Low-Cost Fluid Flow Sensor to Enable Electronic Control of Fractional Distillation Columns

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***Abstract*—A sensor is described that measures fluid flow up to 20 ml/minute, and down to 0.001 ml/minute. The measurement involves counting drips as they fall through a pair of optical beams. The beams are formed using a pair of ordinary optical proximity sensors arranged to face each other so that each photo-receiver sees the other sensor's emitter. The beams operate at two different frequencies so as to prevent reflected signals interfering. Only two sensors, an 8-pin microcontroller, and four resistors are required for the sensing. Calibration for a specific fluid is straightforward. An ethanol-water mixture produces 16 drips/ml, significantly different from the default pharmaceutical value of 12 drips/ml.**

***Index Terms*—Sensors, Microcontrollers, Fluid flow measurement, Measurement techniques, Calibration, Infrared**

I. INTRODUCTION

Fluid flow is perhaps the most common and yet most varied and difficult measurement to make, with many different technologies finding application. [1] Much of the literature is targeted at measurement of large flows in industrial situations, and often for billing rather than feedback-control application, simply because the most money is to be made there. [2] It would be impractical to take in all the literature, but techniques include induction [1], [3], metering or positive-displacement, [1], [4], ultrasonic [5], Coriolis [1], thermal [1], [6], and the common impeller-in-pipe or paddlewheel meters categorised as "rotary element" flowmeters. [1] Factors affecting choice of technology and specific meter include fluid viscosity, minimum and maximum volume & fluid speed, cost, accuracy, and resolution.

In this manuscript we address the need for a flow sensor suitable for use with electronic control systems controlling fractionating stills. Distillation systems with heating power from $300\,\mathrm{Watts}$ to $5\,\mathrm{kW}$ are commonly available. Stone describes the theory and design of such equipment in great detail, favouring a boiler power around $0.75\,\mathrm{kW}$. [7] Stone comments

> New Zealand has recently (1996) legalized amateur distillation, probably as a result of its isolated location in the south Pacific and freedom to think for itself.

This has resulted in considerable activity, including the rise of boutique gin and vodka producers plus manufacturers of small-scale distillation equipment. An example of a cooling-management design with a $2\,\mathrm{kW}$ boiler is the Copperhead still [8], while the Alcoengine stills represent a fluid-management design of similar capacity [9]. Some chemistry and arithmetic [7] determines that the yield of product will be around 5 millilitres per minute per kilowatt of input power. A drip of alcohol-water mixture will be shown to contain around one-sixteenth of a millilitre. Thus $5\,\mathrm{ml/minute}$ corresponds to between one and two drips per second. A still using the common $2\,\mathrm{kW}$ boiler will typically run at around three drips per second.

In this manuscript we report the design and testing of a flow sensor that operates by counting drips that fall from a nozzle. The end design is quite sufficiently accurate, and cheap to realise.

II. SENSOR HARDWARE

The drip flow hardware has two parts. The first part is a structure that receives the output flow to be measured, typically from the output of the still condenser, and causes it to fall through a nozzle into a stream of drips that pass an optical sensor. The second part is a small electronic circuit that optically detects and counts drips. This is achieved using a low-cost 8-pin microcontroller interfaced to a pair of reflective optical proximity sensors.

A. Fluid Dripper Geometry

A drip of liquid will form at the end of a pipe, such as in the case of the familiar eye dropper. The volume of fluid of given composition in a drip from a given nozzle is relatively constant. Figure 1 shows a drip of ethanol water mixture falling from an eye dropper nozzle. The drop is between $5\,\mathrm{mm}$ and $6\,\mathrm{mm}$ in diameter. The volume of a sphere is $\frac{4}{3}\pi r^3$, where r is radius, so an initial estimate of its volume would be between $\frac{1}{15}^{\mathrm{th}}$ and $\frac{1}{9}^{\mathrm{th}}$ of a millilitre. The common value of "drops per millilitre" used for drug calculations by pharmacists in New Zealand is 12 per millilitre, which is in the middle of this range, although different systems can have very different values. [10]

The drip detection will operate by passing two beams of light across the path of the falling drop, and registering a

