MRO Delay Line

Trolley Electronics Design Description

INT-406-VEN-0112

The Cambridge Delay Line Team

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Change Record

Revision	Date	Authors	Changes
0.1	2007-06-28	EBS	First draft.
0.2	2007-07-02	EBS	Referenced other documents by title.
0.3	2007-07-02	EBS	Added MF's preamp section.
0.4	2007-07-03	EBS	Incorporated additions and changes from MF and RCB.
0.5	2007-07-03	EBS	Added appendix with MF's circuit diagrams.
0.6	2007-07-06	EBS	Incorporated additions and changes from DMAW.
0.7	2007-07-06	EBS	Proofreading, minor tweaks to preamp figure.
0.8	2007-07-10	EBS	Added reference to limits document, correction by MF.
1.0	2007-07-10	EBS	Corrected digital channel info, marked document as complete.
1.1	2007-12-04	EBS	Updated power section, limit switch section. Edited electronics overview figure accordingly.
1.2	2008-01-24	EBS	Added low-latency link and tip-tilt text and circuit diagrams from RCB. Added connection circuit diagram from RCB. Added wi-fi information. Referenced other documents by document numbers where possible. Proofreading.
1.3	2008-01-29	EBS	Added RCB's breakout board circuit diagrams. Added info on limit switches.

Objective

To describe the design and implementation of the electronics, including the computer interfacing, of the delay line trolley computer.

Scope

This document forms part of the documentation for the delay line final design review. It describes the trolley electronics, including the interaction between delay line hardware and the trolley computer. For a functional description of the trolley software, please see document INT-406-VEN-0102, “Trolley Software Functional Description”.

Contents

1 Introduction

The delay line trolley contains many electronic subsystems. These include two computers and onboard actuators, motors and sensors that all cooperate to provide the required functionality. A block diagram illustrating the various subsystems and their interaction is shown in Figure 1.

The core components are a Central Processing Unit (CPU), a Programmable Multi-Axis Controller (PMAC), two analog input/output boards and a power board. They are connected via a PC104 bus that also allows them to be mechanically stacked together. Overall control of the trolley is imposed by the CPU, which communicates with the other core components via the PC104 bus and with peripherals via serial, ethernet and I^2C lines.

The two analog boards are used for measurement of the catseye drive preamplifier, focus, trolley roll, thermometers, accelerometers, limit switch status, supply voltages and some motor signals. They also output control signals to the preamplifier, secondary mirror tip/tilt and focus.

Control of the steering and drive motors is delegated to the PMAC, which receives feedback from the respective motor encoders. The PMAC also accepts inputs from limit switches to restrict drive motor behaviour when necessary.

The catseye drive preamplifier accepts a tracking distance error signal from the metrology system via an analog radio link and converts it into a voice coil drive signal which in turn moves the catseye to minimise the tracking error. A differential position sensor measures the position of the catseye with respect to the trolley, which is monitored by the CPU via an analog I/O card. If the catseye is not in the middle of its range, the CPU tells the PMAC to vary the drive motor speed such that the catseye moves towards the mid-range setting.

The CPU can adjust the preamp behaviour by setting the values of onboard digital resistors connected to its I^2C bus. It also communicates with the drive motor amplifier via a serial line and with the local network via a wireless ethernet link.

The subsystems are described in more detail in the sections below and a diagram showing the subsystem interconnections in detail (Figure 6) can be found in Appendix A.

2 The Trolley Computer

The delay line trolley CPU is a single board computer embedded in the electronics bay of the trolley. It performs many tasks:

- Receipt of commands from the workstation and streams of data from the metrology system and shear camera via a wireless ethernet link.

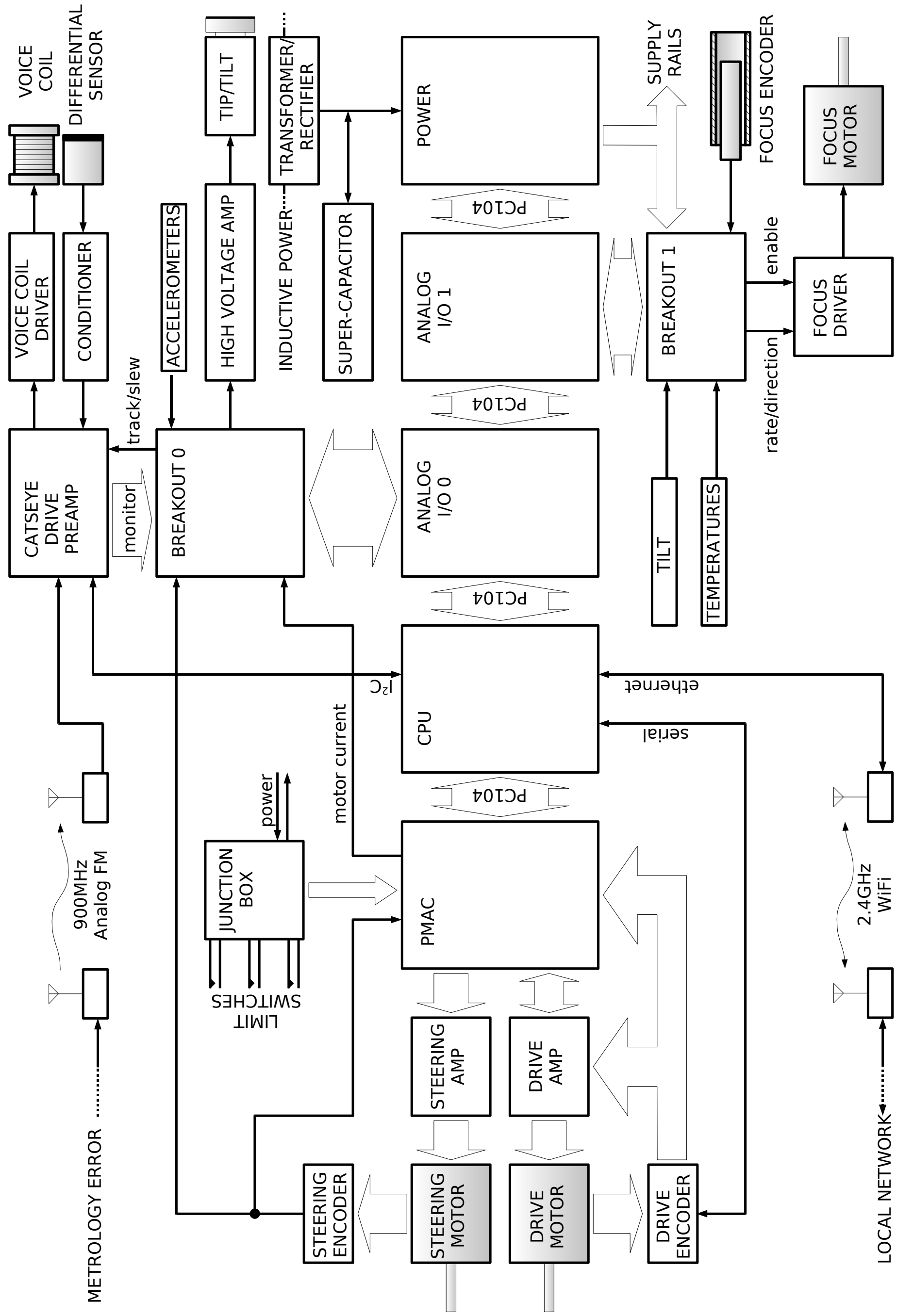

Figure 1: Overview of Trolley Electronics

- Control of actuators and motors on the trolley.
- Measurement of on-board sensors in order to close servo loops and provide real time feedback and telemetry data for the user.
- Transmission of telemetry data to the workstation for logging and user feedback via the wireless ethernet link.

The computer is a Eurotech Viper V1I6 single board computer (this will be a V2I4 in the production trolley). It features an Intel PXA255 400MHz ARM compatible processor, five serial ports, an ethernet port and an I^2C interface. The bus is PC104 compatible, allowing the computer and various peripheral boards to be stacked together into a robust, compact unit. The bus is used to communicate with the motor controller and two analog input/output cards, while power is derived from a PC104 compatible switch-mode power supply.

This computer was chosen for its low power consumption, which is vital as there is limited power and heatsinking available. The large number of serial ports was also considered attractive in the early protoyping stages of the design, although most communications functions have since been transferred to the PC104 bus. The availability of a linux development kit also proved useful.

It should be noted that the processor does not contain a floating point unit, hence all floating point calculations are handled in software. While this has been proven to suffice for the prototype trolley, changes made to the floating point load should be tested to ensure there is sufficient processor capacity to handle them.

2.1 Ethernet interface

The trolley computer is equipped with an ethernet interface which is responsible for receipt of commands from the workstation and receipt of remote data from the metrology and shear camera systems (for closure of slow servo loops that span the network). It also transmits its status and diagnostic telemetry information to the workstation for real-time user feedback and diagnostic logging. Finally, an engineer can use the interface to log in remotely to perform tasks beyond the scope of the trolley software.

