LDR analogue linearization circuit for a bubble light tracking

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Abstract: Light dependant resistors (LDR) are widely used in robotic world to detect or avoid obstacles or to measure light level in home automation system. Such commercial sensors have a non linear response curve. This paper presents a simple and clever analogue COTS circuit to obtain a linear response. Theoretical design is explained; simulation and measurement results are commented. An example of application is given for a small scale solar tracking system with two LDR sensors.

Key words: Analogue circuit design, sensor linearization, COTS components, light tracking

1. Introduction

Light following, tracking or avoidance is one of the classical subjects in small rolling or walking robot system [1], [2], [3], [4]. The proposed circuit aims to process analogue voltage provided by photo resistor sensors in order to deliver proper information to a decision module able to decide of the robot motion strategy. It is enough complex to demonstrate the principle of tracking and to illustrate feedback loop circuit basics design difficulties.

2. Bubble light tracking circuit

2.1 Tracking system principles and schematic

The design of a light tracker is based on a simple circuit with one rotation axis control [5]. Figure 1 shows the bubble light tracking block diagram.

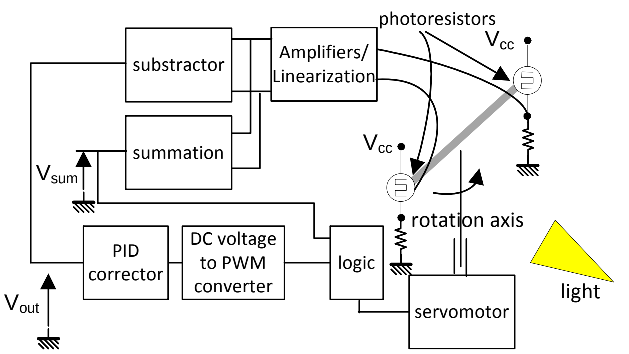

Figure 1: Sun tracking system

It works like two human eyes able to detect a light thanks to the stereoscopic vision and to move the head into the light direction. Here, the two light sensors (light dependant resistors, i.e. LDR), located on left and right side of a mechanical arm receive the light. When the system is well aligned in bubble light direction, the received left and right signals are equal. The voltage difference "left minus right" sensor signals V_{out} is null and the hobbyist servomotor do not move. When it is not, the V_{out} error signal becomes positive or negative depending on the rotation direction. Then, the feedback loop moves the servo motor into the good direction to cancel the error signal V_{out} (Cf. figure 2).

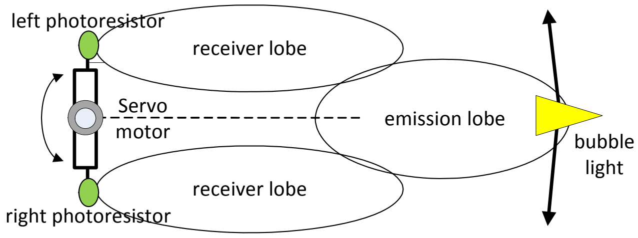

Figure 2: Bubble light alignment

Summing the two sensors voltage allows the system to distinguish dark and light situation. Thus, if the light is "OFF", the servo is deactivated to avoid unwanted movements.

2.2 Design challenge

The described system is a looped system. In this situation, designer must take care about possible unstable behavior, saturation and non-linear effects.
The critical components in the system might be here, the light sensors as explained in the next paragraph.

2.3 Impact of LDR sensor's non linearity

Since LDR sensors are deeply non-linear, it yields to several consequences [6]:

- A non constant sensitivity over the full luminous flux possible range, (the system must operate properly whatever the light power in a given range)
- A higher difficulty to match the two sensors response (a mismatching between sensors may lead to severe angular static error compared to the light direction),
- A possible instability since the LDRs affects the loop gain in the feedback loop path.

2.4 Sensor non linearity compensation strategy

Thus, linearize the sensor response is required. It can be done in two ways:

-by using digital memory with a tabulated conversion table or by using a micro controller and calibration equations,

- by using analogue circuit with voltage dependant gain circuit (diode or multiplier design).

According to a low cost design, we tried to design with a minimum number of COTS robust components. Thus, we propose here, a clever linearization analogue circuit.

Unfortunately, light dependant resistors have scattering specifications. For that reason, a precise experimental characterisation of LDR behaviour must be first performed.

3. LDR characterisation

Due to the manufacturing process, LDR behaviour's varies a lot. For a correct and symmetric operation of the tracking system, the two LDR sensors must be matched as well as possible. A fine selection of two similar LDR is required.

