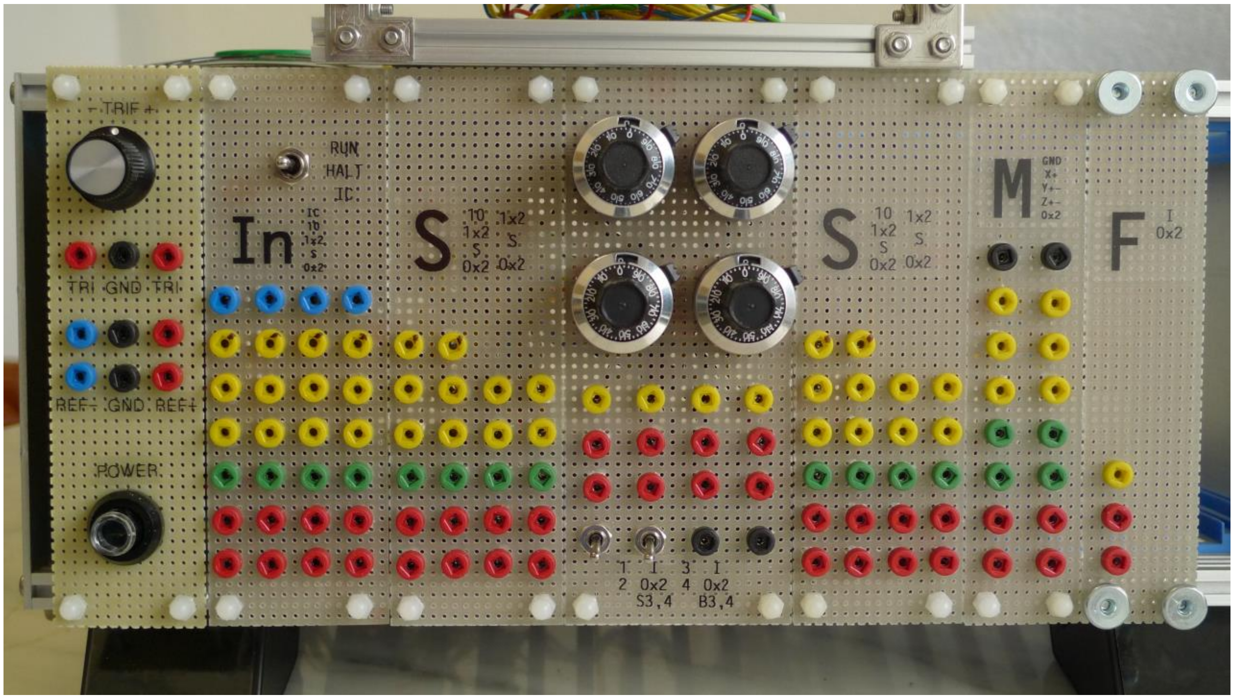
An Educational Analogue Computer

1 Introduction

Searching for an electronics project simple enough to be completed in a reasonably small amount of time and complex enough to be interesting, I stumbled over analogue computers. A great web site in English and German can be found at http://www.analogmuseum.org/.

A design of a homebrew analogue computer for educational purposes by Dr. F. Vogel appeared to meet the criteria. I also had an old card rack laying around collecting dust and looking for a new use. It proved to be a near perfect match for the project. See the picture of the finished computer below. Well, almost finished, the function generator module F is empty.



As I had that card rack for the case, it was obvious to go for a modular design. The original is a dual board construction. This also allowed me to build the computer step by step and having the option to start over with a small part in case of failure or need for improvement.

Electronically, I very much copied the original design. Exceptions were the Op-Amps and the precision resistors, due to availability restrictions. So, I used LF356 instead of LF357 and 0.1% resistors instead of 0.05%.

Due to space restrictions I also left out the build-in volt meter and simply use an external multimeter, or even several of them at the same time.