The Ethernet port is connected to a commercial Ethernet-wireless bridge (a D-Link DWL-G810). The omni-directional antenna is replaced by a double quad antenna with a gain of approximately 10dB mounted on the back of the delay line trolley. A similar antenna is mounted at the end of the delay line pipe and is connected to a commercial wireless access point (a D-Link DWL-2100AP) which relays data to and from the local wired network.

Both wireless transceivers are IEEE 802.11g compliant. To prevent dropouts due to potential dead zones within the pipe, the access point is allowed to determine and (if necessary) change the optimal transceiver frequency automatically. WPA encryption is currently also used as this is a university requirement.

2.2 I^2C interface

The trolley computer's I^2C interface will be used to change the values of digital I^2C potentiometers on the catseye coil drive board, which in turn modify the board's analog servos. Hence these servos can be adjusted while the trolley is otherwise inaccessible within the delay line pipe, and test points described in Table 1 can be used to monitor the effects of these changes. This aspect of the design is not yet implemented on the prototype – the loops are currently tuned using manual trimpots.

It would have been possible to implement the servos in an almost entirely digital fashion, but the analog approach chosen has minimal latency, no digital artefacts and retains some remote adjustment flexibility.

3 The Analog Input/Output Boards

The majority of the interfacing is handled by two Diamond Systems Diamond-MM-48-AT PC104 boards. Each has 16 analog inputs, 8 analog outputs, 4 digital lines (input or output), 4 optocoupled inputs and 8 relays. They were selected for the wide variety and number of inputs and outputs offered, allowing excellent flexibility during the trolley design phase.

The CPU communicates with the boards by reading from and writing to assigned addresses in the PC104 bus memory space. DMA-style data transfer is not available.

3.1 Analog Inputs

The purpose of the analog input section is to sample on-board sensors and test-point voltages in order to close local servo loops and to transmit information to the workstation for diagnostic logging and real-time user interaction.

Each board has 16 analog inputs, each of which is sampled in turn by a single on-board 16 bit analog to digital converter. Hence the inputs are not sampled simultaneously. The time between adjacent channel samples is configureable and has been set to 5μs. This phase lag between channels is allowed for in the messaging protocol (described in the internal document "Network Message Protocols and Telemetry/Status/Commands Log File Format").

Each board has an on-board clock that can be used to run the digitiser. On board 0 this has been set to scan through all 16 channels every 200μs (5kHz), selected as the rate necessary to capture the most rapidly changing signals on the trolley (the accelerometers). The clock signal is available on an output pin and is connected to the external clock input of board 1, which is thereby slaved to sample at the same rate and time as board 0. It is the board 0 clock rather than the CPU clock or an external reference that governs the sample rate and cycle time of the trolley program. This prevents aliasing due to the clocks drifting with respect to each other, and as samples are time stamped by the system clock, time-based comparisons with other data are still possible.

There is a 2048 sample buffer on each board that temporarily stores the digitised data before it is read by the CPU. The buffering is sufficient to allow a program running within a non-real-time operating system to capture all the data.

The buffer provides interrupts to notify the CPU when it is one eighth full and half full. Unfortunately, it was discovered during development that the CPU cannot detect interrupts generated by the board because the board supports shared interrupts while the CPU does not, even though both claim to be PC104 compatible. However, flags indicating the buffer state are also available and as a workaround these are polled every 6.4ms to achieve a similar result.

The allocated inputs and net sample rates as of 23 January 2008 are listed in Table 1. Although all the inputs are sampled at 5kHz, some (such as temperature or supply rail voltage inputs) are not expected to change quickly, and are downsampled in software before conversion into “real” (floating point) quantities to reduce CPU workload and data transmission volume.

3.2 Analog Outputs

Each board is equipped with eight 12-bit digital to analog converters. No buffering or timing is used for these, they simply change value on demand and hold that setting until the next update. Three of the channels are used, all of them to control actuators in the secondary mirror cell. Two are for the orthogonal actuators for the tip-tilt mechanism that closes the shear servo loop, and the other is a rate signal for the focus actuator, which in conjunction with the focus position value in Table 1 closes the local focus loop.

The converters generate voltages of between 0 and 4.096V, so analog gain and offset stages have been used to make the signals compatible with the tip-tilt stage and the focus mechanism. For circuit diagrams of the tip-tilt and focus signal conditioning, please refer to Figures 7 and 8 respectively in Appendix A.

3.3 Digital Channels

There are also four digital channels available on each board, with selectable direction. Two channels are used on the trolley as outputs. The first is a signal that sets the

Table 1: COAST Trolley Analog Inputs

Input	Sample Rate (Hz)
Catseye coil drive current	5000
Catseye differential position	5000
Catseye differential velocity	5000
Catseye coil preamp test point 1	5000
Catseye coil preamp test point 2	5000
Motor demand current	100
Motor actual current	100
Axial catseye acceleration	5000
Vertical catseye acceleration	5000
Axial carriage acceleration	5000
Vertical carriage acceleration	5000
Timing synchronisation signal	5000
Roll angle	5000
Secondary mirror focus position	10
Uncommitted temperature sensor	10
Raw transformer voltage	100
+5V supply rail	10
+12V supply rail	10
-12V supply rail	10
Secondary cell temperature	10
Primary cell temperature	10
Front carriage temperature	10
Rear carriage temperature	10
Analog RF signal strength	10
-5V supply rail	10
Energy storage system voltage	10

mode of the catseye coil preamplifier to either “track” or “slew”: in track mode, the preamplifier tries to keep the catseye at the correct position as specified by the low-latency analog signal from the metrology system, while in slew mode the catseye flexure legs are held vertical by a local control loop around the differential position sensor to prevent excessive catseye motion while the trolley is slewing.

The second channel enables the focus drive controller. When the controller is disabled its power consumption is reduced. As focusing is rarely necessary, significant power savings can be made by enabling the controller only when it is needed.

Limit switches are not monitored via these channels. They are instead wired directly to the PMAC as control overrides (Subsection 4.2) and their status determined by interrogation of the PMAC. For further information on the limit switch implementation, please refer to document INT-406-VEN-0116, “Limits Design Description”.

The digital channels use 3.3V logic, which is buffered to 5V for compatibility with the focus drive enable input (Figure 8 in Appendix A). Any changes to digital output interfacing should be designed to detect a logic high of 2.4 to 3.3V.

3.4 Other Interfaces

The analog boards are also equipped with optocoupled inputs and relays. Relays are not used in the current design due to the inaccessable and low pressure environment of the delay line: semiconductor alternatives are available that are not susceptible to mechanical failure or low pressure arcing. The optocouplers are not used simply because there has been no need for them.

4 Trolley Control and the PMAC Motion Controller

4.1 PMAC control

The PMAC2A PC104 Motion Controller is an industry standard motion control device in PC104 format. It has four independent channels of motion control and can control most kinds of actuators, including stepper motors. Apart from encoder and flag inputs for each channel the PC104 card has two independent analogue input channels.

The PMAC card controls two of the trolley servo loops: the trolley drive and the trolley steering mechanism. Each loop is described in more detail below and is followed by a basic list of tasks that the PMAC performs in controlling these functions.

4.2 Trolley Drive

The trolley drive comprises a Maxon EC60 brushless motor with integral incremental encoder and a Maxon DES50/5 servo amplifier. The servo-amplifier closes loops with the motor Hall-effect signals and an incremental encoder to produce properly commutated motion. A schematic of the PMAC arrangement for control of the trolley drive is shown in Figure 2.

PMAC is used to control the trolley velocity and Channel 1 is allocated for this purpose. The command signal is a voltage from channel 1 to the ‘set value input’ on the Maxon servo-amplifier which is set up for torque control. This voltage controls the current to the motor and is also linked to the PC104 analogue I/O card for monitoring purposes. The output of the incremental encoder is also connected to the channel

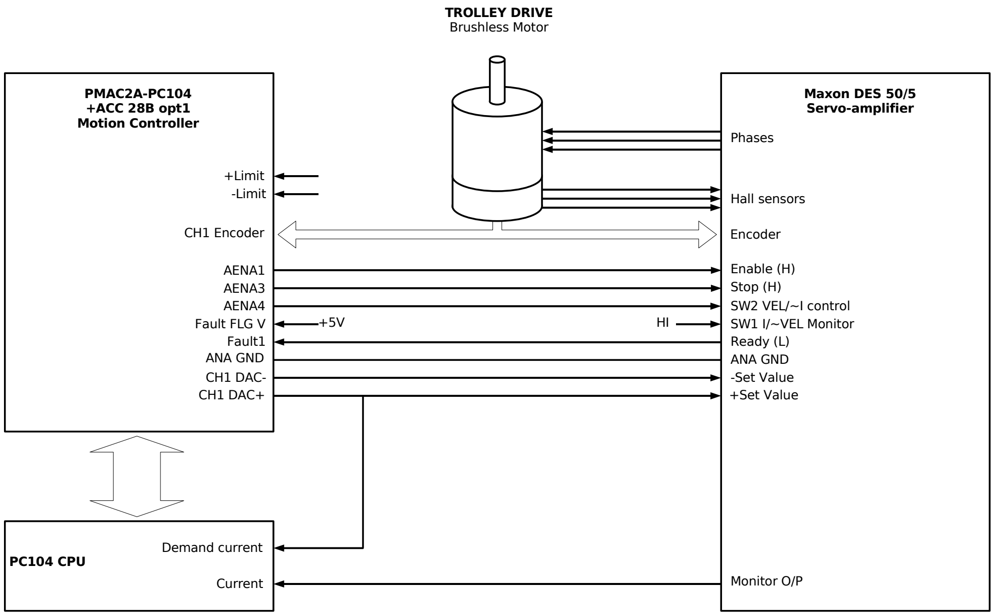

Figure 2: PMAC arrangement for control of the trolley drive.

