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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Design Group	CPA
Lab market (see list "Stage 2 &3 report markers", on labweb)	Dr T Constandinou
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Design Project Spring Report

During the first stage of the group project, the design specifications were analysed and the tasks were distributed between each member in order to develop suitable solutions. In the second phase, different solutions were then considered, brought together and discussed throughout different meetings. Respecting the management plan, the group achieved its objective of designing and implementing a prototype meeting the requirements.

In this report, the management and the general progress of the project are initially compared with the original plan. Then, the developed design is explained from a high and low level perspectives and different simulations are carried out. Finally, selecting appropriate components, a prototype is successfully constructed as well as tested, and possible enhancements are presented.

Project Summary

With respect to the original plan and the established deadlines, two minor issues occurred. The first one happened when we decided to change the timing mechanism from a digital-based solution to an analogue one. Consequently, we fell back in the schedule by a week. The second issue presented itself because of an order mistake: the components were received later than expected. These issues were solved by a little extra work and by the flexibility of our planning. For the rest, the plan was followed properly and no changes in the management structure were made.

The group's members and their assigned role, specific tasks and contribution are described in *Table 1*. All the members attended the meetings and contributed to the success of the project. The main issue to be highlighted is the meetings. In fact, we decided to have regular meetings on Wednesday afternoons. Although it accommodated most of the members, this clashed with some of the member's personal timetables. To solve this, separate meetings with flexible times for specific tasks were organised.

Name	Position	Specific Task	Contributions	Issues
Lorenzo SCUTIGLIANI	Secretary	Logic	Passionate about circuit design, he also helped others with their tasks.	None
Alexandre HADJ-CHAIB		Logic	Alexandre contributed to the logic circuit design and helped in testing the bug prototype.	None
Quentin MCGAW	Leader	Sensor	Quentin helped elaborate the detecting sensor circuit and choosing the components.	None
Leonardo IALONGO	Treasurer	Sensor	Leonardo designed the sensor's amplification circuit and ensured the components ordered were appropriate.	Was sometimes late to meetings.
Hao DING	Counter signatory	Timing	Designed an initial digital version of the timing mechanism. He checked orders submitted were correct and helped for the prototype testing.	Had to leave early on Wednesdays because of other appointments.
Guang YANG		Timing	Contributed to the timing mechanism design and helped in the testing.	None

Table 1: Member's assigned roles, specific tasks and contribution

High Level Design

The final version of the circuit is composed of five different blocks: *time enabling system, sensor's amplification, spiral enabling system, motors' state assessment* and *motors' control system*. Each stage is discussed and analysed separately from a high level perspective in terms of inputs and outputs. All of the functional blocks relationships are summarised in the following figure (*Figure 1*):

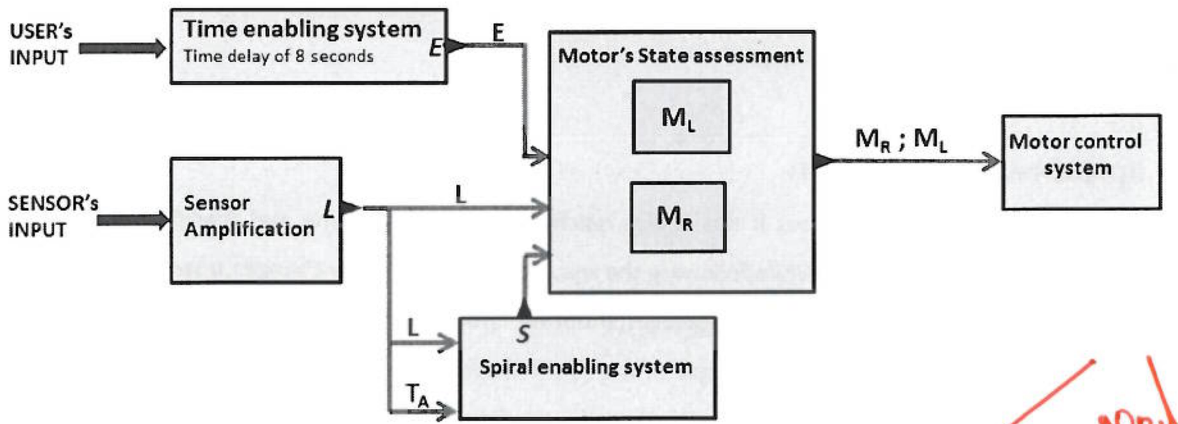


Figure 1: *Relationships between each functional block*

good.

Time enabling system

This initial function dictates the state of the whole circuit (*ON* or *OFF*) and is time-controlled, since the circuit is required to begin its operation with a delay of 8s. The user's input is processed to produce an output (*E*). The input-to-output relationship is summarised below (*Table 2*):

USER's INPUT	8s from INPUT	OUTPUT (E)
LOW	LOW	LOW
LOW	HIGH	LOW
HIGH	LOW	LOW
HIGH	HIGH	HIGH

— not clear.

Table 2: *Time enabling system input-to-output relationships*

Sensor's amplification

This function receives the single sensor's output and amplifies it to allow the successive stages to efficiently process it. In fact, using a single sensor not only reduces the costs but also leaves more flexibility in terms of design enhancements. Therefore, the sensor is used to detect a black line over a white background and produces two discrete states (*ON-line* or *OFF-line*). Its output has to be compatible with the following digital stages, so the function needs to produce two discrete states (*LOW* and *HIGH*). The following table summarises the operation of the function (*Table 3*) :

SENSOR's OUTPUT	OUTPUT (L)
ON-line	HIGH
OFF-line	LOW

Table 3: *Sensor's amplification operation*

This amplification stage does not need to provide exact discrete states for the output, although it needs to tend as much as possible to them. At least, the output's swing is required to lie midway between these two reference states.