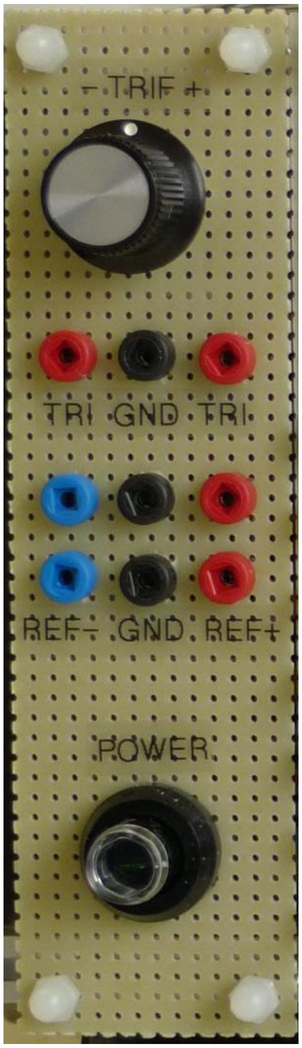
Whilst I happen to be a bit of a pen and paper person, designing circuits using strip boards can be tedious. Thus, I looked for some software support. VeeCAD was a simple and free solution. Later, I bought the full version of VeeCAD to enjoy its advanced features, but the first boards were done with the free version.

The electronics are built on standard 100mm x 160mm strip boards. The font panels are also made of experiment board material. The 0.1in hole pattern allowed for easy cutting and accurate alignment of the numerous 2mm banana jacks.

I found, that for certain experiments, the number of active elements provided by the original design were not enough. The card rack provided sufficient space for more:
4 Integrators
4 Summers
4 Inverters/open amplifiers
2 Multipliers
4 Potentiometers
1 Function generator

2 THE MODULES

2.1 THE POWER SUPPLY



The power supply was the first module I built. It was simple and served as a proof-of-concept, electronically and mechanically. I wanted to see whether the protoboard makes for reasonable front panels (it did). As I used mostly material I already had, it looks slightly different than the later modules.

As this analogue computer was going to contain more active elements than the original design, I had to provide it with a more powerful DC-to-DC converter: TEN5-1223 instead of TEN3-1223, which was luckily pin-compatible.

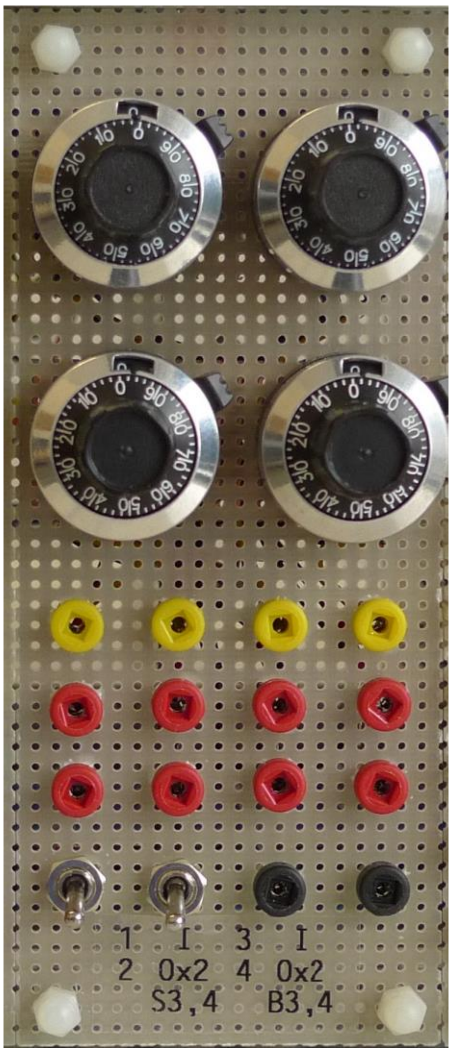
The module provides connections to the positive and negative reference voltages REF+ and REF-, the adjustable triangular oscillator TRI and an ample amount of grounding jacks.

The triangular waveform oscillator can be adjusted with a ten-turn potentiometer, but I found it not necessary to provide it with a counting dial.