1 encoder input of the PMAC which uses the pulses to close a position and velocity loop to control the velocity of the trolley.

To control the trolley velocity the trolley CPU issues a *"Jog Continuous"* command which is communicated to the PMAC via the PC104 bus.

PMAC is set up to utilise the amplifier enable signals as digital outputs so as to control the state of the Maxon amplifier under standby or fault conditions. Channel 1 amplifier enable AENA1 controls the enable state of the amplifier. AENA3 is used to place the amplifier in a stop mode where the motor is still powered but is instructed to maintain position. AENA4 can switch the amplifier between velocity and torque (current) mode which is useful during testing. The amplifier status or Ready signal indicates whether there is a problem with the amplifier and is connected to the FAULT status input of PMAC which will automatically remove the amplifier enable state and flag a fault. The monitor output of the amplifier is set to provide actual motor current and this is connected directly to one of the PC104 analogue input boards for status logging purposes.

Hardware limits are enabled in PMAC so that limit switches mounted on the trolley and connected to PMAC cause the drive to stop with a programmed deceleration when activated. PMAC allows the trolley to drive away from the activated limit switch. The limit switches chosen are RS Electronics 530-8898 ferromagnetic metal proximity sensors, which have normally open contacts. However, the PMAC requires limit switches to be normally closed. While a normally closed version of the RS part is available, it has reduced range, so instead open-collector inverters have been used to interface the normally open switches to the PMAC. The interface circuit is in Figure 9 in Appendix A. For further information on the limit switch implementation, please refer to document INT-406-VEN-0116, "Limits Design Description".

It is necessary to correct the demanded velocity using a signal from the cat's eye differential position sensor in order to ensure that the trolley is maintained directly beneath the cat's eye with very small deflection of the flexures. The cat's eye differential position is brought into the trolley microprocessor via the PC104 AIO board and a velocity correction is calculated and added to the next velocity command. Velocity commands are sent to the PMAC every 100 milliseconds.

The PMAC maintains a count of the pulses from the motor encoder to give motor position and this can be utilized to estimate trolley position within the pipe provided the counter is zeroed at some meaningful position such as the trolley datum position.

4.3 Trolley Steering

The trolley steering mechanism comprises a Servo Systems Inc M-2222-6.0D stepper motor, an Intelligent Motion Systems IB106 stepper motor driver and a Dewit industrial sensors QR30-360B-V-K-5V Quadro-R rotary encoder. The encoder is a one-revolution magnetic non-contact device and is arranged not to 'roll-over' throughout the steering range. The IB106 driver takes care of step sequencing and requires only step and direction information from PMAC. The large stepper motor is chosen for its detent torque and is not required to produce a very large step torque. Hence the maximum current facility of the driver is limited by an external resistor. A schematic of the steering motor drive arrangement for PMAC is shown in Figure 3.

The PMAC is used to close the local steering loop between the stepper motor and the encoder. Channel 2 PFM output is configured to drive the stepper motor drive module and one analogue input is used for encoder feedback. Amplifier enable line AENA2 is used to power up/down the stepper motor driver stage to conserve trolley power.

In normal operation the steering correction demand is provided by the inclinometer mounted on the trolley. This has an analogue output and is interfaced to an analogue input of the PC104 AIO board. There is also a requirement that the workstation should be able to provide a steering set point via the trolley microprocessor for test or recovery purposes. The steering demand is scaled (i.e. the desired rotation angle of the steered wheel in appropriate units is calculated) and passed to the PMAC via the PC104 bus. A purpose written PLC program within PMAC accepts the steering

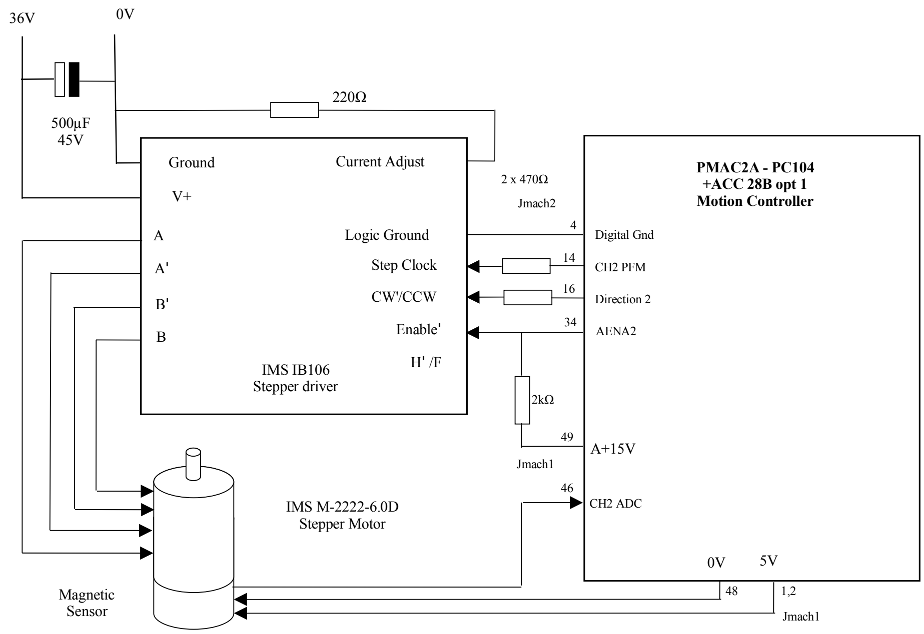

Figure 3: PMAC arrangement for control of the steering motor.

demand and closes the steering loop between motor and encoder. When no steering demand is present PMAC shuts down the stepper motor driver.

4.4 PMAC Status

A specially written PMAC PLC program responds to a status request from the trolley CPU every tenth of a second. Five variables are returned and provide the following information:

- Drive motor encoder position (effectively an odometer reading)
- Drive motor average velocity
- Drive Motor status word 1
- Drive Motor status word 2
- Steering encoder position

4.5 PMAC Tasks

The PMAC:

- Handles all the signals necessary to control the drive motor
- Handles on-board safety features such as velocity and end limits
- Handles the soft limits on encoded value from the steering sensor
- Accepts steering set point commands from the trolley microprocessor
- Closes a position loop around the steering mechanism
- Accepts immediate commands and responds with data via PC104 bus
- Provides status values on demand
- Receives program and parameter download via PC104 bus

4.6 PC104 Interface

The PMAC motion controller commands the trolley's drive and steering motors by responding to requests from the CPU and through the use of local loops. Communication with the CPU occurs via the PC104 bus using a text based protocol: characters are read from and written to a single address in the CPU's PC104 address space. Effectively the PMAC behaves like a text terminal. Hence transmission of a value across the bus involves sending the text representation of that value rather the binary equivalent.

The data written to the PMAC via the PC104 bus are the requested drive motor velocity and steering motor angle. In particular, the CPU closes a loop around the steering motor by using the value of the tilt sensor to compute a steering angle to be sent to the PMAC. The data received via the PC104 bus are the actual drive motor velocity, an approximate odometer reading, the actual steering angle and various status information.

The PC104 version of the PMAC does not use interrupts. Hence, as with the analog I/O cards, it is necessary to poll it to discover if there are characters available to read out. The PMAC is equipped with a 2048 byte buffer which reduces the required polling frequency.

5 Power

Transmission of power to the trolley is via an induction cable that runs the length of the delay line on the bottom inside surface of the pipe. This cable passes through and forms the primary of an onboard power transformer embedded in the underside of the trolley, the secondary of which supplies power that is then rectified and regulated for onboard use. This design avoids cable drag and wear and simplifies cable laying and repair.