Spiral enabling system

This function determines if the device reaches the end of the line and therefore if the spiral process needs to be enabled. While following the line, the sensor regularly changes state from *ON-line* to *OFF-line* with an average period (T_A). However, if during T_A the change of state does not occur and the sensor's output is *OFF-line*, then the end of the line is likely to be reached. Consequently, this stage needs to be time-controlled, processing (*L*) to produce a time-varying output (*S*), lying between the two reference states. The following table summarises the input-to-output relationship (*Table 4*):

INPUT (L)	T_A from INPUT	OUTPUT (S)
LOW	LOW	LOW
LOW	HIGH	HIGH
HIGH	LOW	LOW
HIGH	HIGH	LOW

Table 4: *Spiral enabling system input-to-output relationship*

Since this is not the last amplification stage, the output is not required to be exactly close to the reference states. However, a threshold value should at least be defined above which the time delay T_A is reached and below which it is not.

Motors' state assessment

This stage processes and amplifies the previous functions' outputs to determine the state of both motors (*ON* or *OFF*). This function accepts three inputs (*E, L, S*) and produces two amplified and reliable outputs (M_L , M_R) each accepting the states *LOW* or *HIGH.* The input-to-output relationship is summarised below (*Table 5*):

INPUT (E)	INPUT (S)	INPUT (L)	OUTPUT (M_L)	OUTPUT (M_R)
LOW	LOW	LOW	LOW	LOW
LOW	LOW	HIGH	LOW	LOW
LOW	HIGH	LOW	LOW	LOW
LOW	HIGH	HIGH	LOW	LOW
HIGH	LOW	LOW	LOW	HIGH
HIGH	LOW	HIGH	HIGH	LOW
HIGH	HIGH	LOW	HIGH	HIGH
HIGH	HIGH	HIGH	HIGH	LOW

is motor control a low or high decision? or graded-response?

Table 5: *Motors' state assessment input-to-output relationship*

If the circuit is not enabled (*E LOW*), both motors are turned off (*M_R LOW ; M_L LOW)*. However, if it is enabled (*E HIGH*), then the motors' state is exclusively determined by the states L and S. If the end of the line is not reached (*S, LOW*), then if the sensor is ON-line (*L HIGH*), the device turns right (*M_R LOW ; M_L HIGH*). Otherwise, if the sensor is OFF-line (*L, LOW*), the device turns left (*M_R HIGH ; M_L LOW*). As a result, the device follows the right edge of the line.

Now, if the end of the line is reached (*S, HIGH*), then if the sensor is ON-line (*L, HIGH*), the device still turns right (*M_R LOW ; M_L HIGH*). However, if the sensor is OFF-line (*L, LOW*), then both motors are turned on (*M_R HIGH ; M_L HIGH*). In the last case, by appropriately controlling the speed of each motor, a spiral can be obtained.

Motors' control system

This last stage controls the speed and torque of both motors depending on the output states M_R and M_L. While the device follows the line, the motors are expected to constantly change state with a high frequency. Instead, when the end of the line is reached, both motors should stably turn on. By reducing the speed of both motors over a certain time T_M, resetting each time switching occurs, at high switching frequencies a constant speed is obtained, while at low frequencies it should decrease. If appropriately controlled, this generates a spiral as requested.

Low Level Design

Now, each module previously described from a high level perspective is analysed in details and the circuits behind them as well as their connections are unveiled. The complete circuit with its different blocks is shown in Appendix 1.

Time enabling system

To achieve the previously described time enabling system, the operational amplifier U1 with positive feedback is used. In particular, an inverting Schmitt Trigger configuration with dynamic threshold is implemented. Therefore, assuming no current is drawn by the op-amp inputs and using KCL at its positive input V_{1+} gives:

— where from?

(1) $$\frac{V_{1+}-\frac{3}{2}}{R_1}+\frac{V_{1+}-V_{OUT1}}{R_{F1}}=0$$

Simplifying and rearranging in function of V_{1+} :

(2) $$V_{1+}=\frac{3}{2}+\frac{\left(V_{OUT1}-\frac{3}{2}\right)R_1}{R_1+R_{F1}}$$

referring to what? → hard to follow.

Since the positive and negative supply voltages of the op-amp are respectively 3V and 0V, the op-amp output V_{OUT1} is either 3V or 0V because of positive feedback and the dual threshold is therefore given by:

~~#~~ w/o schemati[c] here.

$$V_{1+} = \frac{3}{2} \pm \frac{3}{2}\frac{R_1}{R_1+R_{F1}} \qquad (3)$$

Consequently, by choosing $R_1=R_{F1}$, the threshold voltage is set at either 2.25V (V_{OUT1} = 3V) or 0.75V (V_{OUT1} = 0V). In particular, R_1 and R_{F1} are chosen to be equal to 1.5MΩ. This reduces the power consumption of the device without compromising its performance.

To control the time switching of the op-amp, a simple RC configuration is implemented at the op-amp's negative input V_{1-}. With this arrangement, if the user's input is 0V (*OFF*) and because of the diode D1, the capacitor C_1 discharges immediately, V_{1-}=0V, V_{out1}=3V and the threshold is set to 2.25V. But if the user's input switches to 3V, then C_1 begins to charge and V_{1-}, assuming no current is drawn, is given by:

$$V_{1-} = 3(1 - e^{(\frac{-t}{R_{T1}C_1})}) \qquad (4)$$

Simplifying and rearranging as a function of R_{T1}:

$$R_{T1} = \frac{t}{C_1 ln(\frac{3}{3-V_{1-}})} \qquad (5)$$

Therefore, since a delay of 8s is required and the threshold voltage is 2.25V (V_{1-}), by choosing C_1=1µF, the value of R_{T1} is determined with equation (5) to 5.8MΩ. To sum up, if the user's input is 0V, then V_{OUT1} immediately becomes 3V, and if the user's input is 3V, then V_{OUT1} switches from 3V to 0V after a delay of 8s.