Power, as +15V, -15V and GND, to the other modules is provided on the rear side by a two-row 6 pin 0.1in pin header. Each module has such a connector which allows daisy-chaining the modules using single row 6 pin connectors. I used two pins per rail to lover resistance.

```
+15V .. +15V
+15V .. +15V
GND  .. GND
GND  .. GND
-15V .. -15V
-15V .. -15V
```

2.2 The Potentiometers



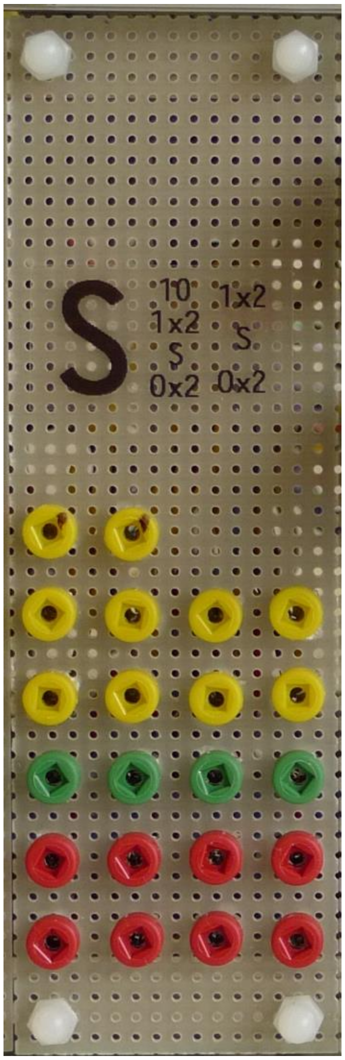
The potentiometer module turned out to be surprisingly more difficult to build than anticipated. The reason was that the multi-turn pots and counting dials (they look cool, I love them) require accurate mechanical construction and precise alignment to turn smoothly. The dials need just the right amount of play between the case and the front panel. About the thickness of thin cardboard.

Potentiometers 3 and 4 can optionally be based to external jacks B3 and B4 using the switches S3 and S4 (in up position). With S3 and S4 in their down position, potentiometers 3 and 4 are based to GND. Despite B3 and B4 being black, they are not GND. I wanted to use grey jacks for these, but I had none.

As an addition to the original design, I have provided the potentiometers with op-amps. Without the op-amps, loading the voltage dividers would throw the counting dials out of calibration. Thus, defeating their use (otherwise they are quite accurate). The module can easily be configured back to the original passive design by removing the op-amps and bridging some internal connections.

The decal at the bottom of the panel: 1, 2, 3, 4 show the dial assignments. I, Ox2 standing for the yellow input- and two red output jacks. S3,4 the two switches

2.3 The Summer



The summer module contains two independent adder circuits a and b as well as two independent open amplifiers c and d which can be used as inverters. I have chosen this arrangement to distribute the active elements more evenly over the entire front panel.

A connection to the summing point allows for a (within certain limits) arbitrary number of additional inputs of any scaling factor using external resistors.

There are two identical summer modules in the system.

The decal denotes the module type S for summer; 10 one times 10 input and 1x2 two times 1 inputs; S the summing point; Ox2 the two outputs. The open amplifier only having times 1 inputs.

```
   a    b    c    d         color     signal  description
,---------------------,
|                     |
|  ()   ()            |     ylw/blk  10      x10 Input (I1)
|                     |
|  ()   ()   ()   ()  |     ylw        1      x1 Input  (I2)
|                     |
|  ()   ()   ()   ()  |     ylw        1      x1 Input  (I3)
|                     |
|  ()   ()   ()   ()  |     grn        S      Summing Point
|                     |
|  ()   ()   ()   ()  |     red        O      Output
|                     |
|  ()   ()   ()   ()  |     red        O      Output
|                     |
'---------------------'
```

The equation of an adder is:

1. `Vout = -(10*I1 + I2 + I3 + x*S)` with x depending on external resistance.

The equation of an open amplifier is:

2. `Vout = -A * (I1 + I2 + x*S)` with x depending on external resistance.

Where A is the open loop gain of the amplifier.