5.1 Pickup and Rectification

Power from the induction cable is picked up by the onboard transformer which consists of a series of 73 ferrite cores[1] (Fair-rite 5978001901) threaded on to a brass tube which serves both as a mechanical support and the single-turn secondary winding. The induction cable which acts as the single-turn primary winding passes through the brass tube which supports it with very little friction.

The whole transformer is mounted in a groove in the underside of the trolley and can be removed without unthreading the induction cable to ease removal of the trolley for maintenance or adjustment.

Power from the transformer is rectified and smoothed before being distributed and regulated for use. The unregulated supply may vary between 30 and 45 volts because of the series impedance of the cable.

The system runs at 20 to 25 Khz. which is a trade-off between increasing impedance of the induction cable at higher frequencies and larger size of transformer necessary at lower ones.

A channel on an analog I/O board is used to monitor the rectified voltage to assist with diagnosing faults.

5.2 Storage

Present measurements of the quiescent or tracking (slow moving) power required by the trolley systems are about 30 W. The power requirements for accelerating, climbing over unevenness in the vacuum pipe, and slewing are being investigated as part of the trolley test program.

The inductive system will be able to supply 50 W continuously, or more if a small voltage drop is allowed. A seven Farad super-capacitor is used to provide additional current sourcing and sinking during acceleration and deceleration,

[1]The minimum requirement is 60 cores, but there is some dimensional variation between batches so the tube is made longer than necessary and then fully loaded with cores.

5.3 Regulation

A commercial PC104 power board (HE104-HV-16) is used to regulate the raw input power. This is a board designed for automotive use and can handle input voltages up to 48V. The outputs are ±5V and ±12V, which are used to power all trolley devices except the drive amplifier differential position sensor and voice coil. These voltages are available on screw terminals as well as on the PC104 bus, where they power all devices in the PC104 stack.

The drive amplifier, differential position sensor and voice coil use a separate 24V regulator (Subsection 8.3).

6 Shear Control (Secondary Tip/tilt)

The secondary mirror can be tilted in two orthogonal axes by a low voltage piezoelectric actuator. This actuator is used in conjunction with the shear camera to close the shear loop but it can also explicitly be commanded to go to a fixed (usually central) position.

6.1 Signal Conditioning

The two tip-tilt signals are generated by the CPU in response to a pair of shear camera signals that arrive via the wireless ethernet link. The CPU programs two D/A converters on an analog I/O board accordingly, which generate a pair of voltages, each between 0 and 4V. Each tip-tilt mirror axis uses two piezos in opposition, so each D/A signal is passed via a unity gain inverting amplifier to give a second output in antiphase. The resulting four signals drive four programmable high voltage power supply modules (EMCO CA02P-5) to generate 0 to 150V outputs to move the piezos of the tip-tilt actuators. In addition the input can be switched to manual control via a pair of potentiometers for testing and fault location.

A circuit diagram of the signal conditioner (Figure 7) can be found in Appendix A.

6.2 Actuator

The tip-tilt actuator is a commercial Piezosystem Jena PSH-10, which can tilt ±5mrad in two orthogonal axes in response to the two pairs of input voltages. No strain gauge is present, nor is one necessary, as any piezoelectric hysteresis is automatically compensated for by the shear servo. This also minimises the size, weight and power consumption of the secondary mirror cell and its associated electronics.

7 Focus

The focus mechanism is used to translate the secondary mirror along the trolley axis, thereby compensating for expected tolerances in the primary mirror focal length during initial assembly and for thermal variations in the catseye length during a night's observing.

The mechanism consists of a New Focus picomotor to move the secondary mirror and a Linear Variable Differential Transformer (LVDT) to sense its position. They are assembled in a custom mount that also contains the tip-tilt actuator and secondary mirror.

7.1 Encoder

The encoder is an RDPE Group D6/05000U LVDT. This encoder is a transformer coil that senses how far a ferrite rod is placed into its core. The sensing is contactless, has resolution limited only by the noise of the driving amplifier and the range is 10mm. However, like all LVDTs it has a null point within its range best avoided for precise measurements. There is sufficient mechanical adjustment available to move this null away from the focus position should the two overlap.

An RDPE group S7AC industrial signal conditioner provides drive signals to the LVDT and amplifies the output to a level suitable for digitisation by an analog I/O board. The CPU can then drive the picomotor until the secondary mirror is at the requested LVDT position.

7.2 Actuator and driver

The actuator is a New Focus 8301 picomotor, a piezoelectric motor that uses a friction drive to directly turn a fine pitch positioning screw that in turn pushes the secondary focus mechanism. It was chosen for its small size, light weight, stiffness and ability to hold position when unpowered.

The picomotor is driven by a New Focus 8703 driver, which sets the picomotor speed and direction according to the sign and magnitude of an analog input voltage. This voltage is set by an analog output on an analog I/O board under CPU control.

The analog I/O board is limited to an output range of 0 to 4V, so this is level shifted and amplified to a range of $\pm$4V for the 8703. This gives the focus a maximum velocity of about 10μm/s that is deliberately limited in hardware for safety and power consumption reasons.

The 8703 also accepts an enable signal, which is provided by a buffered digital output from an analog I/O board under CPU control. When enabled the 8703 draws significant power (up to 5W) so the CPU only enables it on the rare occasions when the focus needs to be changed.

The level shifting and digital buffering circuits are illustrated in Figure 8) in Appendix A.

8 Cat's Eye Voice Coil Preamplifier and Driver

8.1 Voice Coil Preamplifier

Control of the Cat's Eye depends on whether the trolley is in track mode or slew mode. When the trolley is in track mode the position of the cat's eye is controlled by the metrology error signal while the trolley is positioned so as to keep the flexure legs vertical. In this mode the 'metrology loop' is said to be closed. When the trolley is in slew mode the cat's eye position is maintained vertical relative to the trolley by a local sensor which measures the differential position between the cat's eye and the trolley. In this mode the 'local loop' is said to be closed.

The chief purpose of the voice coil preamplifier is to apply suitable servo loop gain and phase compensation to achieve appropriate operating performance according to the mode in which the trolley is operating. There are other loop modifying functions and also some protective features that ensure the cat's eye is controlled sensibly during saturation of the metrology error signal or loss of differential sensor signal. A functional block diagram of the voice coil preamplifier/driver is shown in Figure 4 for reference in the following descriptions.

8.1.1 Low Latency Link

To maintain a high servo bandwidth for the cat's eye the delay between measuring the position with the metrology system, and applying a correction must be kept to a minimum. Various methods were considered but of the commercially available units tested this one met the requirements.

The transmitter is an Applied Wireless T900AU and operates at 922MHz in an unlicensed US wireless band with a frequency response from DC to 20KHz. By good fortune at this frequency the 16 inch delay line pipe acts as a circular waveguide giving low loss and, with a matched aerial, minimal standing wave effects. The single ended output from the metrology system DAC is converted to a differential output with a single IC (Analog Devices SSM2142) intended for audio applications over long distances and transmitted via standard microphone cable 200m to the transmitter. Here it is converted back to a single ended signal, again in a single IC (Analog Devices SSM2143), attenuated and level shifted to modulate the transmitter.

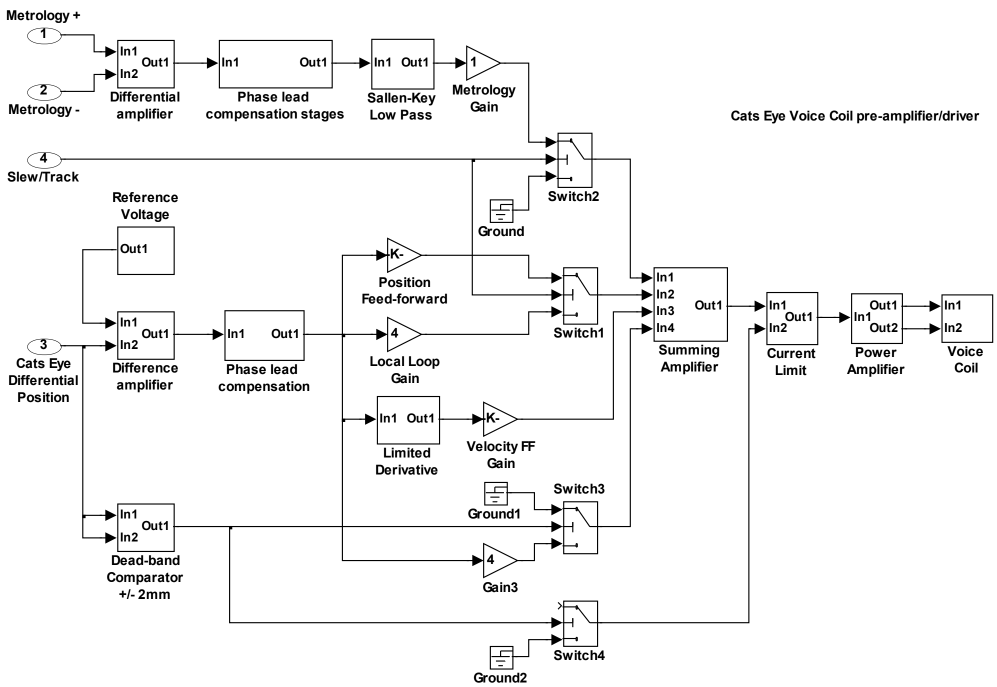

Figure 4: Voice coil preamplifier/driver functional block diagram.