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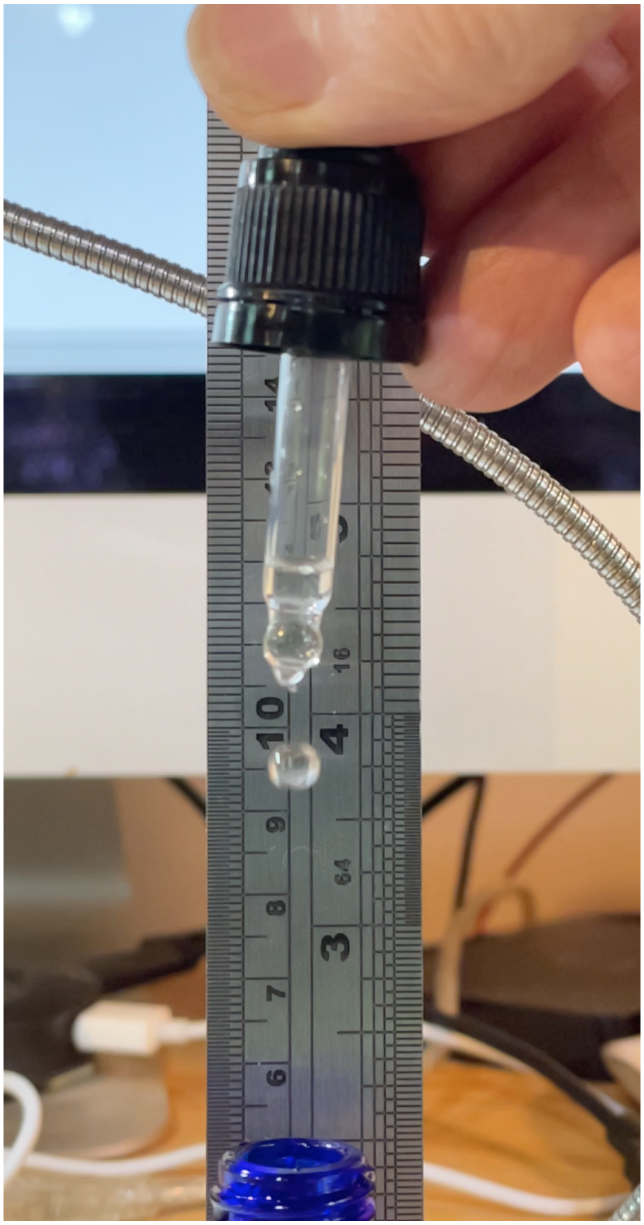


Fig. 1. Image of a drip falling from an eye dropper.

drop when the two beams see a reduction of transmission in sequence. It will be important to know how fast the drop will be travelling as it crosses the beams. This will be set by the distance from the nozzle from which drops disconnect to the beams. Knowing that

$$v = u + at \tag{1}$$

where v is speed at time t, given a starting speed of u, and

$$s = ut + at^2 \tag{2}$$

where s is distance and a is acceleration, some algebra allows elimination of t to give the speed as a function of distance fallen as

$$v = \sqrt{as}. \tag{3}$$

The electronics will measure transmission in both beams every $2\,\mathrm{milliseconds}$. It will be convenient if the drip occludes each beam for at least $6\,\mathrm{milliseconds}$, which would mean that a $5\,\mathrm{mm}$ drop will need a speed less than $0.8\,\mathrm{m/s}$. Knowing that acceleration of gravity $a = 9.8$m/s the drip system should be shorter than $65\,\mathrm{mm}$, which is easy to achieve. We select $\approx 14\,\mathrm{mm}$, meaning that a drip will be travelling at a little less than $0.4\,\mathrm{m/s}$ and so a $5\,\mathrm{mm}$ drop will take no less than $13\,\mathrm{ms}$ to pass through the beam, making for straightforward detection.

The output of stills can be a "multiphase flow" meaning that bursts of gas can accompany the fluid. This has a tendency to disturb drop formation and deflect falling drops. Thus the sensor starts with a funnel to collect drips and reform them in stable conditions. It also finishes with another funnel to collect the falling drops and permit connection of a food-grade, quarter-inch delivery pipe to conduct the product away. Figure 2 shows a schematic diagram of the sensor structure that processes the fluid. The diagram includes all the dimensions that impact the function of the sensor.