Sensor's amplification

To determine if the device is on the black line, an infrared emitter/receiver diode pair is used. Infrared receivers and emitters are preferred to avoid light interferences. From the manufacturer's datasheets, for currents smaller than 10mA, the following relationship between R_{E1} and I_{E1} for the infrared emitter holds:

$$R_{E1} = \frac{1.6}{I_{E1}} \qquad (6)$$

In order to reduce the power consumption, I_{E1} is set to 2mA, so R_{E1} is determined with equation (6) to be around 800Ω.

Now, to a certain current flowing through the emitter corresponds an amount of emitted infrared radiations. Similarly, to a certain amount of received infrared radiations, a certain current is allowed to flow backwards in the receiver. In fact, black absorbs infrared radiations while white reflects them. Pointing both emitter and receiver towards the ground, two discrete current values at the receiver can be recorded, depending on the ground's colour. These values are recorded by pointing the sensors towards the black line (I_Z) and then towards the white background (I_A): I_A=1.88μA and I_Z=0.90μA.

To amplify the receiver's current signal (I_{IN}) a C-E amplifier with a single bipolar transistor is implemented. The following equations are describing its behaviour:

$$I_{C1} = \frac{3 - V_{out-amp1}}{R_{C1}} \tag{7}$$

$$I_{B1} = \frac{I_{C1}}{\beta} = \frac{3 - V_{B1}}{R_{B1}} + I_{IN} \tag{8}$$

Since the output's swing is required to lie midway between 3V and 0V, for V_{C1} = 1.5V:

$$I_{IN} = \frac{I_A + I_Z}{2} \tag{9}$$

Combining (8) and (9) and rearranging as a function of R_{B1}:

$$R_{B1} = \frac{2(3 - V_{B1})}{2\frac{I_{C1}}{\beta} - (I_A + I_Z)} \tag{10}$$

To reduce the power consumption of the device, the collector current I_{C1} is set to 1mA. The value of R_{C1} is then determined using equation (7) with a quiescent output voltage $V_{OUT-AMP1}$=1.5V to be approximately 1.5kΩ. Using the manufacturer's datasheet of the transistor, the beta value is 295 for this collector current. Moreover, assuming V_{B1} = 0.6V and using the previously measured values of I_A and I_Z, the value of R_{B1} is determined using equation (10) to around 1.2MΩ.

Then, the small signal analysis gives the following small signal output voltage swing:

$$v_{out} = \mp \frac{3r_o R_{C1}\beta(3-V_{B1})(I_A-I_Z)}{2(R_{C1}+r_o)[3V_T-V_T\beta R_{C1}(I_A+I_Z)+3(3-V_{B1})]} \quad (11)$$

Assuming $r_o \gg R_{C1}$, V_T = 25mV and V_{B1} = 0.6V, v_{OUT} is determined with equation (11) to be approximately 0.2V.

As a result, if the sensor is on the black line, then the amplified output voltage V_{C1} is expected to be around 1.7V while if it is on the white background, then V_{C1} is expected to be 1.3V.

Spiral enabling system

To implement the spiral enabling function, the op-amp U2 is used as an inverting Schmitt trigger together with an RC circuit. The op-amp acts as a second amplification stage for the sensor's output, while the RC circuit controls the duration *t* the sensor stays off the line.

If the circuit is enabled, the potential divider between the time enabling system's output (0V) and the 3V supply needs to provide 1.5V to the resistance R_2. Consequently, R_{P1} and R_{P2} need to be equal and small enough to supply an unvarying voltage, but not too small to avoid large power consumption. Consequently, a value of 1.5kΩ is chosen for them.

With this potential divider, the relation between R_2, R_{F2} and the dual threshold voltage of U2 is the same as in (3). Since the output voltage swing with respect to 1.5V of the amplified sensor's output is 0.2V, it is reasonable to set the dual threshold voltage swing to $\pm 0.1V$. Using equation (3) only considering the threshold voltage swing (*x*) with respect to 1.5V and rearranging as a function of R_{F2}:

$$R_{F2} = \frac{(1-\frac{2}{3}x)}{\frac{2}{3}x} R_2 \quad (12)$$

For x = 0.1V, R_{F2} is determined with equation (12) to be 15 times R_2. R_{F2} and R_2 are hence chosen to be respectively 1.8MΩ and 120kΩ. Consequently, if the sensor is on the line, the op-amp output $V_{OUT-AMP2}$ is expected to be 0V while if the sensor is off the line, $V_{OUT-AMP2}$=3V.

The op-amp output is then connected to the capacitor C_2 in series with the resistor R_S, which is connected to the time enabling system's output V_{OUT1}. Moreover, the grounded diode D2 is connected towards the function's output V_{SPIRAL}, situated between R_s and C_2. Now, if the circuit is enabled (V_{OUT1}=0V), then when $V_{OUT\text{-}AMP2}$=0V (on the line), no matter the charge across C_2, $V_{OUT\text{-}AMP2}$ stays at 0V. In fact, if C_2 is charged and $V_{OUT\text{-}AMP2}$=0V, then V_{SPIRAL} is negative and current immediately flows through the diode D2 to discharge C_2 bringing V_{SPIRAL} to 0V. Now when $V_{OUT\text{-}AMP2}$=3V (off the line), then V_{SPIRAL} varies with time according to the following equation:

$$\textbf{(13)} \qquad V_S = 3e^{\left(\frac{-t}{R_S C_2}\right)}$$

Simplifying and rearranging in function of R_S:

$$\textbf{(14)} \qquad R_S = \frac{t}{C_2\, ln\left(\frac{3}{V_S}\right)}$$

Consequently, the longer the sensor stays off the line, the lower V_{SPIRAL} is. Now, defining a threshold voltage V_T = 0.75V below which the sensor stays more than T_A = 0.5s off the line and setting C_2=1μF, R_S is determined using equation (14) to be 360kΩ.