A matching quarter wave stub aerial is mounted in the centre of the rear plate of the trolley.

The receiver on the trolley is the matching device from Applied Wireless (R900AU) and the 1V peak-peak output signal is amplified and level shifted to provide approximately ±5V drive for the cat's eye drive preamplifier. Both the signal and an auxiliary RSSI (radio signal strength indicator) output are digitised and fed to the trolley computer for transmission as telemetry diagnostics.

A circuit diagram of the low latency link transmitter and receiver (Figure 11) can be found in Appendix A.

8.1.2 General arrangement

The metrology error signal received from the VME system via the RF link is buffered by a differential receiver and then applied to two stages of phase lead which can provide sufficient gain and phase margin for a loop bandwidth of up to approximately 200 Hz. (The actual bandwidth achievable is dependent on the first axial resonant frequency of the cat's eye and also on the total latency of the metrology loop but is expected to lie between 100Hz and 200 Hz). A further loop shaping filter is provided by a low pass filter stage with a cut-off frequency of 5 KHz. The compensated metrology signal is passed through an analogue switch to a summing amplifier where other circuit functions are incorporated, depending on the state of the system.

The differential position sensor signal is generated by a "micro-Epsilon" eddy current sensor which is attached to the trolley bulkhead plate (on which the voice coil is mounted) and senses the position between the bulkhead and the cat's eye. The sensor provides a voltage centred on approximately 5V with a scale of 0.67V/mm. The differential signal, centred on approximately 5V, is compared with two voltages representing deflections of the cat's eye by +2mm and -2mm from the centre position. If either of these limits is exceeded the dead-band comparator operates and the logical signal generated is used to control two protection mechanisms, described later.

For the purposes of closing the local loop an adjustable voltage reference of approximately 5V is subtracted from the differential position sensor signal to give a nominal 0V level when the cat's eye is centred in its range of travel (i.e. with the flexure legs vertical). The centre position can thus be adjusted if necessary by control of the voltage reference. The balanced differential position signal is applied to a phase lead stage for loop stability but only a moderate bandwidth of around 20 Hz is required for this local loop. The compensated differential position signal is now processed further for several purposes:

1. It is passed through an analogue switch (in local loop i.e. slew mode) to be amplified by the summing amplifier and passed to the voice coil drive circuit.

2. It is passed to a limited derivative circuit to provide a velocity signal over a limited bandwidth which is used to offset the damping action of the voice coil in metrology loop mode. In slew mode this signal adds a small amount of phase lead which helps to stabilise the local loop.

3. A small proportion of it is passed though an analogue switch (in metrology loop i.e. track mode) to the summing amplifier to provide a position feedback term which has the effect of setting the virtual natural frequency of the cat's eye on its flexures to about 0.5 Hz. (This provides further substantial rejection of disturbances below 0.5 Hz).

4. It is passed through an analogue switch operated by the dead-band comparator and applied with gain to the summing amplifier. In the event that the metrology signal saturates, causing the cat's eye to drive towards a mechanical limit, this signal takes over control and holds the cat's eye firmly at the electronic limit.

The summing amplifier, which provides gain according to the loop which is closed, passes the voltage drive to the voice coil power amplifier via a current limiting network operated by the displacement comparator. This network clamps the output drive voltage and thus limits the current in the voice coil in the event that the differential position sensor fails. The circuit also operates at power on because the differential sensor electronics takes a second or so to stabilise. This prevents the cat's eye experiencing a sudden acceleration.

8.1.3 Local loop Operation during Slew Mode

During slew mode the Slew/Track input, which is controlled by the trolley microprocessor, signals two analogue switches to operate. Switch2 disconnects the metrology error input from the summing amplifier while Switch 1 connects the differential position signal but with high gain. The local loop thus holds the cat's eye in the centre position while the trolley is slewed under command from the VME system or the Workstation. If the differential position sensor fails so as to cause the cat's eye to be driven to one mechanical limit or the other the dead-band comparator operates causing Switch 4 to clamp the preamplifier output voltage, thus limiting the voice coil drive current to a sustained but safe level and holding the cat's eye against the soft mechanical stop. Note that Switch 3 is also operated by the comparator, increasing the input to the summing amplifier, but its action is ultimately defeated by the current limit.

8.1.4 Metrology Loop Operation during Track Mode

During track mode the metrology error is coupled through to the summing amplifier via Switch 1 and a small proportion of the differential sensor position signal is also coupled via Switch 2 to provide the feed-forward signal necessary to reduce the cat's eye natural frequency. The metrology loop provides a stiff servo with high disturbance rejection at frequencies below 0.5 Hz and a linear 2^{nd} order slope rejection characteristic from 0.5 Hz to 0dB at around 150 Hz. The small velocity feed-forward term produced by the limited derivative circuit provides compensation for the damping effect of the voice coil which is due to eddy currents in the aluminium coil former. This reduces unwanted coupling between the trolley and the cat's eye.

8.2 Voice Coil Driver/Power Amplifier

The voice coil driver is a bi-directional trans-conductance power amplifier based on two power op-amps connected in an H-Bridge driving configuration. A schematic of the arrangement is shown in Figure 5. The amplifier is based on two OPA541 power operational amplifiers operated from unbalanced supplies and can deliver 5A continuous and 10A peak.

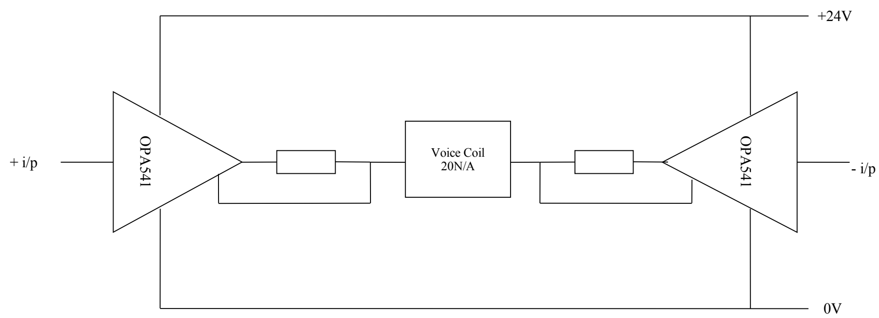

Figure 5: Voice coil power amplifier schematic.

Under normal conditions, during tracking, the current through the voice coil is very small, typically a few milliamps RMS. If there is a small tilt of the trolley due to delay line pipe deviations then the mean current may rise to 10 mA or so to keep the cat's eye in position. Most power will be used during slewing, particularly for periods of acceleration or deceleration of the trolley.

The amplifier should be able to hold the cat's eye during maximum controlled deceleration of the trolley which occurs when a trolley pre-limit is activated. To bring the trolley to a halt from $1ms^{-1}$ within a distance of 250mm a deceleration of 0.2g is required. This deceleration applied to the 20kg cat's eye requires 40N of force for 0.5 seconds. To achieve this, the voice coil requires 2A and so this is well within the capability of the amplifier.

If the trolley were to hit the mechanical buffers within the delay line pipe the deceleration imposed would be of order 0.5g, requiring 5A for 0.2 seconds. This also is within the capability of the amplifier.

The amplifiers and current sense resistors are mounted on a heat-sink which is mechanically and thermally connected to the trolley electronics' frame while the rest of the power amplifier circuitry is mounted on the preamplifier circuit board.

8.3 Power Supplies

The voice coil preamplifier uses ±15V supplies provided by an efficient switching regulator derived from a 24V supply. The 24V supply is derived from the trolley power bus and is well regulated. It supplies both the power amplifier and the differential position sensor electronics module.

8.4 Circuit Diagrams

Circuit diagrams of the pre-amplifier and power amplifier circuits are provided in Appendix A.

