Imperial College of Science Technology and Medicine
Department of Electrical and Electronic Engineering
1st Year Electronics Laboratory
EEBUG Group Design Project

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Tutor	Dr S Wright
Design Group *(tutor's initials, followed by group number)*	SWW - 2B
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EEBug Design Report Part 2

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March 23, 2016

Abstract

In this project we intended to demonstrate the capabilities of analogue circuitry in performing a complex task such as following a line followed by predetermined manoeuvres. To do this we designed circuitry to control an EEBug to complete this task without the use of programmable micro controllers. In order not only to prove the adequacy of analogue logic but also to prove its ability to compete with programmable designs in data efficiency we also aimed to complete the task with only one of the two sensors allowed in this project.

1 Design Goals & Concept Development

1.1 The Challenge Brief

On the basis of the EEBug lab conducted in the autumn term, the group must design and implement an improved EEBug, which will execute the following two-staged function:

- Stage one: follow a track marked in fading greyscale on a white background, leaving a mark to show where it has been.
- Stage two: At the end of the track, it must continue straight for 10cm, then draw a spiral with decreasing radius, completing at least one full turn before stopping.

The full specification was as follows:

- The bug must follow a track marked in fading greyscale leaving a marked trail where it has been.
- At the end of this track the bug must continue for straight on for 10cm and then draw a spiral with decreasing radius.
- Must complete at least one full turn before stopping.
- The bug must draw a line indicating the path it has taken throughout the test.
- NB extra functions will gain extra marks.

The playing field:

- Dimensions 1250mm x 610mm.
- Clear polycarbonate cover covering a sheet of paper (white A1) with the track drawn on.
- The track is approximately 6mm wide.
- Minimum curve radius of 7cm.
- 20mm thick black border around the edge. Eebug design constraints:

- The design must implement an improved version of the stock Eebug.
- Enhancements must not exceed 8 per bug.
- Maximum of two sensors.
- All circuits nodes must be represented on the supplied breadboard.
- Maximum of 4 AA batteries.
- Must be completely autonomous.
- Basic bug architecture must not be altered.
- Microprocessors must not exceed 8 pins.
- The bug must not be confused by uneven lighting conditions.
- Must have a single switch (or equivalent system) to start. Making a bread board connection is not acceptable.
- Logbooks must contain a single page of operating instructions.
- Must work with used batteries (I ¿ 4A when shorted through an AVO set to 10A DC range).

1.2 Goals and Constraints

Beyond the limitations imposed in the design brief for the project we intended to further constrain our design to explore a more unique solution to the problem presented, unique in comparison to other teams working on this project. The reasons for particular decisions were spelled in out in greater detail in the previous management report. The main constraints and our design goals were, in no particular order:

Aim 1 The EEBug must not use any programmable micro controllers.

Aim 2 Active sensing of the track must be restricted to one sensor.

Aim 3 The EEBug should be able to function in a wide range of lighting conditions.

Aim 4 We aim to execute the final straight line and spiral manoeuvre as close to the end of the grey scale as is possible.

1.3 Design Concept

Although these constraints limited us somewhat, a couple compliment each other quite well. Although **Aim 2** limits the us in the manner we follow the track, the now available extra sensor makes **Aim 3** and **Aim 4** easier to implement. As will be discussed later on the idea of using the second unused sensor as a 'white' or 'black' reference was mooted as a contingency plan lest a single sensor solution could not perform both tasks of following the line and detecting the end of the line. In fact the use of a reference sensor has several advantages in terms of accuracy. The benefit of a reference sensor is that of reducing the impact of variable lighting conditions and allows more precise sensing of the fading grey scale section of the track. The most restricting of our aims was **Aim 1** since the more complicated nature of following a line using one sensor lends itself quite well to the abilities of a micro controller. Nevertheless, the aim our our project was to explore the capabilities of analogue electronics in a role most would delegate to programmable digital circuits.

2 Management

2.1 Financial Report

Table 1 tabulates expenses mainly for the purposes of prototyping up to date. So far expenses have overrun the prototyping budget of £8 given to us by 72p however we elected to move 1 from the budgets of the our individual Bugs in order to give ourselves more room to prototype and test ideas. This being the case our expenses are still within thee budget we set. Additionally, since several of the components could only bought in greater quantities than that required for prototyping we bought enough to equip all three of our Bugs. These were items 1, 7 and 8. Contributing to greater than expected expenditure we also had a poorly selected component, namely item 3 the quad comparator, which was found to have unsuitably low output voltage. Also, as will be explained in the design sections of this report, the total of five Op Amps in the final design was not required and therefore only item 12, the quad op amp, and not item 2, the dual op amp, will be required in the finished prototype.

	Item Description	Supplier	Date (2016)	Ref. No.	Quantity	Price	Subtotal
1	NMOSFET BS170	EED Stores	29/02	SD0225	3	£0.21	£0.63
2	TL072CP Dual Op Amp	EED Stores	02/03	SI0170	1	£0.52	£0.52
3	LM338N Quad Comparator	RS	02/03	5338237	1	£0.60	£0.60
4	IN916 Diode	EED Stores	09/03	SD0010	4	£0.02	£0.08
5	PCB Mounting Block 6/6	EED Stores	09/03	PCB005	2	£0.06	£0.12
6	L-794PWC White LED	Rapid	09/03	55-1888	2	£0.49	£0.98
7	Brass Standoff	OneCall	10/03	1466796	6	£0.39	£2.34
8	Vero Board Medium	EED Stores	10/03	VB0025	1	£1.48	£1.48
9	LED Green 5mm	EED Stores	10/03	SD0115	1	£0.08	£0.08
10	LED Red 5mm	EED Stores	10/03	SD0115	1	£0.12	£0.12
11	LED Amber 5mm	EED Stores	10/03	SD0125	1	£0.12	£0.12
12	TL074CNE4 Quad Op Amp	OneCall	16/03	1256325	1	£0.41	£0.41
13	DG419-DJE3 Analogue Switch	OneCall	16/03	1077115	1	£1.24	£1.24
				Expenditure			£8.72
				Remaining Budget			£23.28

Table 1: Current expenses (22/03/2016)

The cost of the components for each of our bugs is projected to be approximately £5.22. Of course this does not take into to account any subsequent enhancements made to the individual bugs. The largest contributor to the price of the completed Bug is the DG419 analogue switch at £1.24 arising due to the lack of choice in analogue switches. Going forward we intend to optimise our selection for both optimal performance but also for better economy. We believe the greatest improvement in price could be derived from sourcing cheaper lighting LEDs. For more information on the projected costs of individual components please refer to appendix B.