To sum up, if the sensor stays more than 0.5s off the line, $V_{OUT\text{-}AMP2}$=3V and V_{SPIRAL}<0.75V, the device needs to enter the spiral phase. However, if the circuit is disabled, then V_{OUT1} switches to 3V. The potential divider provides 3V to U2 and the dual threshold increases to either 3V or approximately 2.8V. Since U2's negative input V_{2-} ranges from 1.3V to 1.7V, $V_{OUT\text{-}AMP2}$ stays at 3V. Consequently, V_{SPIRAL}=3V, no matter the sensor's state.

Motors' state assessment

To assess the state of both motors (*ON* or *OFF*), the two op-amps U3 and U4 are respectively used as an inverting Schmitt trigger and as a NON-inverting Schmitt trigger. Now, the voltage V_{DIV} of the previously discussed 1.5k/1.5k potential divider is connected to the negative input V_{4-} of U4 and to the resistance R_3 itself connected to the positive input V_{3+} of U3. The output V_{SPIRAL} is then connected to V_{3-}. The resistance R_4 in front of the positive input V_{4+} of U4 is connected to the second amplification stage output voltage $V_{OUT\text{-}AMP2}$.

If the circuit is enabled, the relation between R_3, R_{F3} and the dual threshold voltage of U3 is the same as in (3). However, the relation between these three quantities is different for U4. More specifically, assuming no current is drawn by the op-amp inputs and using KCL at V_{4+} gives:

$$(15) \qquad \frac{V_{div} - V_{OUT-AMP2}}{R_4} + \frac{V_{div} - V_R}{R_{F4}} = 0$$

Replacing V_{DIV}=1.5V and rearranging in function of $V_{OUT-AMP2}$:

$$(16) \qquad V_{OUT-AMP2} = \frac{3}{2} + \frac{\left(V_R - \frac{3}{2}\right) R_3}{R_{F3}}$$

Since the supply voltages of U4 are 3V and 0V, V_R is either 3V or 0V because of positive feedback and therefore the dual threshold is given by:

$$(17) \qquad V_{OUT-AMP2} = \frac{3}{2} \pm \frac{3}{2} \frac{R_3}{R_{F3}}$$

The inverting Schmitt Trigger has to amplify V_{SPIRAL}. Since the spiral should start when V_{SPIRAL}<0.75V, the lower dual voltage needs to be 0.75V. Therefore, the same resistance values used in U1 in the *time enabling system* can be used. In other words, R_3=R_{F3}=1.5MΩ.

However, the purpose of the NON-inverting Schmitt Trigger is simply to maintain the signal coming from $V_{OUT-AMP2}$ (*Spiral enabling function*) in phase with the amplified V_{SPIRAL}. Actually, U3 and U4's output controls the state of one of the motors. If the NON-inverting op-amp is omitted, the circuit would still work but a motor would switch *ON* and *OFF* faster than the other. Consequently, the values of R_4 and R_{F4} are not important. However, for the sake of consistency the dual threshold voltage is set to the same in both op-amps. Therefore, to obtain the same dual threshold voltage, equation (17) can be rearranged, giving:

$$(18) \qquad R_{F4} = \frac{3}{2} \frac{R_4}{\left(V_{OUT-AMP2} - \frac{3}{2}\right)}$$

For $V_{OUT-AMP2}$=2.25V, R_{F4} is determined with equation (18) to be twice R_4. To maintain low power consumption, R_{F4} and R_4 are chosen to be respectively 1.5MΩ and 750kΩ.

Now, if the circuit is enabled and the sensor on the line, then $V_{OUT-AMP2}$=V_{SPIRAL}=0V. Furthermore, the inverting amplifier output V_L=3V while the NON-inverting output V_R=0V. As a result, since the device needs to follow the right edge of the line, U3 assesses the state of the left motor (M_L) while U4 assesses the state of the right motor (M_R). On the other hand, if the sensor is off the line, then initially $V_{OUTAMP2}$=V_{SPIRAL}=3V. Consequently, V_L=0V while V_R=3V as expected. However, if the sensor stays off the line for more than 0.5s, V_{SPIRAL}<0.75V and V_L switches to 3V.

Finally, in the case where the circuit is disabled, $V_{OUT-AMP2}$=V_{SPIRAL}=V_{DIV}=3V.Consequently, because of the positive feedback, V_L and V_R would eventually switch to 0V and both motors are turned off.

Motors' control system

To implement the motors' control system, a symmetrical circuit for each motor is designed with two power bipolar transistors and an RC circuit. The motor is connected between the 1.5V power supply and the collector of transistor Q5 (or Q3 symmetrically) whose emitter is grounded. Only 1.5V supplies the motor to limit its speed, giving enough time to the sensor and the circuit to detect the change of state and process it. Moreover, to protect the transistor, a diode is connected in parallel between the inputs of the motor.

The base of Q5 is connected to the emitter of a second transistor Q4 whose collector is connected to the 3V power supply. Finally, a resistor R_5 and a capacitor C_3 (or symmetrically R_6, C_4) are connected in series between Q4's base and V_L (or symmetrically V_R). This controls the current through the motor and therefore its speed decreases as C_3 charges. A diode is connected from the 0V towards the node between R_5 and C_3 in order to promptly discharge C_3 if the motor state is 0V.