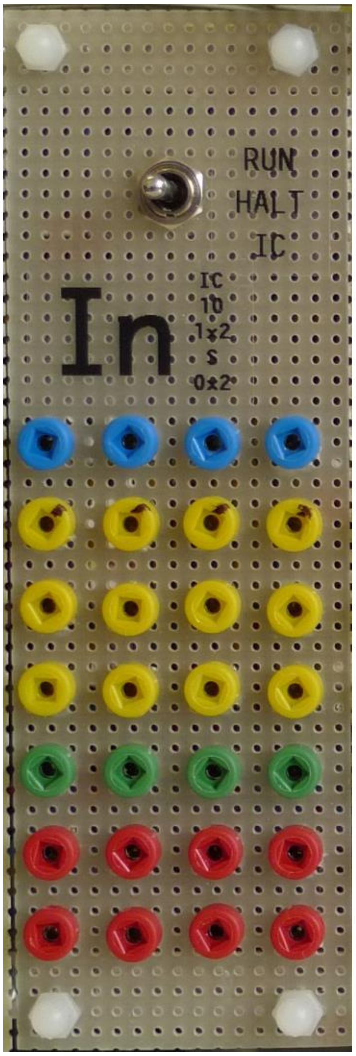
To operate an open amplifier as an inverter, a feedback connection needs to be installed between one of the outputs and the summing point using a patch cable like:

```
1       Input value X

S--,
   |
O--'

O       Output result -X
```

With the equation in 2. and very high A, thus `Vout/0 = 0`, this results to:

`0 = -(I1 + I2 + Vout) => Vout = -(I1 + I2)`

2.4 The Integrator



The integrator module contains four independent integrator circuits a to d.

The operation switch allows setting the operation mode to either load initial conditions (IC), halt or compute (RUN).

Only manual operation switching is provided by this module.

A connection to the summing point allows for a (within certain limits) arbitrary number of additional inputs of arbitrary multiplication factor using external resistors.
The original design did not provide for a summing point connection.

The integration time is about 1s (with 4.7uF capacitor and 220kOhm resistor) for each of the four integrators. This is very slow, but seems appropriate for demonstration purposes.

The decal denotes the module type In for integrator. IC the initial condition input; 10 one times 10 input; 1x2 two times 1 inputs; S the summing point and Ox2 the two outputs.

```
   a    b    c    d        color    signal  description
,---------------------,
|                     |
|            RUN      |
|        (°) HALT     |                         Operation switch
|            IC       |
|                     |
|                     |
|  ()   ()   ()   ()  |    blu      IC      Initial Condition
|                     |
|  ()   ()   ()   ()  |    ylw/blk  10      x10 Input
|                     |
|  ()   ()   ()   ()  |    ylw       1      x1 Input
|                     |
|  ()   ()   ()   ()  |    ylw       1      x1 Input
|                     |
|  ()   ()   ()   ()  |    grn       S      Summing Point
|                     |
|  ()   ()   ()   ()  |    red       O      Output
|                     |
|  ()   ()   ()   ()  |    red       O      Output
|                     |
'---------------------'
```

2.4.1 Zero Adjustment Procedure

To adjust the op-amp compensation trimmers for zero output follow this procedure for each individual integrator a to d:

1. Connect the respective IC input to one of the available GND jacks.
2. Set the operation switch to the IC position.
3. Measure the voltage between the respective integrator output and GND.
4. Adjust the trimmer potentiometer to a zero reading.

