Reference                Part

    1     C1                       22uF
    4     C2,C3,C4,C5              100nF

    1     EC1                      DIN41216-32a,b

    1     IC1                      LM2940CT5
    1     IC2                      74ACT04
    1     IC3                      IQXD-1000-5MHz Oscillator

    1     L1                       100uH

    1     LED1                     Green LED
    1     LED2                     Red LED
    1     LED3                     Yellow LED

    4     R1,R2,R6,R7              10k
    3     R3,R4,R5                 220R

    1     SW1                      DIP 4-way SPST

    1     TR1                      BC107

    1     ZD1                      24V
```

Appendix E

Control system software

This Appendix lists the suspension control programs for the vehicle and the single electromagnet systems. The three development support programs are also described. The various system software components, all of which are written in occam, are listed below:

E.1 Occam

The features which differentiate occam from conventional languages are now outlined to assist the reader in understanding the control system software. The description of occam is comprised of six parts namely: primitive processes; combining processes; data types; channels; timers and program configuration.

E.1.1 Primitive processes

Occam programs are built up using processes, the simplest of which is an action (primitive process). The primitive processes include assignment, input, output, skip and stop. Table E.1 lists examples of these occam primitive processes.

Table E.1 Occam primitive processes

PRIMITIVE PROCESS	ACTION
assignment	x := y + 4
input	keyboard ? character
output	screen ! character
no action, terminate	SKIP
no action, never terminate	STOP

E.1.2 Combining processes

The action of one or more processes can be combined by a construction. A construction builds a process of the kinds listed in Table E.2. The SEQ, IF, PAR and ALT constructions can be replicated by the addition of an index specifier similar to that found in a conventional FOR loop statement.

Table E.2 Occam combining processes

COMBINING PROCESS	CONSTRUCTION
sequential	SEQ
conditional	IF
selected	CASE
repeated	WHILE
parallel	PAR
alternative	ALT

E.1.3 Data types

The primitive data types supported by occam are boolean values, bytes, integers (16, 32 and 64 bits) and ANSI/IEEE standard floating point numbers (32 and 64 bits). Non-primitive data types are limited to arrays, including multi-dimensional arrays. There is no structured data support similar to conventional record structures. The occam handling of arrays of differing sizes when used as process parameters is more flexible than with many conventional languages.

E.1.4 Channels

Channels provide unbuffered, unidirectional, point-to-point communication of data between two concurrent processes. The format and type of data passed via a channel is specified by the channel protocol. The protocol declaration is similar to a record declaration in a conventional language. Variant protocols are supported in a similar way to conventional variant records. When a channel is declared, its type can be specified either by a data type or by a protocol. Channels are vitally important in concurrent systems because they facilitate synchronised communication between the concurrent program threads. Figure E.1 lists an example process which performs channel input and output using a replicated sequential construction.

```
PROTOCOL input.p IS INT, BYTE :

PROC data.expander( CHAN OF input.p  data.in,
                    CHAN OF BYTE  data.out )

  INT  length :
  BYTE  character :

  SEQ
    data.in ? length, character
    SEQ  index = 1 FOR length
      data.out ! character
:
```

Figure E.1 Occam channel example

E.1.5 Timers

A timer provides a real-time clock facility. Timer is a primitive type, just like channels and data types. Only two operations are permitted on a timer: input and input-after. Input simply receives the present clock time, whilst input-after waits until the specified time before performing an input. Timers are very useful within control systems for generating signals at fixed or variable time intervals. Figure E.2 lists an example process which generates a periodic trigger signal. Modulo arithmetic must be used with timers since the hardware timer counters will restart periodically.

```
PROC Pulse.Generator(CHAN OF BOOL  trigger,
                     VAL INT  time.period )

TIMER  clock :
INT    time :

SEQ
  clock ? time
  WHILE TRUE
    SEQ
      trigger ! TRUE
      time := time PLUS time.period
      clock ? AFTER time
:
```

Figure E.2 Occam timer example

E.1.6 Program configuration

Having coded an algorithm, configuration information dependent on the physical resources being used may be needed. There are three areas that may require configuration. First, where a multi-processor system is used, the top hierarchical level of the program consists of a PLACED PAR construction which allocates processes to processors. Secondly, the channels linking processes which execute on different processors must use PLACE CHAN to allocate the channels to physical transputer links. The PLACE configuration can also be used to allocate variables to specific memory locations, eg. for memory mapped hardware devices. Finally, the processes within a parallel process construction can be prioritised using PRI PAR. However, this is limited to only two levels of priority on the T2, T4 and T8 series of processors. Figure E.3 lists a program configuration example.

```
CHAN OF REAL32  signal :

PLACED PAR

  PROCESSOR 1 T8
    PLACE signal AT link0out :
    signal.generator( signal )

  PROCESSOR 2 T2
    PLACE signal AT link1in :
    convert.signal( signal )
```

Figure E.3 Occam configuration example

E.2 Vehicle suspension controller

E.2.1 Top-level Program configuration

```
#USE "system.tsr"
#USE "controll.tsr"
#USE "executiv.tsr"
#USE  userio

PROC  Head.Controller.Process( CHAN OF BOOL  data.conversion.request,
    CHAN OF converter.signal.p  ADConverter.in,

              CHAN OF signal.p  signal.exchange.out,
              CHAN OF signal.p  signal.exchange.in,

          CHAN OF controller.p  export.controller.params,
           CHAN OF exception.p  import.exception.reports,

                  CHAN OF ANY  PC.screen,
                  CHAN OF INT  PC.keyboard )

  -- Head.Controller() is the separately compiled process for all the processes
  -- running on the First main controller processor (T800-25 Mhz, 1MB preferably).


  CHAN OF converter.signal.p  dummy.DACs :
  CHAN OF signal.p  reference.signals :

  [2]CHAN OF signal.p  accs.to.mode.cont, gaps.to.mode.cont :
  [2]CHAN OF signal.p  refs.to.mode.cont, force.from.mode.cont :
  [2]CHAN OF signal.p  gaps.forces.to.mag.cont, current.from.magnet.cont :

  [2]CHAN OF signal.p  mode.cont.data, magnet.cont.data :
  CHAN OF monitor.p    data.to.buffer, data.to.monitor, temp :

  CHAN OF controller.p  controller.params :
  CHAN OF BOOL          exception.manager.reset, exception.shutdown :

  [2]CHAN OF controller.p  mode.cont.params, magnet.cont.params :
  [6]CHAN OF exception.p   exception.reports :
  CHAN OF BOOL             dummy.switch :
  CHAN OF exception.p      exception.notification :

  CHAN OF signal.gen.p   ref.signal.params, ref.signal.status :
  CHAN OF data.buffer.p  data.buffer.params :
  CHAN OF BOOL           buffer.data.request :


  PROC Buffer( CHAN OF monitor.p in, out)
    REAL32 time :
    [4][num.magnets]REAL32 magnet.data :
    [7][num.magnets]REAL32 mode.data :
    WHILE TRUE
      SEQ
        in ? time; magnet.data; mode.data
        out ! time; magnet.data; mode.data
  :


  PRI PAR
    PAR
      Signal.Data.Manager( head.processor, ADConverter.in, reference.signals,
                           accs.to.mode.cont, gaps.to.mode.cont,
                           refs.to.mode.cont, force.from.mode.cont,
                           gaps.forces.to.mag.cont, current.from.magnet.cont,
                           dummy.DACs,
                           signal.exchange.out, signal.exchange.in,
                           mode.cont.data, magnet.cont.data, data.to.buffer )

      Command.Message.Manager( head.processor, controller.params,
                               magnet.cont.params, mode.cont.params,
                               export.controller.params, exception.manager.reset )

      Reference.Signal.Generator( data.conversion.request, reference.signals,
                                  ref.signal.params, ref.signal.status,
                                  exception.shutdown, exception.reports[0] )
```

```
      PAR index = 0 FOR 2
        Vehicle.Mode.Controller( index, refs.to.mode.cont[index],
                            accs.to.mode.cont[index], gaps.to.mode.cont[index],
                            force.from.mode.cont[index], mode.cont.data[index],
                            mode.cont.params[index], exception.reports[index+1] )

      PAR index = 0 FOR 2
        Magnet.Force.Controller( index, gaps.forces.to.mag.cont[index],
                                 current.from.magnet.cont[index],
                                 magnet.cont.data[index],
                                 magnet.cont.params[index],
                                 exception.reports[index+3] )

      Monitor.Data.Buffer( data.to.buffer, buffer.data.request,
                           data.to.monitor, data.buffer.params,
                           exception.reports[5] )

      Buffer( data.to.monitor, temp )

      Exception.Report.Manager( head.processor, exception.manager.reset,
                                import.exception.reports, exception.reports,
                                dummy.switch, exception.notification,
                                exception.shutdown )

    -- LOW priority process --
    User.Interface( ref.signal.params, ref.signal.status,
                    controller.params, data.buffer.params,
                    PC.keyboard, PC.screen,
                    buffer.data.request, temp,
                    exception.notification )
:


#USE "system.tsr"
#USE "controll.tsr"

PROC  Tail.Controller.Process( CHAN OF converter.signal.p  currents.to.DACs,
                  CHAN OF BOOL  DAC.switch,

              CHAN OF signal.p  signal.exchange.out,
              CHAN OF signal.p  signal.exchange.in,

           CHAN OF exception.p  export.exception.reports,
          CHAN OF controller.p  import.controller.params )

  -- Tail.Controller() is the separately compiled process for all the processes
  -- running on the Second main controller processor (T800-20 Mhz 32KB, ideally).

  CHAN OF converter.signal.p  dummy.ADC :
  CHAN OF signal.p            dummy.sig.gen :

  [2]CHAN OF signal.p  accs.to.mode.cont, gaps.to.mode.cont :
  [2]CHAN OF signal.p  refs.to.mode.cont, force.from.mode.cont :
  [2]CHAN OF signal.p  gaps.forces.to.mag.cont, current.from.magnet.cont :

  [2]CHAN OF signal.p   mode.cont.data, magnet.cont.data :
  CHAN OF monitor.p  dummy.buffer.data :

  CHAN OF controller.p  dummy.params.out :
  CHAN OF exception.p  dummy.exception.report :
  CHAN OF BOOL  exception.manager.reset, dummy.shutdown :

  [2]CHAN OF controller.p  mode.cont.params, magnet.cont.params :
  [4]CHAN OF exception.p   exception.reports :


  PRI PAR
    PAR
      Signal.Data.Manager( tail.processor, dummy.ADC, dummy.sig.gen,
                           accs.to.mode.cont, gaps.to.mode.cont,
                           refs.to.mode.cont, force.from.mode.cont,
                           gaps.forces.to.mag.cont, current.from.magnet.cont,
                           currents.to.DACs,
                           signal.exchange.out, signal.exchange.in,
                           mode.cont.data, magnet.cont.data, dummy.buffer.data )

      Command.Message.Manager( tail.processor, import.controller.params,
                               magnet.cont.params, mode.cont.params,
                               dummy.params.out, exception.manager.reset )

      PAR index = 0 FOR 2
```

```
        Vehicle.Mode.Controller( (index + 2), refs.to.mode.cont[index],
                                accs.to.mode.cont[index], gaps.to.mode.cont[index],
                                force.from.mode.cont[index], mode.cont.data[index],
                                mode.cont.params[index], exception.reports[index] )

      PAR index = 0 FOR 2
        Magnet.Force.Controller( (index + 2), gaps.forces.to.mag.cont[index],
                                 current.from.magnet.cont[index],
                                 magnet.cont.data[index],
                                 magnet.cont.params[index],
                                 exception.reports[index+2] )

      Exception.Report.Manager( tail.processor, exception.manager.reset,
                                dummy.exception.report, exception.reports,
                                DAC.switch, export.exception.reports,
                                dummy.shutdown )
    PAR
      SKIP
:


#USE "system.tsr"
#USE "converte.tsr"

PROC  ADC.Process( CHAN OF BOOL  start.conversion.in,
     CHAN OF converter.signal.p  ADC.signals.out )

  -- ADC.Process() is the separately compiled process for all the processes
  -- running on the ADC card processor (T212 - 16 bit integer processor).


  -- Define PORTs for the ADC hardware --
  PORT OF INT  multiplexor :
  PLACE  multiplexor AT #6100 :

  PORT OF INT  adc :
  PLACE  adc AT #6000 :

  CHAN OF BOOL  end.of.conversion :
  VAL event IS  8 : -- Transputer external hardware interrupt channel
  PLACE  end.of.conversion AT event :


  --  Program code for ADC.Process()  --
  PRI PAR
    ADC.Driver( start.conversion.in, ADC.signals.out,
                multiplexor, adc, end.of.conversion )
    SKIP
:


#USE "system.tsr"
#USE "converte.tsr"

PROC  DAC.Process( CHAN OF converter.signal.p  DAC.signals.in,
                                CHAN OF BOOL  switch.pressed.out )

  -- DAC.Process() is the separately compiled process for all the processes
  -- running on the DAC card processor (T212 - 16 bit integer processor).


  -- Define PORTs for the DAC hardware --
  PORT OF INT  dac1, dac2, dac3, dac4 :
  PLACE  dac1 AT #6100 :
  PLACE  dac2 AT #6200 :
  PLACE  dac3 AT #6300 :
  PLACE  dac4 AT #6400 :

  -- Define a PORT for the watchdog timer --
  PORT OF INT  watchdog :
  PLACE  watchdog AT  #6700 :

  -- Define a PORT for the front panel push switch --
  PORT OF INT  switch :
  PLACE  switch AT  #6000 :


  --  Program code for ADC.Process()  --
  PRI PAR
    DAC.Driver( DAC.signals.in, dac1, dac2, dac3, dac4, watchdog )
    Switch.Monitor( switch, switch.pressed.out )
```

```
:



-- Define physical link addresses --
VAL link0out IS 0 :
VAL link1out IS 1 :
VAL link2out IS 2 :
VAL link3out IS 3 :
VAL link0in IS 4 :
VAL link1in IS 5 :
VAL link2in IS 6 :
VAL link3in IS 7 :


CHAN OF BOOL                conversion.request :
CHAN OF converter.signal.p  sensor.signals :

CHAN OF signal.p  signals.to.tail :
CHAN OF signal.p  signals.to.head :

CHAN OF controller.p  tail.controller.params :
CHAN OF exception.p   tail.exception.reports :

CHAN OF converter.signal.p  current.demands :
CHAN OF BOOL                DAC.switch.pressed :

CHAN OF ANY  PC.screen :
CHAN OF INT  PC.keyboard :


PLACED PAR

  PROCESSOR 1 T8  -- Head.Controllers
    PLACE conversion.request AT link1out :
    PLACE sensor.signals   AT   link1in :

    PLACE signals.to.tail AT link3out :
    PLACE signals.to.head AT link3in :

    PLACE tail.controller.params AT link2out :
    PLACE tail.exception.reports AT link2in :

    PLACE PC.screen  AT  link0out :
    PLACE PC.keyboard AT link0in :

    Head.Controller.Process( conversion.request, sensor.signals,
                             signals.to.tail, signals.to.head,
                             tail.controller.params, tail.exception.reports,
                             PC.screen, PC.keyboard )

  PROCESSOR 2 T8  -- Tail.Controllers
    PLACE current.demands   AT  link2out :
    PLACE DAC.switch.pressed AT link2in :

    PLACE signals.to.head AT link0out :
    PLACE signals.to.tail AT link0in :

    PLACE tail.exception.reports AT link1out :
    PLACE tail.controller.params AT link1in :

    Tail.Controller.Process( current.demands, DAC.switch.pressed,
                             signals.to.head, signals.to.tail,
                             tail.exception.reports, tail.controller.params )

  PROCESSOR 3 T2  -- ADC
    PLACE conversion.request AT link2in :
    PLACE sensor.signals   AT   link2out :

    ADC.Process( conversion.request, sensor.signals )

  PROCESSOR 4 T2  -- DAC
    PLACE current.demands   AT  link0in :
    PLACE DAC.switch.pressed AT link0out :

    DAC.Process( current.demands, DAC.switch.pressed )
```

E.2.2 System Constants & Comms Protocols Library

```
-- CONSTANTS --

VAL  num.magnets IS  4 :  -- Number of vehicle magnets to be controlled
VAL  num.modes  IS   4 :  -- Number of vehicle modes to be controlled

VAL head.processor IS  TRUE :
VAL tail.processor IS  NOT head.processor :

-- Controller modes --
VAL  local IS  0 :
VAL  vehicle IS  local + 1 :
VAL  user IS vehicle + 1 :


-- PROTOCOLS --

PROTOCOL  exception.p  IS  -- Used to convey exception reports --
    INT::[]BYTE;   -- Exception message text
    BYTE;          -- Magnet or mode index
    REAL32;        -- Exceptional or errant signal value
    BOOL:           -- Severity flag (de-levitation requirement)



PROTOCOL  controller.p  -- Used to convey commands to the controllers --
  CASE
    magnet.control.params; -- Conveys parameters to magnet force controllers
        REAL32;                -- Control system sampling interval
        [num.magnets][num.modes]REAL32  -- Modes-magnets transformation matrix
    mode.control.params;   -- Conveys parameters to suspension mode controllers
        REAL32;                -- Control system sampling interval
        [num.modes][num.magnets]REAL32;  -- Magnets-modes transformation matrix
        REAL32;                -- State estimator filter frequency
        REAL32;                -- Track trajectory filter frequency
        [num.modes]REAL32;     -- Mode controller integral action time constant
        [num.modes]REAL32;     -- Mode controller position feedback gain
        [num.modes]REAL32;     -- Mode controller velocity feedback gain
        [num.modes]REAL32;     -- Mode controller acceleration feedback gain
        INT;                   -- Control mode
        BOOL                   -- Reference signal injection select
    initialise.system      -- Requests relevant system initialisation
:


PROTOCOL  data.buffer.p  -- Used to convey commands to the data buffer --
  CASE
    data.buffer.params;  -- Conveys parameters for storage of logged data
        REAL32;            -- Data logging sample interval
        REAL32             -- Data logging duration
    data.buffer.log      -- Commands storage of data at next ref signal cycle start
    data.buffer.select;  -- Select source of data output from data buffer
        BOOL               -- Output stored data (NOT on-line data stream)
:


PROTOCOL  signal.gen.p  -- Used to convey commands to the signal generator --
  CASE
    signal.gen.params;   -- Conveys parameters to the reference signal generator
        REAL32;            -- Control system sampling interval
        REAL32;            -- Mean value of air gap reference
        [num.modes]REAL32; -- Mean air gap mode factors
        BOOL;              -- Dynamic reference signal select
        BOOL;              -- Select sine wave reference signal (NOT square wave)
        REAL32;            -- Reference signal frequency
        REAL32;            -- Reference signal amplitude
        [num.modes]REAL32  -- Position reference mode factors
    signal.gen.levitate; -- Command vehicle levitation up/down
        BOOL               -- Levitate vehicle (NOT de-levitate)
    signal.gen.levitated;-- Status report from signal generator
        BOOL               -- Vehicle levitated (NOT de-levitated)
:

PROTOCOL  converter.signal.p  -- Used to convey converter signals --
  CASE
    ADC.acc.raw.t;  INT16         -- Raw ADC acc measurement
    ADC.gap.raw.t;  INT16         -- Raw ADC gap measurement
    DAC.I.mA.t;     BYTE; INT16   -- Magnet index; current in mA
```

```
:

PROTOCOL  signal.p  -- Used to convey controller signals (all high priority) --
  CASE

    time.stamp.t;      REAL32               -- Test signal time reference
    mode.pos.refs.t;   [num.modes]REAL32    -- Mode position references

    magnet.gap.t;      BYTE; REAL32         -- Magnet index; magnet air gap
    magnet.gaps.t;     [num.magnets]REAL32  -- Magnet air gaps

    magnet.acc.t;      BYTE; REAL32         -- Magnet index; magnet acceleration
    magnet.accs.t;     [num.magnets]REAL32  -- Magnet accelerations

    mode.force.t;      BYTE; REAL32         -- Mode index; mode force demand
    mode.forces.t;     [num.modes]REAL32    -- Mode force demands

    magnet.current.t;  BYTE; REAL32         -- Magnet index; magnet current demand
    magnet.currents.t; [num.magnets]REAL32  -- Magnet index; DAC current value

    magnet.force.t;    BYTE; REAL32         -- Magnet index; magnet force demand

    mode.block.t;   -- Transfer block for internal mode controller signals --
        BYTE;       -- Mode index
        REAL32;     -- Mode air gap
        REAL32;     -- Mode acceleration
        REAL32;     -- Mode velocity
        REAL32;     -- Mode position
        REAL32      -- Mode track position
:

PROTOCOL  monitor.p  IS  -- Used to convey signals to the data buffer & monitor --
    REAL32;                 -- Time reference (see above)
    [4][num.magnets]REAL32; -- Magnets gap, acceleration, force & current
    [7][num.modes]REAL32:   -- Modes pos.ref, gap, acc, vel, pos, trk.pos & force
```

E.2.3 ADC and DAC Driver processes Library

```
#USE "system.tsr"

PROC  ADC.Driver( CHAN OF BOOL  data.request.in,
    CHAN OF converter.signal.p  ADC.signals.out,
                  PORT OF INT  multiplexor, adc,
                 CHAN OF BOOL  end.of.conversion )

  -- ADC.Driver waits for a start conversion trigger signal and then requests the
  -- A/D conversion of each acceleration and air gap signal before scaling them and
  -- outputting them to the data signal pool manager.
  --
  -- This process uses no external variables and must be configured for
  -- high priority operation on the ADC card processor (T212).