Consequently, Q5, directly controlling the motor's current and voltage, acts as a switch, while Q4, controlling Q5's base, acts as an amplifier. The following relations are derived:

$$I_{B5} = \frac{I_{C5}}{\beta_S} \approx I_{C4} \approx I_{B4}\beta_A \tag{19}$$

Rearranging in function of I_{B2}:

$$I_{B4} \approx \frac{I_{C5}}{\beta_S \beta_A} \tag{20}$$

Assuming the motor draws at maximum 0.7A (I_{C5}), and the beta value of the power transistor is 20(β_S) in saturation mode and 340(β_A) in active mode (datasheet), then from equation (20) I_{B2} should be at maximum 100μA. Assuming the voltage drop base-emitter is 0.8V for the saturated mode and 0.7V for the active mode of the transistor, if the motor state is 3V, the RC circuit simply has a potential difference of 1.5V across its ends. The current I_{B4} is:

$$I_{B4} = \frac{1.5}{R_5} e^{\left(\frac{-t}{R_5 C_3}\right)} \tag{21}$$

Since I_{B4} should be 100µA at maximum (t=0), then R_5 is determined by:

$$R_5 = \frac{1.5}{I_{B4}} \quad (22)$$

So, with I_{B2}=100µA, we have R_5=15kΩ. By altering the value of C_3, the rate at which I_{B4} decreases, rate changes. The rate at which the motor's speed decreases is hence modified according to equation (21).

If the motors' states change with high frequency, then the speed of both motors is constant and equal to each other. However, if the motors' states become constant (spiral phase), then the capacitors decrease the motors' speed depending on their respective capacitance, resulting in a spiral until both capacitors are completely charged.

Simulation

Before building a prototype, a PSPICE simulation is performed to ensure the circuit behaves according to the theoretical models. For this purpose, the PSPICE models of the chosen transistors are used. Since the manufacturer doesn't provide a PSPICE model for the selected op-amps, ideal ones from the PSPICE library are used instead.

To perform the simulation, the user's input is replaced by a constant $3V_{DC}$ signal. The sensor's output is a square wave current generator of period 0.5s oscillating between 0.90µA and 1.88µA. A transient analysis of 14s is executed: the amplified sensor output, the state of the motors and their speeds are displayed (*Appendix 2*):

Overall, it appears the simulation reflects the theoretical expectations. During the first 8s both motors states are switched to 0V and the motors are turned off. Then both motors start changing state according to the amplified sensor's output displaying in each case a certain speed. Finally, when the sensor's amplified output remains constant, the left motor switches from 0V to 3V after 0.5s as expected and the motor's speed effectively reaches a certain peak before decreasing exponentially at the same rate as the capacitors charge.

Costs and Procurement

The following table lists the selected components for the prototype (*Table 6*). Overall, a suitable compromise between cost and required performance was used to select them.

Components	**Manufacturer Part No**	**Price (£)**	**Quantity**	**Company**
High Speed Infrared Emitting Diode	TSFF5210-CS12	0.47	1	VISHAY
Silicon PIN Photodiode	BPV10NF	0.64	1	VISHAY
Low voltage fast-switching NPN power transistors	2STX1360	0.124	4	STMICROELECTRONICS
Rail-to-Rail Op Amp	MCP6284-E/P	1.35	1	MICROCHIP
Resistors		0.01	19	
Capacitor Ceramic		0.05	2	
Capacitor Electrolytic		0.20	2	
Transistor-BC548	2N5089G	0.15	1	
TOTAL		**3.796**		

Table 6: *Costs and procurement list*

under budget

Prototype

Following the simulation, a prototype is built based on the designed circuit and the ordered components. The disposition of the components on the breadboard is shown below (*Figure 2*) :

component labels?

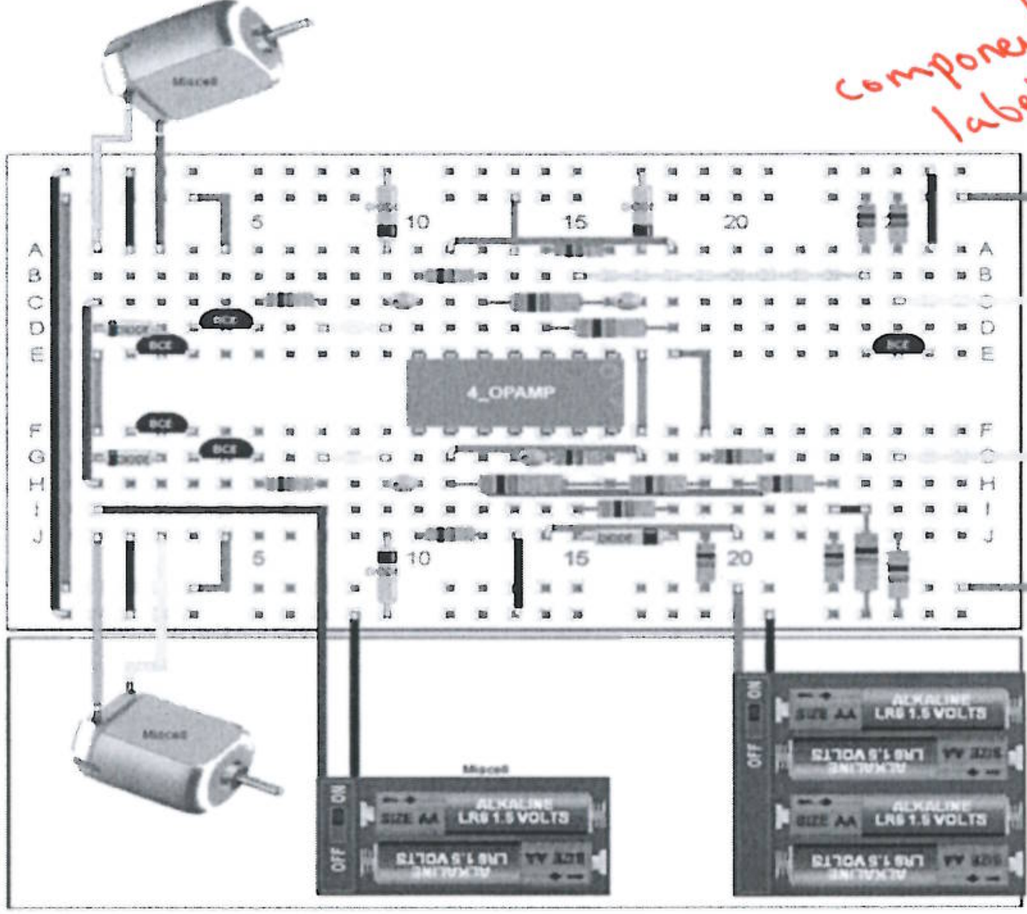


Figure 2: *The components disposition on the breadboard.*

The connections and the nodal behaviours are checked using a DMM with the motors disconnected. Once all the mistakes in the circuit construction are corrected, the motors are connected and a test track is built using white papers and a black permanent marker. The thickness of the line is 0.6cm. Moreover, 10µF capacitors are used in the motors' control system to start with. The device is placed at the beginning of the line and the user's input set to 0V.