2.4.2 Integrator Testing Procedure

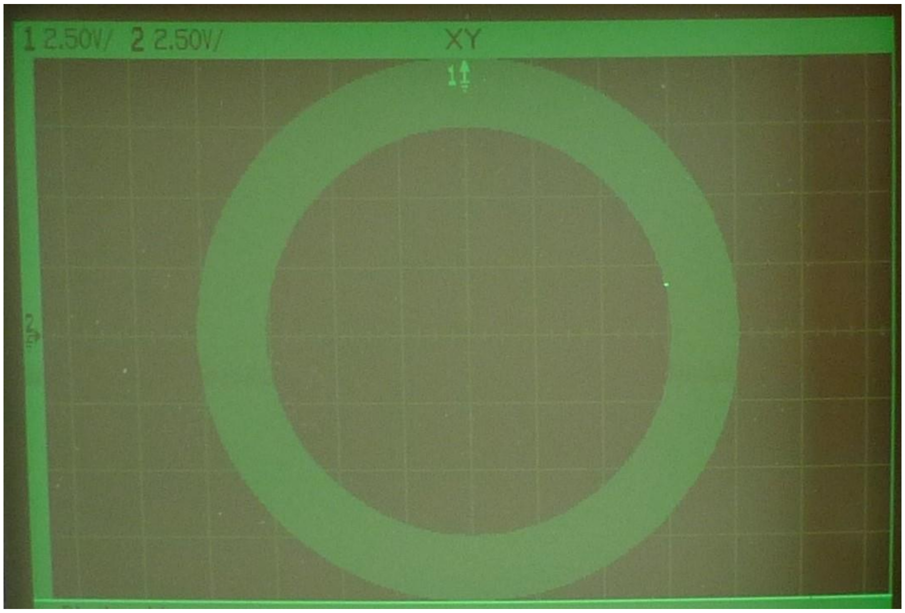
A simple way of testing the integrators is using them in a circuit calculating a circle. The circuit tests two integrators and an inverter at the same time.

```
     GND             ,-----,
      |              |     |feedback
      |IC            '-|   |
,----[>-+----[>-+----(>--+--,  [> Integrator
|       |       |           |  (> Open Amplifier/Inverter
|       X       Y           |
'---------------------------'
```

2.4.3 Integrator Leakage

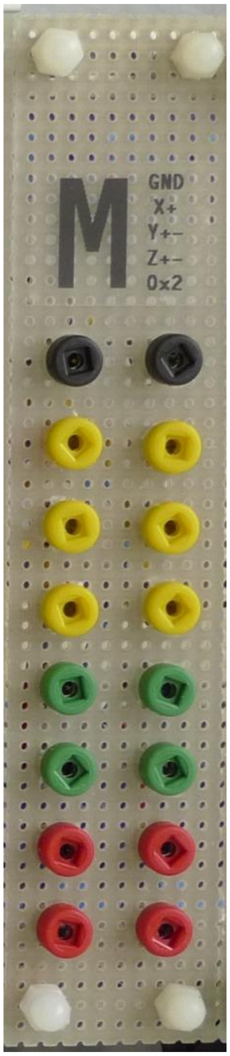
With the circle circuit described above, it was possible to measure the total leakage, but I assume it is mostly due to capacitor leakage. The leakage causes the circle on the oscilloscope shrink in diameter with time. I measured the time during which the voltage dropped by one division or 2.50 Volt.

tdiv = 38min = 2280s (1div = 2.50V)
leakage/s = 2.50V/2280s = 0.0011V/s = 110ppm/s @ 10V full scale.



The oscilloscope (Agilent 54621A) is set to XY mode; 2.5V/div on X and Y; averaging acquisition.

2.5 The Multiplier



The multiplier module contains two independent places a and b to accept multiplier ICs. Different types of multiplier ICs may be used, if they are pin-compatible. Even non-pin-compatible multipliers can be used with an adapter. This allows for experiments comparing different multiplier chips.

The original design asks for an AD534K, but I could only get hold of some AD534J (beautiful “old” ones in ceramic package) which are slightly less accurate.