Then, a set of LDR were tested as indicated hereafter.

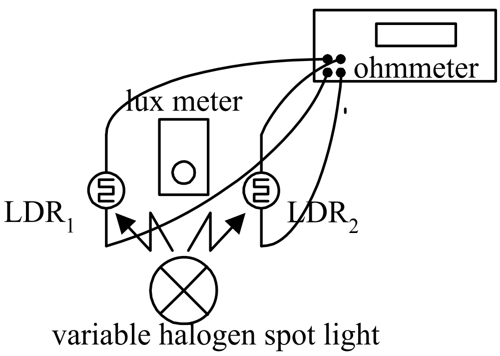

Figure 3: LDR test bench

The chosen LDR are submitted to a variable luminous flux (F) (given in lux) under an halogen spot light. A Lux meter ROline -1332 is placed just near the LDRs and a digital ohmmeter is connected to the LDRs to get its values. As the components are very close, the ambient temperature does not have significant impact on the measurements or has the same impact on the two. . Several tests were performed to be sure of the results reproducibility. Figure 4 shows the experimental results for two selected LDRs.

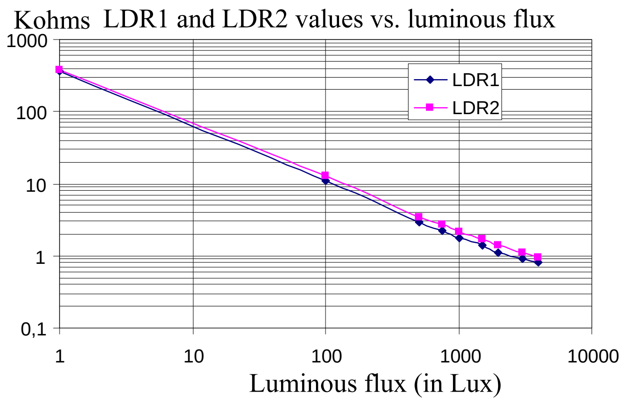

Figure 4: LDR characterisation

From several tests, commercial LDRs vary over 3 decades as a non-integer power of the luminous flux (i.e. from $F^{-0.5}$ to $F^{-0.7}$). Among tested LDRs, we selected the ones who have the closest behaviour to:

$$\mathrm{LDR}(\Omega) = k\frac{1}{\sqrt{F}}.$$

4. Linearization circuit

The designed circuit is based on the principle (cf. figure 5), described in applications notes of multiplier circuits manufacturers [7], [8].

Analogue multiplier circuits are usually used for amplitude or phase modulation [9], [10]. However, it can also be used in DC applications, like it was in old analogue computers. For example, including a multiplier in a OP amp feedback loop as indicated in figure 5, makes the multiplier output W equals to a constant DC voltage value V_{ref}.

Thus, X.Y= V_{ref}: Considering Y the output and X the input of the circuit, an hyperbolic function can be synthesised since Y= V_{ref} /X.

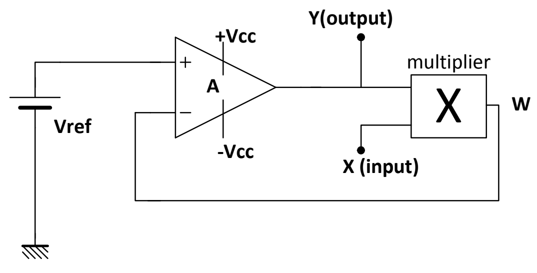

Figure 5: Hyperbolic function

Here, we propose to combine two analogue multipliers to linearize LDR response over the widest possible range (i.e. 2 or 3 decades).

4.1 Detailed linearization circuit analysis

For the electronic design we chose robust and well-known components:
- A classical TL 071 Op amp, Ft =3MHz,
- A four quadrant analogue multiplier AD 633 Fc=1MHz, internal gain G=1/10 (V^{-1}). [11]
- Power supply: +/-15V

Schematic (PROTEUS CAD software) is shown on figure 6.