The user's input is switched to 3V and a stop watch is used to record the time. Initially, the device waits around 7.4s before starting to follow the line. This is probably due to the fact the op-amp in the time enabling system draws current, reducing the capacitor charging time. To solve this problem the resistance R_{T1} is increased to 6.2MΩ. The device follows the line but once the end of the line is reached, it performs a 180° turn before reaching the line again and following it in the opposite direction.

Checking the spiral enabling system behaviour, this time with the motors connected, its output V_{SPIRAL} seems never to drop below 0.75V. This is probably due to the op-amp effectively drawing current again at the input. However, after disconnecting the motors, V_{SPIRAL} can drop below 0.75V. As a result, it seems the more current the op-amp needs to provide, the more input current is drawn. The amount of current flowing in the RC circuit of the spiral system is thus increased without modifying the RC product. Consequently, the capacitance is fixed to 10µF and the resistance to 36kΩ.

With these modifications, the starting timing delay is effectively 8s and a spiral path is followed once the end of the line is reached.

Design Enhancements

From the described circuit, two possible enhancements which would lower the power consumption and simplify the user's input mechanism can straightforwardly be implemented. The first consists in replacing the power bipolar transistors used in the motors' control system by power MOSFETs while the second is about implementing a sound sensor which would control the user's input.

Power MOSFETs

Replacing bipolar transistors with FETs would be an enhancement for the power consumption and for the circuit reliability. In fact, the main factor determining power consumption is current. Lowering current would therefore lower power consumption. Since FETs are controlled by the voltage at their base, and BJTs by the current flowing in their base, FETs definitely consume less power. base current only?

Only a single power MOSFET would be needed, replacing the present transistor connected to the motor. The exact same RC circuit would be kept but the resistor and capacitor would be connected in series between the motor state output and the ground, while the node shared by both components would be connected to the MOSFET's gate. This new circuit design is shown below (*Figure 3*).

is this saving significant?

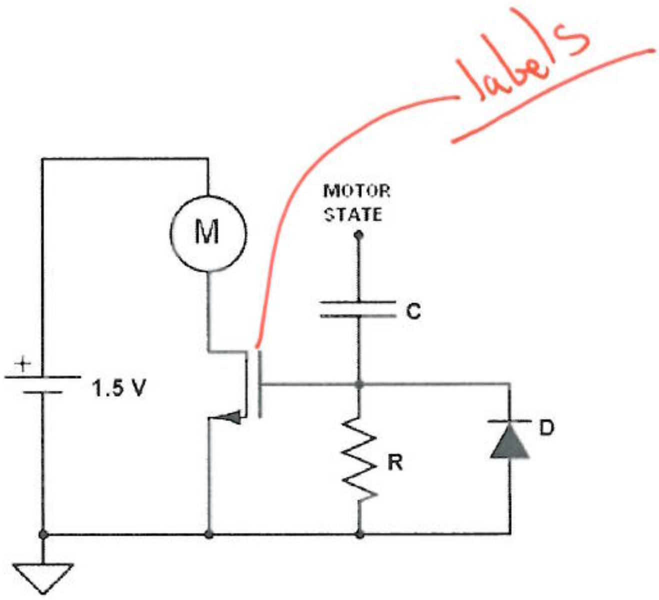


Figure 3: *Circuit design improvement with Power MOSFETs*

The resistor and capacitor values would depend on the MOSFET characteristics, but overall the resistance should be high and the capacitance low to reduce power consumption. Moreover, this would decrease the current provided by the motor control op-amps, which would increase the resistance and decrease the capacitance in the spiral RC circuit as well.

Sound sensor

A sound sensor could be used to control the user's input. This sensor would trigger it ON or OFF in response to a certain frequency sound produced by the user. For instance, clapping would switch either ON or OFF the user's input and therefore enable or disable the circuit.

To achieve this, a simple sound sensor combined with a D-Flip Flop could be implemented. The negative terminal of the sensor would be grounded and the positive connected to the Flip-Flop clock input. The flip flop input would be connected to its inverted output, while its non-inverted output would be connected to the user's input. The sound sensor system is shown below (*Figure 4*). In this way, each time the user claps his hands, a clock pulse would be produced which would enable the circuit if it is currently disabled and vice versa.