  -- Gap and Acc sensor multiplexor addresses :
  VAL gap1.chan IS  1 :
  VAL gap2.chan IS  2 :
  VAL gap3.chan IS  4 :
  VAL gap4.chan IS  8 :
  VAL acc1.chan IS  16 :
  VAL acc2.chan IS  32 :
  VAL acc3.chan IS  64 :
  VAL acc4.chan IS  128 :

  -- Channel sequence definition (accs & gaps must be ordered 1-4).
  -- Accelerations are read first since they can be processed before the air
  -- gap signals are needed.
  VAL INT num.adc.reads IS  2 * num.magnets :
  VAL [num.adc.reads]INT  sensor.sequence IS
                               [ acc1.chan, acc2.chan, acc3.chan, acc4.chan,
                                 gap1.chan, gap2.chan, gap3.chan, gap4.chan ] :


  BOOL   go, done :
  INT    adc.reading, value, time :
  TIMER  clock :

  SEQ

    adc ? adc.reading  -- Start the converter rolling

    WHILE TRUE
      SEQ
        -- ADC conversions are achieved by setting the multiplexor channel address,
        -- then reading the ADC (which gives the previous conversion value and starts
        -- the next conversion.  End of conversion is notified by a channel.

        multiplexor ! sensor.sequence[ 0 ]  -- Select first multiplexor channel
        clock ? time
        clock ? AFTER (time PLUS 3)  -- 3 us settling time for multiplexer

        data.request.in ? go      -- Wait for request for data

        end.of.conversion ? done  -- Clear last end of conversion notification
        adc ? adc.reading         -- Start conversion of first channel

        -- Read each sensor signal and then scale and output --
        SEQ  chan.index = 0 FOR num.adc.reads
          SEQ
            multiplexor ! sensor.sequence[ (chan.index + 1) REM num.adc.reads ]
            clock ? time
            clock ? AFTER (time PLUS 3)  -- 3 us settling time for multiplexer

            end.of.conversion ? done            -- Wait for conversion to complete
            adc ? adc.reading                   -- Read value from the ADC
            value := (adc.reading /\ #FFF0)     -- 12 bit ADC, mask other bits

            CASE  sensor.sequence[ chan.index]

              acc1.chan, acc2.chan, acc3.chan, acc4.chan
                ADC.signals.out ! ADC.acc.raw.t;  INT16 value

              gap1.chan, gap2.chan, gap3.chan, gap4.chan
                ADC.signals.out ! ADC.gap.raw.t;  INT16 value
:
```

```
#USE "system.tsr"

PROC  DAC.Driver( CHAN OF converter.signal.p  DAC.signals.in,
                               PORT OF INT  dac0, dac1, dac2, dac3,
                               PORT OF INT  watchdog )

  -- DAC.Driver scales the magnet current demands and sends them to the DACs
  -- It also resets the watchdog timer each time a current demand is processed.
  --
  -- This process uses no external variables and must be configured for
  -- high priority operation on the DAC card processor (T212).


  -- DAC specification --
  VAL levels.per.fsd  IS  4096 (INT32):
  VAL volts.per.fsd   IS    10 :
  VAL min.DAC.level   IS     0 :
  VAL max.DAC.level   IS  4095 :

  -- Electromagnet current amplifier details --
  VAL amps.per.volt IS  2 :

  -- Calculate composite denominator term --
  VAL INT32 mA.per.fsd IS  INT32 (1000 * (amps.per.volt * volts.per.fsd)) :


  BYTE   magnet :
  INT16  I.mA :
  INT  DAC.drive :


  WHILE TRUE
    SEQ
      DAC.signals.in ? CASE  DAC.I.mA.t;  magnet; I.mA

      DAC.drive := INT (((INT32 I.mA) * levels.per.fsd) / mA.per.fsd)
      IF
        (DAC.drive < min.DAC.level)
          DAC.drive := min.DAC.level
        (DAC.drive > max.DAC.level)
          DAC.drive := max.DAC.level
        TRUE
          SKIP

      CASE  INT magnet
        0
          dac0 ! DAC.drive
        1
          dac1 ! DAC.drive
        2
          dac2 ! DAC.drive
        3
          dac3 ! DAC.drive

      watchdog ! 0
:
```

```
#USE "system.tsr"

PROC  Switch.Monitor( PORT OF INT  switch,
                      CHAN OF BOOL  switch.pressed )

  -- Switch.Monitor generates an exception message each time the push switch
  -- on the front panel of the DAC card is pressed.  Debouncing and hysteresis
  -- are required before accepting a switch actuation.

  -- This process uses no external variables and MUST be configured for low
  -- priority operation.


  VAL [5]BYTE message IS  [0 (BYTE), 0(BYTE), 68 (BYTE), 65 (BYTE), 67 (BYTE) ] :
  VAL REAL32 zero IS  0.0(REAL32) :
  VAL INT sample.time.ticks IS 156 :  -- approximately 10 ms

  INT  filter, time, input :
  BOOL  pressed, pressed.before :
  TIMER  clock :


  SEQ
    filter := 0
    pressed := FALSE
    clock ? time

    WHILE TRUE
      SEQ
        switch ? input
        input := (input /\ 1) * 1000

        -- Debounce the switch output using a low-pass filter with Tc = 10 Ts
        filter := ( (filter * 9) + input ) / 10

        -- Detect switch transitions and apply debouncing --
        pressed.before := pressed
        pressed := (filter > 500)
        IF
          pressed AND (NOT pressed.before)
            SEQ
              filter := filter + 500
              switch.pressed ! TRUE
          (NOT pressed) AND pressed.before
            filter := filter - 500
          TRUE
            SKIP

        -- Wait for next sampling instant --
        time := time PLUS sample.time.ticks
        clock ? AFTER time
:
```

E.2.4 Control processes Library

```
#USE  "system.tsr"
#USE   snglmath

PROC  Reference.Signal.Generator( CHAN OF BOOL request.data.conversion.out,
          CHAN OF signal.p  ref.signals.out,

      CHAN OF signal.gen.p  parameters.in,
      CHAN OF signal.gen.p  status.out,
              CHAN OF BOOL  shutdown.request.in,
       CHAN OF exception.p  exception.report.out )


  -- Reference.Signal.Generator() receives parameters and commands from the user
  -- interface and exception report manager.  It initiates each iteration of the
  -- control system by requesting the ADC to read the sensor signals.  It also
  -- generates a time reference signal and a position refernce signal for a smooth
  -- startup and shutdown as well as generating periodic signals for test purposes.
  --
  -- This process uses no external variables and must be configured for
  -- high priority operation.


  --  Worldly & other constants  --
  VAL two.pi IS  2.0 (REAL32) * 3.1415926 (REAL32) :
  VAL set.down.on.track IS  0.008 (REAL32) :
  VAL start.stop.time.constant IS  0.5 (REAL32) :

  -- General variables --
  CHAN OF signal.gen.p  status.buffer :
  BOOL  buffered.status :

  BOOL    running, levitate, fully.up, fully.down, previously.fully.down :
  BOOL    dynamic.ref.selected, sine.wave.selected :
  REAL32  sample.interval, mean.gap, ref.freq, ref.amplitude :
  [num.modes]REAL32  mean.gap.coeffs, dyn.ref.coeffs, mode.refs :
  REAL32  filter.decay.coeff, filter.input.coeff, filter1, filter2 :
  REAL32  gap.ref, mean.ref, dyn.ref, time, sine.wave, cosine.wave :

  --  Sampling values and variables --
  VAL    ticks.per.sec IS 1000000.0 (REAL32) :
  INT    sample.interval.ticks, sample.time, time.now :
  REAL32 cycle.time :
  TIMER  clock :


  PAR
    WHILE TRUE
      SEQ
        status.buffer ? CASE signal.gen.levitated;  buffered.status
        status.out ! signal.gen.levitated;  buffered.status
    SEQ
      running := FALSE
      previously.fully.down := TRUE
      WHILE TRUE
        PRI ALT

          ALT
            shutdown.request.in ? levitate
              levitate := FALSE
            parameters.in ? CASE
              signal.gen.levitate;  levitate
                SKIP
              signal.gen.params;  sample.interval; mean.gap; mean.gap.coeffs;
                          dynamic.ref.selected; sine.wave.selected; ref.freq;
                          ref.amplitude; dyn.ref.coeffs
                SEQ
                  sample.interval.ticks := INT ROUND (ticks.per.sec * sample.interval)
                  filter.decay.coeff := exp(-(sample.interval/start.stop.time.constant))
                  filter.input.coeff := 1.0 (REAL32) - filter.decay.coeff
                  ref.amplitude := ref.amplitude / 2.0 (REAL32)  -- was pk-pk
                  IF
                    NOT running  -- Then Initialise system --
                      SEQ
                        running := TRUE
                        levitate := FALSE
                        filter1 := set.down.on.track
                        filter2 := filter1
```

```
            time := 0.0 (REAL32)
            clock ? sample.time
          TRUE
            SKIP

running & SKIP
  SEQ
    -- Set mean reference gap for either up or down --
    IF
      levitate
        gap.ref := mean.gap
      NOT levitate
        SEQ
          gap.ref := set.down.on.track
          time := 0.0 (REAL32)

    -- Ensure smooth startup & shutdown by filtering the reference signal --
    filter1 := (filter1 * filter.decay.coeff)+(gap.ref * filter.input.coeff)
    filter2 := (filter2 * filter.decay.coeff)+(filter1 * filter.input.coeff)
    mean.ref := filter2
    fully.up := (mean.ref < (mean.gap + 1.0E-4(REAL32)))
    previously.fully.down := fully.down
    fully.down := (mean.ref > (set.down.on.track - 1.0E-4(REAL32)))

    -- Add dynamic reference to mean reference if required --
    IF
      (fully.up AND dynamic.ref.selected)
        SEQ
          -- Advance time and limit domain to prevent loss of precision --
          IF
            (time < (1.0(REAL32) / ref.freq))
              time := time + sample.interval
            TRUE
              time := 0.0 (REAL32)

          -- Generate dynamic reference component --
          sine.wave := ref.amplitude * SIN( two.pi * (ref.freq * time) )
          cosine.wave := ref.amplitude * COS( two.pi * (ref.freq * time) )
          IF
            sine.wave.selected
              dyn.ref := sine.wave
            TRUE  -- square wave --
              IF
                (sine.wave > 0.0 (REAL32))
                  dyn.ref := ref.amplitude
                TRUE
                  dyn.ref := - ref.amplitude
      TRUE
        dyn.ref := 0.0(REAL32)

    --  Wait for next sampling time  --
    clock ? time.now
    cycle.time := REAL32 TRUNC (time.now MINUS sample.time)
    sample.time := sample.time PLUS sample.interval.ticks
    IF
      (time.now AFTER sample.time)
        VAL []BYTE message IS "Error: Sampling period too short, cycle time:":

        SEQ
          exception.report.out ! SIZE message::message; BYTE 0;
                       (cycle.time / ticks.per.sec) * 1000.0 (REAL32); TRUE
          sample.time := time.now
      TRUE
        clock ? AFTER sample.time

    IF
      NOT fully.down
        SEQ
          -- Request conversion of sensor signals by the ADC --
          request.data.conversion.out ! TRUE

          -- Output the time reference and mode reference signals --
          SEQ index = 0 FOR num.modes
            mode.refs[index] := (mean.ref * mean.gap.coeffs[index]) +
                                (dyn.ref * dyn.ref.coeffs[index])
          --mode.refs[2] := (cosine.wave * dyn.ref.coeffs[2])

          ref.signals.out ! time.stamp.t;  time
          ref.signals.out ! mode.pos.refs.t;  mode.refs
      (fully.down AND (NOT previously.fully.down))
        status.buffer ! signal.gen.levitated;  FALSE
```

```
              TRUE
                SKIP
:

#USE  "system.tsr"

PROC  Signal.Data.Manager( VAL BOOL  head.manager,

    CHAN OF converter.signal.p  from.analogue.converter,
              CHAN OF signal.p  sig.gen.refs.in,
            []CHAN OF signal.p  accs.to.mode.cont, gaps.to.mode.cont,
            []CHAN OF signal.p  refs.to.mode.cont, force.from.mode.cont,
            []CHAN OF signal.p  gaps.and.forces.to.mag.cont, current.from.mag.cont,
    CHAN OF converter.signal.p  to.analogue.converter,

              CHAN OF signal.p  exchange.data.out, exchange.data.in,

            []CHAN OF signal.p  data.from.mode.cont,
            []CHAN OF signal.p  force.from.magnet.cont,
             CHAN OF monitor.p  data.to.monitor.buffer )

  -- Signal.Data.Manager() runs on both main processors and controls
  -- the flow of all signals from the ADC through to the DAC.  The Boolean
  -- 'head.manager' determines which processes are connected to this process.
  --
  -- This process uses no external variables and should be configured for
  -- high priority operation.


  VAL num.local.magnet.controllers IS SIZE gaps.and.forces.to.mag.cont :
  VAL num.local.mode.controllers IS SIZE accs.to.mode.cont:

  -- ADC input voltage range --
  VAL  volts.per.fsd IS 5.0 (REAL32) / 32768.0 (REAL32) :

  -- Accelerometer details --
  VAL  Gs.per.volt IS 0.2 (REAL32):
  VAL  G IS 9.81 (REAL32) :
  VAL  acc.multiplier IS  (volts.per.fsd * Gs.per.volt) * G :

  -- Gap sensor details --
  VAL  metres.per.volt IS  0.00125 (REAL32) :
  VAL  gap.multiplier  IS  volts.per.fsd * metres.per.volt :
  VAL  sensor.offset   IS  0.0032 (REAL32) :                -- 3.2 mm
  VAL  net.track.gap   IS  0.009 (REAL32) :                 -- 9 mm
  VAL  gap.offset      IS  (net.track.gap - sensor.offset) :

  BYTE  magnet, MAGNET, mode, MODE :
  INT  m, M :

  INT16  magnet.acc.raw, magnet.gap.raw :

  REAL32  time, magnet.acc, magnet.gap, magnet.current, MAGNET.CURRENT :
  [num.magnets]REAL32  magnet.accs, magnet.gaps, magnet.currents :
  REAL32  magnet.force, MAGNET.FORCE :
  [num.magnets]REAL32  magnet.forces, MAGNET.FORCES :

  REAL32  mode.force, MODE.FORCE :
  [num.modes]REAL32  mode.pos.refs, mode.forces :

  INT16  magnet.current.mA, MAGNET.CURRENT.mA :

  REAL32  gap, acc, vel, pos, trk.pos, GAP, ACC, VEL, POS, TRK.POS :
  [num.modes]REAL32  gaps, accs, vels, poss, trk.poss :


  WHILE TRUE
    SEQ
      -- Get time stamp and reference signals from the signal generator --
      IF
        head.manager
          SEQ
            sig.gen.refs.in ? CASE time.stamp.t;  time
            sig.gen.refs.in ? CASE mode.pos.refs.t;  mode.pos.refs
            exchange.data.out ! time.stamp.t; time
            exchange.data.out ! mode.pos.refs.t; mode.pos.refs
        NOT head.manager
          SEQ
            exchange.data.in ? CASE time.stamp.t;  time
            exchange.data.in ? CASE mode.pos.refs.t;  mode.pos.refs
```

```
-- And send to the mode controllers --
SEQ  controllers = 0 FOR num.local.mode.controllers
  refs.to.mode.cont[ controllers ] ! mode.pos.refs.t;  mode.pos.refs


-- Get magnet acceleration measurements from the ADC / other processor --
SEQ  magnet.index = 0 FOR num.magnets
  SEQ
    IF
      head.manager
        SEQ
          magnet := BYTE magnet.index
          from.analogue.converter ? CASE ADC.acc.raw.t;  magnet.acc.raw
          magnet.acc := acc.multiplier * (REAL32 ROUND magnet.acc.raw)
          exchange.data.out ! magnet.acc.t;  magnet; magnet.acc
      NOT head.manager
        exchange.data.in ? CASE magnet.acc.t;  magnet; magnet.acc
    magnet.accs[ INT magnet ] := magnet.acc

-- And send to the mode controllers --
SEQ  controllers = 0 FOR num.local.mode.controllers
  accs.to.mode.cont[ controllers ] ! magnet.accs.t;  magnet.accs


-- Get magnet air gap measurements from the ADC / other processor --
SEQ  magnet.index = 0 FOR num.magnets
  SEQ
    IF
      head.manager
        SEQ
          magnet := BYTE magnet.index
          from.analogue.converter ? CASE ADC.gap.raw.t;  magnet.gap.raw
          magnet.gap := gap.offset - (gap.multiplier * (REAL32 ROUND magnet.gap.raw))
          exchange.data.out ! magnet.gap.t;  magnet; magnet.gap
      NOT head.manager
        exchange.data.in ? CASE magnet.gap.t;  magnet; magnet.gap
    magnet.gaps[ INT magnet ] := magnet.gap

-- And send to the mode controllers --
SEQ  controllers = 0 FOR num.local.mode.controllers
  gaps.to.mode.cont[ controllers ] ! magnet.gaps.t;  magnet.gaps

-- Get force demands from mode controllers and exchange with other processor --
SEQ  controllers = 0 FOR num.local.mode.controllers
  SEQ
    force.from.mode.cont[controllers] ? CASE mode.force.t;  mode; mode.force
    PAR
      exchange.data.out ! mode.force.t;  mode; mode.force
      exchange.data.in ? CASE mode.force.t;  MODE; MODE.FORCE
    mode.forces[ INT mode ] := mode.force
    mode.forces[ INT MODE ] := MODE.FORCE

--  And send to the magnet controllers --
SEQ  controllers = 0 FOR num.local.magnet.controllers
  gaps.and.forces.to.mag.cont[ controllers ] ! magnet.gaps.t;  magnet.gaps
SEQ  controllers = 0 FOR num.local.magnet.controllers
  gaps.and.forces.to.mag.cont[ controllers ] ! mode.forces.t;  mode.forces


-- Get current demands from the magnet controllers and exchange --
-- with the other processor --
SEQ  controllers = 0 FOR num.local.magnet.controllers
  SEQ
    current.from.mag.cont[controllers] ? CASE magnet.current.t;
                                          magnet; magnet.current
    magnet.current.mA := INT16 ROUND (1000.0(REAL32) * magnet.current)
    IF
      head.manager
        PAR
          exchange.data.out ! magnet.current.t;  magnet; magnet.current
          exchange.data.in ? CASE magnet.current.t;  MAGNET; MAGNET.CURRENT
      NOT head.manager
        SEQ
          PAR
            exchange.data.out ! magnet.current.t;  magnet; magnet.current
            exchange.data.in ? CASE magnet.current.t;  MAGNET; MAGNET.CURRENT
            to.analogue.converter ! DAC.I.mA.t; magnet; magnet.current.mA
          MAGNET.CURRENT.mA := INT16 ROUND (1000.0(REAL32) * MAGNET.CURRENT)
          to.analogue.converter ! DAC.I.mA.t; MAGNET; MAGNET.CURRENT.mA
    magnet.currents[ INT magnet ] := magnet.current
    magnet.currents[ INT MAGNET ] := MAGNET.CURRENT
```