2.2 General Progress

The group continues to work corporately within the timeframe and the group structure established in the last term. The weekly group meeting is still held for discussion of key issues and delegation of tasks. The Facebook group is continued to be used as a way for effective communication. The use of Microsoft One Drive is established for the sharing of the written works and test results within the group, each member is able to conveniently edit and update the files. However, a few technical issues of files being synced back to older versions have resulted in loss of some progress.

The high level design was developed mainly through group meetings. The major discussion was revolved around the method for line following, considering the self-constrain of using only one sensor to sense the track.

Through discussions the optimal method was chosen. Then the design was as planned divided into subdivisions, namely: Line Following Method, Sensor, Motor Control, Line End Detection and Final Maneuvre. The concept for each subdivision was discussed in detail previously in the High Level Design section. With the deliverable high level design completed, each member of the group is equally assigned with tasks to design the detailed circuits for each division.

The detailed circuit design was carried out by all group members and finished before the nominated deadline and suitable components were ordered accordingly. The parameter of the some components were designed to be not specified, and adjustment potentiometers were implemented in the circuits, these choices enabled the group to adjust the circuit to give the desirable characteristics during the following testing stage.

In building and testing the bug prototype group meetings halted in favour of using the time to construct the circuits in the lab. Management of the building stage revolved around using the subdivisions of the circuit, described in High Level design Section 3, to build the full in smaller blocks whose functions could be individually tested before combination with the other circuits. The main advantage of this approach was the subdividability of the work and the ease with which errors in the detailed design could be discovered.

Since the last report, the team have generally succeeded in meeting the timetable set out in December. However slow ordering combined with ill selected components has reduced our ability to effectively prototype our design within the time constraints given.

2.3 Plans for Future Work

In the final stage of the project we intend to achieve a few goals. We have prioritised these quite strongly in the following way.

1. Completion of final testing and problem shooting.
2. Optimisation of selected components and circuit design both in terms of performance and economy.
3. Fabrication of our individual Bugs.
4. Development of 'super bug' functionality not necessarily on an individual basis.

3 High Level Design

Since the various components of the design were strongly interdependent, the high level design was largely developed in group meetings to avoid mistakes in compatibility between various sections of the design. More significant delegation of tasks started for the low level design later on. This will be expounded on in more detail in the management section.

3.1 Line Following Method

The first concept that needed tackling was the method by which the Bug would follow the line. A common method that can be seen in similar projects is to use two sensors either side of the line to give indication as to which side of the line the Bug is on. This is then compensated by driving the motors at different speeds to bring the Bug back in line. This method lends itself particularly well to negative feedback set ups. However, due to our self enforced design constraints, namely to use only one sensor to sense the line, another solution had to developed.

The main issue with a one sensor solution is knowing which side of the line the bug is moving. We came up with two solutions to this issue. The first was to use a toggling system to make the Bug alternate between turning left and right every time it crosses the black line.

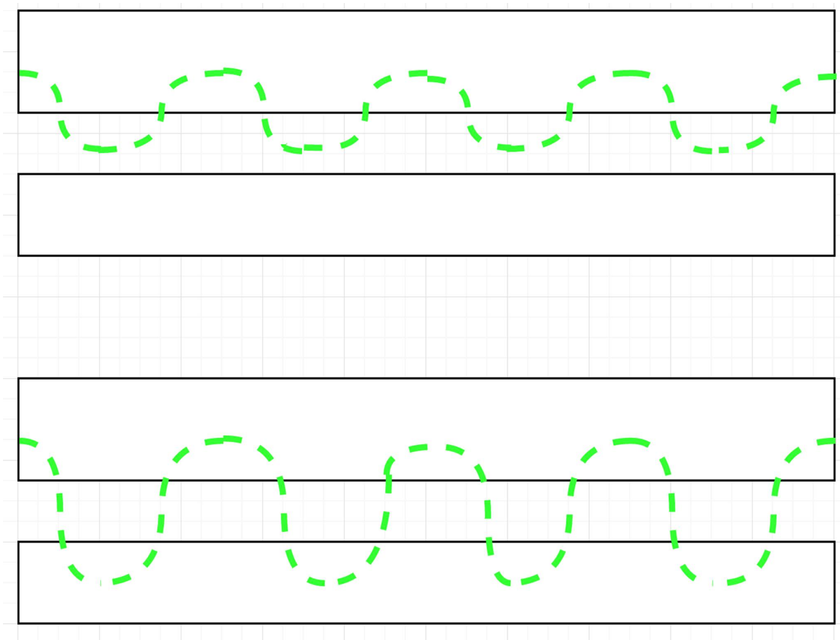


Figure 1: INSERT DIAGRAM HERE

The advantages of the solution illustrated in **Figure 1** (bottom) are quite significant. Most importantly this scheme makes it hard for the Bug to lose the track. even if it over shoots the line by a wide margin the Bug will always be turning towards the line. Only under the circumstance that track curves rapidly towards the path of the Bug will its incident angle be greater than 90°causing it to retrace the line in the opposite direction.

Although this is a desirable trait, it comes with a few but important trade offs:

- Significant 'meandering' in the Bug's path becomes inevitable. This increases in severity with a thicker track.
- The implementation of the toggling might involve the use of Flip Flops which tend to come in IC packages of four or more. Otherwise a toggling circuit must be designed with discrete transistors.
- On a maximum turn, and depending on its incidence angle, the bug could spend significant time off the line which could adversely affect its end of line detection capability
- If a 'white' reference sensor is used it may be more likely to accidentally cross the black and cause an error in the analogue logic.

Another, and our preferred, solution is to work off a single edge of the track, see figure 1 (top). In essence this is like following a black border, the only difference being overshooting the line will cause the Bug to lose the position of the line. Whenever the sensor is over white the Bug will turn right, whenever it is over black the Bug will turn left or vice versa. This solution, although less redundant, lacks several of the problems of the previous:

- Theoretically the 'meandering' of the Bug due to the left and right turning is significantly less.
- The implementation is simpler since all that is required is comparison between the active sensor and the reference sensor.
- Since the Bug stays exclusively on one side of the track, it is easier to prevent a reference sensor accidentally crossing the track.

3.2 Subdivision of Circuit Design

In order to simplify the task into smaller, more manageable, easier to delegate portions we divided up the concept into four functions. These were sensors, motor control, line end detection and final manoeuvre timing. The way these separate circuits are to interact is illustrated in Figure 2 below. Certain blocks such as the left/right turn were omitted given their relative simplicity but these will expanded on in more detail in the detailed design section(4) of this report.