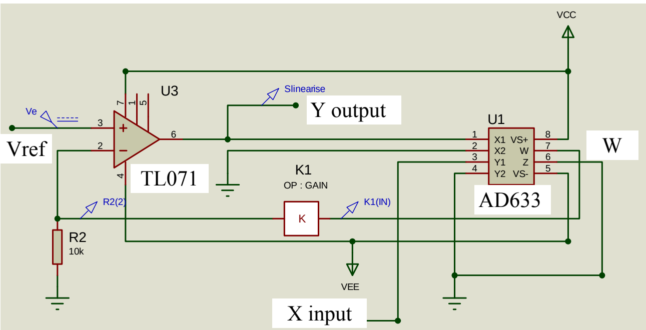

Figure 6: Hyperbolic circuit schematic

4.1.1 Simple first order static analysis

Assuming that:
- the equation of a classical analogue multiplier is :

$$W(t) = G.\ X(t).Y(t).$$

Where G: internal multiplier coefficient, in V^{-1}.

- V_{ref} is a constant DC voltage,
- OP amp is perfect ($A \Rightarrow \infty$),
- K an optional constant gain on the feedback loop return path,

Then, from static point of view, it yields:

$$W(t)=K.G.X(t).Y(t)= V_{ref}$$

Hence:

$$Y(t)= V_{ref}/\ K.G.X(t) \quad (1)$$

DC transfer curve is thus a hyperbolic function.
This is confirmed by a DC sweep simulation on the X multiplier input (cf. figure 7) over one voltage decade (1V to 10V).
Vertical scale: Y output (in V)
Horizontal scale: X input (in V)

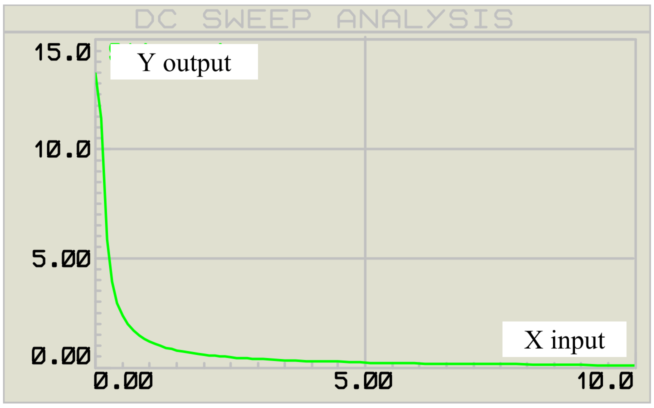

Figure 7: DC sweep analysis.

4.1.2 Frequency analysis

As the circuit is looped, instability could occur. It must be checked.
For that purpose, we calculate the closed loop function $T(p)=Y(p)/Vref(p)$ assuming :

- the OP amp transfer equal to a first order function:

$$A(p)= Ao/(1+\tau p),$$

with $Ft = Ao\ .(1/2\pi.\tau) = 3MHz$ (from datasheet spec),

- X input equal to a constant DC voltage, Vc (so, the multiplier can be seen as a simple 'gain' between its Y input and W output),

- the multiplier AD633 transfer function M(p) is first order, (cut-off frequency 1MHz)

$$M(p)= W(p)/Y(p) = G.(1/(1+\tau' p)),\ (\ X=\text{constant})$$

Then:

$$Y(p)= A(p).[V_{ref}(p)-K.Vc.M(p).Y(p)]$$

As $T(p) =Y(p)/V_{ref}(p)$, it yields:

$$T(p)= A(p)/(1+K.Vc.A(p).M(p)) \quad (2)$$

Closed loop transfer function is thus a second order function.
The corresponding simulation of the circuit is given in figure 8.
Red curve: Y voltage, (20 dB gain in the bandwidth comes logically from the multiplier G factor equal to 1/10),
Green curve: voltage on op amp negative input. (0dB in the bandwidth means that it is equal to V_{ref} according to feedback loop theory.
Vertical scale (in dB)
Horizontal scale Frequency (in Hz)

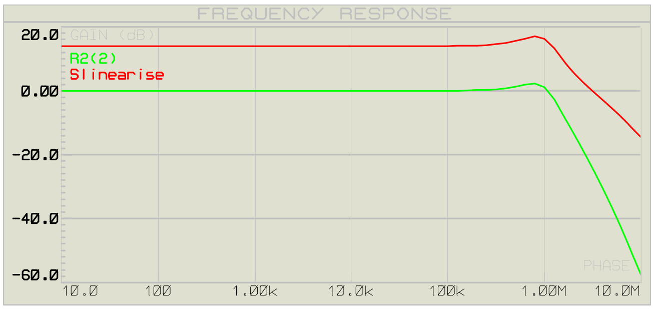

Figure 8: Closed loop response simulation

The feedback loop operates properly. However, damping factor might be not optimal: a light correction with a gain/integrator correction might be required to avoid instability, on the feedback loop return path.