```
      -- Get the internal signals from the magnet controllers --
      SEQ  controllers = 0 FOR num.local.magnet.controllers
        SEQ
          force.from.magnet.cont[controllers] ? CASE magnet.force.t;
                                                  magnet; magnet.force
          PAR
            exchange.data.out ! magnet.force.t;  magnet; magnet.force
            exchange.data.in ? CASE magnet.force.t;  MAGNET; MAGNET.FORCE
          magnet.forces[ INT magnet ] := magnet.force
          magnet.forces[ INT MAGNET ] := MAGNET.FORCE


      -- and the internal signals from the mode controllers --
      SEQ  controllers = 0 FOR num.local.mode.controllers
        SEQ
          data.from.mode.cont[controllers] ? CASE mode.block.t;  mode; gap; acc;
                                                                 vel; pos; trk.pos
          PAR
            exchange.data.out ! mode.block.t;  mode; gap; acc; vel; pos; trk.pos
            exchange.data.in ? CASE mode.block.t;  MODE; GAP; ACC; VEL; POS; TRK.POS
          m, M := INT mode, INT MODE
          gaps[m],accs[m],vels[m],poss[m],trk.poss[m] := gap,acc,vel,pos,trk.pos
          gaps[M],accs[M],vels[M],poss[M],trk.poss[M] := GAP,ACC,VEL,POS,TRK.POS

      -- And send ALL control system data signals to the data monitor's buffer --
      IF
        head.manager
          [4][num.magnets]REAL32  magnet.data :
          PLACE  magnet.data IN VECSPACE :
          [7][num.modes]REAL32  mode.data :
          PLACE  mode.data IN VECSPACE :
          SEQ
            magnet.data[0] := magnet.gaps
            magnet.data[1] := magnet.accs
            magnet.data[2] := magnet.forces
            magnet.data[3] := magnet.currents
            mode.data[0] := mode.pos.refs
            mode.data[1] := gaps
            mode.data[2] := accs
            mode.data[3] := vels
            mode.data[4] := poss
            mode.data[5] := trk.poss
            mode.data[6] := mode.forces
            data.to.monitor.buffer ! time; magnet.data; mode.data
        TRUE
          SKIP
:


#USE "system.tsr"
#USE  snglmath

PROC  Vehicle.Mode.Controller( VAL INT  mode.index,
          CHAN OF signal.p  position.references.in,
          CHAN OF signal.p  magnet.accs.in, magnet.gaps.in,
          CHAN OF signal.p  mode.force.out,
          CHAN OF signal.p  internal.signals.out,

      CHAN OF controller.p  parameters.in,
       CHAN OF exception.p  exception.out )


  -- Calculate.Mode.Force() performs the following tasks:
  -- 1. Receives the air gap and acceleration sensor signals for each magnet.
  -- 2. Transforms the sensor signals to vehicle mode 'mode.index' signals.
  -- 3. Estimates the mode velocity, position and track position.
  -- 4. Filters the track position to form a reference track trajectory.
  -- 5. Controls the absolute vehicle mode position using the above as a reference.
  -- 6. Outputs the resultant vehicle mode force demand.

  -- This process uses no external variables and should be configured for
  -- high priority operation.


  VAL  pi IS  3.1415926 (REAL32) :
  VAL  two.pi IS  2.0 (REAL32) * pi :

  VAL  vel.limit IS  0.1 (REAL32) :  -- 0.1 mm/ms velocity limit --
  VAL  [] BYTE warning.message IS  "Warning: Excessive velocity, V = " :
```

```
REAL32  sample.interval :
REAL64  sample.interval.r64 :
[num.modes][num.magnets]REAL32  magnets.to.modes.transform :
[num.magnets]REAL32  mode.transform :
[num.modes]REAL32  integral.times, stiffnesses, dampings, massnesses :
REAL32  integral.time, stiffness, damping, massness :
INT     control.mode :
BOOL    track.ref.select :

REAL32  est.cutoff.Hz, traj.cutoff.Hz :
REAL64  est.input.factor, est.decay.factor :
REAL64  traj.input.factor, traj.decay.factor :

REAL64  mode.pos.ref :
[num.modes]REAL32  mode.pos.refs :
REAL64  track.pos.ref, pos.ref :
[num.magnets]REAL32  magnet.gaps, magnet.accs :
REAL32  gap, acc :
REAL64  acc.r64, acc.lp, acc.hp, vel.hp, pos.hp, pos.error :
REAL64  track.pos, traj.pos.f1, traj.pos.f2, track.trajectory :
REAL32  acc.feedback, vel.feedback, pos.feedback, int.feedback, pos.error.r32 :
REAL32  min.integral.force, max.integral.force :
REAL32  force.demand, acc.hp.r32, vel.hp.r32, pos.hp.r32, track.pos.r32 :


WHILE TRUE
  ALT
    parameters.in ? CASE
      mode.control.params;  sample.interval; magnets.to.modes.transform;
                            est.cutoff.Hz; traj.cutoff.Hz;
                            integral.times; stiffnesses; dampings; massnesses;
                            control.mode; track.ref.select
        SEQ
          --  Select relevant mode control parameters  --
          mode.transform := magnets.to.modes.transform[ mode.index ]
          integral.time := integral.times[ mode.index ]
          stiffness:= stiffnesses[ mode.index ]
          damping := dampings[ mode.index ]
          massness := massnesses[ mode.index ]
          CASE  control.mode
            local, user
              SEQ
                min.integral.force := 200.0(REAL32)
                max.integral.force := 500.0(REAL32)
            vehicle
              IF
                (mode.index = 0)  -- heave mode
                  SEQ
                    min.integral.force :=  700.0(REAL32)
                    max.integral.force := 2500.0(REAL32)
                TRUE
                  SEQ
                    min.integral.force := -1000.0(REAL32)
                    max.integral.force :=  1000.0(REAL32)

          --  Calculate filter coefficients --
          sample.interval.r64 := REAL64 sample.interval
          est.decay.factor := REAL64 exp((-two.pi)*(est.cutoff.Hz*sample.interval))
          est.input.factor := 1.0 (REAL64) - est.decay.factor
          traj.decay.factor:=REAL64 exp((-two.pi)*(traj.cutoff.Hz*sample.interval))
          traj.input.factor := 1.0 (REAL64) - traj.decay.factor

        initialise.system
          SEQ -- reset filters etc.
            acc.lp := 0.0 (REAL64)
            vel.hp := 0.0 (REAL64)
            pos.hp := 0.0 (REAL64)
            track.pos := 0.0 (REAL64)
            traj.pos.f1 := track.pos
            traj.pos.f2 := traj.pos.f1
            int.feedback := 0.0 (REAL32)

      position.references.in ? CASE mode.pos.refs.t;  mode.pos.refs
        SEQ  -- run controller
          mode.pos.ref := REAL64 mode.pos.refs[ mode.index ]
          IF
            track.ref.select
              track.pos.ref, pos.ref := mode.pos.ref, 0.0 (REAL64)
            TRUE
              track.pos.ref, pos.ref := 0.0 (REAL64), mode.pos.ref
```

```
PAR
  SEQ
    --  Input the magnet air gaps  --
    magnet.gaps.in ? CASE magnet.gaps.t;  magnet.gaps

    --  Transform the magnet gaps to obtain the mode gap  --
    gap := 0.0 (REAL32)
    SEQ index = 0 FOR num.magnets
      gap := gap + (mode.transform[index] * magnet.gaps[index])

  SEQ
    --  Input the (high pass filtered) magnet accelerations  --
    magnet.accs.in ? CASE magnet.accs.t;  magnet.accs

    --  Transform the magnet accelerations to the mode acceleration  --
    acc := 0.0 (REAL32)
    SEQ index = 0 FOR num.magnets
      acc := acc + (mode.transform[index] * magnet.accs[index])

    --  High-pass filter the acceleration to remove any offset  --
    acc.r64 := REAL64 acc
    acc.lp := (acc.lp * est.decay.factor) + (acc.r64 * est.input.factor)
    acc.hp := acc.r64 - acc.lp
    acc.hp.r32 := REAL32 ROUND acc.hp


    --  Estimate the absolute velocity and position --
    vel.hp := (vel.hp * est.decay.factor) + (acc.hp * sample.interval.r64)
    vel.hp.r32 := REAL32 ROUND vel.hp
    pos.hp := (pos.hp * est.decay.factor) + (vel.hp * sample.interval.r64)
    pos.hp.r32 := REAL32 ROUND pos.hp

--  Estimate the absolute track position  --
track.pos := (pos.hp + track.pos.ref) - (REAL64 gap)
track.pos.r32 := REAL32 ROUND track.pos

--  and filter to form the track trajectory --
traj.pos.f1 :=(traj.pos.f1*traj.decay.factor)+(track.pos*traj.input.factor)
traj.pos.f2 :=(traj.pos.f2*traj.decay.factor)+(traj.pos.f1*traj.input.factor)
track.trajectory := traj.pos.f2

--  Calculate the absolute position error --
pos.error := (pos.hp - pos.ref) - track.trajectory
pos.error.r32 := REAL32 ROUND pos.error

--  Calculate the feedback components --
acc.feedback := massness * acc.hp.r32
vel.feedback := damping * vel.hp.r32
pos.feedback := stiffness * pos.error.r32
IF
  (int.feedback < min.integral.force)
    int.feedback := min.integral.force
  (int.feedback > max.integral.force)
    int.feedback := max.integral.force
  (integral.time > 0.0 (REAL32) )
    int.feedback := int.feedback +
        ( (pos.error.r32*sample.interval) * (stiffness/integral.time) )
  TRUE
    int.feedback := 0.0 (REAL32)

--  Total the force requirement  --
force.demand := ((int.feedback + pos.feedback)+(vel.feedback + acc.feedback))

PAR
  --  Output mode force demand  --
  mode.force.out ! mode.force.t;  BYTE mode.index; force.demand

  --  Output internal signals for monitoring  --
  internal.signals.out ! mode.block.t;  BYTE mode.index; gap; acc.hp.r32;
                               vel.hp.r32; pos.hp.r32; track.pos.r32

  --  Check velocity signal magnitude --
  IF
    (vel.hp.r32 < (-vel.limit)) OR (vel.hp.r32 > vel.limit)
      exception.out ! SIZE warning.message::warning.message;
                      BYTE mode.index; vel.hp.r32; TRUE
    TRUE
      SKIP

:
```

```
#USE "system.tsr"
#USE  snglmath

PROC  Magnet.Force.Controller( VAL INT  magnet.index,
          CHAN OF signal.p  gaps.and.forces.in,
          CHAN OF signal.p  current.out,
          CHAN OF signal.p  magnet.force.out,

      CHAN OF controller.p  parameters.in,
       CHAN OF exception.p  exception.out )

  -- Calculate.magnet.current uses the nonlinear magnet force model to determine
  -- the required current for the demanded force at the present airgap.


  -- Worldly constants --
  VAL  pi IS 3.1415926 (REAL32) :
  VAL  mu.air IS 1.2566E-6 (REAL32) :  -- Permeability of free space
  -- These are used to make the equations more readable --
  VAL  zero IS 0.0 (REAL32) :
  VAL  one IS 1.0 (REAL32) :
  VAL  two IS 2.0 (REAL32) :
  VAL  four IS 4.0 (REAL32) :


  -- Electromagnet parameters --
  VAL  y IS 0.0015 (REAL32) :  -- Lateral offset between magnet & track poles
  VAL  l IS 0.200  (REAL32) :  -- Magnet length
  VAL  w IS 0.033  (REAL32) :  -- Width between the magnet pole pieces
  VAL  h IS 0.063  (REAL32) :  -- Height of the magnet pole pieces
  VAL  t IS 0.030  (REAL32) :  -- Width between the track pole pieces
  VAL  p IS 0.0095 (REAL32) :  -- Width of the pole pieces

  VAL  N.coils IS 274.0 (REAL32) :       -- Number of coil turns
  VAL  min.current IS  0.0 (REAL32) :    -- Impose current limit
  VAL  max.current IS 20.0 (REAL32) :    -- Impose current limit
  VAL  mu.iron IS 2000.0 (REAL32) :      -- Maximum permeability of core material
  VAL  flux.roll.start IS 1.0 (REAL32) : -- Start of permeability roll-off (/Tesla)
  VAL  flux.roll.stop IS 1.7 (REAL32) :  -- End of permeability roll-off (/Tesla)

  VAL  T.eddy IS 0.0015 (REAL32) :     -- Target eddy current time constant
  VAL  N.phase.lead IS 3.0 (REAL32) :  -- Phase-lead ratio to achieve the above

  -- Input and transformation variables --
  REAL32  sample.interval, mag.force :
  [num.magnets][num.modes]REAL32  modes.to.magnets.matrix :
  [num.modes]REAL32  magnet.transform, mode.forces :
  [num.magnets]REAL32  magnet.gaps :

  -- Nonlinear magnet model variables --
  REAL32  T.phase.lead, input.factor, decay.factor :
  REAL32  flux.LP, flux.comp :
  REAL32  R.track, R.leakage, R.airgap, R.magnet :
  REAL32  force.demand, airgap, force.per.pole :
  REAL32  airgap.flux, flux.squared, leakage.flux, magnet.flux :
  REAL32  flux.density, mu.magnet :
  REAL32  airgaps.plus.track.mmf, magnet.mmf :
  REAL32  current.demand :


  -- Calculate the track and leakage reluctances --
  VAL R.track IS  ( t + (four*p) ) / ( (mu.iron*mu.air) * (l*p) ) :
  VAL R.leakage IS  w / ( mu.air * ( (l+((two*w)/pi)) * ((h/two)+(w/pi)) ) ) :

  WHILE TRUE
    ALT
      parameters.in ? CASE
        magnet.control.params;  sample.interval; modes.to.magnets.matrix
          SEQ
            --  Select relevant magnet control parameters  --
            magnet.transform := modes.to.magnets.matrix[ magnet.index ]

            -- Calculate phase-lead compensator coefficients  --
            IF
              (T.eddy > sample.interval)
                T.phase.lead := T.eddy
              TRUE
                T.phase.lead := sample.interval

            decay.factor := exp(- (sample.interval / T.phase.lead))
            input.factor := one - decay.factor
```

```
  initialise.system
    flux.LP := zero  -- Reset phase-lead compensator

gaps.and.forces.in ? CASE magnet.gaps.t;  magnet.gaps
  SEQ
    -- Calculate airgap reluctance --
    airgap := magnet.gaps[ magnet.index ]
    R.airgap := airgap / ( (mu.air*l) * ( p + ((two/pi)*airgap) ) )

    gaps.and.forces.in ?  CASE mode.forces.t;  mode.forces
    mag.force := 0.0 (REAL32)
    SEQ index = 0 FOR num.modes
      mag.force := mag.force + (magnet.transform[index] * mode.forces[index])

    IF
      (force.demand < zero)
        force.demand := zero
      TRUE
        force.demand := mag.force

    -- Calculate the gross force per pole --
    force.per.pole := force.demand /
        ( two * ( one - ( ((y*y)/airgap) / (airgap+((pi*p)/two)) ) ) )

    -- Calculate the required airgap flux --
    flux.squared := force.per.pole * ( (two*airgap) / R.airgap )
    IF
      (flux.squared > zero)
        airgap.flux := SQRT( flux.squared )
      TRUE
        airgap.flux := zero

    -- Calculate the mmf required to overcome the airgap and track reluctances
    airgaps.plus.track.mmf := airgap.flux * ( (two*R.airgap) + R.track )

    -- Calculate the consequential leakage flux --
    leakage.flux := airgaps.plus.track.mmf / R.leakage

    -- Calculate the resulting electromagnet flux --
    magnet.flux := airgap.flux + leakage.flux

    -- Apply phase lead compensation to the magnet flux demand --
    flux.LP := (flux.LP * decay.factor) + (magnet.flux * input.factor)
    flux.comp := (N.phase.lead * magnet.flux) - ((N.phase.lead-one) * flux.LP)

    -- Calculate the magnet reluctance at this flux level --
    flux.density := magnet.flux / (l * p)
    IF
      (flux.density < flux.roll.start)
        mu.magnet := mu.iron
      (flux.density < flux.roll.stop)
        mu.magnet := mu.iron * (1.1(REAL32) - ( (flux.density-flux.roll.start)/
                                    (flux.roll.stop - flux.roll.start) ) )
      TRUE
        mu.magnet := mu.iron * 0.1(REAL32)
    R.magnet := ( (two*h) + (w+(two*p)) ) / ( (mu.air*mu.magnet) * (l*p) )

    -- Calculate the mmf required to overcome the magnet reluctance --
    magnet.mmf := flux.comp * R.magnet

    -- Finally, calculate the current required to produce the total mmf --
    current.demand := (airgaps.plus.track.mmf + magnet.mmf) / N.coils
    IF
      (current.demand > max.current)
        current.demand := max.current
      (current.demand < min.current)
        current.demand := min.current
      TRUE
        SKIP

    --  Output magnet current demand (and force demand for monitoring)  --
    PAR
      current.out ! magnet.current.t;  BYTE magnet.index; current.demand
      magnet.force.out ! magnet.force.t; BYTE magnet.index; mag.force
:
```

```
#USE  "system.tsr"

PROC  Command.Message.Manager( VAL BOOL  head.manager,
                    CHAN OF controller.p  commands.in,
                  []CHAN OF controller.p  magnet.controller.commands,
                  []CHAN OF controller.p  mode.controller.commands,
                    CHAN OF controller.p  commands.out,
                            CHAN OF BOOL  exception.manager.reset )

  VAL num.local.magnet.controllers IS SIZE magnet.controller.commands :
  VAL num.local.mode.controllers IS SIZE mode.controller.commands :

  REAL32  sample.time, est.freq, traj.freq, mass :
  [num.modes][num.magnets]REAL32  input.matrix :
  [num.magnets][num.modes]REAL32  output.matrix :
  [num.modes]REAL32  integral.T, stiffness, damping, massness :
  INT   control.mode :
  BOOL  ref.sig.injection.select :

  WHILE TRUE
    commands.in ? CASE

      magnet.control.params;  sample.time; output.matrix
        SEQ
          IF
            head.manager
              commands.out ! magnet.control.params;
                             sample.time; output.matrix
            TRUE
              SKIP

          SEQ channels = 0 FOR num.local.magnet.controllers
            magnet.controller.commands[ channels ] ! magnet.control.params;
                                                     sample.time; output.matrix

      mode.control.params;  sample.time; input.matrix; est.freq; traj.freq;
                            integral.T; stiffness; damping; massness;
                            control.mode; ref.sig.injection.select
        SEQ
          IF
            head.manager
              commands.out ! mode.control.params;
                             sample.time; input.matrix; est.freq; traj.freq;
                             integral.T; stiffness; damping; massness;
                             control.mode; ref.sig.injection.select
            TRUE
              SKIP

          SEQ channels = 0 FOR num.local.mode.controllers
            mode.controller.commands[ channels ] ! mode.control.params;
                             sample.time; input.matrix; est.freq; traj.freq;
                             integral.T; stiffness; damping; massness;
                             control.mode; ref.sig.injection.select

      initialise.system
        SEQ
          IF
            head.manager
              commands.out ! initialise.system
            TRUE
              SKIP

          SEQ channels = 0 FOR num.local.magnet.controllers
            magnet.controller.commands[ channels ] ! initialise.system

          SEQ channels = 0 FOR num.local.mode.controllers
            mode.controller.commands[ channels ] ! initialise.system

          exception.manager.reset ! TRUE
:
```

```
#USE "system.tsr"

PROC  Exception.Report.Manager( VAL BOOL  head.manager,
                                CHAN OF BOOL  manager.reset,
                      CHAN OF exception.p  exception.in,
                     []CHAN OF exception.p  exceptions.in,
                                CHAN OF BOOL  switch.pressed.in,
                        CHAN OF exception.p  exception.out,
                                CHAN OF BOOL  shutdown.request)

  VAL num.exception.channels IS SIZE exceptions.in :

  BOOL    reset, send.report, report.received :

  INT     message.length, b.message.length :
  [80]BYTE message :
  PLACE    message IN VECSPACE :
  [80]BYTE b.message :
  PLACE    b.message IN VECSPACE :
  BYTE    index, b.index :
  REAL32  value, b.value :
  BOOL    delevitate, b.delevitate :
  BOOL    switch.pressed :

  CHAN OF exception.p  exception.buffer :

  SEQ
    report.received := FALSE
    send.report := TRUE
    PAR
      WHILE TRUE
        SEQ
          PRI ALT
            ALT channels = 0 FOR num.exception.channels
              exceptions.in[ channels ] ? message.length::message; index; value; delevitate
                report.received := TRUE
            exception.in ? message.length::message; index; value; delevitate
              report.received := TRUE
            switch.pressed.in ? delevitate
              SEQ
                message.length := 0
                report.received := TRUE
            manager.reset ? reset
              SEQ
                report.received := FALSE
                send.report := TRUE

          switch.pressed := report.received AND (message.length = 0)

          IF
            switch.pressed AND send.report
              SEQ
                exception.buffer ! message.length::message; index; value; delevitate
                report.received := FALSE
            report.received AND send.report
              SEQ
                exception.buffer ! message.length::message; index; value; delevitate
                send.report := FALSE
            TRUE
              SKIP

      WHILE TRUE
        SEQ
          exception.buffer ? b.message.length::b.message; b.index; b.value; b.delevitate
          IF
            head.manager AND b.delevitate
              shutdown.request ! TRUE
            TRUE
              SKIP
          exception.out ! b.message.length::b.message; b.index; b.value; b.delevitate
:
```

E.2.5 Executive processes Library

```
#USE "system.tsr"

PROC  Monitor.Data.Buffer( CHAN OF monitor.p  monitor.data.in,
                  CHAN OF BOOL  data.request.in,
              CHAN OF monitor.p  monitor.data.out,

          CHAN OF data.buffer.p  commands.and.params.in,
            CHAN OF exception.p  exception.report.out )

  -- Monitor.Data.Buffer() receives all data signals from the control system for
  -- each iteration of the loop.  This data can be optionally stored at a
  -- specified sampling rate and duration.  The output data can then be either
  -- from the on-line data or from that stored in the buffer.
  --
  -- This process uses no external variables and should be configured for
  -- high priority operation.