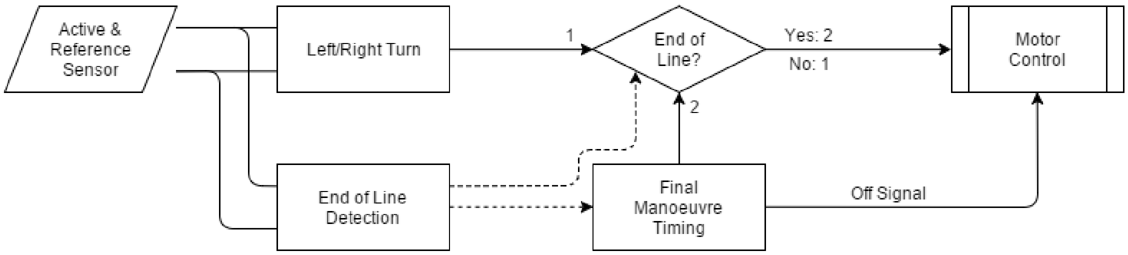


Figure 2: Flow chart illustrating the input to output flow of the enhanced EEBug. Dashed lines indicate input used as a trigger and this case they latch.

3.3 Sensors

As set out in **Aim 2** our objective was to use only one sensor. This being the case no reference sensor would available and thus the single sensor would have to be compared with a set calibrated reference to show whether the Bug as on or off the line. In order to function effectively the sensor set up would have to be very unresponsive to ambient lighting conditions. In order to achieve this we decided to shroud the sensing area to block out any external lighting sources and then to provide our own constant lighting source using a bright LED.

Since the complexity of our project was already significantly increased by our ambitious goals we selected a relatively simple sensor design consisting of an LDR with an illuminating LED. During initial tests we realised that the operation of LDR in potential dividers as sensors was relatively simple and effective.

In terms of the circuit processing the input, we decided two outputs were desirable. These would be an output to drive the motors left and right and another to indicate when the end of the line was found. The former would simply compare the value of the output by the sensor to a reference a value calibrated to the colour of the white and thus give out a high or low value indicating whether the Bug is on the black or the white. The latter would go active when the Bug reaches the end of the line. This will be explained in greater detail in Section 3.5.

3.4 Motor Control Circuit

Due to the complexity of using analogue circuits to process information from the sensors, a motor control circuit that takes as input only one signal is useful. This means that the inputs only need to processed down into one motor driving signal. It seemed reasonable, given the 6V power rail available to us, to design a circuit that would vary the current through each motor based on a a single 0V to 6V signal. The first motor current would increase with increasing voltage, while the other would decrease with increasing voltage. This made turning left or right as simple as inputting 0V or 6V. Of course this would mean that the Bug would be unable to remain stationary as one or both the motors must be running at any one time. To remedy this another input to cut off the power supply to the motors would stop both motors.

Another aspect that would need addressing is the speed at which the motors spin up and spin down. Our solutions for following the line require accurate transitioning between turning and left and right else overshooting and losing the line is a strong possibility. In terms of braking the motors, we thought to use some system to short the motors through a resistive load when not in use in order to dynamically brake them.

3.5 Line End Detection Circuit

Line end detection relied on the ability to compare the value sensed over the black and the value sensed over the white. Initially we intended to use a circuit to hold the value sensed over the black to be compared with the held value sensed over white. When these two values converged it would indicate the line had faded away. However this relied on the line following method causing sufficient meandering in the Bug's path to bring the single sensor fully over both black and white colours.The advantage of this method would have been that high accuracy in finding the end of the line.

As will be discussed in more detail in the Detailed Design Section 4, the lack of sufficient meandering in the Bug's path and other considerations such as the maximum turn rate of the Bug would render this solution infeasable. Unfortunately this was only realised in an advanced stage of the detailed design.

3.6 Final Manoeuvre Timing Circuit

The trickiest area of the design lays in the timing and driving of the final manoeuvre. This requires the Bug to drive straight for 10cm and then do a spiral of decreasing radius for at least one full turn. We wanted this circuit to be a one shot circuit that would be triggered when the line end detection circuit finds the end of the line. It would also be necessary for this circuit to end the Bug's movement by shutting off power to the motors.

4 Detailed Design

4.1 Design Subdivision

The design, as stated previously, was subdivided into smaller sections which could be, to a large extent, designed separately and later coupled together to produce the final circuit. These were the sensors, motor control, line end detection and final manoeuvre timing.

Given that we were working in analogue, much of the circuit had to incorporate potentiometers in order to negate imprecise component values and to fine tune the circuit to the desired behaviour. These potentiometers will not be represented in this section but will be detailed in the Testing Section(4) later on and in the overall circuit diagram in Appendix A.

4.2 Motor Control Circuit

In the high level design we specified that the motor driving circuit would take two inputs. One to govern the differential between the two wheels and another to turn the motors on on or off. A simple way to implement this is to use an inverting and a non-inverting amplifier with the two motors as their respective loads. In this case we decided to use BJT common emitter amplifiers. These can be seen on the right of Figure 3. This has the problem that, with mismatched βvalues and motor impedances, the motors will not run at an equal speed when the input voltage is between the power rails. To solve this and also to give more leeway in the value of the input voltage, a potentiometer is connected in combination with the normal base resistors. This allows the differential between the two motors to be trimmed, this is more essential when taking the straight line manoeuvre into account.