4.2 Full Circuit theory

The circuit presented in §4.1 provides a hyperbolic transfer curve. It is not enough to fully compensate the LDR response since the LDR variation are depending on inverse square root of the luminous flux (cf. §3):

$$LDR(\Omega) = k\frac{1}{\sqrt{F}}$$

So the circuit is modified as indicated on figure 9: a second multiplier is included to process the square root. And a constant current source I_{ref} flows into the LDR.

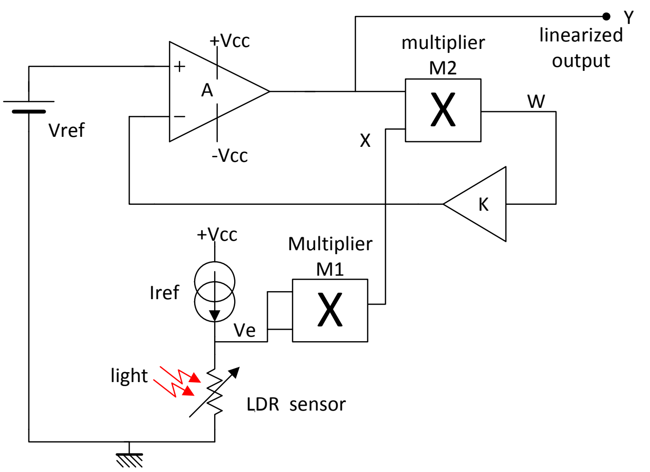

Figure 9: Full circuit diagram

The voltage across the LDR, Ve, is equal to:

$$Ve = I_{ref}.\left(k\frac{1}{\sqrt{F}}\right)$$

The output of multiplier M1 is equal to X :

$$X = G.Ve^2$$

Hence:

$$X = G.\ I^2_{ref}.\left(k\frac{1}{\sqrt{F}}\right)^2$$

Remembering that:

$$Y = V_{ref}/\ K.G.X$$

We obtain:

$$Y = V_{ref}/\ (K.G^2.\ I^2_{ref}.\left(k\frac{1}{\sqrt{F}}\right)^2)$$

$$Y = (F).\ Vref/\ (K.G2.\ I2ref.\ k^2) \qquad (3)$$

Supposing that: $H = V_{ref}/\ (K.G^2.\ I^2_{ref}.\ k^2)$

We get a simple linear equation between luminous flux F and output voltage Y:

$$Y = (F).H \qquad \text{(with Y in V, F,in Lux)}$$

Y output voltage is thus proportional to luminous flux as wanted. The global electronic circuit is shown on figure 10. Proteus CAD software allows changing parameters of LDR modelling. Here, transfer function power exponent was set up at -0.5 to represent the inverse square root effect, and maximum resistor value in the dark was adjusted according to experimental characterisation.

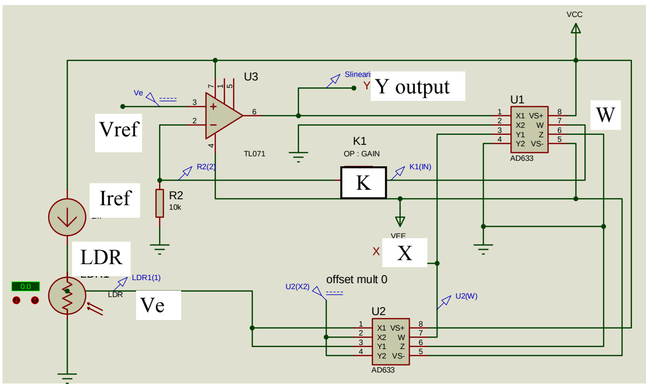

Figure 10: Full circuit Proteus schematic

4.3 Final circuit simulation

A parametric DC sweep simulation is done on luminous flux across the LDR over two decades (from 10^2 to 10^4 Lux). Result is shown in figure 11.