The decal denotes the module type M for multiplier. GND for ground; X+ the first row of yellow jacks; Y+- the second row of yellow jacks for Y+ and the third row of yellow jacks Y-; Z+- the first green row of jacks for Z+ and the second row of green jacks for Z-; Ox2 the two outputs.

```
   a    b          color    signal  description
,------------,
|            |
|  ()   ()   |     blk      GND     Signal Ground/0 potential
|            |
|  ()   ()   |     ylw      X+      Input X1
|            |
|  ()   ()   |     ylw      Y+      Input Y1
|            |
|  ()   ()   |     ylw      Y-      Input Y2
|            |
|  ()   ()   |     grn      Z+      Input Z1
|            |
|  ()   ()   |     grn      Z-      Input Z2
|            |
|  ()   ()   |     red      O       Output
|            |
|  ()   ()   |     red      O       Output
|            |
'------------'
```

The basic equation of the multiplier is:

$$Vout = A * \left(\frac{(X1 - X2)*(Y1 - Y2)}{SF} - (Z1 - Z2) \right),$$

with SF = 10 and very high A.

A being the open loop gain of the multiplier.
SF being a scale factor, internally trimmed to 10.

The X- signals of both multipliers are internally connected to ground, thus the above equation reduces to:

$$Vout = A * \left(\frac{X1*(Y1 - Y2)}{SF} - (Z1 - Z2) \right)$$

2.5.1 Multiplication

Multiplication operation is achieved by making the following connections using patch cables:

```
GND-----,  using a y-cable
X1      |  Input factor X
Y1      |  Input factor Y
Y2------+
Z1--,   |
Z2--|---'
O---'
O          Output result X*Y/SF
```

With these connections, the resulting formula is:

`Vout = A * (1/SF * X1 * Y1 - Vout)` and with very high A, thus `Vout/A = 0` follows:

`0 = 1/SF * X1 * Y1 - Vout =>` <u>`Vout = 1/SF * X1 * Y1`</u>

2.5.2 Division

Division operation can be achieved using similar patch connections as follows:

```
GND-----,  using a y-cable
X1      |  Input divisor X
Y1--,   |
Y2 -|---+
Z1  |   |  Input dividend Z
Z2 -|---'
O---'
O          Output result SF*Z/X
```

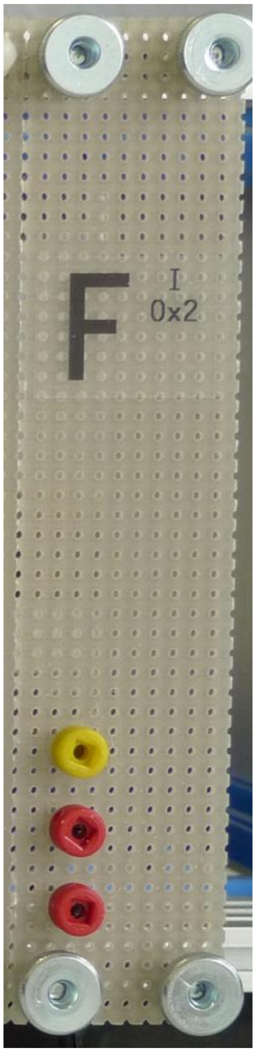
With these connections, the resulting formula is:

`Vout = A * (1/SF * X1 * Vout - Z1)` and with very high A, thus `Vout/A = 0` follows:

`0 = 1/SF * X1 * Vout - Z1 => z1 = 1/SF * X1 * Vout =>`

```
           Z1
Vout = ---------
       1/SF * X1
```

2.6 The Function Generator



The function generator behind the panel is supposed to be exchanged easily, thus the panel is fixed with thumb screws. The panel only provides an input and two output jacks and is connected to the function gerenator board through a connector. This way one generic panel can be re-used with a variety of function generator boards.

The decal denotes the module type F for function. I is one input, Ox2 is the two outputs.

A function generator is not currently implemented.

2.7 Accessories

Patch-Cables
Two lengths of patch cables, short (15cm) and long (25cm), in different colours with 2mm banana connectors.

Y-Cables
Short Y-cables, mainly to be used with the multipliers.

R-Cables
Short cables with a resistor. The resistor was placed away from the centre on purpose.

Connector Cables
Relatively long cables with 2mm banana connectors on one side and 4mm banana connectors on the other side. Mainly used to connect to multimeters or an oscilloscope.
Shorter cables with hook clamps to connect to wired external components.

Power Breakout Cable
This is handy to hook-up a module outside the card cage for testing and adjustment.