B. Electronics

The sensor uses two TCRT1000 Reflective Optical Sensors. [11] Figure 3 shows how the TCRT1000 is intended to be used: as a reflective proximity sensor. In this system, two will be mounted facing each other across the path of falling drops. The position of the two sensors is shown in Figure 2. The circuit diagram and circuit layout are to be found in A. All of the work of the circuit is carried out in the microcontroller. The output is either a detection pulse sent to a host controller, or flow rate sent as serial data. The algorithms for both of these processes will be discussed in section II-C.

Arranged to face each other, the sensors provide two pairs of transmitter & receiver, one a few millimetres above the other. In order to prevent the two beams interfering with each other they are organised to operate at two different frequencies. One is modulated at $488\,\mathrm{Hz}$ and the other at $0.977\,\mathrm{kHz}$. A four-phase measurement is carried out with each phase lasting $512\,\mathrm{us}$. The signals from each channel can then be reliably separated and protected from ambient light and drifts.

C. Firmware Algorithms

The code to implement drop detection runs every time the interrupt service routine (ISR) runs. This is $512\,\mathrm{us}$ in this example. The controller first performs an analog-to-digital conversion on the two optical receiver signals. This happens in the first 12 lines of the example code below. Then the data from each channel is appropriately summed. The routine

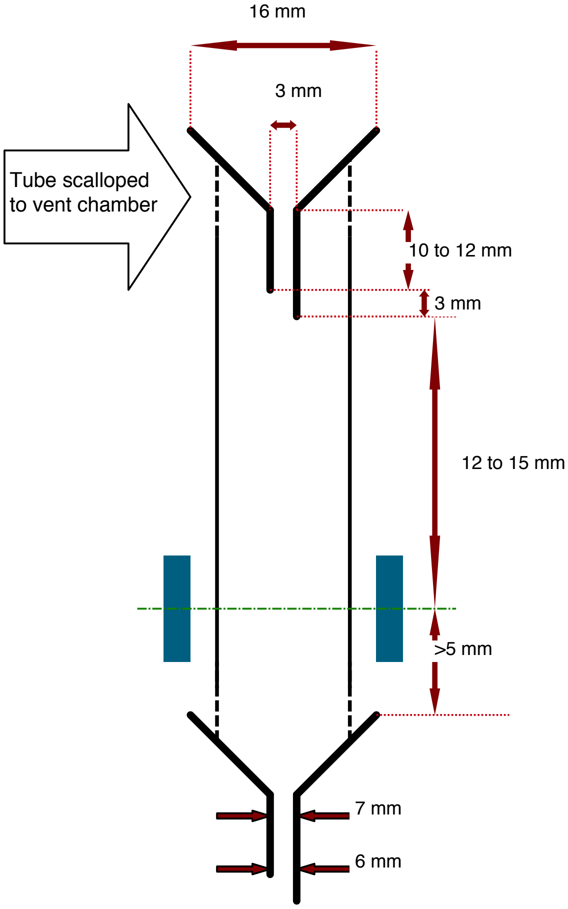


Fig. 2. Notional schematic diagram of the geometry required in a fluid dripper. Black lines represent glass. Dimensions shown are explained in the text. Unspecified dimensions are not critical. The two rectangles show the location of the optical sensors. Any construction that has the dimensions and aspects of this layout is suitable.

effectively carries out two four-point Fourier transforms, but it is easier to think of the action in the time domain. Each of the running sums adds its respective channel's data whenever its own LED transmitter is on, and subtracts when it is off. This removes the quiescent value from the sum, as it is added and then subtracted twice. The timing over the four phases is such that each channel adds in the signal from the other channel that may have leaked across once, but also subtracts it once, so that signal visible from the opposite channel is cancelled out. Finally the code checks to see if there have been at least 2 detections in each channel in the last three observations, registering a drip if so. Finally the code advances through the four phases of an observation. The code snippet is in figure 4.