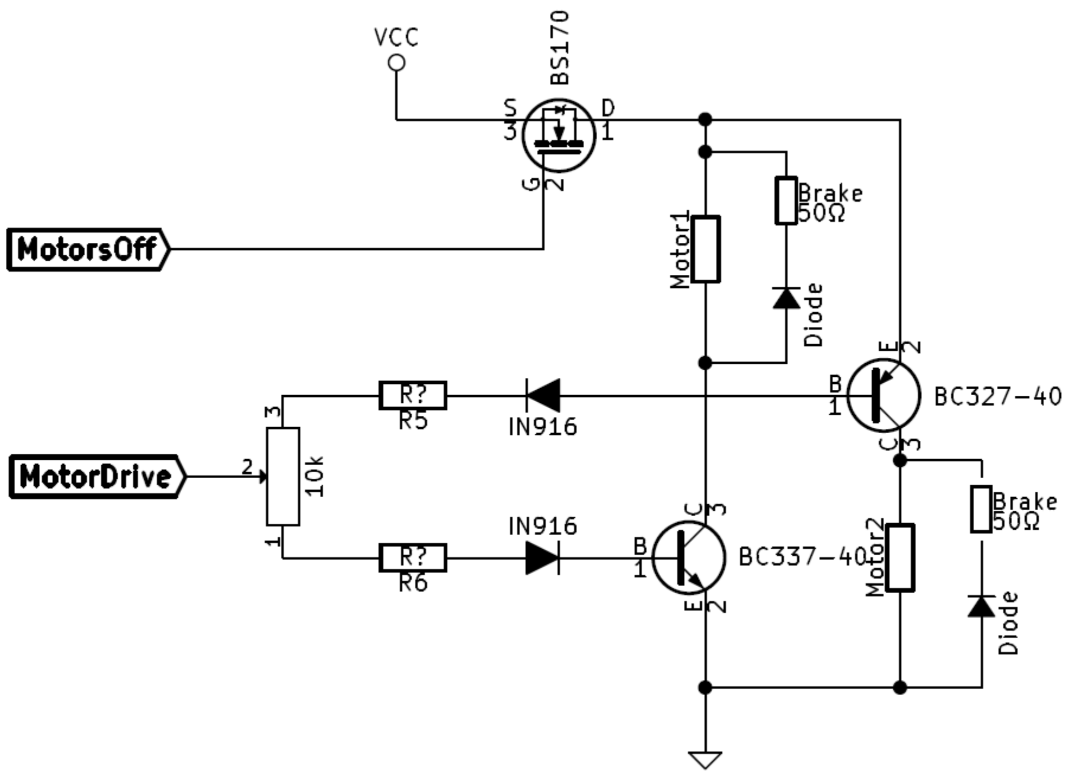


Figure 3: EEBug motor control circuit. The values of R5 and R6 are subject to further testing and have not yet specified

Given that the motors are inductive loads, they cannot be relied on to spin up and spin down quickly without some kind of braking solution. Not only do the inductance of the motor coils but also the inertia of the Bug itself reduce the transition time between different speeds. In our design we decided to dynamically brake the motors using a a resistor in parallel with the motors. Since the a parallel resistor would be constantly dissipating energy and, due to their low resistance, requiring a larger collector current on each transistor, we decided to put small diodes in series with them to prevent dissipation of constant dissipation of power while the Bug is turned on. When the transistors are put into their respective cut off regions the current the through the motors continues to flow through the braking resistor and diode. This dissipates the energy stored in the motors, both inductive and mechanical. This way of braking does effect the energy efficiency of the Bug but this was considered to be a reasonable trade off for simpler design and drastic improvement in line following.

As will be shown in Section 4.3 on the line sensing circuit, the Motor Drive input of this circuit will come directly from the output of an operation amplifier and therefore will not be capable of reaching the positive or ground rails of the Bug. Thus if the input were connected simply through resistors to the bases of each amplifier then the control would circuitry would not be able to bring each transistor into the cut off region when required. There would always be a collector current and therefore limit the braking capability described previously. To fix this diodes were placed in series with the resistors to create an extra voltage drop of approximately 0.7V. In total this increases the voltage to approximately 1.4V below which the transistors moves into the cut off region. This optimisation of the switching on and off of the motors is quite desirable since it allows the motors to brake faster and also reduces power dissipation from small currents due to transistors that are not fully switched off.

The final element of this circuit is the input which cuts of the current supply to the motors. We decided to simply implement this using a single n-channel MOSFET. When the motor off signal (MotorsOff in Figure 3) from the final manoeuvre timing circuit goes high it the n-mosfet cuts off the current supply to the motors stopping the bug in its position.

4.3 Line Sensing Circuit

The line sensing circuit was specified in the high level design to provide two outputs to other elements of the circuit. These were an output indicating whether the bug was on or off the line measuring perpendicular to the line and an output indicating whether it had reached the end of the line. In the design specified here the sensor inputs are two potential dividers incorporating a variable resistor. One of these variable resistors would be the light dependent resistor (LDR) used to follow the line while the other could either be a reference LDR that follows the colour of the fading black colour of the track. This circuit is illustrated in Figure /reffig:linesensing.

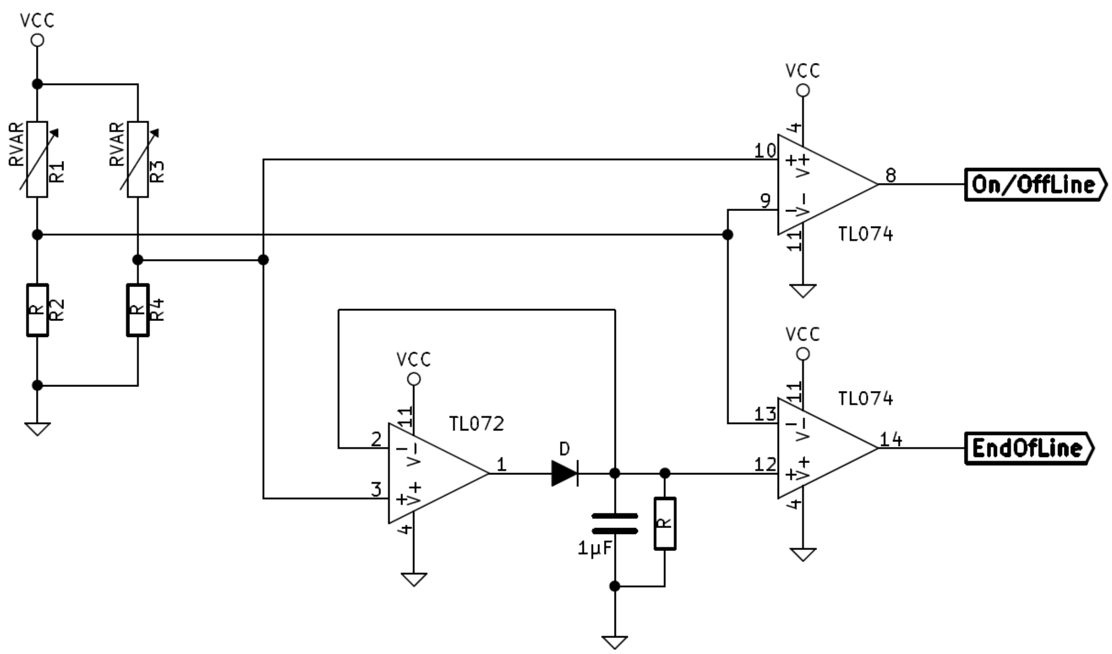


Figure 4: Our first design for the line end detection implementing a peak detector circuit

The On/Off Line output was the simplest in design consisting of only one op amp (top right Figure 5) used as a comparator to compare whether the reference voltage or the sensor voltage is higher. This creates a square wave output who's rising and falling edges correspond to moving onto and off the line. This is then later used to drive the Bug left and right through the motor driving circuit described earlier. The choice of which direction the Bug turns, that is if it turns right on the black or if it turns left on the black, is to a large extent arbitrary and only effects whether the Bug will follow the left hand or the right hand side of the line.