  BOOL logging, log.pending, data.complete, use.stored.data, request.data :

  REAL32  time.stamp, sample.time, sample.interval, sample.duration :
  [4][num.magnets]REAL32  magnet.data :
  [7][num.modes]REAL32  mode.data :

  VAL  buffer.size IS  2000 :
  INT  write.index, read.index :

  -- Place the large buffer arrays in slow off-processor memory --
  [buffer.size]REAL32  buffered.time.stamp :
  PLACE buffered.time.stamp IN VECSPACE :
  [buffer.size][4][num.magnets]REAL32  buffered.magnet.data :
  PLACE buffered.magnet.data IN VECSPACE :
  [buffer.size][7][num.modes]REAL32  buffered.mode.data :
  PLACE buffered.mode.data IN VECSPACE :

  SEQ
    logging := FALSE
    log.pending := FALSE
    data.complete := FALSE

    -- Reset variable storage
    time.stamp := 0.0(REAL32)
    SEQ  var.index = 0 FOR 4
      SEQ  magnet.index = 0 FOR num.magnets
        magnet.data[var.index][magnet.index] := 0.0 (REAL32)
    SEQ  var.index = 0 FOR 7
      SEQ  mode.index = 0 FOR num.modes
        mode.data[var.index][mode.index] := 0.0 (REAL32)

    WHILE TRUE
      PRI ALT
        monitor.data.in ? time.stamp; magnet.data; mode.data
          SEQ
            --  Log data into buffer when appropriate  --
            logging := logging OR (log.pending AND (time.stamp = 0.0(REAL32)))
            log.pending := log.pending AND (NOT logging)
            IF
              logging AND (time.stamp >= sample.time)
                SEQ
                  write.index := write.index + 1
                  buffered.time.stamp[write.index] := time.stamp
                  buffered.mode.data[write.index] := mode.data
                  buffered.magnet.data[write.index] := magnet.data
                  data.complete := (write.index = (buffer.size-1)) OR
                                       (sample.time >= sample.duration)
                  sample.time := sample.time + sample.interval
              logging
                data.complete := (time.stamp = 0.0(REAL32))
              TRUE
                SKIP
            logging := logging AND (NOT data.complete)

        commands.and.params.in ? CASE
          data.buffer.select;  use.stored.data  -- Select output source
            SKIP
          data.buffer.params;  sample.interval; sample.duration
            SKIP
```

```
          data.buffer.log  -- Start storing data to buffer
            SEQ
              logging := FALSE
              log.pending := TRUE
              data.complete := FALSE
              sample.time := 0.0 (REAL32)
              write.index := -1
              read.index := -1

        data.request.in ? request.data
          IF
            use.stored.data AND (logging OR data.complete)
              SEQ
                read.index := (read.index + 1) REM (write.index + 1)
                monitor.data.out ! buffered.time.stamp[read.index];
                                   buffered.magnet.data[read.index];
                                   buffered.mode.data[read.index]
            TRUE
              monitor.data.out ! time.stamp; magnet.data; mode.data

:

#USE  "system.tsr"
#USE   userio

PROC  User.Interface( CHAN OF signal.gen.p  signal.gen.params.out, signal.gen.status.in,
          CHAN OF controller.p  controller.params.out,
         CHAN OF data.buffer.p  data.buffer.params.out,

                   CHAN OF INT  keyboard,
                   CHAN OF ANY  screen,

                  CHAN OF BOOL  data.request,
              CHAN OF monitor.p  monitor.data.in,

            CHAN OF exception.p  exception.reports.in )


  -- User.Interface() provides the overall executive control of the suspension system.
  -- A terminal can be connected (optically) to the vehicle to access a menu-driven
  -- facility which permits levitation control as well as as modification of all
  -- control system parameters.  User.Interface() also provides data monitoring
  -- facilities either asynchronously for fast sampling or synchronously to provide
  -- real-time monitoring.  The push button switch on the DAC card can also be used
  -- to levitate and de-levitate the vehicle.


  -- MENU MANIPULATION PROCEDURES --
  PROC  Menu.Title( VAL [] BYTE  title )
    -- Menu.Title() centres, underlines and displays the supplied text.
    VAL offset IS  (80 - (SIZE title)) / 2 :
    SEQ
      goto.xy( screen, 0,0 )
      clear.eos( screen )
      goto.xy( screen, offset,0 )
      write.text.line( screen, title )
      goto.xy( screen, offset,1 )
      SEQ index = 1 FOR SIZE title
        write.char( screen, '~' )
      SEQ index = 1 FOR 3
        newline( screen )
  :

  PROC  Menu.Line( VAL []BYTE option )
    -- Menu.Line() offsets and displays the supplied text.
    SEQ
      SEQ index = 1 FOR 20
        write.char( screen, ' ' )
      write.text.line( screen, option )
  :

  PROC  Menu.Line.b( VAL []BYTE option, true.mesg, false.mesg, VAL BOOL value )
    -- Menu.Line.b() offsets and displays the supplied option text.
    -- It also uses the supplied Boolean value to selectively display a second
    -- text message.
    SEQ
      SEQ index = 1 FOR 20
        write.char( screen, ' ' )
      write.full.string( screen, option )
      IF
        (value = TRUE)
```

```
        write.text.line( screen, true.mesg )
      (value = FALSE)
        write.text.line( screen, false.mesg )
:

PROC  Menu.Line.r( VAL []BYTE option, units, VAL REAL32 value, VAL INT i,d )
  -- Menu.Line.r() offsets and displays the supplied option text.
  -- It also displays the supplied REAL32 value followed by the units text.
  SEQ
    SEQ index = 1 FOR 20
      write.char( screen, ' ' )
    write.full.string( screen, option )
    write.real32( screen, value, i,d )
    write.text.line( screen, units )
:

PROC  Menu.Line.ra( VAL []BYTE option, units,  VAL []REAL32 value,
                    VAL REAL32 divisor,        VAL INT i,d )
  -- Menu.Line.ra() offsets and displays the supplied option text.
  -- It also displays the supplied []REAL32 values followed by the units text.
  SEQ
    SEQ index = 1 FOR 20
      write.char( screen, ' ' )
    write.full.string( screen, option )
    SEQ index = 0 FOR SIZE value
      SEQ
        write.real32( screen, value[index]/divisor, i,d )
        write.char( screen, ' ' )
    write.text.line( screen, units )
:

PROC  Get.Option( INT char )
  -- Get.Option() prompts the user for a single character input.
  SEQ
    write.full.string( screen, "*c*n          Select option: " )
    keyboard ? char
    char := (char /\ #DF)
:

PROC Get.Value.r( VAL []BYTE prompt, REAL32 new.value, VAL REAL32 factor )
  -- Get.Value.r() prompts the user with the supplied prompt and then
  -- inputs and scales returns a REAL32 value from the keyboard.
  INT  delimiter :
  SEQ
    write.text.line( screen, prompt )
    write.full.string( screen, "          Enter new parameter value: " )
    new.value := 0.0 (REAL32)
    delimiter := INT ' '
    read.echo.real32( keyboard, screen, new.value, delimiter )
    new.value := new.value * factor
:

PROC Get.Value.ra( VAL []BYTE prompt, []REAL32 new.value, VAL REAL32 factor )
  -- Get.Value.ra() prompts the user with the supplied prompt and then
  -- inputs and scales returns []REAL32 values from the keyboard.
  INT  delimiter :
  SEQ
    write.text.line( screen, prompt )
    write.full.string( screen, "     Enter new parameter values: " )
    SEQ index = 0 FOR SIZE new.value
      SEQ
        new.value[index] := 0.0 (REAL32)
        delimiter := INT ' '
        read.echo.real32( keyboard, screen, new.value[index], delimiter )
        new.value[index] := new.value[index] * factor
:


-- VARIABLE DECLARATIONS TO HOLD COMPLETE SET OF SYSTEM PARAMETERS --

-- Reference signal generator variables --
REAL32  sample.interval, mean.gap :
BOOL    dynamic.ref.signal, sine.wave.ref.signal :
REAL32  ref.frequency, ref.amplitude :
[num.modes]REAL32  mean.gap.coeffs :
[num.modes]REAL32  pos.ref.coeffs :

-- Controller parameters --
INT  control.mode :

[num.modes][num.magnets]REAL32  input.matrix :
```

```
  [num.magnets][num.modes]REAL32  output.matrix :
  [num.modes]REAL32  integral.T, stiffness, damping,  massness :
  REAL32  est.cutoff.Hz, traj.cutoff.Hz :
  BOOL    track.reference :

  -- Data signal buffer parameters --
  REAL32  buffer.interval, buffer.duration :
  BOOL    buffer.output :


  #USE "Defaults.tsr"

  PROC  Initialise.Reference.Signal.Generator.Parameters( )
    -- This procedure initialises all parameters for the ref signal generator.
    SEQ
      sample.interval      := default.sample.interval
      mean.gap             := default.mean.gap
      dynamic.ref.signal   := default.dynamic.ref.signal
      sine.wave.ref.signal := default.sine.wave.ref.signal
      track.reference      := default.track.reference
      IF
        track.reference
          ref.frequency    := default.track.ref.frequency
        NOT track.reference
          ref.frequency    := default.pos.ref.frequency
      ref.amplitude        := default.ref.amplitude
      CASE  control.mode
        local
          pos.ref.coeffs := default.local.ref.coeffs
        vehicle
          pos.ref.coeffs := default.vehicle.ref.coeffs
        user
          pos.ref.coeffs := default.user.ref.coeffs
  :


  PROC  Reference.Signal.Generator.Menu( )
    -- This procedure enables interactive modification of the reference signal
    -- generator parameters.
    BOOL  finished :
    INT   option :
    SEQ
      finished := FALSE
      WHILE  NOT finished
        SEQ
          Menu.Title( "MAGLEV VEHICLE SUSPENSION - Signal Generator Parameters" )

          Menu.Line( "Reset all parameters to default values" )
          newline( screen )
          Menu.Line.r( "Sampling interval ( ", " ms )", sample.interval*kilo,3,2 )
          Menu.Line.r( "Operating air gap ( ", " mm )", mean.gap*kilo,1,2 )
          Menu.Line.b( "Dynamic reference signal ( ", "On )", "Off )", dynamic.ref.signal )
          Menu.Line.b(  "Waveform  of  dynamic  reference  signal  (  ",  "Sine  )",  "Square  )",
sine.wave.ref.signal )
          Menu.Line.b( "Track/Vehicle reference signal ( ", "Track )", "Vehicle )", track.reference
)
          Menu.Line.r( "Frequency of reference signal ( ", " Hz )", ref.frequency,2,2)
          Menu.Line.r( "Amplitude of reference signal ( ", " mm )", ref.amplitude*kilo,2,2 )
          Menu.Line.ra( "Mode distribution of reference ( ", " )", pos.ref.coeffs,one,1,1 )
          newline( screen )
          Menu.Line( "Quit this menu." )

          Get.Option( option )
          CASE  BYTE option
            'R'
              Initialise.Reference.Signal.Generator.Parameters( )
            'S'
              Get.Value.r( "Sampling interval", sample.interval, one/kilo )
            'O'
              Get.Value.r( "Air gap", mean.gap, one/kilo )
            'D'
              dynamic.ref.signal := NOT dynamic.ref.signal
            'W'
              sine.wave.ref.signal := NOT sine.wave.ref.signal
            'T'
              track.reference := NOT track.reference
            'F'
              Get.Value.r( "Reference frequency", ref.frequency, one )
            'A'
              Get.Value.r( "Reference amplitude", ref.amplitude, one/kilo )
            'M'
```

```
            Get.Value.ra( "Factors for each mode reference", pos.ref.coeffs, one)
          'Q'
            finished := TRUE
          ELSE
            beep( screen )
        IF
          (sample.interval < 0.0001 (REAL32))
            sample.interval := 0.0001 (REAL32)
          (sample.interval > 0.99 (REAL32))
            sample.interval := 0.99 (REAL32)
          TRUE
            SKIP
:


PROC  Initialise.Controller.Parameters( )
  -- This procedure initialises all parameters for the mode and magnet controllers.
  SEQ
    CASE  control.mode
      local
        SEQ
          input.matrix := local.matrix
          output.matrix := local.matrix
      vehicle
        SEQ
          input.matrix  := veh.input.matrix
          output.matrix := veh.output.matrix
      user
        SEQ
          input.matrix  := user.input.matrix
          output.matrix := user.output.matrix
    est.cutoff.Hz := default.est.cutoff.Hz
    traj.cutoff.Hz := default.traj.cutoff.Hz
    CASE  control.mode
      local
        SEQ
          integral.T := local.integral.T
          stiffness  := local.stiffness
          damping    := local.damping
          massness   := local.massness
      vehicle
        SEQ
          integral.T := veh.integral.T
          stiffness  := veh.stiffness
          damping    := veh.damping
          massness   := veh.massness
      user
        SEQ
          integral.T := user.integral.T
          stiffness  := user.stiffness
          damping    := user.damping
          massness   := user.massness
    -- Also set the mode reference coefficients for the ref signal generator --
    CASE  control.mode
      local
        pos.ref.coeffs := default.local.ref.coeffs
      vehicle
        pos.ref.coeffs := default.vehicle.ref.coeffs
      user
        pos.ref.coeffs := default.user.ref.coeffs
    CASE  control.mode
      local
        mean.gap.coeffs := default.local.gap.coeffs
      vehicle
        mean.gap.coeffs := default.vehicle.gap.coeffs
      user
        mean.gap.coeffs := default.user.gap.coeffs

:


PROC  Controller.Menu( )
  -- This procedure enables interactive modification of the mode and magnet
  -- controller parameters.
  BOOL  finished :
  INT   option :
  SEQ
    finished := FALSE
    WHILE  NOT finished
      SEQ
        Menu.Title( "MAGLEV VEHICLE SUSPENSION - Controller Parameters" )
```

```
        Menu.Line.b( "Local mode controller ", "- Selected", "", (control.mode=local) )
        Menu.Line.b( "Vehicle mode controller ", "- Selected", "", (control.mode=vehicle) )
        Menu.Line.b( "User defined controller ", "- Selected", "", (control.mode=user) )
        newline( screen )
        Menu.Line.r( "Estimation filter frequency ( ", " Hz )", est.cutoff.Hz,1,2)
        Menu.Line.r( "Track trajectory filter frequency ( ", " Hz )", traj.cutoff.Hz,2,1 )
        newline( screen )
        Menu.Line( "Absolute Position Controller Parameters" )
        Menu.Line.ra( "Integral time constant ( ", " s )", integral.T,one,1,1 )
        Menu.Line.ra( "Stiffness ( ", " kg/mm )", stiffness,kilo.g,3,1 )
        Menu.Line.ra( "Damping   ( ", " kg/(mm/s) )", damping,kilo.g,3,1 )
        Menu.Line.ra( "Massness  ( ", " kg )", massness,one,3,1 )
        newline( screen )
        Menu.Line( "Quit this menu." )

        Get.Option( option )
        CASE  BYTE option
          'L','V','U'
            SEQ
              CASE  BYTE option
                'L'
                  control.mode := local
                'V'
                  control.mode := vehicle
                'U'
                  control.mode := user
              Initialise.Controller.Parameters( )
          'E'
            Get.Value.r( "Estimation filter frequency", est.cutoff.Hz, one)
          'T'
            Get.Value.r( "Trajectory filter frequency", traj.cutoff.Hz, one )
          'I'
            Get.Value.ra( "Integral action time constant", integral.T, one )
          'S'
            Get.Value.ra( "Stiffness", stiffness, kilo.g )
          'D'
            Get.Value.ra( "Damping", damping, kilo.g )
          'M'
            Get.Value.ra( "Massness", massness, one )
          'Q'
            finished := TRUE
          ELSE
            beep( screen )
:


PROC  Initialise.Signal.Buffer.Parameters( )
  -- This procedure initialises all parameters for the signal data buffer.
  SEQ
    buffer.interval := default.buffer.interval
    buffer.duration := default.buffer.duration
    buffer.output   := default.buffer.output
:


PROC Signal.Buffer.Menu( )
  -- This procedure enables interactive modification of the parameters for the
  -- signal data buffer.
  BOOL  finished :
  INT   option :
  SEQ
    finished := FALSE
    WHILE  NOT finished
      SEQ
        Menu.Title( "MAGLEV VEHICLE SUSPENSION - Signal Buffer Parameters" )

        Menu.Line( "Reset all parameters to default values" )
        newline( screen )
        Menu.Line.r( "Interval between buffer samples( ", " ms )", buffer.interval*kilo,2,1 )
        Menu.Line.r( "Duration (maximum) of buffer sampling( ", " s )", buffer.duration,2,1)
        newline( screen )
        Menu.Line( "Log signals into buffer now" )
        newline( screen )
        Menu.Line.b( "Select buffer output source ", "- stored data",
                                            "- real-time data", buffer.output )
        newline( screen )
        Menu.Line( "Quit this menu." )

        Get.Option( option )
        CASE  BYTE option
          'R'
```

```
            Initialise.Signal.Buffer.Parameters( )
          'I'
            Get.Value.r( "Buffer interval", buffer.interval, one/kilo )
          'D'
            Get.Value.r( "Buffer duration", buffer.duration, one )
          'L'
            SEQ
              data.buffer.params.out ! data.buffer.params;  buffer.interval;
                                                            buffer.duration
              data.buffer.params.out ! data.buffer.log
          'S'
            buffer.output := NOT buffer.output
          'Q'
            finished := TRUE
          ELSE
            beep( screen )
:


--  LOCAL VARIABLE DECLARATIONS FOR USER.INTERFACE()  --

-- Menu control variables --
BOOL  levitate, key.pressed :
INT  option :

-- Exception report variables --
INT     message.length :
[80]BYTE  message :
BYTE    index :
REAL32  value :
BOOL    delevitate, switch.pressed :


--  Procedure code for User.Interface()  --

#USE "Monitor.tsr"
SEQ
  control.mode := vehicle  -- Select multi-variable vehicle control mode.