With:
K=2, V_{ref} =250mV, I_{ref}=1mA and $LDR(\Omega) = k.\ F^{-0.5}$

Horizontal scale: Luminous flux F, (in Lux)
Vertical scale: (in V)
Blue curve: Y output voltage
Green curve: Ve voltage (across LDR)
Red curve : X voltage (M1 multiplier output)

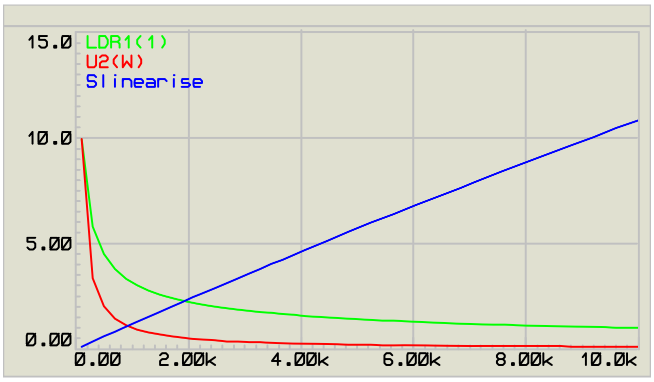

Figure 11: DC sweep simulation results

As wanted, the output voltage Y varies linearly with the luminous flux. Linear regression gives the equation:

$$Y\ (V) = 0.0011.F(Lux) + 0.1893$$

According to §3, it is lastly necessary to check the impact of manufacturing variations of LDR.
Figure 12 shows a worst case (i.e. when LDR's response is LDR(Ω) =k. $F^{-0.7}$ instead of k. $F^{-0.5}$), with K=2, V_{ref} = 250mV, I_{ref} = 6mA.

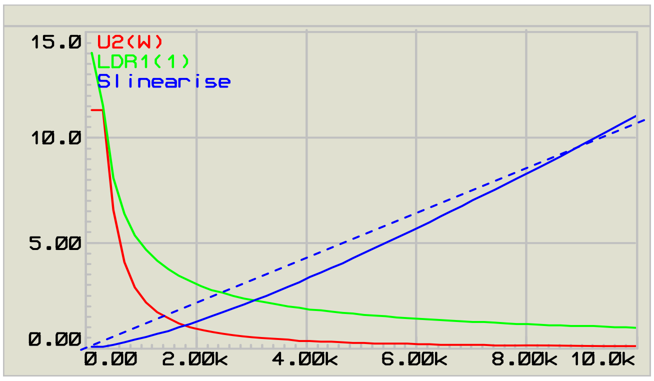

Figure 12: DC sweep simulation results (LDR(Ω) =k. $F^{-0.7}$)

Linearization is obviously not so perfect than in figure 11(blue dotted line superposed). A second order approximation better fits the curve:

$$Y\ (V) = 4E\text{-}08.F^2 + 0.0008.F - 0.2077$$

However, second order coefficient remains small compared to the others and result is still acceptable.

The last simulation (figure 13) represents the response of the system to sudden change in I_{ref} current source value. This is not a realist simulation because the voltage across LDR will never change so fast since its intrinsic response time is very low (a few ten milliseconds), but we did it to be sure of the stable behaviour of the circuit. No oscillations are observed.

Horizontal scale: time (in ms)
Vertical scale: (in V)
Blue curve: Y output voltage
Green curve: Ve voltage (across LDR)

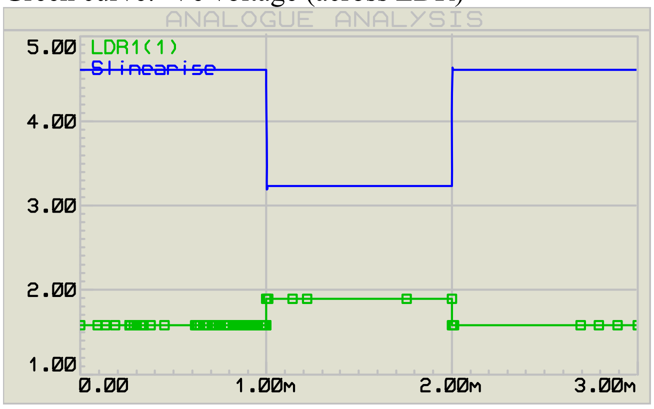

Figure 13: Transient response to pulse

4.4 Comparison with a simple resistor bridge

To be fully convinced of the advantage of our linearizing circuit, we can compare the result with the one obtained with LDR inserted in a simple resistor bridge, connected to Vcc supply (cf. figure 14).

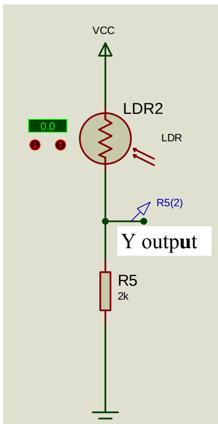

Figure 14: Simple resistor bridge

The output voltage is:

$$Y = R5/(R5+LDR).Vcc$$

Thus, Y voltage is roughly depending on luminous flux as $\sqrt{F}$. This nonlinear response is easily confirmed by a DC sweep simulation performed in the same conditions than in §4.3. (Cf. figure 15).