A Circuit Diagrams

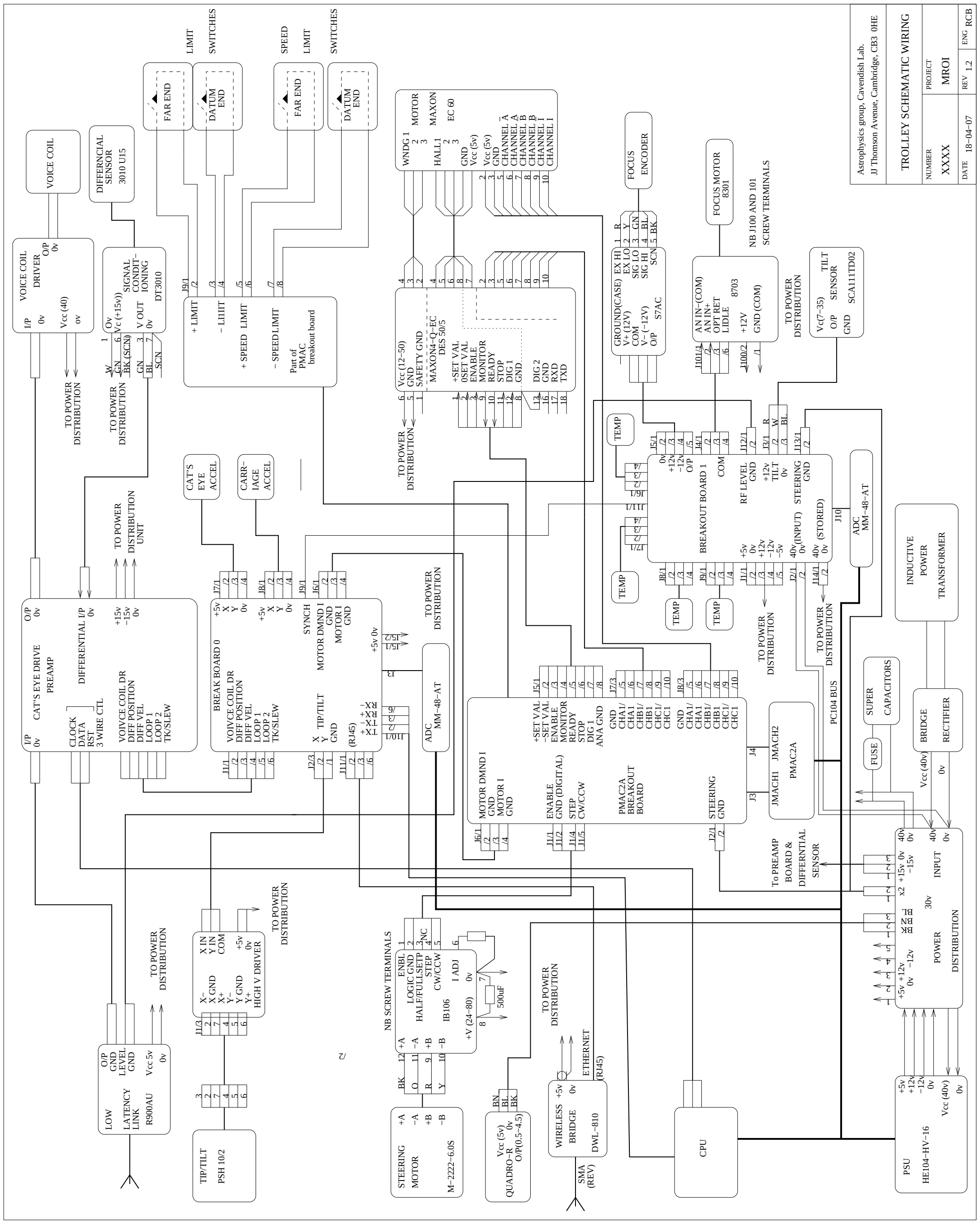

Figure 6: Trolley subsystem interconnections.

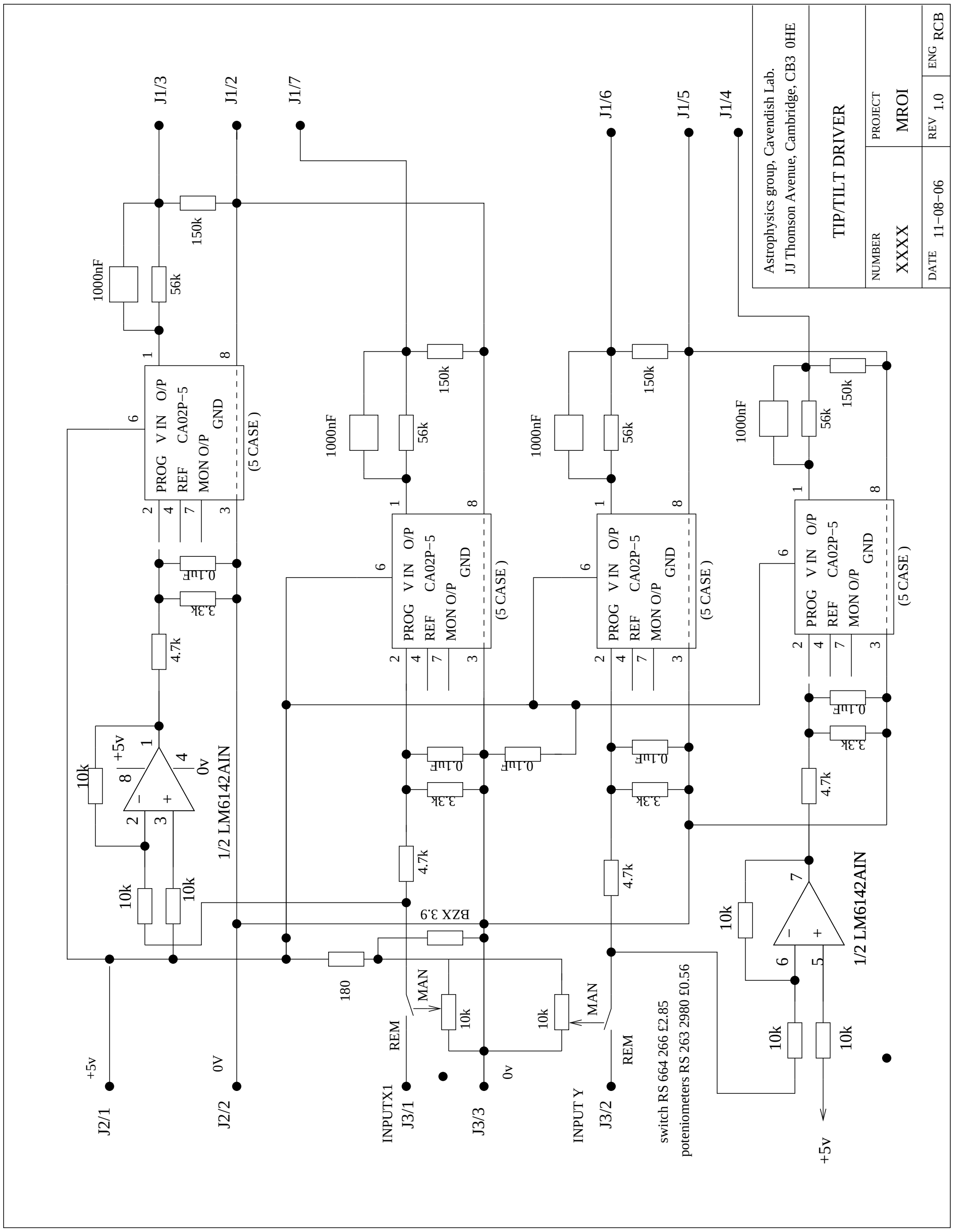

Figure 7: Tip-tilt signal conditioner.