Originally our design was intended to use a single sensor and therefore was a little more complex. Since we were using only one sensor to sense the line the sensor would therefore move onto and off the black line to in order to steer the bug. Because of this constant transitioning between black and white colours we could not simply compare the signal from the sensor directly with a reference voltage for white.This would cause the Bug to commence its final manoeuvre as soon as it left the line in any way. Instead we needed to hold the value of the sensor as it over the black line while it moved back onto the white. From this we could then compare a diminishing black colour as it faded to grey with the white reference voltage. To hold the value of the grey scale track we used a peak detector circuit to take the maximum value of the sensor. To achieve this we intended to incorporate a peak detector to sample and hold values of black 'intensity' sensed as the bug meanders back and forth over the track boundary. This peak detector consisted of a diode connected to a capacitor forming a rectifier circuit. Since the diode will have a forward voltage drop associated with it an op amp is implemented with negative feedback to bring the potential across the capacitor to that of the input. This essentially creates an 'ideal' diode with negligible voltage drop and therefore much better correlation with the actual peak of the input signal. A resistor was to be placed in parallel with this capacitor to allow the stored voltage to drop over time, periodically being refreshed when the sensor crosses the black. In this manner the held value of the black track could be compared with the reference voltage. When this dipped below the reference voltage, an op amp comparator would then output a high signal triggering the final stage manoeuvre.

It is important to realise that this implementation places a few constraints on the operation of the EEBug. Firstly, since it uses this peak detector circuit set up, it must always begin from being on the line else the peak detector will not be charged up and the final manoeuvre will commence prematurely. Secondly, the bug must be constantly encountering the line in order that the peak value to be constantly refreshed. If not, the peak detector may discharge before it has encountered the end of the line and also cause premature triggering of the final manoeuvre. On any straight section of line this is not an issue, but on any minimum radius turn this will present a challenge. Since the minimum radius of the track is only slightly larger than half the axle width of the Bug, this could present a real problem if the Bug does not follow the edge of the line perfectly. Additionally this minimum radius is measured from the centre of the line not the edge therefore our Bug design has approximately 3.5mm less turning radius to work with. As a contingency the peak detector circuit could be replaced with black sensing sensor. Given the restriction to only two sensors, this would only be possible if we used a potentiometer as our white reference. Also this would violate **Aim 2** specified in the Section 1.2.

It was realised later on in the prototyping stage that the reliance of the mode of line end detection relied heavily on the meandering of the bug. As a consequence of the implementation of dynamic breaking in the motor driving circuit the Bug would never fully stray onto the middle of the black line and thus this method of sampling would never sample a true sensor value over the black. The design for detecting the end of the line mentioned above is retained in this report since we still believe it to be a viable solution to the one sensor problem if the method of following the line was changed, possibly to the first method mentioned in Section 3.1.

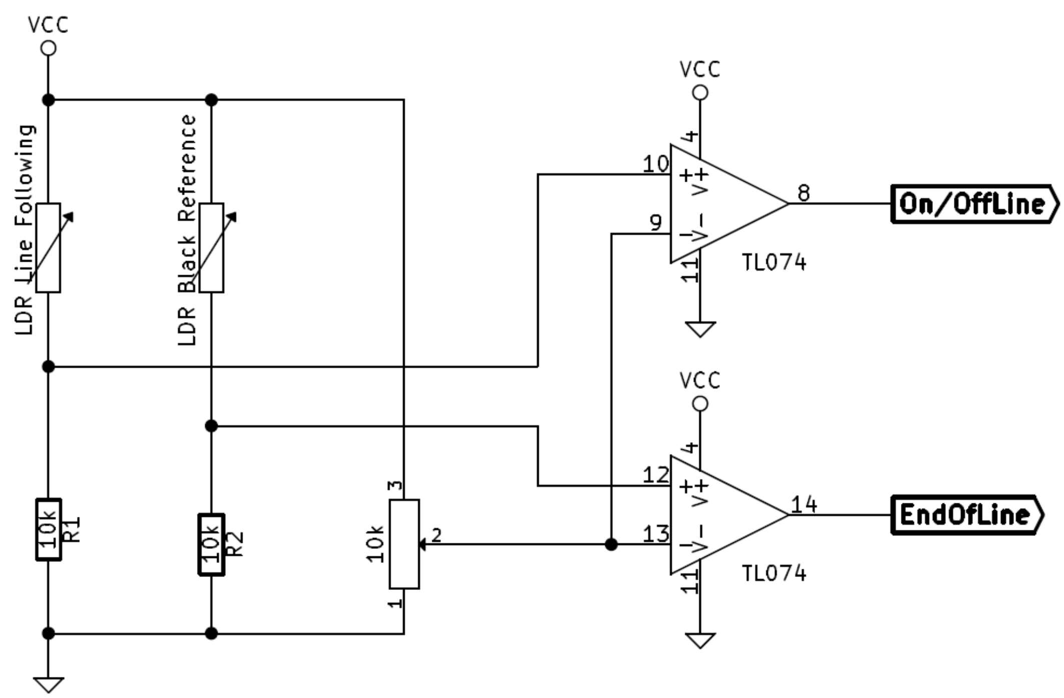


Figure 5: Line sensing circuit used to process the input from the two sensors against a fixed reference voltage

At this point, for the sake of creating a working Bug, we decided to use a two sensor solution. Using the same method of following the line mentioned above we decided to detect the end of the line using another sensor positioned over the middle of the black line. This gives us a very accurate way of comparing the fading colour of the track to our reference voltage. Although this violates one of our aims to use only a single sensor, we still believe it is an interesting solution which actually allows for accurate line end detection, since one sensor is solely employed in monitoring the intensity of the black track.