Horizontal scale: Luminous flux F, (in Lux)
Vertical scale: (in V)

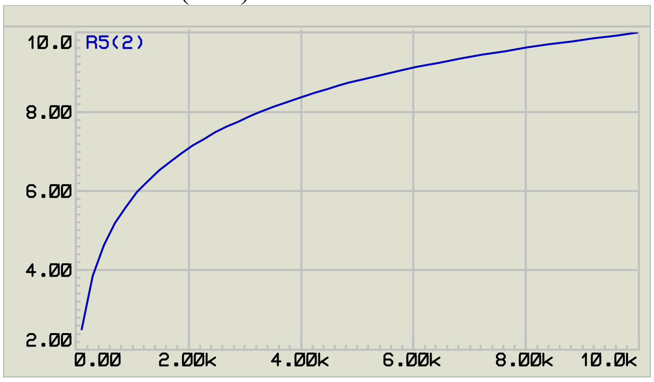

Figure 15: resistor bridge response

Thus, whatever the response figure 11 (best case) or 12 (worst case), effect of the linearizing circuit is then proved. The "price to pay" to get an almost linear response is obviously to design a more complex circuit than a simple resistor bridge.

5. Linearization circuit measurements

For experimental design, an integral corrector has been added in the loop as suggested in §4.1.2.PCB circuit is shown on figure 16. An "unknown LDR from the shelf" was chosen. So, adjustments of I_{ref} and V_{ref} values were necessary to maintain the output voltage into the range 0-15V, when the flux varies from 0 to 10000 Lux.

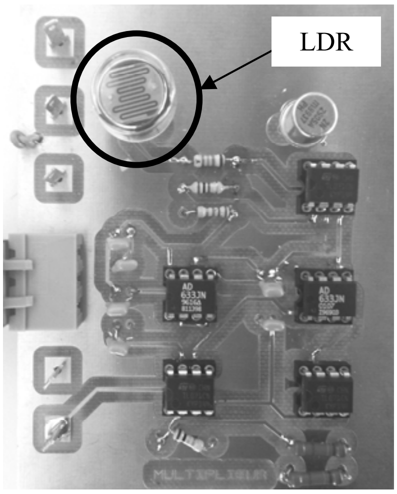

Figure 16: LDR test circuit

Measurement was performed using the same test bench as described in §3. Experimental curve is given in Figure 17. It can be easily and successfully compared to figure 12.

Green curve: Ve voltage across LDR
Blue curve: Y output voltage

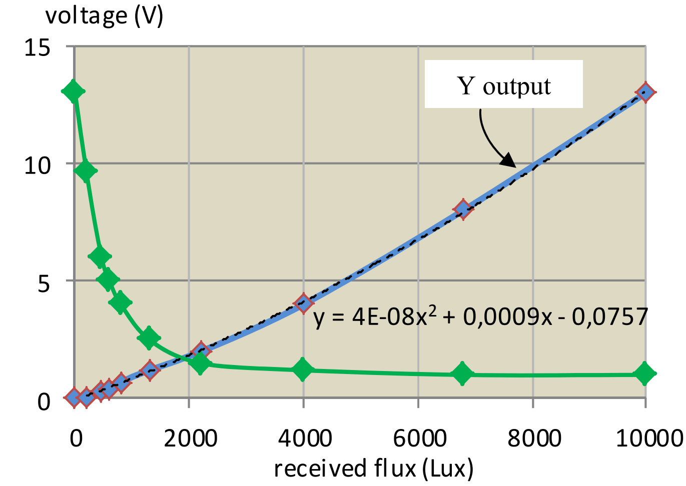

Figure 17: experimental linearization curve

Response curves can never be perfect carbon copy of simulations, due to the large dispersion of intrinsic LDR parameters. But, the resulting shape shows the positive and huge effect of the linearizing circuit.
Lastly, response to a step of luminous flux was performed as follow: a flat object similar to a cardboard was placed between the bubble light and the LDR. It was removed as suddenly as possible. So, a large luminous flux step from around 7500 to 10 lux was created. Response (Y voltage and LDR voltage Ve) was recorded with oscilloscope in one shot trigger mode. It is shown on figure 18.