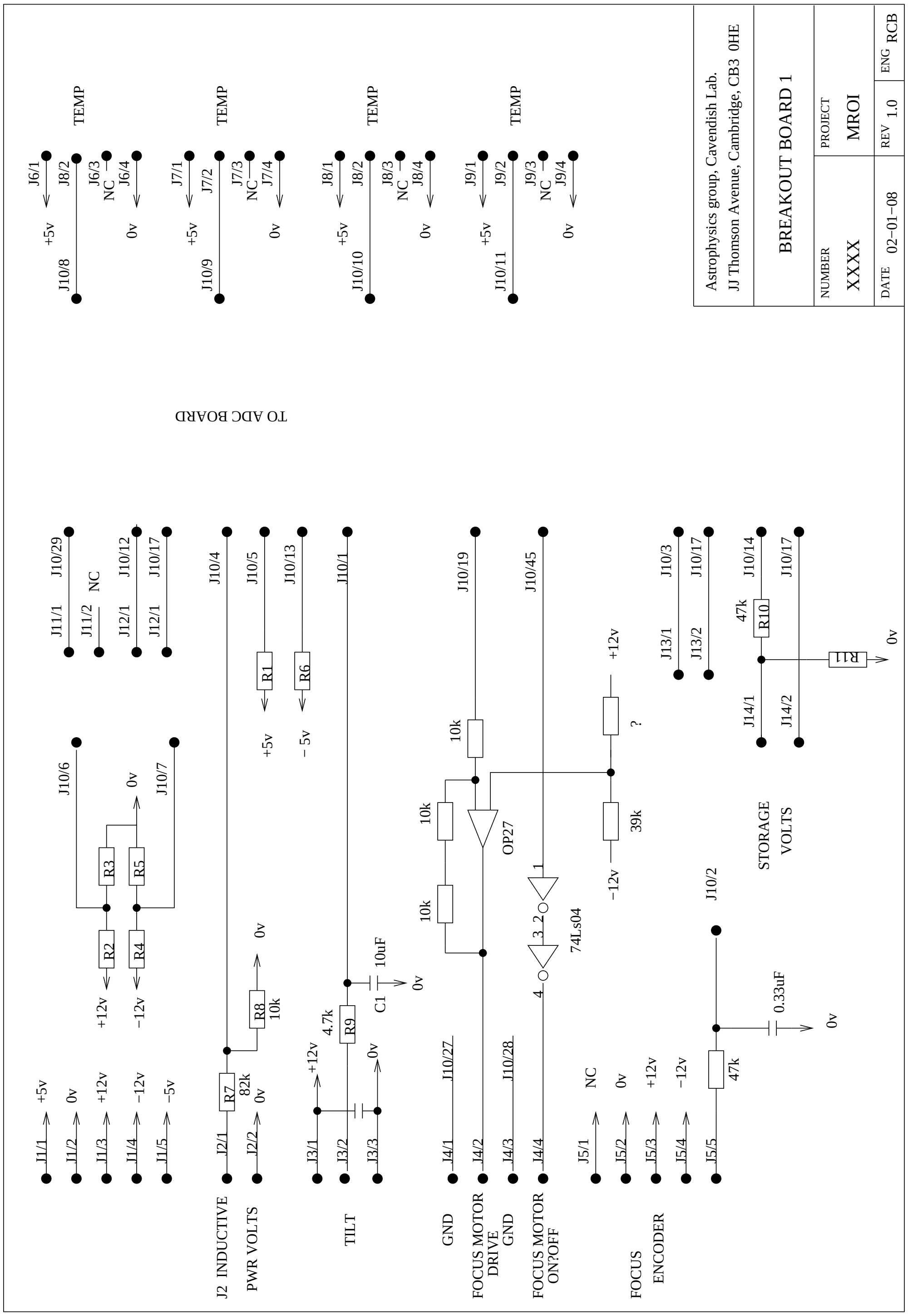

Figure 8: Analog breakout board 1 connections and signal conditioning.

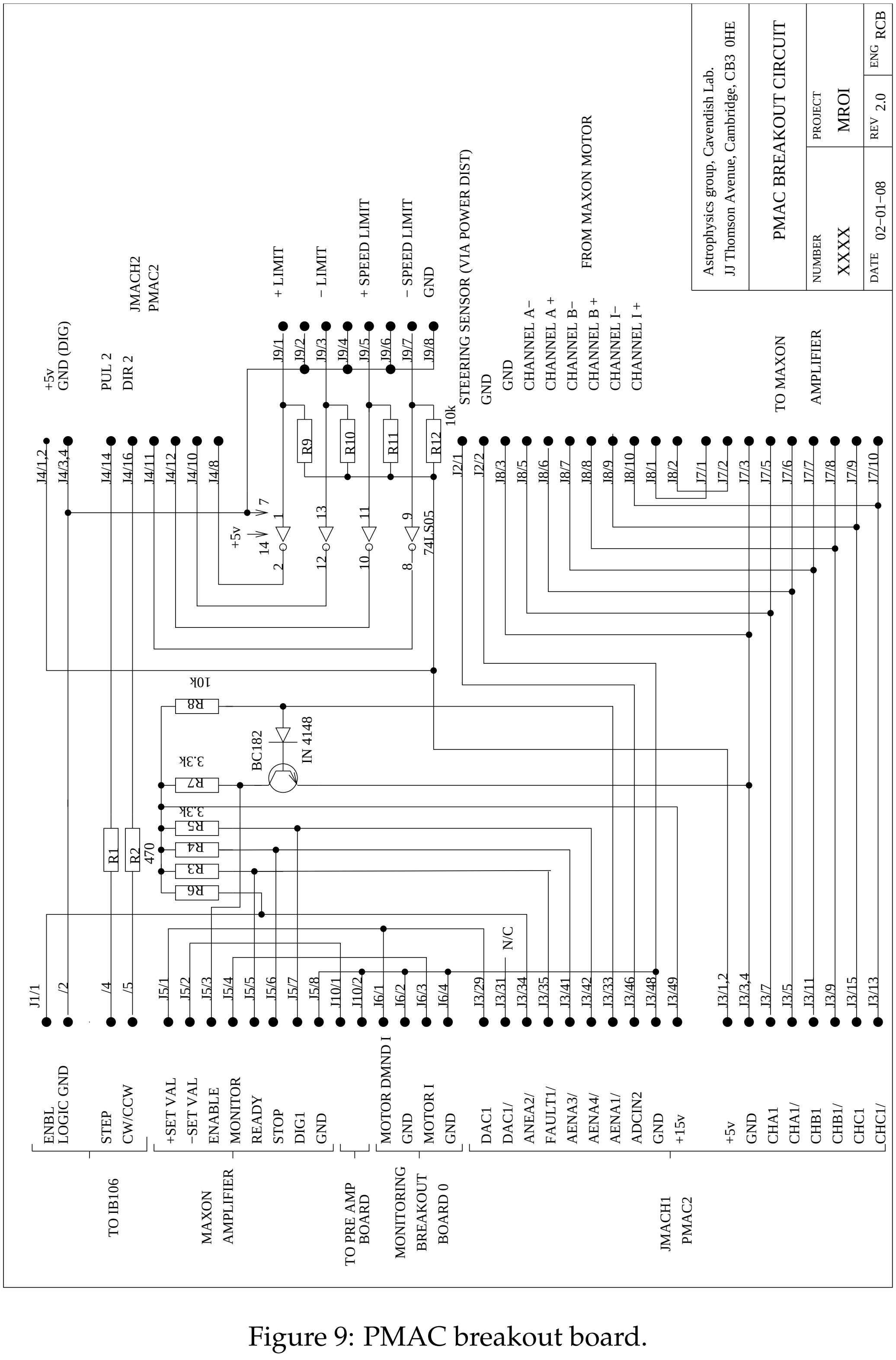

Figure 9: PMAC breakout board.

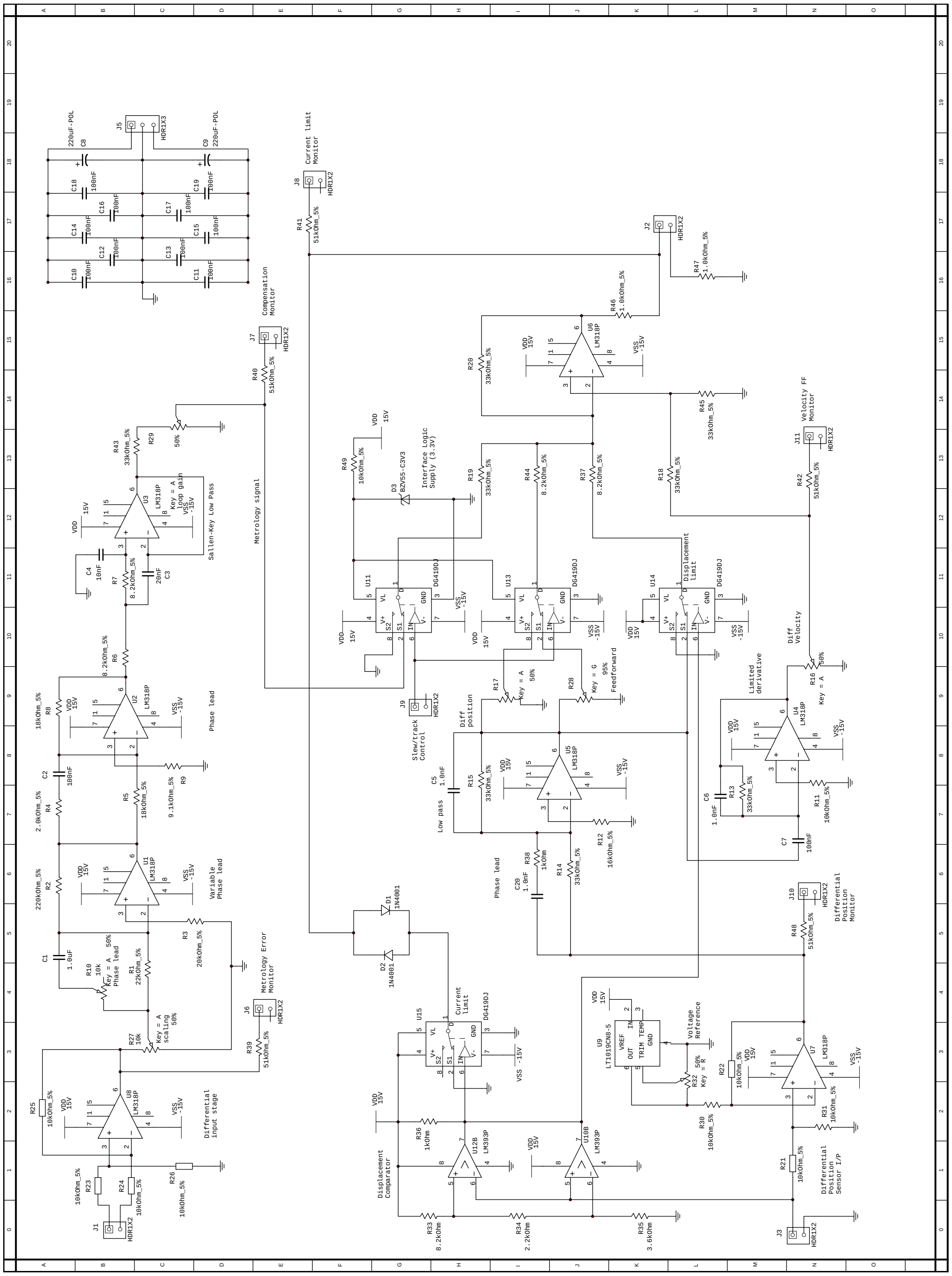

Figure 10: Catseye voice coil preamplifier.