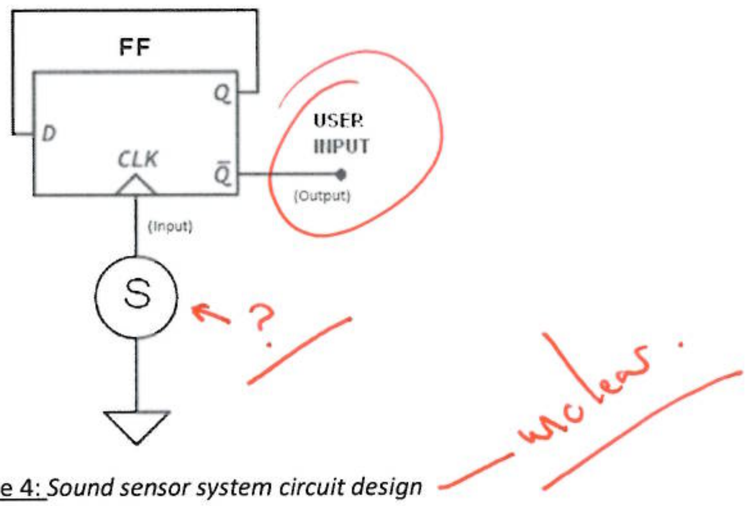
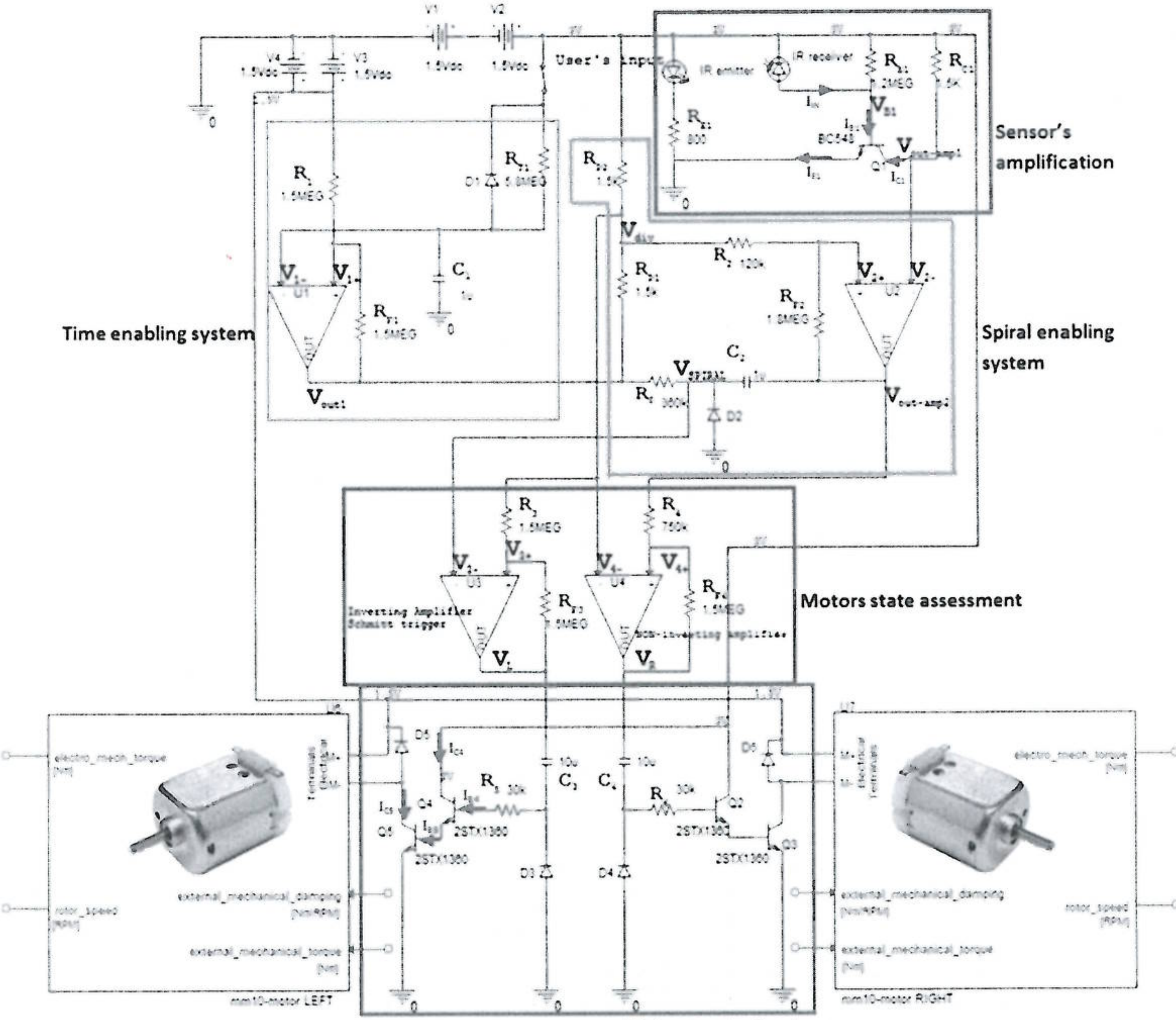