Elsewhere, in the same controller or in a host controller, code looks at the timing of detections and converts this into a flow rate. The time recorded is in milliseconds, held in the variable *interval*. Provided that the interval is credible, the flow rate in "milli drips per second" is placed in variable *mdps*. Finally a counter is started that will be used to reduce the recorded flow rate if the next expected detection does not arrive. This is important in a control loop, as long

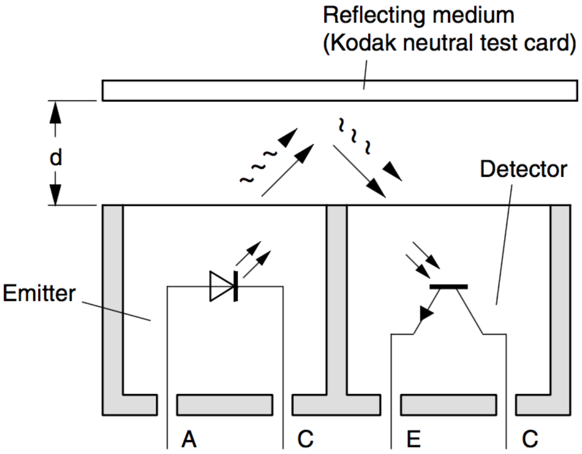
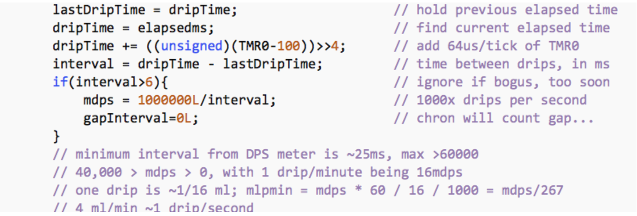


Fig. 3. Diagram of intended mode of use for TCRT1000 sensors.

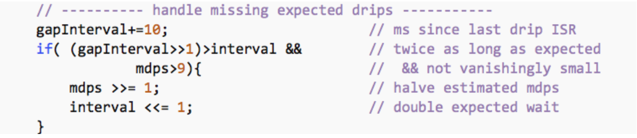
```
//  ------------------ Deal with OPTICS ------------------------
    GO_nDONE=1;                              // trigger ADC on XR1
        while(T0IF==0){LATA5=0;LATA5=1;}    // should never get here: flash forever
        T0IF=0;                              // clear flag
    while(GO_nDONE){;}                       // wait for ADC to finish
    xr1lev=ADRESL+(ADRESH<<8);               // grab light level #1
    SELRX2;                                  // ADC to XR2
        if(dlyhms){dlyhms-=1;}               // boot & main line delay timer
        for(cdly=10;cdly;cdly--){;}          // allow MPX to settle
    GO_nDONE=1;                              // trigger ADC on XR1
    while(GO_nDONE){;}                       // wait for ADC to finish
    xr2lev=ADRESL+(ADRESH<<8);               // grab light level #2
    SELRX1;                                  // set up MPX for next ISR

    if(phase==0){                            // first data
        sum1 = xr1lev;
        sum2 = xr2lev;
    }
    if(phase==1){                            // chan 1 now ON, chan 2 still OFF
        sum1 += xr1lev;
        sum2 -= xr2lev;
    }
    if(phase==2){                            // chan 1 now OFF, chan ON
        sum1 -= xr1lev;
        sum2 += xr2lev;
    }
    if(phase==3){                            // cycle done, write out result
        delta1 = sum1 - xr1lev;
        delta2 = sum2 - xr2lev;
        //  ------------------ Deal with detection ------------------------
        if(a1){a2=TRUE;}else{a2=FALSE;}                         // move a1 to a2
        if(a0){a1=TRUE;}else{a1=FALSE;}                         // move a0 to a1
        if(b1){b2=TRUE;}else{b2=FALSE;}                         // move b1 to b2
        if(b0){b1=TRUE;}else{b1=FALSE;}                         // move b0 to b1
        if(quies1-delta1>thresh1){a0=TRUE;}else{a0=FALSE;}  // ch1 obscured now?
        if(quies2-delta2>thresh2){b0=TRUE;}else{b0=FALSE;}  // ch2 obscured now?
        if(((a0 && a1) || (a1 && a2)) && ((b0 && b1) || (b1 && b2))){
            drip=TRUE;      // 2 sequential hits in each channel in last 3 checks
            active=TRUE;    // second flag to control quiescent averaging
        }                   // (uncertain which channel might be seen first)
    }

    if(++phase>3){phase=0;sync=0;}      // 4 phases
    if(phase&0x01){TX1=1;}else{TX1=0;}  // first channel LED, 500Hz
    if(phase&0x02){TX2=1;}else{TX2=0;}  // second channel, 250Hz
```