Vertical scale: 5V/div
Horizontal scale: 25ms/div
Orange curve: Y output voltage
Blue curve: Ve across the LDR

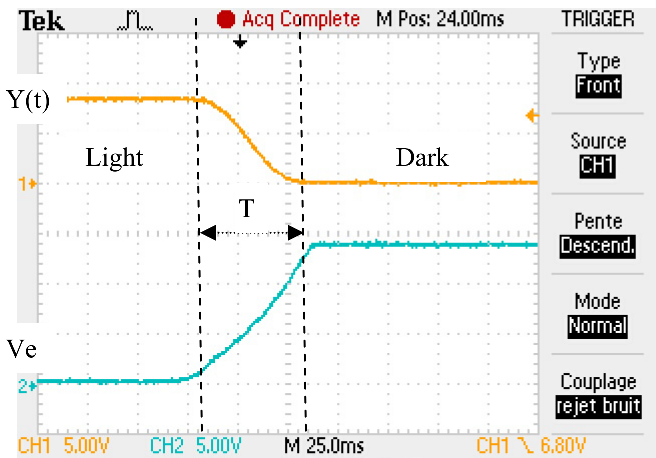

Figure 18: transient response to a step of luminous flux

Behaviour is stable and the response time T which includes LDR intrinsic time constant (predominant) and time constant of the feedback loop is coherent with what we can predict.

6. Global light tracking circuit design

The two LDR sensors are associated with the designed linearization circuit. Output signals are rescaled and subtracted using rail to rail OP amps LMC6482 (figure 19) to have the widest dynamic range.

Difference is applied to a PID corrector. The resulting DC voltage value is converted linearly (i.e. pulse width proportional to DC voltage value) into a PWM signal, to control a classical Futaba servomotor. According to hobbyist standard, rotation angle (0 to 180°) is proportional to the pulse width (1ms to 2ms). So, the system will be able to track a light over a 180° range.

A view of the practical design is given in figure 20.

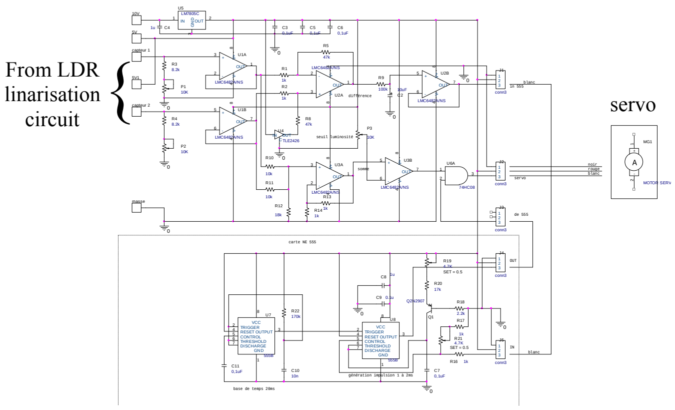

Figure 19: Feedback loop Control circuit

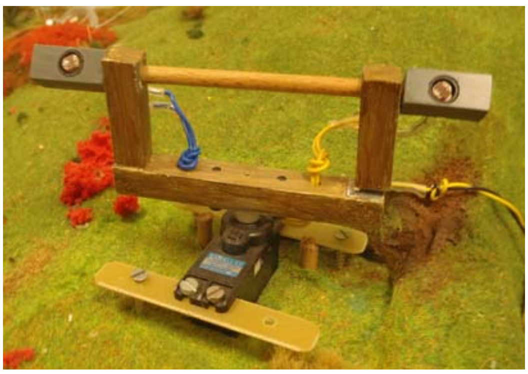

Figure 20: Bubble light tracking system

7. Global experiment

7.1 Bubble light tracking circuit "static open loop" characterisation

System (figure 20) was placed in a dark room in front of a bubble light (1meter far), servomotor deactivated. Then, turning manually the bubble light 180° around the system (figure 21), we get the experimental open loop curve "Sensor voltage static difference V_{out} versus alignment angle θ", (cf. figure 22).

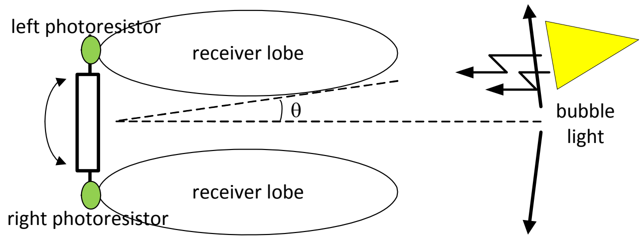

Figure 21: Static open loop characterisation

V_{out} being rescaled for electronic design reasons, the sensor voltage difference V_{out} varies from 0 to 5V with a mid-point centered on 2.5V (system perfectly aligned with light direction). It looks like a "S curve" with a maximum (when the light is exactly in front of the left sensor) and a minimum (when the light is just in front the right sensor). The active area where feedback control can operate properly is between the maximum and minimum. When angle θ" reaches plus or minus 90°, light becomes tangent to the LDR surfaces and equal on each sensor. So, the "S" returns asymptotically to the mid-point.