4.4 Final Manoeuvre Timing Circuit

The final manoeuvre that the Bug makes after it has reached the end of line consists of driving in a straight line for 10cm and then making spiral of decreasing radius. In order to do this a signal needs to be passed to the Motor Drive input of the motor control circuit (Figure 3). The signal begins with a constant value of approximately half the rail voltage followed by a gradual drop off towards zero volts. The first constant voltage corresponds to an equal current through both left and right motors and thus a straight line move. In the second part of the signal where the signal drops off one motor will speed up while the other will slow down causing the bug to turn with a gradually increasing rate of turn. Originally our design incorporated a rising edge at the beginning of the signal but taking into account the way in which we switch between the normal line following signal and the final manoeuvre signal this rising edge using an analogue swithc this was completely unnecessary and complicated the circuit needlessly. Additionally our original designs used two timing circuits in parallel to time the manoeuvre and the switch off at the end. We realised that this meant the switch off timer had to have a much larger time constant, one which could easily cause errors due to the bias currents in the op amps. We remedied this by putting the timers in line so that the first effectively triggered the second.

To implement this we used a a combination of two low pass RC filters and two op amps as shown Figure 6. As shown in Section 4.3 on line sensing, the signal that triggers the final manoeuvre is essentially a heavy side function. If this is fed through a low pass filter it results in a slowly rising voltage, since a rising is a discontinuity and thus equivalent to a high frequency component. In this case the response will look like a capacitor charging curve dependent on the RC time constant. By using an op amp to compare this to a reference voltage we can create a delay between the input rising edge and a corresponding falling edge on the output of the op amp.

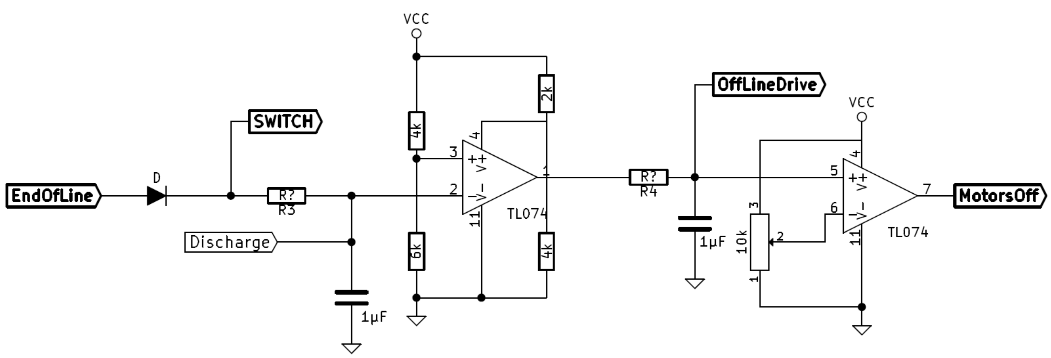


Figure 6: Final manoeuvre timing circuit

We want a gradual drop off in the output to the motors. By passing the output of the op amp through another RC low pass filter we get a gradual drop off of the falling edge in the form of a capacitor discharge curve. Although a linear drop off might sound more desirable, a discharge curve of in manner is quite effective since it quickly moves the bug from a straight line into a relatively sharp turn which, given the small playing field the Bug has to move within, is optimal.

The right most op amp of the circuit is concerned with turning off the motors off after a given amount of time to manoeuvre. It is triggered off the timing of the output of the first op amp. The only difference is this delay is much greater. In order to increase the delay a larger RC time constant must be used. We decided to keep the capacitor value the same on all filters and only have varying resistor the values. The reasoning behind

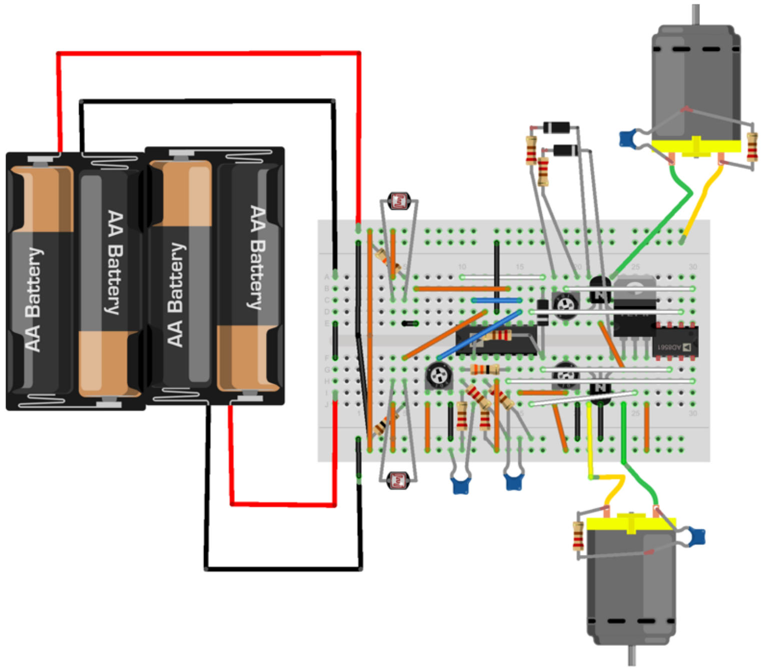


Figure 7: Breadboard layout

this was that capacitors with small leakage currents such as polyester are more expensive than resistors and therefore capacitors could be bought in bulk to reduce prices. Since we are dealing in very long time delays in the order of seconds large resistor values coupled with the leakage current of the capacitors and the input bias current of the op amps can result in fairly large voltage offsets that interfere with the timing. This was actually encountered during preliminary tests using electrolytic capacitors. Therefore we decided that polyester capacitors were suitable with their low leakage current. The extra cost was of little consequence given the relative cheapness of the overall circuit and the size of our budget.

The third and crucial output of this circuit is the SWITCH output (top left Figure 5). This output is essentially equivalent to the End of Line output from the line sensing circuit except with one difference. Using a diode the charge built up across the capacitors of the low pass filters is trapped. This is because this entire node is connected is connected to either the diode, the capacitor or the inputs of an op amp. This acts as a crude peak detector which holds the value of SWITCH high, disregarding any current leakage through the op amps or the capacitors. This is important because it not only make the timing circuit one shot but also prevents the Bug from switching back to its line following mode. This will be explained in more detail in Section 4.5 on combining the various elements of the circuit. The issue thrown up by this charge trap is that every time the bug is used the capacitors must be discharged else it will cause undefined or no behaviour to occur. This is solved using a single pole double throw switch used to turn the Bug on and off. When the Bug is off the switch will short circuit the capacitors, when it is on the switch will connect the negative of the battery to the ground rail. This functionality is represented by the Discharge label 6.