  Initialise.Signal.Buffer.Parameters( )
  Initialise.Controller.Parameters( )
  Initialise.Reference.Signal.Generator.Parameters( )

  controller.params.out ! initialise.system

  levitate := FALSE
  key.pressed := FALSE

  WHILE TRUE
    SEQ
      controller.params.out  ! mode.control.params;  sample.interval; input.matrix;
                               est.cutoff.Hz; traj.cutoff.Hz; integral.T; stiffness;
                               damping;  massness; control.mode; track.reference
      controller.params.out  ! magnet.control.params;  sample.interval; output.matrix
      data.buffer.params.out ! data.buffer.params;  buffer.interval; buffer.duration
      data.buffer.params.out ! data.buffer.select;  buffer.output
      signal.gen.params.out  ! signal.gen.params;  sample.interval; mean.gap;
                               mean.gap.coeffs; dynamic.ref.signal; sine.wave.ref.signal;
                               ref.frequency; ref.amplitude; pos.ref.coeffs
      PRI ALT
        keyboard ? option
          SEQ
            key.pressed := TRUE
            option := (option /\ #DF)
            CASE  BYTE option
              'L'
                IF
                  NOT levitate
                    SEQ
                      levitate := TRUE
                      controller.params.out ! initialise.system
                      signal.gen.params.out ! signal.gen.levitate;  levitate
                  TRUE
                    SKIP
              'D'
                SEQ
                  levitate := FALSE
                  signal.gen.params.out ! signal.gen.levitate;  levitate
              'C'
                Controller.Menu( )
              'R'
```

```
                Reference.Signal.Generator.Menu( )
              'S'
                Signal.Buffer.Menu( )
              'M'
                 Data.Monitor(    data.request,    monitor.data.in,    keyboard,    screen,
data.buffer.params.out )
              ELSE
                beep( screen )

            Menu.Title( "MAGLEV  VEHICLE  SUSPENSION  CONTROL  SYSTEM" )
            Menu.Line.b("", "De-levitate vehicle.", "Levitate vehicle.", levitate )
            Menu.Line( "Controller parameters." )
            Menu.Line( "Reference signal parameters." )
            Menu.Line( "Signal buffer parameters." )
            Menu.Line( "Monitor controller signals." )
            write.full.string( screen, "*c*n          Select option: " )

          signal.gen.status.in ? CASE signal.gen.levitated;  levitate
            controller.params.out ! initialise.system

          exception.reports.in ? message.length::message; index; value; delevitate
            SEQ
              switch.pressed := (message.length = 0)
              IF
                switch.pressed
                  SEQ
                    levitate := NOT levitate
                    signal.gen.params.out ! signal.gen.levitate;  levitate
                NOT switch.pressed
                  SEQ
                    IF
                      NOT key.pressed
                        keyboard ? option
                      TRUE
                        newline( screen )
                    newline( screen )
                    write.len.string( screen, message.length, message )
                    write.real32( screen, value, 3,3 )
                    newline( screen )
                    newline( screen )
                    write.full.string( screen, "*c*n          Select option: " )

:
```

E.2.6 Default parameters Library for Executive

```
--  DEFAULT VALUES FOR ALL CONTROL SYSTEM PARAMETERS --

--  Useful constants (to improve readability) --
VAL  zero IS 0.0 (REAL32) :
VAL  qrt  IS 0.25 (REAL32) :
VAL  half IS 0.5 (REAL32) :
VAL  one  IS 1.0 (REAL32) :
VAL  kilo IS 1000.0 (REAL32) :
VAL  g    IS 9.81 (REAL32) :
VAL  kilo.g IS kilo * g :

-- Default parameter values for the Reference Signal Generator --
VAL default.sample.interval      IS  0.00125 (REAL32) :  -- 1.25 ms
VAL default.mean.gap IS  0.003 (REAL32) :  -- 3.0 mm
VAL default.local.gap.coeffs     IS  [ one,  one,  one,  one ] :
VAL default.user.gap.coeffs      IS  [ one,  one,  one, zero ] :
VAL default.vehicle.gap.coeffs   IS  [ one, zero, zero, zero ] :

VAL default.dynamic.ref.signal   IS  FALSE :  -- constant gap ref
VAL default.sine.wave.ref.signal IS  TRUE :
VAL default.track.reference      IS  TRUE :

VAL default.pos.ref.frequency    IS  10.0 (REAL32) :  -- 10 Hz
VAL default.track.ref.frequency  IS  0.5 (REAL32) :  -- 0.5 Hz
VAL default.ref.amplitude        IS  0.001 (REAL32) :  -- 1 mm pk-pk

VAL default.local.ref.coeffs     IS  [ one,  one,  one,  one ] :
VAL default.user.ref.coeffs      IS  [ one,  one,  one, zero ] :
VAL default.vehicle.ref.coeffs   IS  [ one, zero, zero, zero ] :


-- Default parameter values for the Mode & Magnet Controllers --
VAL  local.matrix  IS      [ [ one, zero, zero, zero],
                             [zero,  one, zero, zero],
                             [zero, zero,  one, zero],
                             [zero, zero, zero,  one] ] :

VAL  veh.input.matrix  IS  [ [ qrt,  qrt,  qrt,  qrt],
                             [ qrt, -qrt, -qrt,  qrt],
                             [ qrt,  qrt, -qrt, -qrt],
                             [ qrt, -qrt,  qrt, -qrt] ] :

VAL  veh.output.matrix IS  [ [ qrt,  qrt,  qrt,  qrt],
                             [ qrt, -qrt,  qrt, -qrt],
                             [ qrt, -qrt, -qrt,  qrt],
                             [ qrt,  qrt, -qrt, -qrt] ] :

VAL  user.input.matrix IS  [ [ one, zero, zero, zero],
                             [zero,  one, zero, zero],
                             [zero, zero, half, half],
                             [zero, zero, zero, zero] ] :

VAL  user.output.matrix IS [ [ one, zero, zero, zero],
                             [zero,  one, zero, zero],
                             [zero, zero, half, zero],
                             [zero, zero, half, zero] ] :


VAL REAL32  default.est.cutoff.Hz IS  0.1 (REAL32) :
VAL REAL32  default.traj.cutoff.Hz IS  4.0 (REAL32) :

VAL  veh.integral.T IS [ one, one, one, zero ] :  -- seconds
VAL  veh.stiffness IS
  [100.0E+4 (REAL32),100.0E+4 (REAL32),100.0E+4 (REAL32), zero ] : -- N/m
VAL  veh.damping  IS
  [  2.6E+4 (REAL32),  2.6E+4 (REAL32),  2.6E+4 (REAL32), 2.6E+4 (REAL32) ] : -- N/m/s
VAL  veh.massness  IS
  [ 60.0 (REAL32),    60.0 (REAL32),    60.0 (REAL32),   60.0 (REAL32) ] : -- kg

VAL  local.integral.T IS [ one, one, one, one ] :  -- seconds
VAL  local.stiffness IS
  [ 25.0E+4 (REAL32), 25.0E+4 (REAL32), 25.0E+4 (REAL32), 25.0E+4 (REAL32)] : -- N/m
VAL  local.damping  IS
  [  0.65E+4 (REAL32), 0.65E+4 (REAL32), 0.65E+4 (REAL32), 0.65E+4 (REAL32)] : -- N/m/s
VAL  local.massness  IS
  [ 15.0 (REAL32),    15.0 (REAL32),    15.0 (REAL32),    15.0 (REAL32)  ]: -- kg
```

```
VAL  user.integral.T IS [ one, one, one, zero ] :  -- seconds
VAL  user.stiffness IS
  [ 25.0E+4 (REAL32), 25.0E+4 (REAL32), 50.0E+4 (REAL32),  zero ] : -- N/m
VAL  user.damping  IS
  [  0.65E+4 (REAL32), 0.65E+4 (REAL32),  1.3E+4 (REAL32),  zero ] : -- N/m/s
VAL  user.massness  IS
  [ 15.0 (REAL32),    15.0 (REAL32),    30.0 (REAL32),    zero ] : -- kg


-- Default parameter values for the Signal Buffer --
VAL default.buffer.interval IS   0.005 (REAL32) :  -- 5 ms
VAL default.buffer.duration IS  99.000 (REAL32) :  -- 99 s
VAL default.buffer.output   IS   FALSE :  -- Select on-line signals
```

E.2.7 Data Monitor process Library for Executive

```
#USE  "system.tsr"
#USE   userio
#USE   strings

PROC  Data.Monitor( CHAN OF BOOL  data.request.out,
          CHAN OF monitor.p  monitored.data.in,

                CHAN OF INT  keyboard,
                CHAN OF ANY  screen,

      CHAN OF data.buffer.p  data.buffer.params.out )

  --  Data.Monitor receives data from the control system via the data buffer.
  --  Data selected by the keyboard is the sent to the screen.  Each data item
  --  is toggled on/off using its initial letter.  'B' toggles  bar graph/tabular
  --  output, and 'W' causes the output to wait briefly to allow the Network
  --  Monitor EXE program to break free from the data stream, thus allowing the
  --  Data Logger EXE program to be run to log data to disc.


  --  Display variable tables etc.  --
  VAL  num.vars IS 12 :

  VAL  one    IS    1.0 (REAL32) :
  VAL  ten    IS   10.0 (REAL32) :
  VAL  twenty IS   20.0 (REAL32) :
  VAL  kilo   IS 1000.0 (REAL32) :

  VAL [num.vars][2]BYTE  var.name IS
    [ "T=",  "G=",  "A=",  "F=",  "I=",  "r=",  "g=",  "a=",  "v=",  "p=",  "t=",  "f=" ] :
  VAL [num.vars]REAL32 var.scaler IS
    [  one,  kilo,   one,   one,   one,  kilo,  kilo,   one,   one,  kilo,  kilo,   one ] :
  VAL [num.vars]REAL32  var.FSD IS
    [  one,   ten,   one,  kilo, twenty,   ten,   ten,   one,   one,   ten,   ten,  kilo ] :
  VAL [num.vars]INT  var.bp IS
    [    2,     1,     1,     4,     2,     1,     1,     1,     1,     1,     1,     4 ] :
  VAL [num.vars]INT  var.ap IS
    [    3,     3,     3,     1,     2,     1,     3,     3,     3,     3,     3,     1 ] :
  VAL [num.vars]BOOL  unipolar.var IS
    [ TRUE,  TRUE, FALSE,  TRUE,  TRUE,  TRUE, FALSE, FALSE, FALSE, FALSE, FALSE,  TRUE ] :
  VAL [num.vars]BOOL  initial.display.vars IS
    [ TRUE,  TRUE, FALSE, FALSE, FALSE,  TRUE, FALSE, FALSE, FALSE, FALSE, FALSE, FALSE ] :

  [num.vars]BOOL display.on :
  [num.vars][4]REAL32 display.table :


  [80]BYTE  display.line :
  [200]BYTE string :
  INT       char, string.index, line.index :
  REAL32    time :
  BOOL      bar.display.selected, buffer.output, finished :

  SEQ
    display.on := initial.display.vars
    bar.display.selected := TRUE
    buffer.output := FALSE
    finished := FALSE
```

```
WHILE NOT finished
  SEQ
    PRI ALT
      keyboard ? char
        SEQ
          CASE  BYTE char
            'W','w'
              SEQ index1 = 1 FOR 30000
                SEQ index2 = 1 FOR 100
                  SKIP
            'B','b'
              bar.display.selected := NOT bar.display.selected
            'L','l'
              data.buffer.params.out ! data.buffer.log
            'S','s'
              SEQ
                buffer.output := NOT buffer.output
                data.buffer.params.out ! data.buffer.select; buffer.output
            'Q','q'
              finished := TRUE
            ELSE
              SEQ  index = 1 FOR num.vars - 1
                IF
                  ((BYTE char) = var.name[index][0])
                    display.on[index] := NOT display.on[index]
                  TRUE
                    SKIP

      TRUE & SKIP
        SKIP

    --  Get some data from the controller --
    data.request.out ! TRUE
    monitored.data.in ? time;  -- reference signal time stamp
                        [display.table FROM 1 FOR 4]; -- magnet signals
                        [display.table FROM 5 FOR 7]  -- mode signals

    IF
      (time = 0.0 (REAL32))
        write.endstream( screen )
      TRUE
        SKIP

    --  Scale the variables before display  --
    SEQ  var.index = 1 FOR num.vars - 1
      IF
        display.on[ var.index ]
          SEQ index = 0 FOR 4
            display.table[var.index][index] := var.scaler[var.index] *
                                               display.table[var.index][index]
        TRUE
          SKIP

    --  Display value of each selected variable  --
    IF
      bar.display.selected
        SEQ
          goto.xy( screen, 0, 24 )
          clear.eol( screen )
      TRUE
        SKIP

    string[0] := '*c'
    string[1] := '*n'
    string.index := 2

    -- Copy time stamp to display string --
    append.text( string.index, string, var.name[0])
    append.real32( string.index, string, time, var.bp[0], var.ap[0] )
    string[ string.index ] := ' '
    string.index := string.index + 1

    -- Copy other required signals --
    SEQ  var.index = 1 FOR num.vars-1
      IF
        display.on[ var.index ]
          SEQ
            append.text( string.index, string, var.name[ var.index ])
            SEQ index = 0 FOR 4
              SEQ
                append.real32( string.index, string, display.table[var.index][index],
```

```
                                var.bp[var.index], var.ap[var.index] )
                    string[ string.index ] := ' '
                    string.index := string.index + 1
              TRUE
                SKIP
          write.len.string( screen, string.index, string )

          IF
            bar.display.selected
              SEQ  --  Display line graph for each selected variable  --
                SEQ  index = 0 FOR SIZE display.line
                  display.line[ index ] := ' '
                SEQ  index = 1 FOR 9
                  display.line[ index * 8 ] := '.'
                display.line[  0 ] := '|'
                display.line[ 40 ] := '|'

                SEQ  var.index = 1 FOR num.vars - 1  -- exclude time  --
                  SEQ index = 0 FOR 4
                    IF
                      display.on[ var.index ]
                        SEQ
                          line.index := INT ROUND ((80.0 (REAL32) * display.table[var.index][index])
                                                   / var.FSD[var.index])
                          IF
                            NOT unipolar.var[ var.index ]
                              line.index := line.index + 40
                            TRUE
                              SKIP
                          IF
                            (line.index > 79)
                              line.index := 79
                            (line.index < 0)
                              line.index := 0
                            TRUE
                              SKIP
                          display.line[line.index] := var.name[var.index][0]
                          IF
                            (display.line[line.index] <> 'r')
                              display.line[ line.index ] := BYTE (index + 49)
                            TRUE
                              SKIP
                      TRUE
                        SKIP

                goto.xy( screen, 0, 23 )
                write.full.string( screen, display.line )
            TRUE
              SKIP
:
```

E.3 Single magnet suspension controller

```
PROC Maglev.Controller( CHAN OF INT  keyboard,
                        CHAN OF ANY  screen,
                       CHAN OF INT16  ADC.in, ADC.out,
                                      DAC.in, DAC.out )

  ##############################################################################

  Single Magnet (Cantilever) Controller

  Features: - Track trajectory filter
            - Absolute position controller (4 term)
            - Full non-linear magnet force model for current calculation
            - Real time data monitoring and logging

  Author: Neil McLagan
  Version 1.0
  Last modified: 24-1-91

  All variables are in elementary units (eg. secs, metres, Hz, metres/sec)
  unless the variable name is post-fixed with an alternative, eg. airgap.mm
  Airgap is positive, velocity and acceleration have same direction as airgap.

  ##############################################################################

  #USE "Protocols.tsr"
  #USE  userio

  ------------------------------------------------------------------------------

  PROC Set.default.parameters(REAL32 integral.time, stiffness, damping, massness,
                      sampling.period, estim.cutoff.Hz, track.cutoff.Hz,
                      mass, operating.airgap,
                      airgap.frequency, airgap.amplitude, logging.period,
                BYTE  airgap.waveform )

    --  Set default values for controller parameters  --

    SEQ
      --  Default ride characteristics  --
      integral.time :=      1.0  (REAL32)  -- seconds
      stiffness     := 250000.0  (REAL32)  -- Newtons/metre
      damping       :=   6500.0  (REAL32)  -- Newtons/(metre/second)
      massness      :=     15.0  (REAL32)  -- Newtons/(metre/second^2) = Kilogrammes

      --  Initialise sampling period and filter cut-off frequencies  --
      sampling.period := 0.0005 (REAL32)
      estim.cutoff.Hz := 0.1 (REAL32)
      track.cutoff.Hz := 4.0 (REAL32)

      --  Default mass  --
      mass := 13.0 (REAL32)

      --  Default airgap reference characteristics --
      operating.airgap := 0.003 (REAL32)  -- 3 mm --
      airgap.frequency := 0.05 (REAL32)  -- 0.05 Hz --
      airgap.amplitude := 0.001 (REAL32)  -- 1 mm --
      logging.period := 0.020 (REAL32) -- 20 ms --
      airgap.waveform := 'C'  -- Constant airgap --


  :


  ------------------------------------------------------------------------------
  #USE "Protocols.tsr"

  PROC Read.ADC( CHAN OF INT16  ADC.in, ADC.out,
                      VAL INT  mux.channel,
                       REAL32  adc )

    -- Read.ADC requests an ADC conversion for each selected channel.
    -- It then scales the values appropriately before outputting them.

    INT16 adc.value :
    REAL32  adc.volts, sensor.gap, magnet.gap :

    VAL REAL32  metres.per.volt IS 0.00125 (REAL32) :
```

```
  VAL REAL32  sensor.offset IS 0.003500 (REAL32) :
  VAL REAL32  magnet.offset IS 0.003740 (REAL32) :
  VAL REAL32  magnet.sensor.length.ratio IS 1.446 (REAL32) :

  SEQ
    ADC.out ! INT16 mux.channel
    ADC.in ? adc.value

    adc.volts := (REAL32 ROUND adc.value) / 6553.6(REAL32)  -- convert to volts

    IF
      (mux.channel = 1)  -- airgap channel request
        SEQ
          sensor.gap := (adc.volts * metres.per.volt) + sensor.offset
          magnet.gap := (sensor.gap - magnet.offset) * magnet.sensor.length.ratio
          adc := magnet.gap

      (mux.channel = 16)  -- acceleration channel request
        SEQ
          adc := -(adc.volts / 5.0(REAL32))  -- convert to g's
          adc := adc * 9.81(REAL32)  -- convert to m/s/s

:


--------------------------------------------------------------------------------

PROC Write.DAC( CHAN OF INT16  DAC.in, DAC.out,
                VAL REAL32  current.demand )

  --  Write.DAC scales the requested current drive and sends it to the DAC.

  VAL  min.current IS  0.0 (REAL32) :
  VAL  max.current IS  19.9 (REAL32) :
  REAL32  current :

  SEQ
    current := current.demand
    IF
      current > max.current
        current := max.current
      current < min.current
        current := min.current
      TRUE
        SKIP

    DAC.out ! INT16 ROUND( current * 204.8(REAL32) )

:


--------------------------------------------------------------------------------
VAL  num.airgap.chans IS 3 :
VAL  num.acc.chans IS 2 :

PROC Interface.to.outside.world( CHAN OF INT16  ADC.in, ADC.out,
                                                DAC.in, DAC.out,
                           CHAN OF control.p  trigger,
                              CHAN OF data.p  current,
            [num.airgap.chans] CHAN OF data.p  airgap.chan,
               [num.acc.chans] CHAN OF data.p  acc.chan,
                           CHAN OF control.p  cycle.finished,
                         CHAN OF exception.p  exception )

  --  Interface.to.outside.world communicates the current demands and
  --  sensor values to and from the DAC and ADC drivers.