Fig. 4. Code within the ISR that deals with the optical detection.



```
    lastDripTime = dripTime;                    // hold previous elapsed time
    dripTime = elapsedms;                       // find current elapsed time
    dripTime += ((unsigned)(TMR0-100))>>4;      // add 64us/tick of TMR0
    interval = dripTime - lastDripTime;         // time between drips, in ms
    if(interval>6){                             // ignore if bogus, too soon
        mdps = 1000000L/interval;               // 1000x drips per second
        gapInterval=0L;                         // chron will count gap...
    }
    // minimum interval from DPS meter is ~25ms, max >60000
    // 40,000 > mdps > 0, with 1 drip/minute being 16mdps
    // one drip is ~1/16 ml; mlpmin = mdps * 60 / 16 / 1000 = mdps/267
    // 4 ml/min ~1 drip/second
```

Fig. 5. Code snippet that looks at the time since the last drip detection so as to calculate flow rate, in this case in “milli drops per second”. The dripTime is calculated in milliseconds, although the code does not need to run that often.



```
    // ---------- handle missing expected drips -----------
    gapInterval+=10;                            // ms since last drip ISR
    if( (gapInterval>>1)>interval &&            // twice as long as expected
             mdps>9){                           //  && not vanishingly small
        mdps >>= 1;                             // halve estimated mdps
        interval <<= 1;                         // double expected wait
    }
```

Fig. 6. When the flow rate slows, a growing delay since the last pulse is used to divide down the flow rate value. This keeps a controller updated with the flow rate.

intervals would otherwise leave the controller with a frozen measurement value. This code snippet is in figure 5. Finally the code snippet in figure 6 shows how the lengthening gap between pulses updates the flow rate.

III. MEASUREMENTS

Figure 7 is a picture of the prototype sensor assembly.

Figure 8 shows typical signals on analog inputs of the microcontroller as a single drop falls past the sensor. This screen capture shows a lot of information. The two channel frequencies are easily discerned. The obscurity time of this drip can be checked in each channel; they agree that the drip took about 3.5 divisions or $8.75\,\mathrm{ms}$ to pass. Drip effective diameter could be calculated from the known drip fall distance (the “drip drop”). The quiescent signal level is visible on each channel. It is about 2.3 divisions on the $500\,\mathrm{Hz}$ channel, which is $460\,\mathrm{mV}$ which corresponds to about 94 LSBs, well above noise and quantisation limits. The quiescent level is a little lower on the $1\,\mathrm{kHz}$ channel, and it is obvious that the square wave edges are rounded, suggesting that the frequency is at the high end of the workable range. In this instance it is likely to be a consequence of the loading of the ’scope probe.

Note that the flow rate has been returned in units of “drips/time”. In other words, no calibration is included in the code; that must be applied when it is desired to get into calibrated units of volume/time. The particular setups we used here were calibrated by running a peristaltic pump at constant speed and feeding the fluid from the bottom funnel directly into a measuring cylinder. We obtained values between 15 and 16 drips per millilitre averaged over a 10ml volume. This is more than sufficiently accurate for the purpose of controlling the reflux in a still.