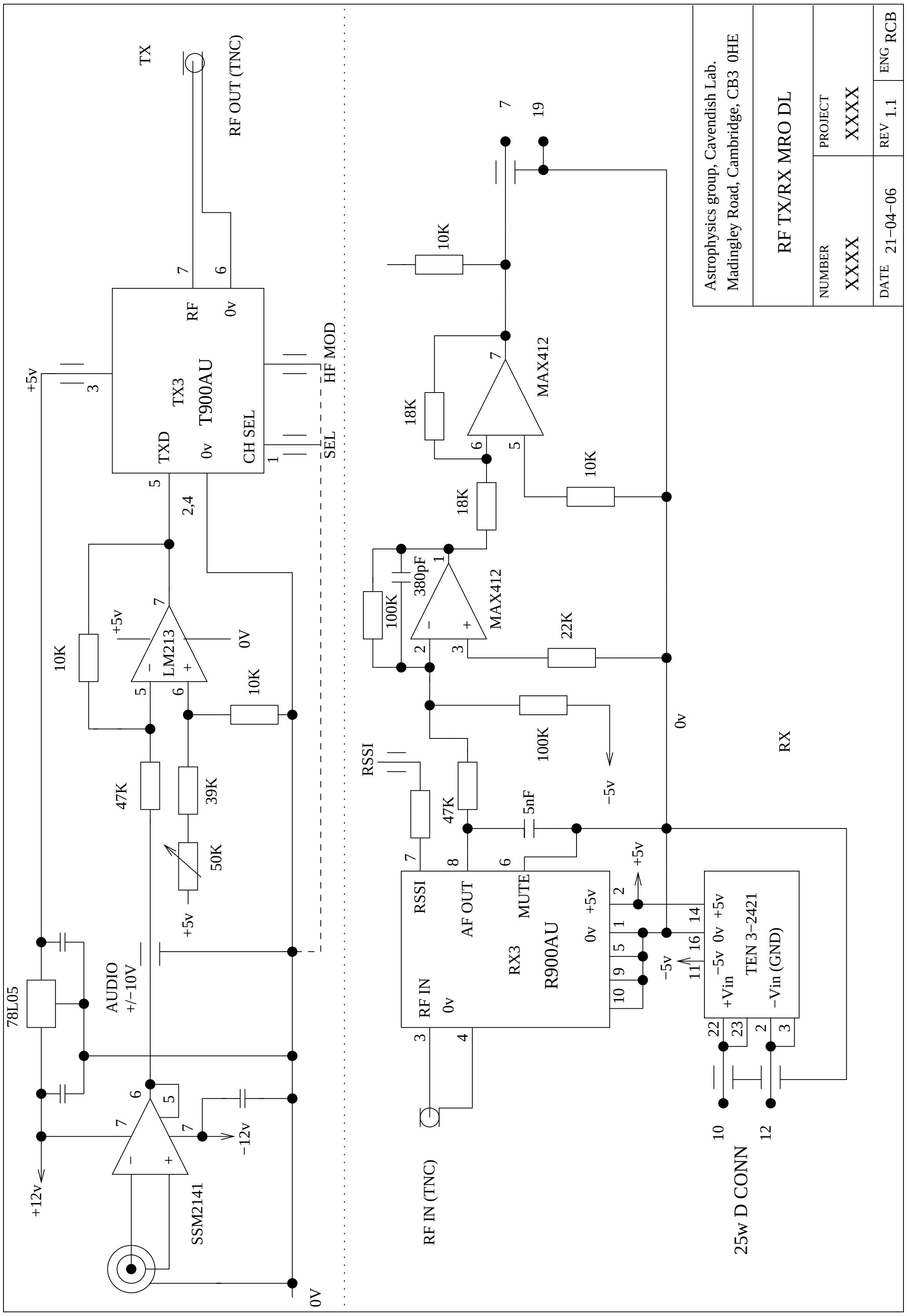

Figure 11: Low latency transmitter and receiver.

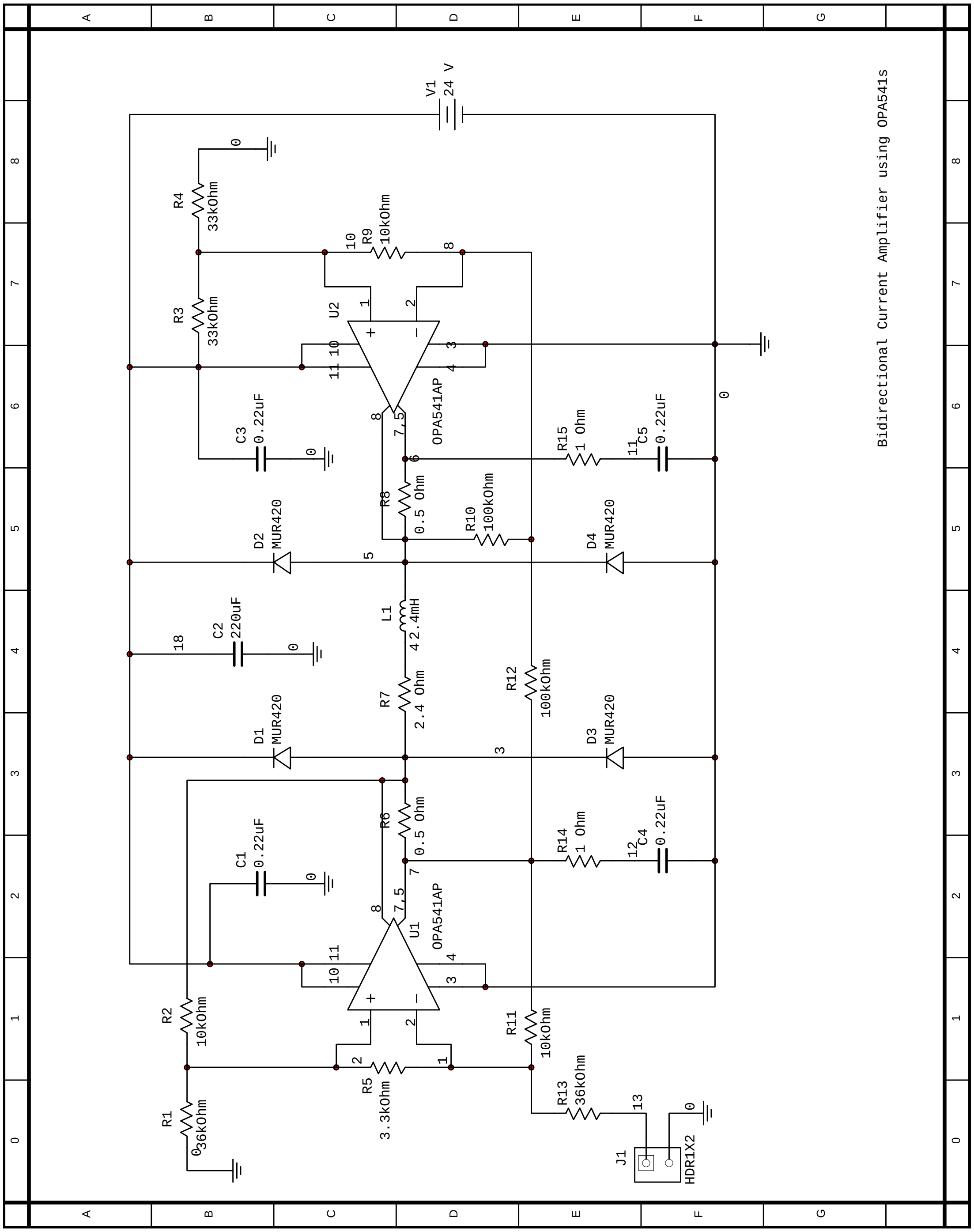

Figure 12: Catseye voice coil power amplifier.