  --  A-D converter sensor addresses  --
  VAL acc.sensor IS 16 :
  VAL airgap.sensor IS 1 :

  BOOL  final.trigger, final.current, start.converting :
  REAL32  acc, airgap, current.demand :

  SEQ
    final.current := FALSE
    WHILE NOT final.current
      ALT
        trigger ? final.trigger; start.converting
          SEQ
            --  Read in acceleration  --
```

```
            Read.ADC( ADC.in, ADC.out, acc.sensor, acc )
            PAR i = 0 FOR num.acc.chans
              acc.chan[i] ! final.trigger; acc

            --  Read in position  --
            Read.ADC( ADC.in, ADC.out, airgap.sensor, airgap )
            PAR i = 0 FOR num.airgap.chans
              airgap.chan[i] ! final.trigger; airgap

          --  Output current demand to magnet current amplifier  --
          current ? final.current; current.demand
            SEQ
              IF
                final.current
                  Write.DAC( DAC.in, DAC.out, 0.0 (REAL32) )
                TRUE
                  Write.DAC( DAC.in, DAC.out, current.demand )
              cycle.finished ! final.current; TRUE
:


--------------------------------------------------------------------------------
#USE "Protocols.tsr"
#USE  dblmath

VAL  num.force.chans IS 2 :
VAL  num.velocity.chans IS 1 :

PROC Calculate.magnet.force( CHAN OF data.p  airgap.in, airgap.ref.in, acc.in,
            [num.force.chans] CHAN OF data.p  force.out,
          [num.velocity.chans] CHAN OF data.p  velocity.out,
                         CHAN OF exception.p  exception.out,
                                  VAL REAL32  integral.time, stiffness, damping, massness,
                                              mass,
                                              sampling.period,
                                              est.cutoff.Hz, track.cutoff.Hz )

  -- Calculate.magnet.force receives airgap and acceleration signals and performs
  -- the functions of track trajectory filter and absolute position control.

  VAL  pi IS  3.1415926 (REAL64) :
  VAL  two.pi IS  2.0 (REAL64) * pi :
  VAL  gravity.acc IS  9.81 (REAL32) :

  VAL  int.force.limit IS  500.0 (REAL32) :  -- 500 Newton integral limit
  VAL  vel.limit IS  0.2 (REAL32) :  -- 0.2 mm/ms velocity limit --
  VAL  [] BYTE warning.message IS  "Warning: Excessive velocity, V = " :

  BOOL  final.airgap, final.airgap.ref, final.acc, final.force :

  REAL64  est.input.factor, est.decay.factor :
  REAL64  track.input.factor, track.decay.factor :

  REAL32  airgap, airgap.ref, acc.meas :
  REAL64  acc.meas.r64, acc.lp, acc.hp, vel.hp, pos.hp, pos.error :
  REAL64  track.pos, track.pos.f1, track.pos.f2, track.trajectory :
  REAL32  acc.feedback, vel.feedback, pos.feedback, int.feedback :
  REAL32  force.demand, vel.r32 :

  SEQ
    --  Set filter factors --
    est.decay.factor := Dexp( (- two.pi) * (REAL64 (est.cutoff.Hz * sampling.period)) )
    est.input.factor := 1.0 (REAL64) - est.decay.factor

    track.decay.factor := Dexp( (- two.pi) * (REAL64 (track.cutoff.Hz * sampling.period)) )
    track.input.factor := 1.0 (REAL64) - track.decay.factor

    --  Initialise filters and integrators  --
    PAR
      airgap.in ? final.airgap; airgap
      airgap.ref.in ? final.airgap.ref; airgap.ref
      acc.in ? final.acc; acc.meas

    final.force := (final.airgap AND (final.airgap.ref AND final.acc))
    PAR
      PAR i = 0 FOR num.force.chans
        force.out[i] ! final.force; 0.0 (REAL32)
      PAR i = 0 FOR num.velocity.chans
        velocity.out[i] ! final.force; 0.0 (REAL32)

    acc.lp := 0.0 (REAL64)
```

```
    vel.hp := 0.0 (REAL64)
    pos.hp := 0.0 (REAL64)

    track.pos := REAL64 (airgap.ref - airgap)
    track.pos.f1 := track.pos
    track.pos.f2 := track.pos.f1

    int.feedback := 0.0 (REAL32)

    WHILE NOT final.force
      SEQ
        PAR
          --  Input the airgap and airgap reference  --
          airgap.in ? final.airgap; airgap
          airgap.ref.in ? final.airgap.ref; airgap.ref

          SEQ
            --  Input the (high pass filtered) acceleration  --
            acc.in ? final.acc; acc.meas

            --  Estimate the absolute acceleration --
            acc.meas.r64 := REAL64 acc.meas
            acc.lp := (acc.lp * est.decay.factor) + (acc.meas.r64 * est.input.factor)
            acc.hp := acc.meas.r64 - acc.lp

            --  Estimate the absolute velocity and position --
            vel.hp := (vel.hp * est.decay.factor) + (acc.hp * (REAL64 sampling.period))
            pos.hp := (pos.hp * est.decay.factor) + (vel.hp * (REAL64 sampling.period))

        --  Estimate the absolute track position --
        track.pos := (REAL64 (airgap.ref - airgap)) + pos.hp

        --  and filter to form the track trajectory --
        track.pos.f1 := (track.pos.f1*track.decay.factor) + (track.pos*track.input.factor)
        track.pos.f2 := (track.pos.f2*track.decay.factor) + (track.pos.f1*track.input.factor)
        track.trajectory := track.pos.f2

        --  Calculate the absolute position error --
        pos.error := (pos.hp - track.trajectory)

        --  Calculate the feedback components --
        acc.feedback := massness * (REAL32 ROUND acc.hp)
        vel.feedback := damping * (REAL32 ROUND vel.hp)
        pos.feedback := stiffness * (REAL32 ROUND pos.error)
        IF
          (int.feedback < (-int.force.limit))
            int.feedback := -int.force.limit
          (int.feedback > int.force.limit)
            int.feedback := int.force.limit
          (integral.time > 0.0 (REAL32) )
            int.feedback := int.feedback +
                    ( ((airgap-airgap.ref)*sampling.period) * (stiffness/integral.time) )
          TRUE
            int.feedback := 0.0 (REAL32)

        --  Total the force requirement (and account for mass)  --
        force.demand := ( (int.feedback + pos.feedback) +
                          (vel.feedback + acc.feedback) ) + (mass * gravity.acc)

        -- Output force demand & velocity --
        final.force := (final.airgap AND (final.airgap.ref AND final.acc))
        vel.r32 := REAL32 ROUND vel.hp
        PAR
          PAR i = 0 FOR num.force.chans
            force.out[i] ! final.force; force.demand
          PAR i = 0 FOR num.velocity.chans
            velocity.out[i] ! final.force; vel.r32

        --  Check velocity signal magnitude --
        IF
          (vel.r32 < (-vel.limit)) OR (vel.r32 > vel.limit)
            exception.out ! SIZE warning.message::warning.message; vel.r32
          TRUE
            SKIP

:
```

```
--------------------------------------------------------------------------------
#USE "Protocols.tsr"
#USE  snglmath

VAL num.current.chans IS 2 :

PROC Calculate.magnet.current( CHAN OF data.p  airgap.in,
                                               force.demand.in,
           [num.current.chans] CHAN OF data.p  current.required.out,
                               CHAN OF exception.p  exception.out,
                                        VAL REAL32  sampling.period )

  -- Calculate.magnet.current uses the nonlinear magnet force model to determine
  -- the required current for the demanded force at the present airgap.

  -- Worldly constants --
  VAL  pi IS 3.1415926 (REAL32) :
  VAL  mu.air IS 1.2566E-6 (REAL32) :  -- Permeability of free space
  -- These are used to make the equations more readable --
  VAL  zero IS 0.0 (REAL32) :
  VAL  one IS 1.0 (REAL32) :
  VAL  two IS 2.0 (REAL32) :
  VAL  four IS 4.0 (REAL32) :


  -- Electromagnet parameters --
  VAL  y IS 0.0015 (REAL32) :  -- Lateral offset between magnet & track poles
  VAL  l IS 0.200  (REAL32) :  -- Magnet length
  VAL  w IS 0.033  (REAL32) :  -- Width between the magnet pole pieces
  VAL  h IS 0.063  (REAL32) :  -- Height of the magnet pole pieces
  VAL  t IS 0.030  (REAL32) :  -- Width between the track pole pieces
  VAL  p IS 0.0095 (REAL32) :  -- Width of the pole pieces

  VAL  N.coils IS 274.0 (REAL32) :  -- Number of coil turns
  VAL  min.current IS  0.0 (REAL32) :  -- Impose current limit
  VAL  max.current IS 20.0 (REAL32) :  -- Impose current limit
  VAL  mu.iron IS 2000.0 (REAL32) :  -- Maximum permeability of the core material
  VAL  flux.roll.start IS 1.0 (REAL32) : -- Start of permeability roll-off (/Tesla)
  VAL  flux.roll.stop IS 1.7 (REAL32) : -- End of permeability roll-off (/Tesla)

  VAL  T.eddy IS 0.0015 (REAL32) :  -- Target eddy current time constant
  VAL  N.lead.lag IS 3.0 (REAL32) :  -- Lead lag ratio to achieve the above

  -- Nonlinear magnet model variables --
  REAL32  T.lead.lag, lead.lag.input.factor, lead.lag.decay.factor :
  REAL32  flux.low.pass, flux.lead.lag :
  REAL32  R.track, R.leakage, R.airgap, R.magnet :
  REAL32  force.demand, airgap, force.per.pole :
  REAL32  airgap.flux, flux.squared, leakage.flux, magnet.flux :
  REAL32  flux.density, mu.magnet :
  REAL32  airgaps.plus.track.mmf, magnet.mmf :
  REAL32  current.demand :

  BOOL  final.airgap, final.force, final.output :

  SEQ
    -- Determine lead lag compensator coefficients and initialise --
    IF
      (T.eddy > sampling.period)
        T.lead.lag := T.eddy
      TRUE
        T.lead.lag := sampling.period

    lead.lag.decay.factor := exp( - (sampling.period / T.eddy) )
    lead.lag.input.factor := one - lead.lag.decay.factor
    flux.low.pass := zero

    -- Calculate the track and leakage reluctances --
    R.track := ( t + (four*p) ) / ( (mu.iron*mu.air) * (l*p) )
    R.leakage := w / ( mu.air * ( (l+((two*w)/pi)) * ((h/two)+(w/pi)) ) )

    final.output := FALSE
    WHILE NOT final.output
      SEQ
        PAR
          force.demand.in ? final.force; force.demand
          airgap.in ? final.airgap; airgap

        IF
          (force.demand < zero)
            force.demand := zero
```

```
      TRUE
        SKIP

    -- Calculate airgap reluctance --
    R.airgap := airgap / ( (mu.air*l) * ( p + ((two*airgap)/pi) ) )

    -- Calculate the gross force per pole --
    force.per.pole := force.demand /
        ( two * ( one - ( ((y*y)/airgap) / (airgap+((pi*p)/two)) ) ) )

    -- Calculate the required airgap flux --
    flux.squared := force.per.pole * ( (two*airgap) / R.airgap )
    IF
      (flux.squared > zero)
        airgap.flux := SQRT( flux.squared )
      TRUE
        airgap.flux := zero

    -- Calculate the mmf required to overcome the airgap and track reluctances
    airgaps.plus.track.mmf := airgap.flux * ( (two*R.airgap) + R.track )

    -- Calculate the consequential leakage flux --
    leakage.flux := airgaps.plus.track.mmf / R.leakage

    -- Calculate the resulting electromagnet flux --
    magnet.flux := airgap.flux + leakage.flux

    -- Apply lead lag compensation teh the magnet flux demand --
    flux.low.pass := (flux.low.pass * lead.lag.decay.factor) +
                                    (magnet.flux * lead.lag.input.factor)
    flux.lead.lag := (N.lead.lag * magnet.flux) - ( (N.lead.lag-one) * flux.low.pass )

    -- Calculate the magnet reluctance at this flux level --
    flux.density := magnet.flux / (l * p)
    IF
      (flux.density < flux.roll.start)
        mu.magnet := mu.iron
      (flux.density < flux.roll.stop)
        mu.magnet := mu.iron * ( 1.1(REAL32) - ( (flux.density - flux.roll.start) /
                                    (flux.roll.stop - flux.roll.start) ) )
      TRUE
        mu.magnet := mu.iron * 0.1(REAL32)
    R.magnet := ( (two*h) + (w+(two*p)) ) / ( (mu.air*mu.magnet) * (l*p) )

    -- Calculate the mmf required to overcome the magnet reluctance --
    magnet.mmf := flux.lead.lag * R.magnet

    -- Finally, calculate the current required to produce the total mmf --
    current.demand := (airgaps.plus.track.mmf + magnet.mmf) / N.coils
    IF
      (current.demand > max.current)
        current.demand := max.current
      (current.demand < min.current)
        current.demand := min.current
      TRUE
        SKIP

    final.output := (final.airgap AND final.force)
    PAR i = 0 FOR num.current.chans
      current.required.out[i] ! final.output; current.demand
:
```

```
--------------------------------------------------------------------------------
#USE "Protocols.tsr"

PROC Handle.exceptions( [] CHAN OF exception.p  exceptions.in,
                                CHAN OF BOOL  stop.system.out,
                                     [] BYTE  message,
                                         INT  message.length,
                                      REAL32  message.value )

  --  Handle.exceptions initiates a controlled system shutdown upon receiving
  --  any exception message (including a user requested shutdown).

  VAL  number.of.error.channels IS SIZE exceptions.in :
  VAL  terminate IS 0 :

  [80] BYTE  ignore.message :
  INT  ignore.length :
  REAL32  ignore.value :

  BOOL  finished :

  SEQ
    --  Get first exception from the system  --
    ALT  i = 0 FOR number.of.error.channels
      exceptions.in[i] ? message.length::message; message.value
        SKIP

    finished := FALSE
    PAR
      --  Instruct system to shut down  --
      stop.system.out ! TRUE

      --  Accept (but ignore) any further exceptions  --
      WHILE  NOT finished
        ALT  i = 0 FOR number.of.error.channels
          exceptions.in[i] ? ignore.length::ignore.message; ignore.value
            finished := (i = terminate)
:


--------------------------------------------------------------------------------
#USE "Protocols.tsr"

PROC Data.Buffer( CHAN OF data.p  v1.in,v1.out, v2.in,v2.out, v3.in,v3.out,
                                  v4.in,v4.out, v5.in,v5.out, v6.in,v6.out,
                  CHAN OF BOOL  output.required )

  --  Data.Buffer buffers data between the control system and the data
  --  monitoring system, allowing them to run asynchronously.

  REAL32  v1.data, v2.data, v3.data, v4.data, v5.data, v6.data :
  BOOL  v1.finished, v2.finished, v3.finished, v4.finished, v4.finished,
        v5.finished, v6.finished :

  BOOL  ready, output.notified:

  SEQ
    v1.finished := FALSE
    output.notified := FALSE

    PAR
      WHILE NOT (v1.finished AND output.notified)
        --  Continuously read in all variables  --
        PRI ALT
          output.required ? ready
            PAR
              v1.out ! v1.finished; v1.data
              v2.out ! v2.finished; v2.data
              v3.out ! v3.finished; v3.data
              v4.out ! v4.finished; v4.data
              v5.out ! v5.finished; v5.data
              v6.out ! v6.finished; v6.data
              output.notified := v1.finished

          NOT v1.finished & SKIP
            PAR
              v1.in ? v1.finished; v1.data
              v2.in ? v2.finished; v2.data
              v3.in ? v3.finished; v3.data
              v4.in ? v4.finished; v4.data
              v5.in ? v5.finished; v5.data
```

```
            v6.in ? v6.finished; v6.data
:


--------------------------------------------------------------------------------
#USE "Protocols.tsr"
#USE userio
#USE strings

PROC Data.Monitor( CHAN OF data.p  gap.in, vel.in, acc.in,
                                   force.in, current.in, gap.ref.in,
                   CHAN OF BOOL    data.input.trigger,
                   CHAN OF exception.p  exception.out,
                   CHAN OF INT     keyboard,
                   CHAN OF ANY     screen,
                    VAL REAL32     logging.period )

  --  Data.Monitor receives data from the control system via the data buffer.
  --  Data selected by the keyboard is the sent to the screen.  Each data item
  --  is toggled on/off using its initial letter.  'T' toggles tabular/graph
  --  output, and 'P' causes the output to pause briefly to allow the Network
  --  Monitor EXE program to break free from the data stream, thus allowing the
  --  Data Logger EXE program to be run to log data to disc.

  INT  char :
  BYTE  option :

  BOOL  final.gap, final.vel, final.acc,
        final.force, final.current, final.gap.ref,
        finished :

  --  Display variable tables etc.  --
  VAL  num.vars IS 7 :

  VAL [num.vars] [2] BYTE  var.name IS
      [  "T=",    "R=",    "G=",    "V=",    "A=",    "I=",    "F=" ] :
  VAL [num.vars] INT  var.scaler IS
      [     1,    1000,    1000,       1,       1,       1,       1 ] :
  VAL [num.vars] INT  var.FSD IS
      [     1,      10,      10,       1,       1,      20,    1000 ] :
  VAL [num.vars] INT  var.bp IS
      [     2,       1,       1,       1,       1,       2,       4 ] :
  VAL [num.vars] INT  var.ap IS
      [     3,       1,       3,       3,       3,       2,       1 ] :
  VAL [num.vars] BOOL  initial.display.vars IS
      [  TRUE,    TRUE,    TRUE,   FALSE,   FALSE,    TRUE,    TRUE ] :

  [num.vars] BOOL display.on :
  [num.vars] REAL32 display.table :

  VAL  ticks.per.second IS 15625.0 (REAL32) :
  TIMER  clock :
  [80]  BYTE display.line :
  INT  display.time.interval, display.time, time, last.time, line.index :
  REAL32  time.interval, real.time :
  REAL32  gap.ref, last.gap.ref :
  BOOL  bar.display.selected :

  INT  string.index :
  [200] BYTE  string :

  SEQ
    display.time.interval := INT TRUNC ( logging.period * ticks.per.second )
    display.on := initial.display.vars

    SEQ var.index = 0 FOR num.vars
      display.table[ var.index ] := 0.0 (REAL32)

    bar.display.selected := TRUE
    finished := FALSE
    clock ? time
    clock ? display.time
    real.time := 0.0 (REAL32)
    last.gap.ref := 0.1 (REAL32)

    WHILE NOT finished
      SEQ
        PRI ALT
          keyboard ? char
            SEQ
              option := BYTE (char /\ #DF)
```

```
      IF
        (option = 'L')
          write.endstream( screen )
        (option = 'P')
          SEQ index1 = 1 FOR 30000
            SEQ index2 = 1 FOR 100
              SKIP
        (option = 'Q')
          exception.out ! 0::""; 0.0(REAL32)
        (option = 'T')
          bar.display.selected := NOT bar.display.selected
        TRUE
          SEQ  index = 1 FOR num.vars - 1
            IF
              (option = var.name[index][0])
                display.on[index] := NOT display.on[index]
              TRUE
                SKIP

  TRUE & SKIP
    SKIP

clock ? AFTER display.time
display.time := display.time PLUS display.time.interval

--  Get some data from the controller --
data.input.trigger ! TRUE

last.time := time
clock ? time
time.interval := (REAL32 TRUNC (time MINUS last.time))/ticks.per.second

PAR
  gap.ref.in ? final.gap.ref; display.table[1]
  gap.in ? final.gap; display.table[2]
  vel.in ? final.vel; display.table[3]
  acc.in ? final.acc; display.table[4]
  current.in ? final.current; display.table[5]
  force.in ? final.force; display.table[6]
finished := final.gap

gap.ref := display.table[1]
IF
  ((gap.ref - 0.00009(REAL32)) > last.gap.ref)
    SEQ
      write.endstream( screen )
      display.table[1] := last.gap.ref
      clock ? display.time
      real.time := 0.0 (REAL32)
  TRUE
    real.time := real.time + time.interval
last.gap.ref := gap.ref

display.table[0] := real.time

--  Scale the variables before display  --
SEQ  var.index = 1 FOR num.vars - 1
  IF
    display.on[ var.index ]
      display.table[ var.index ] := display.table[ var.index ] *
                              (REAL32 TRUNC var.scaler[ var.index ])
    TRUE
      SKIP

--  Display value of each selected variable  --
IF
  bar.display.selected
    SEQ
      goto.xy( screen, 0, 24 )
      clear.eol( screen )
  TRUE
    SKIP

string[0] := '*c'
string[1] := '*n'
string.index := 2
SEQ  var.index = 0 FOR num.vars
  IF
    display.on[ var.index ]
      SEQ
        append.text( string.index, string, var.name[ var.index ])
```

```
              append.real32( string.index, string,
                display.table[var.index], var.bp[var.index], var.ap[var.index] )
              string[ string.index ] := ' '
              string.index := string.index + 1
            TRUE
              SKIP
        write.len.string( screen, string.index, string )

        IF
          bar.display.selected
            SEQ  --  Display line graph for each selected variable  --
              SEQ  index = 0 FOR SIZE display.line
                display.line[ index ] := ' '
              SEQ  index = 1 FOR 9
                display.line[ index * 8 ] := '.'
              display.line[ 0 ] := '|'

              SEQ  var.index = 1 FOR num.vars - 1  -- exclude time  --
                IF
                  display.on[ var.index ]
                    SEQ
                      line.index := INT ROUND ((80.0 (REAL32) * display.table[var.index]) /
                                                              (REAL32 TRUNC var.FSD[var.index]))
                      IF
                        (line.index > 79)
                          line.index := 79
                        (line.index < 0)
                          line.index := 0
                        TRUE
                          SKIP
                      display.line[ line.index ] := var.name[ var.index ][ 0 ]
                  TRUE
                    SKIP

              goto.xy( screen, 0, 23 )
              write.full.string( screen, display.line )
          TRUE
            SKIP
:


--------------------------------------------------------------------------------
#USE "Protocols.tsr"
#USE  snglmath

VAL  num.ref.chans IS 2 :

PROC Controller( CHAN OF control.p  cycle.finished.in,
                 CHAN OF control.p  start.cycle.out,
     [num.ref.chans] CHAN OF data.p  airgap.reference.out,
                      CHAN OF BOOL  stop.system.in,
                CHAN OF exception.p  exception.out,
                         VAL REAL32  sampling.period,
                         VAL REAL32  operating.airgap, airgap.frequency,
                                     airgap.amplitude,
                           VAL BYTE  airgap.waveform )

  --  Controller controls the scheduling, start up, and shutdown of the magnet.
  --  It also checks the execution time and generates the reference signal.