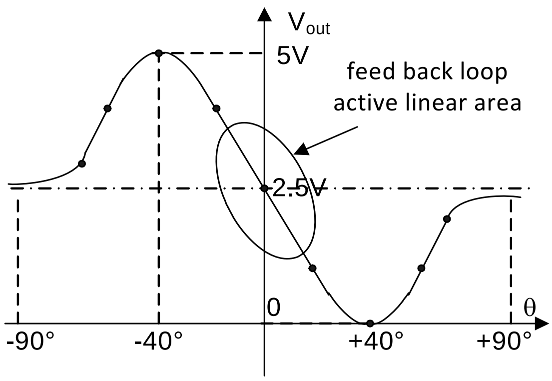

Figure 22: LDR's V_{out} voltage difference vs. light axis angle θ (in degrees)

7.2 Bubble tracking circuit "dynamic" characterisation

A classical AC sweep measurement around the mid-point bias position is performed as indicated on figure 23. PID corrector circuit excluded.

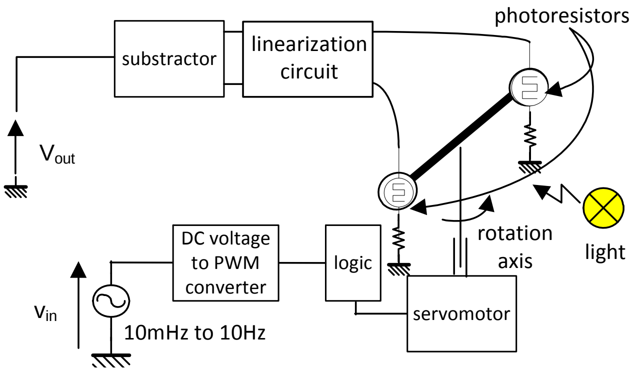

Figure 23: Open loop dynamic characterisation schematic

However, practical open loop response is extremely difficult to measure because of the ultra-slow motion of hobbyist servo (working frequencies less than one Hz) and output voltage low level. The result is given in figure 24 where a realistic +/-5% error margin is indicated.

Without linearization, open and closed loop gain depends on flux F, as described in [5].

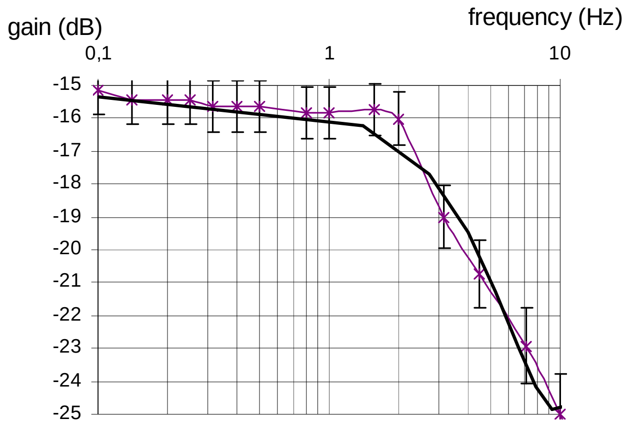

Figure 24: Experimental AC open loop gain $V_{out}./v_{in}$

Here, we checked for 3 different light intensities 500, 1000 and 2000 lux), that loop gain did not change anymore. Thus, efficiency of linearization is proved.
Finally, loop correction has been adjusted to reduce the static angle error at less than 5° which is enough to check the tracking without any oscillation risk. And the system follows correctly the bubble light.

8. Conclusion

A simple but clever analogue linearization COTS circuit has been designed to linearize the LDR response used in a light tracking small scale system.
Since it has been successfully experimented, it can be used in association with LDR for various small rolling or walking robots applications. However, it does not suppress the necessary preliminary sorting and matching of LDR due to their extremely scattered specifications. In some cases, LDR could be advantageously replaced by infrared sensors (for example SHARP GP2Y0xxxx series) which have an almost hyperbolic 'voltage to distance' well matched response. In this situation associating the circuit described in 3.2 could be enough.

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