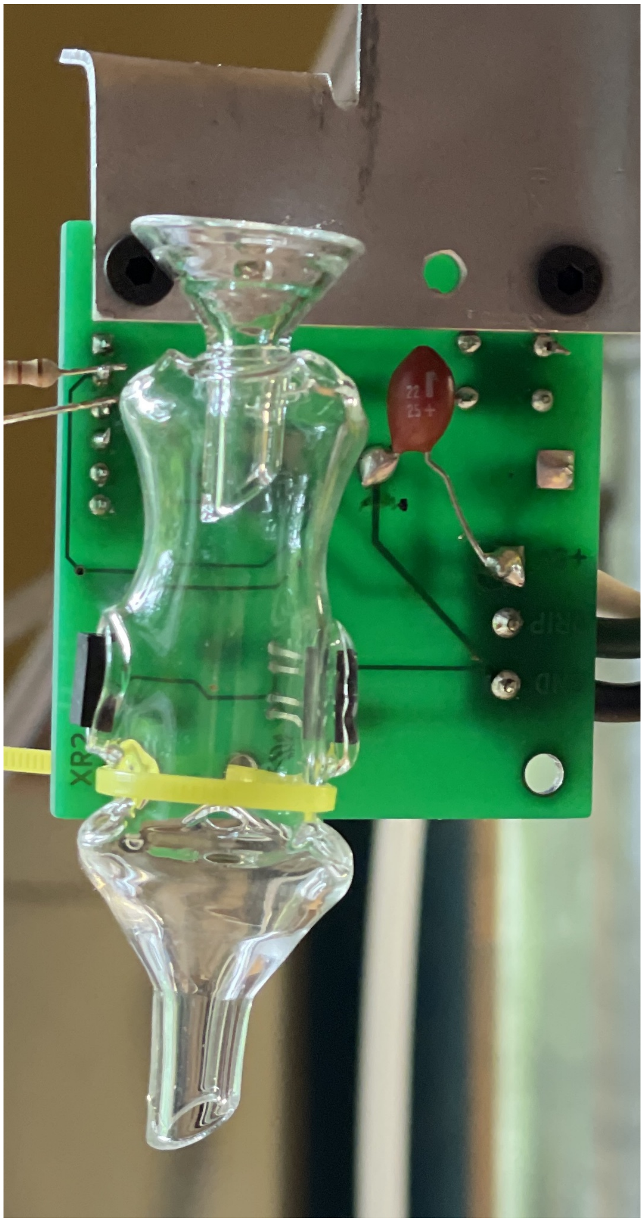


Fig. 7. Photograph of the prototype. The glass dripper assembly adheres to the dimensions in figure 2, although it is rather organic in appearance. It is adhered with cable ties to the electronic board. Note two holes that allow the reflective sensors to operate without the loss of glass in the optical path.

IV. CONCLUSION

Low flow rates are notoriously hard to measure. This sensor has a wide flow rate range that approaches zero. Many flow sensors have rate ranges below 100:1, and some that are not even 10:1. This unit has a potential range of 20,000:1 if a flow of 0.001 DPS is meaningful; more realistically it could be described as 500:1 before evaporation introduces significant error.

The cost of this sensor can be quite low, less than $10

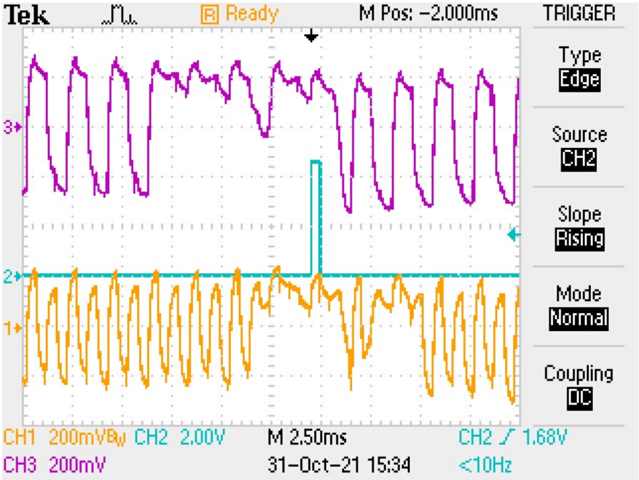


Fig. 8. Analog signals on the two receiving channels as a drip falls past the sensor. Note that one channel's signal drops ahead of the other. Detection occurs at the cyan pulse.

(including a PCB for 5 or so units).

The implementation of these units can form an excellent exercise for students of microcontrollers and metrology.

It would be straightforward to run it on a single lithium battery if the need arose.

On the negative side, the design relies upon gravity and is sensitive to the correct orientation of the vertical tube. It is also sensitive to vibration at certain low frequencies, where the forming drips hang from the upper funnel, and can resonate slightly. This introduces uncertainty in the trajectory of the drop after it disconnects.