  --  Worldly constants  --
  VAL two.pi IS 2.0 (REAL32) * 3.1415926 (REAL32) :

  --  Airgap  --
  VAL airgap.ramp.limit IS 0.010 (REAL32) :
  VAL airgap.ramp.vel IS 0.005 (REAL32) :
  REAL32 t, sine, airgap, amplitude.factor :

  --  Sampling  --
  VAL ticks.per.sec IS 1000000.0 (REAL32) :
  INT sample.interval.ticks, sample.time, time :
  REAL32 cycle.time :
  TIMER sampler :

  BOOL ramp.up, ramp.down, time.to.wind.down, finished, done :

  SEQ
    --  Prepare status  --
    t := 0.0 (REAL32)
    amplitude.factor := airgap.amplitude / 2.0 (REAL32)  -- was pk-pk --
```

```
    airgap := airgap.ramp.limit
    ramp.up := TRUE
    ramp.down := FALSE
    finished := FALSE

    --  Allow for all PROCs to initialise etc before timing  --
    start.cycle.out ! finished; TRUE
    PAR i = 0 FOR num.ref.chans
      airgap.reference.out[i] ! finished; airgap
    cycle.finished.in ? finished; done

    --  Initialise sampling timer  --
    sample.interval.ticks := INT ROUND( ticks.per.sec * sampling.period)
    sampler ? sample.time

    WHILE NOT finished
      SEQ
        PRI ALT
          stop.system.in ? time.to.wind.down
            SEQ
              ramp.up := FALSE
              ramp.down := TRUE
          TRUE & SKIP
            SEQ
              ramp.up := ramp.up AND (airgap > operating.airgap)
              finished := ramp.down AND (airgap > airgap.ramp.limit)

        IF
          ramp.up
            airgap := airgap - (airgap.ramp.vel * sampling.period)
          ramp.down
            airgap := airgap + (airgap.ramp.vel * sampling.period)
          TRUE
            SEQ
              t := t + sampling.period
              sine := SIN( two.pi * (airgap.frequency * t) )
              CASE  airgap.waveform
                'I'  -- sine wave --
                  airgap := operating.airgap + (amplitude.factor * sine)
                'Q'  -- square wave  --
                  IF
                    (sine > 0.0 (REAL32))
                      airgap := operating.airgap + amplitude.factor
                    TRUE
                      airgap := operating.airgap - amplitude.factor
                ELSE  -- constant airgap --
                  airgap := operating.airgap


        --  Wait for next sampling time  --
        sampler ? time
        cycle.time := REAL32 TRUNC (time MINUS sample.time)
        sample.time := sample.time PLUS sample.interval.ticks
        IF
          (time AFTER sample.time)
            VAL [] BYTE message IS "Error: Sampling period is too short, cycle time was:" :
            SEQ
             exception.out ! SIZE message::message; (cycle.time / ticks.per.sec) * 1000.0 (REAL32)
              sample.time := time
          TRUE
            sampler ? AFTER sample.time

        --  Initiate an iteration of the control loop --
        start.cycle.out ! finished; TRUE
        PAR i = 0 FOR num.ref.chans
          airgap.reference.out[i] ! finished; airgap
        cycle.finished.in ? finished; done
:

--------------------------------------------------------------------------------

PROC Levitate( CHAN OF INT  keyboard,
               CHAN OF ANY  screen,
              CHAN OF INT16  ADC.in, ADC.out, DAC.in, DAC.out,
                 VAL REAL32  integral.time, stiffness, damping, massness,
                             sampling.period,
                             est.cutoff.Hz, track.cutoff.Hz,
                             mass, operating.airgap,
                             airgap.frequency, airgap.amplitude, logging.period,
                   VAL BYTE  airgap.waveform )
```

```
--  Levitate executes the component processes of the control and monitoring
--  system, ensuring that appropriate process priorities are allocated and
--  that a controlled system shutdown is achieved.


[3] CHAN OF data.p  gap :
[1] CHAN OF data.p  vel :
[2] CHAN OF data.p  acc, gap.ref, force, current :
CHAN OF data.p  gap.buf, vel.buf, acc.buf, force.buf, current.buf, gap.ref.buf :
[7] CHAN OF exception.p  exception :
CHAN OF control.p  start.cycle, cycle.finished :
CHAN OF BOOL  stop.system, buffer.output.trigger :

VAL  release.exception.handler IS 0 :
VAL  [] BYTE nothing IS "" :

INT  message.length, anychar :
REAL32  message.value :
[80] BYTE  message :

SEQ
  PAR
    SEQ
      PRI PAR
        PAR
          Interface.to.outside.world( ADC.in, ADC.out,
                                      DAC.in, DAC.out,
                                      start.cycle, current[1],
                                      gap, acc,
                                      cycle.finished,
                                      exception[1] )

          Calculate.magnet.force( gap[1], gap.ref[1], acc[1],
                                  force, vel,
                                  exception[3],
                                  integral.time, stiffness, damping, massness,
                                  mass, sampling.period,
                                  est.cutoff.Hz, track.cutoff.Hz )

          Calculate.magnet.current( gap[2], force[1],
                                    current,
                                    exception[4],
                                    sampling.period )

          Controller( cycle.finished,
                      start.cycle, gap.ref,
                      stop.system,
                      exception[5],
                      sampling.period,
                      operating.airgap, airgap.frequency, airgap.amplitude,
                      airgap.waveform )

          Data.Buffer( gap[0], gap.buf, vel[0], vel.buf, acc[0], acc.buf,
                       force[0], force.buf, current[0], current.buf,
                       gap.ref[0], gap.ref.buf,
                       buffer.output.trigger )

        Data.Monitor( gap.buf, vel.buf, acc.buf, force.buf, current.buf,
                      gap.ref.buf,
                      buffer.output.trigger,
                      exception[6], keyboard, screen,
                      logging.period )

      exception[ release.exception.handler ] ! 0::""; 0.0(REAL32)

    Handle.exceptions( exception,
                       stop.system,
                       message, message.length, message.value )

  IF
    (message.length > 0)
      SEQ
        newline( screen )
        newline( screen )
        write.len.string( screen, message.length, message )
        write.real32( screen, message.value, 3,3 )
        newline( screen )
        read.char( keyboard, anychar )
    TRUE
      SKIP
:
```

```
--------------------------------------------------------------------------

PROC Menu( CHAN OF INT  keyboard,
           CHAN OF ANY  screen,
         CHAN OF INT16  ADC.in, ADC.out, DAC.in, DAC.out,
                REAL32  integral.time, stiffness, damping, massness,
                        sampling.period, est.cutoff.Hz, track.cutoff.Hz,
                        mass, operating.airgap,
                        airgap.frequency, airgap.amplitude, logging.period,
                  BYTE  airgap.waveform )

  --  Menu permits the setting of system parameters and initiates a control system run.


  ------------------------------------------------------------------------
  PROC  Write.menu( VAL [] BYTE  option,
                    VAL REAL32  value,
                       VAL INT  i, d,
                    VAL [] BYTE  units )
    SEQ
      write.full.string( screen, "                    " )
      write.full.string( screen, option )
      write.real32( screen, value, i, d )
      write.full.string( screen, units )
      newline( screen )
  :

  ------------------------------------------------------------------------
  PROC  Get.value( VAL [] BYTE  text,
                        REAL32  new.value,
                   VAL REAL32  factor )

    INT delimiter :

    SEQ
      write.text.line( screen, text )
      write.full.string(screen, "        Enter new parameter value: " )
      new.value := 0.0 (REAL32)
      delimiter := INT ' '
      read.echo.real32( keyboard, screen, new.value, delimiter )
      new.value := new.value * factor
  :

  VAL kilo IS 1000.0 (REAL32) :
  VAL kilo.g IS 9810.0 (REAL32) :

  INT  option.int :
  BYTE  option :
  REAL32  factor :
  BOOL  finished :

  SEQ
    finished := FALSE
    WHILE NOT finished
      SEQ
        write.endstream( screen )

        --  Write menu on screen  --
        goto.xy( screen, 0,0 )
        clear.eos( screen )

        write.text.line( screen, "                            MAGLEV CONTROLLER")
        write.text.line( screen, "                            ~~~~~~~~~~~~~~~~~")
        newline( screen )

        Write.menu("I ---- Integral time constant ( ", integral.time, 1,1, " s )")
        Write.menu("S ---- Stiffness ( ", stiffness/kilo.g, 2,1, " kg/mm )")
        Write.menu("D ---- Damping ( ", damping/kilo.g,  1,2, " kg/(mm/s) )" )
        Write.menu("M ---- Massness ( ", massness, 2,1, " kg )" )
        newline( screen )

        Write.menu("P ---- sampling Period ( ", sampling.period*kilo, 1,2," ms )")
        Write.menu("E ---- Estimation cutoff frequency ( ", est.cutoff.Hz, 1,1," Hz )")
        Write.menu("T ---- Track cutoff frequency ( ", track.cutoff.Hz, 2,1," Hz )")
        Write.menu("L ---- suspended Load ( ", mass, 2,1, " Kg )" )
        newline( screen )

        Write.menu("G ---- airGap ( ", operating.airgap*kilo, 1,2, " mm )")
        Write.menu("R ---- Reference signal frequency ( ", airgap.frequency, 2,2, " Hz )")
        Write.menu("A ---- reference signal Amplitude ( ",airgap.amplitude*kilo,1,2," mm pk-pk )")
```

```
            Write.menu("O ---- data lOgging period ( ", logging.period*kilo, 2,1, " ms )")
            write.text.line(screen,"                    W ---- Waveform ")
            newline( screen )

            write.text.line(screen,"                    V ---- leVitate")
            write.text.line(screen,"                    Q ---- Default parameters")

            write.full.string(screen,"*c*n                      Select option: ")
            read.char(keyboard, option.int )

            --  Convert to uppercase and BYTE --
            option := BYTE (option.int /\ #DF)

            CASE option
              'I'
                Get.value( "Integral time constant", integral.time, 1.0 (REAL32) )
              'S'
                Get.value( "Stiffness", stiffness, kilo.g )
              'D'
                Get.value( "Damping", damping, kilo.g )
              'M'
                Get.value( "Massness", massness, 1.0 (REAL32) )
              'P'
                SEQ
                  Get.value( "Sampling period", sampling.period, 0.001(REAL32))
                  IF
                    (sampling.period < 0.0001 (REAL32))
                      sampling.period := 0.0001 (REAL32)
                    TRUE
                      SKIP
              'E'
                Get.value( "Estimation cut-off frequency", est.cutoff.Hz, 1.0(REAL32))
              'T'
                Get.value( "Track cut-off frequency", track.cutoff.Hz, 1.0(REAL32))
              'L'
                Get.value( "Load", mass, 1.0 (REAL32) )
              'G'
                Get.value( "Airgap", operating.airgap, 0.001 (REAL32) )
              'R'
                Get.value( "Reference signal frequency", airgap.frequency, 1.0 (REAL32) )
              'A'
                Get.value( "Reference signal amplitude", airgap.amplitude, 0.001 (REAL32) )
              'O'
                Get.value( "Data logging period", logging.period, 0.001(REAL32))
              'W'
                SEQ
                  write.text.line( screen, "Waveform" )
                  write.full.string( screen, "         None, sIne or sQuare ? " )
                  read.echo.char( keyboard, screen, option.int )
                  airgap.waveform := BYTE (option.int /\ #DF)
              'V'
                SEQ
                  write.text.line( screen, "Levitating" )
                  Levitate( keyboard, screen,
                          ADC.in, ADC.out, DAC.in, DAC.out,
                          integral.time, stiffness, damping, massness,
                          sampling.period, est.cutoff.Hz, track.cutoff.Hz,
                          mass, operating.airgap,
                          airgap.frequency, airgap.amplitude, logging.period,
                          airgap.waveform )
              'Q'
                finished := TRUE
              ELSE
                beep( screen )
:
```

```
--------------------------------------------------------------------------------

PROC Kernel( CHAN OF INT  keyboard,
             CHAN OF ANY  screen,
             CHAN OF INT16  ADC.in, ADC.out, DAC.in, DAC.out )

  -- Kernel is the control system kernel process.

  --  Ride characteristics  --
  REAL32  integral.time, stiffness, damping, massness :
  REAL32  sampling.period, accel.cutoff.Hz, track.cutoff.Hz :
  REAL32  mass, operating.airgap :
  REAL32  airgap.frequency, airgap.amplitude, logging.period :
  BYTE  airgap.waveform :

  SEQ
    WHILE TRUE
      SEQ
        Set.default.parameters( integral.time, stiffness, damping, massness,
            sampling.period, accel.cutoff.Hz, track.cutoff.Hz,
            mass, operating.airgap,
            airgap.frequency, airgap.amplitude, logging.period,
            airgap.waveform )

        Menu( keyboard, screen,
            ADC.in, ADC.out, DAC.in, DAC.out,
            integral.time, stiffness, damping, massness,
            sampling.period, accel.cutoff.Hz, track.cutoff.Hz,
            mass, operating.airgap,
            airgap.frequency, airgap.amplitude, logging.period,
            airgap.waveform )
:


--------------------------------------------------------------------------------
-- Procedure code for Maglev.Controller()

SEQ
  Kernel( keyboard, screen,
          ADC.in, ADC.out,
          DAC.in, DAC.out )
:
```

```
--------------------------------------------------------------------------------
VAL event IS 8 :

PROC ADC.driver( CHAN OF INT16 in, out )

  INT16  channel, volts :
  INT  adc, mux, value :
  BOOL  done :
  CHAN OF BOOL  ready :

  PLACE  ready AT  event :
  PLACE  adc AT  #6000 :
  PLACE  mux AT  #6100 :

  -- The ADC outputs the last conversion result and starts a new
  -- conversion each time it is read.  It then generates an interrupt
  -- upon the end of each conversion which is notified by 'ready'.

  SEQ
    value := adc  -- start conversions & interrupts rolling
    WHILE TRUE
      SEQ
        in ? channel  -- wait for adc channel request

        mux := INT channel  -- select required channel
        ready ? done
        value := adc  -- start conversion
        ready ? done
        value := adc  -- read adc result

        out ! INT16 (value /\ #FFF0)  -- output adc result

:



--------------------------------------------------------------------------------

PROC DAC.driver( CHAN OF INT16  in, out )

  INT16  current :
  BOOL  kill.power :
  INT  dac1, switch, disable :

  PLACE  switch  AT #6000 :
  PLACE  dac1  AT #6100 :
  PLACE  disable  AT #6700 :

  SEQ
    WHILE TRUE
      SEQ
        in ? current  -- wait for DAC output request

        kill.power := (switch /\ 1) = 1  -- check front panel switch

        IF
          kill.power
            dac1 := 0
          ((INT current) < #1000)
            dac1 := (INT current)
          TRUE
            dac1 := #0FFF

        disable := 0  -- reset watchdog timer

:
```

```
--------------------------------------------------------------------------------
-- Process and channel Configuration

-- Transputer link addresses --
VAL link0out IS 0 :
VAL link1out IS 1 :
VAL link2out IS 2 :
VAL link3out IS 3 :
VAL link0in IS 4 :
VAL link1in IS 5 :
VAL link2in IS 6 :
VAL link3in IS 7 :

--  Define inter-processor links --
CHAN OF INT  host.to.controller :
CHAN OF ANY  controller.to.host :

CHAN OF INT16 controller.to.DAC, controller.to.ADC :
CHAN OF INT16 ADC.to.controller, DAC.to.controller :


--  Configure process allocation and links --
PLACED PAR

  PROCESSOR  1  T8  --  Controller
    PLACE controller.to.host AT link0out :
    PLACE host.to.controller AT link0in :

    PLACE controller.to.ADC AT link1out :
    PLACE ADC.to.controller AT link1in :

    PLACE controller.to.DAC AT link2out :
    PLACE DAC.to.controller AT link2in :

    Maglev.Controller( host.to.controller, controller.to.host,
                       ADC.to.controller, controller.to.ADC,
                       DAC.to.controller, controller.to.DAC )


  PROCESSOR  2  T2  --  ADC
    PLACE ADC.to.controller AT link2out :
    PLACE controller.to.ADC AT link2in :

    ADC.driver( controller.to.ADC, ADC.to.controller )


  PROCESSOR  3  T2  --  DAC
    PLACE DAC.to.controller AT link1out :
    PLACE controller.to.DAC AT link1in :

    DAC.driver( controller.to.DAC, DAC.to.controller )
```

E.4 Single electromagnet real-time simulator

```
--------------------------------------------------------------------------------

REAL64 FUNCTION  Magnet.Force( VAL REAL64 airgap, current )

  VAL num.current.points IS 8 :
  VAL [num.current.points] REAL64 current.point IS
      [   2.0 (REAL64),  3.0 (REAL64), 4.0 (REAL64), 5.0 (REAL64),
          6.0 (REAL64),  7.0 (REAL64), 8.0 (REAL64), 9.0 (REAL64) ] :

  VAL num.airgap.points IS 4 :
  VAL [num.airgap.points] REAL64 airgap.point IS
      [ 0.002 (REAL64), 0.003 (REAL64), 0.004 (REAL64), 0.005 (REAL64) ] :

  VAL [num.airgap.points][num.current.points] REAL64 force.table IS
      [[24.0 (REAL64),  75.0 (REAL64),  140.0 (REAL64),  212.0 (REAL64),
           300.0 (REAL64),  405.0 (REAL64),  540.0 (REAL64), 690.0 (REAL64)],
       [12.0 (REAL64),  46.0 (REAL64),  85.0 (REAL64),  132.5 (REAL64),
           185.0 (REAL64),  257.0 (REAL64),  357.5 (REAL64), 485.0 (REAL64)],
       [ 8.0 (REAL64),  20.0 (REAL64),  38.5 (REAL64),   69.0 (REAL64),
           108.0 (REAL64),  156.0 (REAL64),  212.5 (REAL64), 277.5 (REAL64)],
       [ 6.0 (REAL64),  12.5 (REAL64),  23.5 (REAL64),  42.0 (REAL64),
           63.0 (REAL64),   93.0 (REAL64),  125.0 (REAL64), 170.0 (REAL64)]]:


  INT current.index, airgap.index :
  REAL64 extra.current.ratio, extra.airgap.ratio :
  REAL64  corner.current, delta.current :
  REAL64  corner.airgap, delta.airgap :

  REAL64  F.Amin.Imin, F.Amax.Imin, F.Amin.Imax, F.Amax.Imax :
  REAL64  F.Amin, F.Amax, F :