4.5 Combining the Components

Combination of the disparate elements of our circuit was a simpler area of the design and can probably be better explained by simply looking at the full schematic in Appendix A. The breadboard connections themselves can best be summarised as follows:

5 Testing

5.1 Fine Adjustment of Individual Bugs

Much of the testing done centred around fine tweaking the characteristics of the circuit through the adjustment potentiometers to obtain optimal performance. The main areas were sensor sensitivity, motor drive speed and timing of the final move.

The timing is controlled through the RC time constants of the two parallel timing circuits. To time and adjust these a signal generator could be attached to the input of these circuits to provide as input a rising edge. This could be achieved by switching the signal offset on and off. Using the two channels of an analogue oscilloscope and a smart phone stopwatch we could find the timings of the circuits. Using the lap button we could time all points of interest at the same time. These were primarily the time until the signal began falling and the time until the off signal went high. In this way we could select the correct resistor value to gain the correct timing.

Motor speed tuning centred on making the bug drive in a straight line during the final manoeuvre. In order to calibrate this 3V was supplied via jump wire to the Motor Drive input. The potentiometer was then turned until the two motors speeds moved at the same speed

In the line sensing circuit a potentiometer is implemented to set the right reference voltage. To calibrate this potential the line following sensor is placed on the black line sensing black while the reference sensor is sensing the white.The potentiometer is carefully turned to the point that the other motor begins to turn.

The third potentiometer requires calibration is the motor off reference in the Final Manoeuvre Circuit. When calibrating, the bug is tested on the track to execute the functions, the potentiometer is calibrated incrementally after each test until the optimal time period taken for the bug to start the final manoeuvre is reach.

5.2 Power Dissipation

With a one ohm resistor connected in series with the batteries of the Bug circuit we used a Arduino Uno with a SD card adapter to log the voltage across this resistor. In doing so we obtained a plot for the current supplied by the batteries. Along with the voltage of the batteries, which we assumed had negligible changes in voltage during operation, we could calculate the power developed by the Bug with respect to time. For aesthetic reasons more than anything else we used the R programming language to sort these data in Figure 8 for plotting.

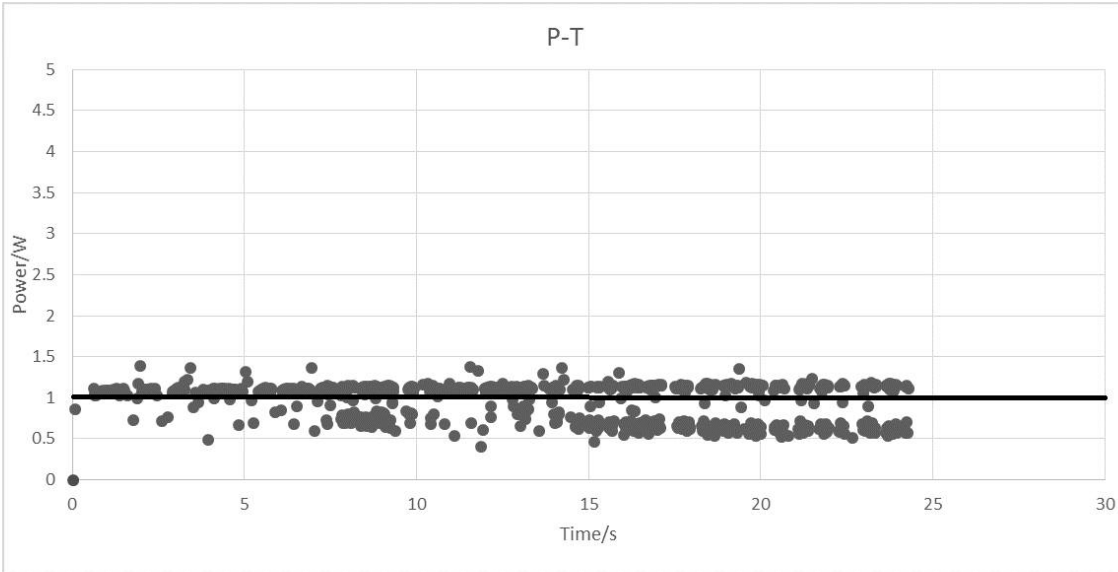


Figure 8: Total power dissipation while following a solid black line. The first seven seconds of data are before the bug was placed in a line.

The data shows an average power of 1W when the bug is following a line. The first seven seconds of data were taken while the bug was not on the line and therefore one of the motors was fully on. At seven seconds the bug was placed on the line and we can see how the constant spinning up and spin down of the motors reduces the current being drawn from the batteries and therefore decreasing the power consumption of the Bug. The average power is also roughly in line with what we expected since we estimated a current of a approximately 100-200 mA through each motor. The speed at which the bug switches between the left and right turning states is also evident from this plot since power dissipated varies rapidly between 1.2W and 0.7W as the bug moves on and off the line. Since the power consumption does not look radically greater than what we expected we believe and the rate of transition between right and left turning is high, we believe that this is confirmation of our dynamic breaking design which both brakes the motors while not dissipating current constantly. However we believe we can improve the power dissipation even more. One idea that we came up with, though too late for inclusion in this report was the idea of capacitive braking, to avoid wasting energy through dissipating the power.

6 Enhancements

At the current stage of the report prototyping and testing has not been fully completed and thus implementations of enhancements has not been started. However we believe further 'super bug' features will present a unique challenge in analogue. Whereas much extra intelligence can be implemented on a digital Bug through the use of programming an analogue Bug must have extra circuitry. A few main ideas are being considered, these may be implemented singularly or in combination. This mainly comes down to the limited number of nodes remaining to us on the breadboard.

- AM Radio Player: Either a dedicated AM radio IC could be installed or a circuit devised to receive AM radio signals and play them as the Bug cruises along the track. The method of receiving the signal would likely be via an inductor in parallel capacitor to form an antenna and fixed tuned receiver. This idea would likely take up a significant number of nodes.
- Indicators: Not so much a super bug function but complimentary to other ideas this would constitute using LEDs to show the various logic states across the circuit. For example, the left and right turning could be shown by LEDs

- Wiggle Pattern: The bug would be made to alternate between stepping over the right hand side of the line and then left hand side of the line repetitively, creating a whimsical wiggle pattern. A toggle circuit would need to be added to our circuit. This way, the bug would switch between turning right and turning left only when it sensed a black to white transition. Essentially this is the same as the method of line following discussed in the high level design which we did select. An issue we already realise about this idea is that realisation of a toggle circuit with flip flops is difficult in the limited space we have. Given that flip flops in through hole packages all have a large number of pins, this super bug function might be difficult to realise with the few nodes we have left on the breadboard.