APPENDIX

The circuit diagram of the processing electronics is shown in figure 9. The printed circuit board layout is shown in figure 10. Together with the photographs in this report it should be straightforward to construct drip flow sensors of this type.

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Steven Newcombe is an Advanced Technical Officer in the Faculty of Science at the University of Waikato, Hamilton, New Zealand. He has been the glassblower serving Chemistry and Engineering for 27 years. He has won more awards than it is seemly to list in a biography.

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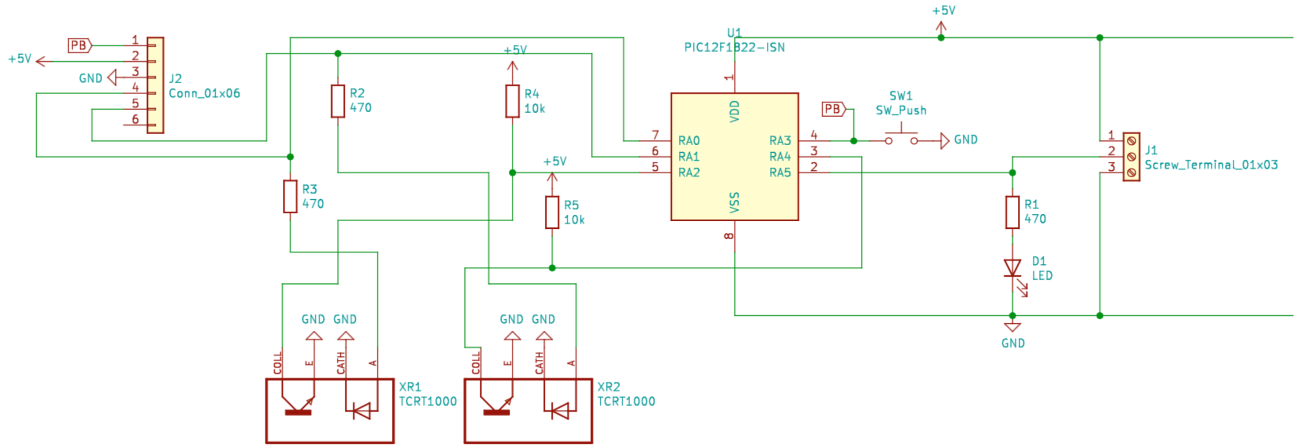

Fig. 9. Circuit schematic diagram of the flow meter electronics including two TCRT1000 reflective optical proximity sensors. There is provision for a programming header, but this would not normally be fitted unless debugging code.

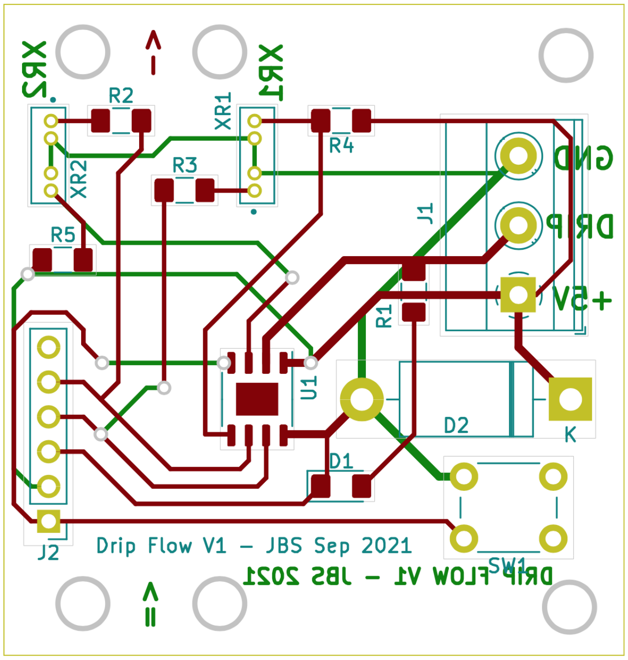

Fig. 10. Printed circuit board for the drip flow meter electronics. The circuit has an added diode for protection from reversed power supply polarity during testing, a screw-terminal connection block, an output indicator LED, etc. These need not be fitted