Figure 4: *Sound sensor system circuit design*

Conclusion

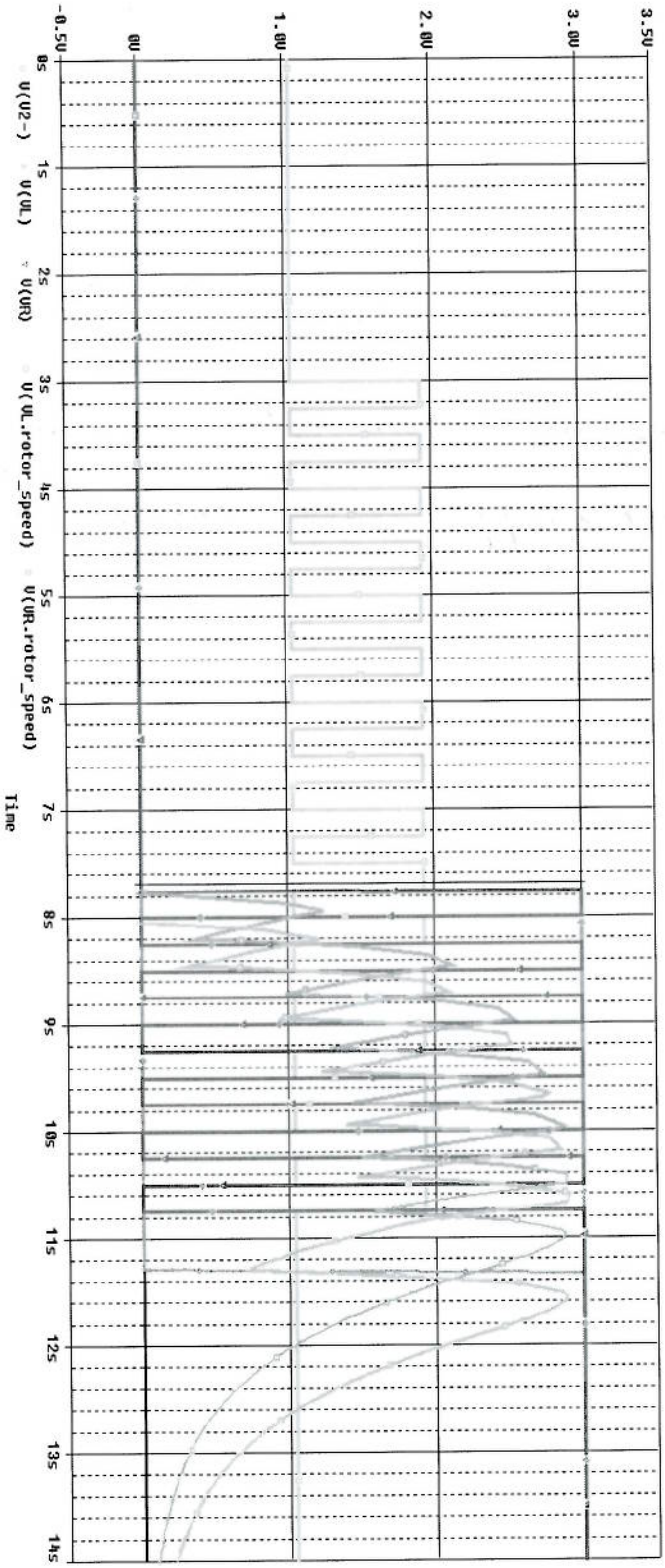
To conclude, the group managed to respect the deadlines set in the management plan of last term. As a result, a final and working product is obtained (*Appendix 3*), meeting the design requirements. Indeed, the BUG has a precise starting delay of 8s before following a 0.6cm-thick black line over a white background. Once the end of the line is reached, a spiral is drawn whose shape can be easily modified by altering capacitances. Moreover, this design offers many enhancement possibilities including a low power consumption implementation with MOSFETs as well as an innovative sound enabling system.

Appendix 1 : *Complete Circuit divided in functional blocks*

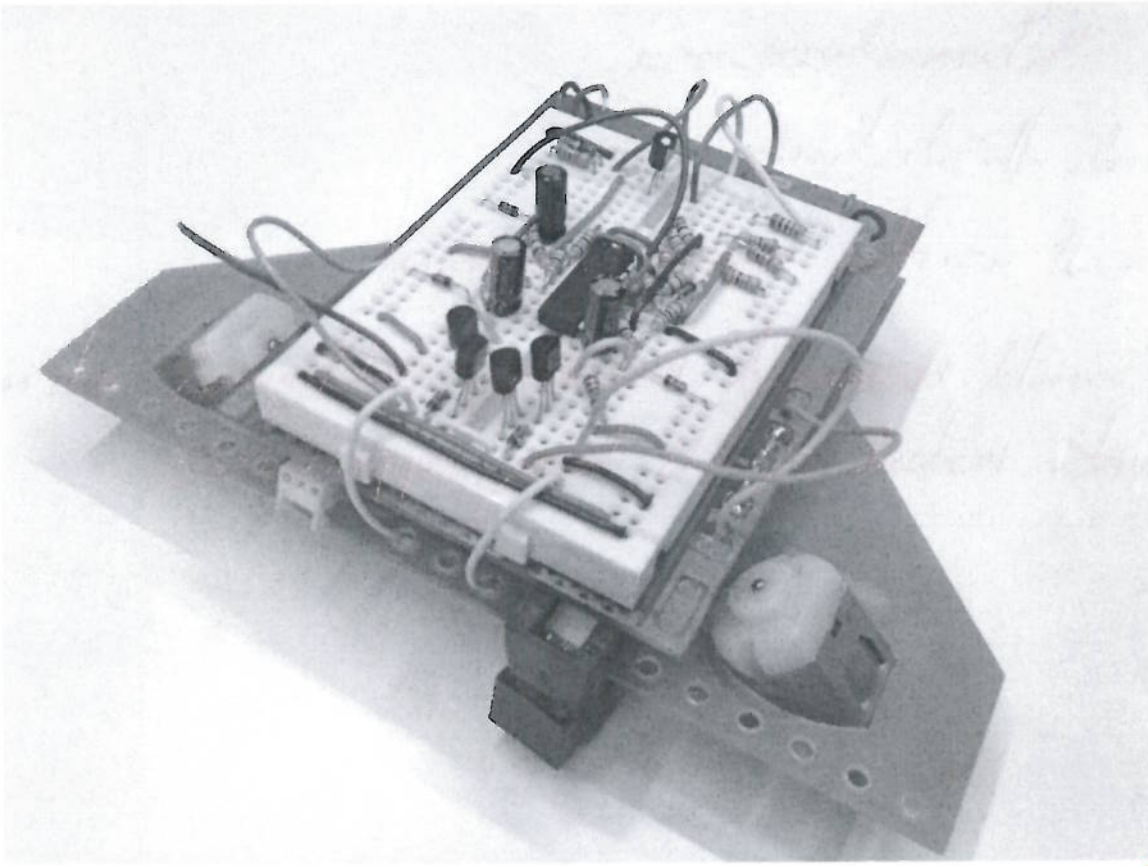


hard to read Schematic

Appendix 2: *Circuit simulation using PSPICE*



Appendix 3: Constructed prototype



- Impressive if you can meet requirements + demonstrate without ~~the~~ microcontroller ✓
- All equations hard to follow as these aren't ~~tied~~ referenced to schematics
- good illustrations
- well written report in general.
- I would recommend including subfigures at relevant points instead of all being appendices.