- Single Sensor: Our original goal and probably the most interesting idea, following the line with the use of a single sensor would best show off the capability of analogue to perform a complex task such as that presented in this project. This particular idea would complemented quite well by the previously stated Wiggle Pattern idea. A sig zagging pattern along the track would solve the issue we encountered in the design of our first design solution since it would bring the single sensor reliably over the black track.

7 Conclusion

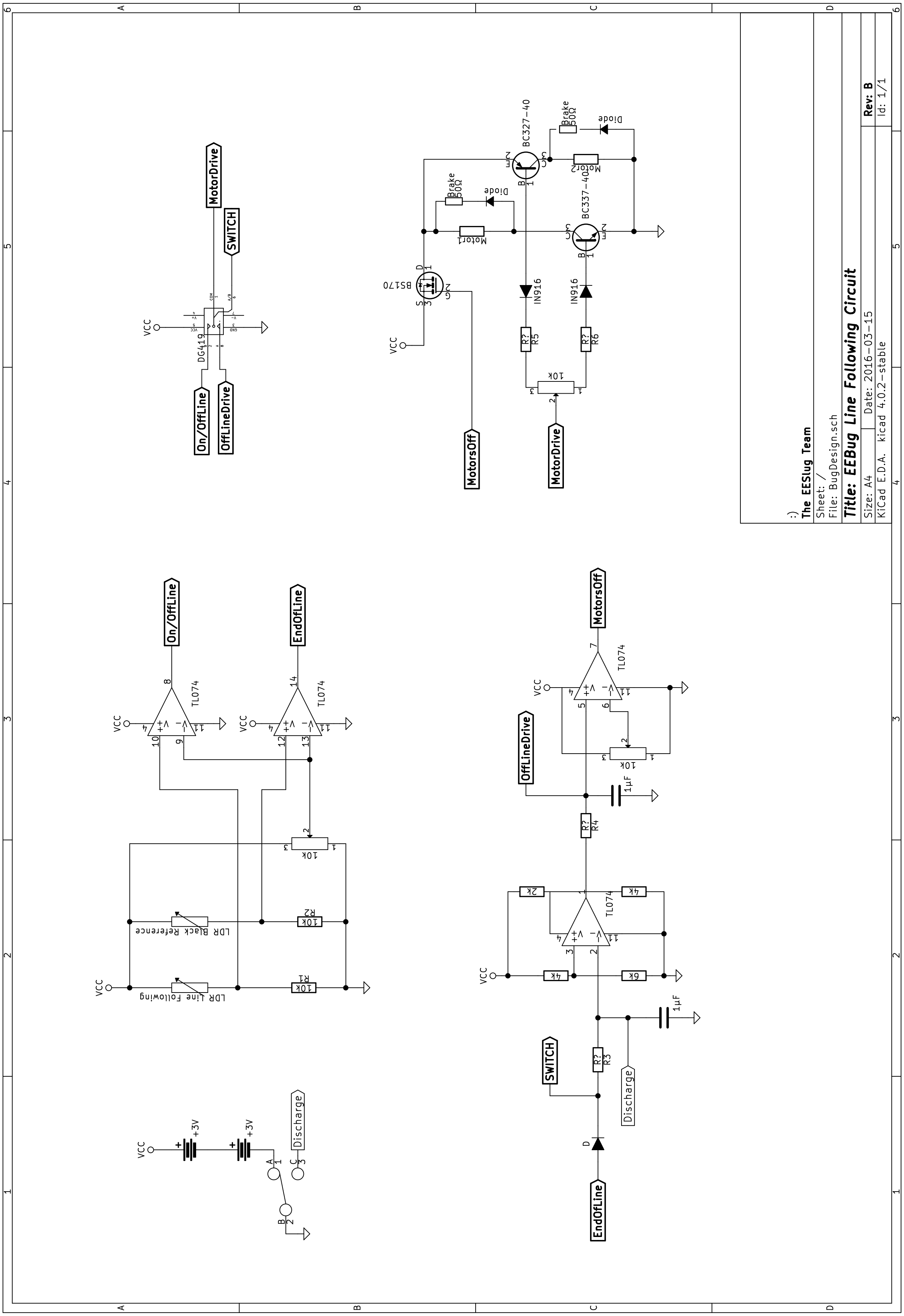
Although at an advanced stage the development of our Bug is not yet complete. However it is already capable of performing the task given to us and thus, if wanted by the members of team, we could begin development of our individual bugs. This being said we still believe that a single sensor solution is attainable with a small change in how the bug follows the line.

The project so far has definitely shown the limitations of analogue circuitry. As was realised, to the detriment of our design and testing progress, the inflexibility of analogue circuitry does not lend itself well to effective prototyping. Although our first designs had no technical faults in them, significant problems were encountered when a problem in the design concept, not its implementation, were found. To change the behaviour of the Bug, significant redesign of the circuit often had to occur. Under time pressure as we were this became a significant problem since the downtime between building prototype circuits could be long. Both redesign of the circuit and ordering of new parts had to occur before the revision of the circuit could be built and tested. The process of building circuits itself was also made harder by the shear number of components that had to be installed on the breadboard without error. In stark contrast, the programmability of micro controllers allows for swift altering of the Bug's behaviour. However, designing and prototyping the simpler functionalities such as line following proved to be much quicker in analogue. Our team was one of the first to have a Bug follow the line. We discovered that the majority of difficulties in prototyping arose exponentially as the circuit size increased.

We found that our solution was competitive in price with some of our digital competitors, mainly those using the PIC micro processor. Despite our much larger circuit and greater number of components, the cost of a single micro controller far outweighed any of our components. This being said, greater costs were incurred by us during the prototyping stage.

Our design of circuit has proved that analogue methods can be just as capable at performing flexible but limited scope tasks as programmable digital circuits. In fact, under certain circumstances analogue solutions can be vastly more accurate due to there simple operation. A prime example of this is the speed with which we created a simple line following Bug, though not line end detecting. Further exploration may yet yield a one sensor solution which we think would ultimately show the capability of analogue 'logic'.

A Circuit Diagram



B Components List

Component	Quantity	Price	SubTotal(GBP)
MOSFET BS170 N	1	0.21	0.21
IN916 DIODE	3	0.02	0.06
TL074 QUAD OP-AMP	1	0.41	0.41
DG419DJ-E3 Analogue Switch	1	1.24	1.24
L-794PWC 8mm White LED	2	0.49	0.98
PCB MOUNTING BLOCK 6/6	1	0.06	0.06
Brass standoff	2	0.39	0.78
Vero Board	1	1.48	1.48
			Total: 5.22

C breadboard layout