  VALOF
    SEQ
      --  Find current index and delta

      current.index := 0
      SEQ each.current = 0 FOR num.current.points - 1
        IF
          (current >= current.point[ each.current ])
            current.index := each.current
          TRUE
            SKIP
      corner.current := current.point[ current.index ]
      delta.current := (current.point[ current.index + 1] - corner.current)
      extra.current.ratio := (current - corner.current) / delta.current

      --  Find airgap index and delta

      airgap.index := 0
      SEQ each.airgap = 0 FOR num.airgap.points - 1
        IF
          (airgap >= airgap.point[ each.airgap ])
            airgap.index := each.airgap
          TRUE
            SKIP
      corner.airgap := airgap.point[ airgap.index ]
      delta.airgap:= (airgap.point[ airgap.index + 1 ] - corner.airgap)
      extra.airgap.ratio := (airgap - corner.airgap) / delta.airgap

      F.Amin.Imin := force.table[ airgap.index ][ current.index ]
      F.Amin.Imax := force.table[ airgap.index ][ current.index + 1 ]
      F.Amax.Imin := force.table[ airgap.index + 1 ][ current.index ]
      F.Amax.Imax := force.table[ airgap.index + 1 ][ current.index + 1 ]

      F.Amin :=F.Amin.Imin+((F.Amin.Imax-F.Amin.Imin)*extra.current.ratio)
      F.Amax :=F.Amax.Imin+((F.Amax.Imax-F.Amax.Imin)*extra.current.ratio)

      F := F.Amin + ( (F.Amax - F.Amin) * extra.airgap.ratio)
    RESULT F
:
```

```
--------------------------------------------------------------------------------

PROC  Simulate.outside.world( CHAN OF INT16  ADC.in, ADC.out,
                                             DAC.in, DAC.out,
                        CHAN OF control.p  trigger,
                           CHAN OF data.p  current,
          [num.airgap.chans] CHAN OF data.p  airgap.chan,
             [num.acc.chans] CHAN OF data.p  acc.chan,
           [num.ext.ref.chans] CHAN OF data.p  ext.ref.chan,
                        CHAN OF control.p  cycle.finished,
                      CHAN OF exception.p  exception,
                               VAL REAL32  sampling.period )

  --  Worldy constants  --
  VAL gravitational.acc IS 9.81 (REAL64) :

  --  Load characteristics --
  VAL mass IS 11.0 (REAL64):

  --  Magnet characteristics  --
  VAL L.magnet IS 0.011 (REAL64) :
  VAL R.magnet IS 0.79 (REAL64) :
  VAL F.min IS 1.0 (REAL64) :
  VAL F.max IS 600.0 (REAL64) :

  --  Current amplifier characteristics --
  VAL k.I.err IS 33.0 (REAL64) :
  VAL V.min IS -1.0 (REAL64) :
  VAL V.max IS 24.0 (REAL64) :
  VAL I.min IS  0.0 (REAL64) :
  VAL I.max IS 15.0 (REAL64) :

  --  Disturbance characteristics --
  VAL airgap.min IS 0.002 (REAL64) :
  VAL airgap.max IS 0.006 (REAL64) :
  VAL airgap.start IS airgap.max :

  --  Feedback sensors time constants and quantization --
  VAL T.airgap.transducer IS 0.0005 (REAL64) :
  VAL quanta.airgap IS 0.000005 (REAL64) :

  VAL w.accel IS 234.4 (REAL64) :
  VAL Z.accel IS 0.55 (REAL64) :
  VAL quanta.accel IS 0.0005 (REAL64) :

  VAL quanta.I IS 0.01 (REAL64):

  --  Simulation calculations --
  REAL64 simulation.calculation.interval :
  VAL num.steps IS 5 :

  --  State variables (and others) --
  BOOL  final.trigger, final.current, start.converting :
  REAL64  acceleration, accel.transducer, accel.tmp :
  REAL64  velocity :
  REAL64  airgap, airgap.transducer :
  REAL64  I.demand, V.magnet, I.magnet, F.magnet :
  REAL32  I.demand.real32, airgap.FB, accel.FB :

  VAL kilo IS 1000.0 (REAL32) :
  VAL  ext.ref.sensor.mm IS 3 :
  REAL32  ext.gap.ref.mm, ext.gap.ref :
  BOOL  ext.gap.ref.aborted :


  --------------------------------------------------------------------------

  PROC  Integrate( REAL64 y,
                   VAL REAL64 x )
    SEQ
      y := y + (x * simulation.calculation.interval)
  :
```

```
PROC  Real.pole( REAL64 y,
             VAL REAL64 x, time.constant )

  --  G(s) = 1/(1+sT)  --

  REAL64 t :
  SEQ
    t := (x-y) / time.constant
    Integrate( y, t )
:


PROC  Complex.pole( REAL64 y, y.dot,
                VAL REAL64 x, p, q )

  --  G(s) = 1/(p.s^2 + q.s + 1)  --

  REAL64 t :
  SEQ
    t := ((x-y) - (q*y.dot)) / p
    Integrate( y.dot, t )
    Integrate( y, y.dot )
:


PROC  Double.integrate( REAL64 x, x.dot, x.dot.dot,
                    VAL REAL64 lower.limit, upper.limit )

  SEQ
    Integrate( x.dot, x.dot.dot )
    Integrate( x, x.dot )
    IF
      (x < lower.limit)
        SEQ
          x := lower.limit
          x.dot := 0.0 (REAL64)
          x.dot.dot := 0.0 (REAL64)
      (x > upper.limit)
        SEQ
          x := upper.limit
          x.dot := 0.0 (REAL64)
          x.dot.dot := 0.0 (REAL64)
      TRUE
        SKIP
:


--------------------------------------------------------------------------------

REAL64 FUNCTION  Bound( VAL REAL64 x, lower.limit, upper.limit )


  REAL64  x.bounded:

  VALOF
    IF
      (x < lower.limit)
        x.bounded := lower.limit
      (x > upper.limit)
        x.bounded := upper.limit
      TRUE
        x.bounded := x
    RESULT  x.bounded
:


--------------------------------------------------------------------------------

REAL64 FUNCTION  Quantize( VAL REAL64 x, quanta )

  INT32 i:

  VALOF
    i := INT32 ROUND (x / quanta)
    RESULT  (REAL64 ROUND i) * quanta
:
```

```
SEQ
  --  Initialise state variables  --
  I.magnet := 0.0 (REAL64)

  airgap := airgap.start
  velocity := 0.0 (REAL64)
  acceleration := 0.0 (REAL64)

  accel.tmp := 0.0 (REAL64)
  accel.transducer := 0.0 (REAL64)
  airgap.transducer := airgap.start

  airgap.FB := REAL32 ROUND airgap.start
  accel.FB := 0.0 (REAL32)

  simulation.calculation.interval :=
              (REAL64 ROUND sampling.period) / (REAL64 ROUND num.steps)


  final.current := FALSE
  WHILE NOT final.current
    ALT
      --  Feedback signals wanted ? --
      trigger ? final.trigger; start.converting
        PAR
          SEQ  --  Read in external airgap reference  --
            Read.ADC( ADC.in, ADC.out,
                     ext.ref.sensor.mm, ext.gap.ref.mm, ext.gap.ref.aborted)
            ext.gap.ref := (ext.gap.ref.mm / kilo)
            PAR i = 0 FOR num.ext.ref.chans
              ext.ref.chan[i] ! final.trigger; ext.gap.ref
            Write.DAC( DAC.in, DAC.out, -(airgap.FB * kilo))

          PAR i = 0 FOR num.airgap.chans
            airgap.chan[i] ! final.trigger; airgap.FB
          PAR i = 0 FOR num.acc.chans
            acc.chan[i] ! final.trigger; accel.FB

      --  Magnet current demand available ? --
      current ? final.current; I.demand.real32
        SEQ
          I.demand := Bound( REAL64 ROUND I.demand.real32, I.min, I.max )
          I.demand := Quantize( I.demand, quanta.I )

          -- Simulate magnet acceleration and airgap --
          SEQ each.step = 1 FOR num.steps
            SEQ
              V.magnet := Bound( k.I.err*(I.demand-I.magnet), V.min, V.max)

              Real.pole( I.magnet, V.magnet/R.magnet, L.magnet/R.magnet )

              F.magnet := Bound(Magnet.Force(airgap,I.magnet), F.min, F.max)

              acceleration := gravitational.acc - (F.magnet / mass)

              Double.integrate( airgap, velocity, acceleration,
                                airgap.min, airgap.max )
              Complex.pole( accel.transducer, accel.tmp, acceleration,
                            1.0(REAL64)/(w.accel*w.accel),
                            2.0(REAL64)*(Z.accel/w.accel)  )
              Real.pole( airgap.transducer, airgap, T.airgap.transducer )

          accel.FB := REAL32 ROUND Quantize(accel.transducer, quanta.accel)
          airgap.FB := REAL32 ROUND Quantize(airgap.transducer, quanta.airgap)

          cycle.finished ! final.current; TRUE

  Write.DAC( DAC.in, DAC.out, 0.0 (REAL32) )
:
```

E.5 Transputer network monitor

```
--------------------------------------------------------------------------------
Network Monitor

Features: - Transfers TDS keyboard and screen across to root transputer
          - Communication may be finished at any time using control-A

Author: Neil McLagan
Version: 1.0
Last modified: 21-12-88
--------------------------------------------------------------------------------

VAL link0out IS 0 :
VAL link1out IS 1 :
VAL link2out IS 2 :
VAL link3out IS 3 :
VAL link0in IS 4 :
VAL link1in IS 5 :
VAL link2in IS 6 :
VAL link3in IS 7 :

[1] CHAN OF ANY from.app :
CHAN OF ANY to.app :
PLACE from.app AT link2in :
PLACE to.app AT link2out :

#USE  userio
#USE  reinit
#USE  interf

PROC Monitor([1] CHAN OF ANY from.app,
             CHAN OF ANY to.screen, to.app,
             CHAN OF INT from.keyboard,
             CHAN OF ANY from.kernel, to.kernel )

  VAL k.get.abort.state IS 15 :
  VAL abort.polling.interval IS 15 :  -- 1 ms

  INT key.to.app, dummy, time, state :
  BOOL aborted, going :
  CHAN OF INT kill, stop :
  TIMER clock :

  SEQ
    newline( to.screen )
    write.text.line( to.screen, "####################################" )
    write.text.line( to.screen, "## Use control-A to return to TDS ##" )
    write.text.line( to.screen, "####################################" )
    newline( to.screen )

    aborted := FALSE
    going := TRUE
    PRI PAR
      PAR
        WHILE going
          SEQ
            clock ? time
            clock ? AFTER (time PLUS abort.polling.interval)
            to.kernel ! k.get.abort.state
            from.kernel ? state
            going := (state = 0)
            IF
              going
                SKIP
              TRUE
                PAR
                  stop ! 1
                  kill ! 1
        WHILE NOT aborted
          ALT
            from.keyboard ? key.to.app
              [4] BYTE key.to.app.table RETYPES key.to.app :
              OutputOrFail.c( to.app, key.to.app.table, kill, aborted )
            kill ? dummy
              aborted := TRUE
      scrstream.multiplexor( from.app, to.screen, stop )
:
SEQ
  Monitor( from.app, screen, to.app, keyboard, from.kernel, to.kernel )
```

E.6 Transputer network data logger

```
--------------------------------------------------------------------------------

Network Logger

Features: - Transfers data from root transputer to DOS file

Author: Neil McLagan
Version: 1.0
Last modified: 26-12-88

--------------------------------------------------------------------------------

VAL link0out IS 0 :
VAL link1out IS 1 :
VAL link2out IS 2 :
VAL link3out IS 3 :
VAL link0in IS 4 :
VAL link1in IS 5 :
VAL link2in IS 6 :
VAL link3in IS 7 :

[1] CHAN OF ANY from.app :
CHAN OF ANY to.app :

PLACE from.app AT link2in :
PLACE to.app AT link2out :

#USE  userio
#USE  interf
#USE  krnlhdr

PROC Logger([1] CHAN OF  ANY from.app,
            CHAN OF ANY  to.screen, to.app,
            CHAN OF INT  from.keyboard,
            CHAN OF ANY  from.filer, to.filer )

  VAL [] BYTE  path.name IS "D:\Neil\spreads\" :
  [abs.id.size] BYTE  file.name :
  INT  name.len, result, anychar :

  CHAN OF ANY  buffer.chan :
  [30000] BYTE  buffer :

  SEQ
    newline( to.screen )
    write.text.line( to.screen, "Network Data Logger" )
    write.text.line( to.screen, "====================" )
    newline( to.screen )
    newline( to.screen )

    write.full.string( to.screen, "Enter data file name: " )
    read.echo.text.line( from.keyboard, to.screen, name.len, file.name, anychar)
    name.len := name.len - 1

    newline( to.screen )
    write.text.line( to.screen, "Getting data from root transputer ..." )
    newline( to.screen )

    PAR
      to.app ! INT 'B'
      SEQ
        scrstream.sink( from.app[0] )
        scrstream.sink( from.app[0] )
    scrstream.sink( from.app[0] )
    scrstream.to.array( from.app[0], buffer )

    PAR
      to.app ! INT 'B'
      scrstream.sink( from.app[0] )

    write.text.line( to.screen, "Writing data file to DOS ..." )
    newline( to.screen )

    PAR
      SEQ
        scrstream.from.array( buffer, buffer.chan )
        write.endstream( buffer.chan )
```

```
      scrstream.to.server( buffer.chan, from.filer, to.filer,
                           name.len, file.name, result )

    IF
      (result = 0)
        write.full.string( to.screen, "File transfer successful, file: " )
      TRUE
        write.text.line( to.screen, "File transfer failed, file:" )

    write.len.string( to.screen, name.len, file.name )
    newline( to.screen )
    newline( to.screen )

    write.full.string( to.screen, "Hit space to finish.")

    read.char( from.keyboard, anychar )

:

SEQ
  Logger( from.app, screen, to.app, keyboard, from.filer, to.filer )
```

Appendix F

Operating instructions

F.1 Introduction

The control system software runs entirely on the processors in the control system sub-rack units, and having loaded and run the software from the development system PC, the PC itself can be disconnected or switched off. There are no ROMs in the system at present, so the control system program must be loaded from the PC each time the control system is powered up. The actions required to power up the system and connect the PC to the control system racks are listed in Table F.1. Table F.2 lists the actions required to load and run the controller software.

F.2 Single magnet controller data monitoring

While the controller is running, data is monitored and sent to the PC. Type the relevant variable index letter to toggle the variable display on and off. The monitored variables include <R>eference, air<G>ap, <V>elocity, <A>cceleration, <F>orce and <I>-current. Typing <T> toggles between the moving bar display and simple tabular output and <Q> causes a controlled shutdown and return to the menu.

When data is scrolling down the screen, breaking off to go to the development system using <Control A> will not always register due to the higher priority of the screen server. If this occurs, type <P> which causes the controller output to pause briefly, thus allowing the <Control A> to be registered.

Table F.1 Mains power and fibre optic signal connections

1) Switch on the mains power to the development system PC.

2) Switch on the mains power to the power supply unit (output set to 5 V) feeding the PC's optical fibre interface unit.

3) Switch on the power to the vehicle OR switch on the power to the single magnet controller sub-rack & its associated high power supply.

4) Using a duplex fibre optic cable, connect the reset-out and error-in signals (top and next connectors respectively) on the PC optical interface unit to the reset-in and error-out signals (top and next connectors respectively) on the rack input interface card in the control system sub-rack.

5) Using another duplex fibre optic cable, connect the data-out and data-in signals (bottom and next connectors respectively) on the PC optical interface unit to the data-in and data-out signals (bottom and next connectors respectively) on the rack input interface card in the control system sub-rack.

6) If debugging facilities are required, also connect the analyse signal using a simplex fibre optic cable.

7) If using the vehicle, check that the rack output interface is suitably connected (ie in a similar fashion to the PC to sub-rack connections) to the DAC card in the sub-rack unit with the power controllers.

F.3 Single magnet controller data logging

Logging of data to a DOS based disc file is achieved by the following:

- select tabular output;
- select the variables to be monitored;
- break out to the transputer development system;
- load the Network Logger EXE <F5> and run it <F6>.

The network logger waits for a few cycles of reference signal in order to clear any buffer queues and then files the selected data for one cycle of reference signal. If the size of the logged data exceeds 32 Kbyte, the Network Logger program will crash (a limitation of an unavoidable system procedure call). Adjust either the number of selected data signals, the output data rate (in the Data.Monitor() process code) or the reference signal frequency. To re-run the Network Monitor or Network Logger at any

Table F.2 Loading and running the controller software

1) Set your working directory to D:\Maglev and start the transputer development system <TDS2>.

2) Toggle the number lock to clear it if necessary and enter <Home> the Maglev system fold.

3) Autoload <Shift F5> the compiler utilities and debugger.

4) Move the cursor to the fold containing the Single Magnet Suspension Controller or the Vehicle Suspension Controller and enter <Home> the fold.

5) Move the cursor to the Network Monitor EXE fold and load <F5> the EXE.

6) Next, move the cursor to the PROGRAM fold and load <ALT 4> the program. If the green reset LED on the PC optical interface doesn't flash during a load, check that the interface unit is powered up. If the reset LEDs on the control system sub-rack cards don't flash during a load, the problem probably lies with the reset+error fibre optic connection. If the LEDs flash but the program doesn't load, the data fibre optic connection is probably wrong.

7) Now run <F6> the loaded Network Monitor EXE to gain access to the controller program.

8) Hit <Enter> and the control system menu should now appear on the screen. You can change the controller parameters or reset them to their default values using various submenus. The system does not prevent parameters being entered which make it unstable. All numbers must be entered with a decimal point and following digit. Failure to do so will crash the system - requiring you to return to the development system <Control A> and go back to step 5.

9) Return to the transputer development system by typing <Control A>.

10) Return to the top level fold by closing the current fold <Page Up> and exit the transputer development system by quitting <Control End>.

stage, sequence through the alternative EXEs <ALT F5> until the right one is found and run it <F6>.

F.4 Vehicle controller data monitoring

While the controller is running, data can be monitored and sent to the PC. Use the 'Signal Monitor Parameters' menu to set the data monitoring sample time and duration and to initiate a data log. Typing the relevant variable index letter toggles the variable display on and off. The monitored variables include <R>eference, air<G>ap, <V>elocity, <A>cceleration, track <P>osition, <F>orce and <I>-current. Upper case letters give electromagnet signals whilst lower case letters give the vehicle mode signals where appropriate.

When data is scrolling down the screen, breaking off to go to the development system using <Control A> will not always register due to the higher priority of the screen server. If this occurs, type <W> which causes the controller output to pause briefly, thus allowing the <Control A> to be registered.

The following keys have special functions:

<B> toggles between the moving bar display and simple tabular output.
<Q> returns to the main menu.
<L> logs data signals into a buffer.
<S> toggles screen output between real-time data and logged data.
<W> waits a few seconds to enable exit to the development system.

F.5 Vehicle controller data logging

Logging of data to a DOS based disc file is achieved by the following:

- select tabular output;
- select the variables to be monitored;
- break out to the transputer development system;
- load the Network Logger EXE <F5> and run it <F6>.

The network logger waits for the current cycle of reference signal to finish and then files the selected data for one cycle of reference signal. The maximum size of the logged data is limited only by the head processor memory size, and is currently set for 2000 samples. To re-run the Network Monitor or Network Logger at any stage, sequence through the alternative EXEs <ALT F5> until the right one is found and run it <F6>.

F.6 Guide to using the vehicle controller

Virtually any system parameters can be changed whilst the system is running. However, if you wish to change the reference signal from a track position reference to a vehicle position reference, you *MUST* first de-levitate before making the change. This is because certain filters in the mode position controllers must be re-initialised.

If the system shuts down due to an internal shutdown request, the error message in the top level menu must be cleared before the vehicle can be re-levitated. This is primarily relevant when using the vehicle switch to levitate and de-levitate the system.

There is a problem with the process scheduling which sometimes causes the screen driver to run when the higher priority control code should be running. This causes glitches which disturb the system. When logging data for monitoring purposes, use the 'Signal monitor parameters' menu to initiate a data log to avoid screen output and hence disturbances during the logging period.

The screen output very occasionally halts due to noise pickup on the PC data link. Should this occur, de-levitate the vehicle using the vehicle switch and re-load the controller program.