Mixed Spice and 3D virtual modelling of a two axis small scale solar tracking system for an eco-friendly house model

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Abstract: Renewable power generation is one of the important challenges for the future generations. In that way, private companies are currently working on optimisation of solar panel power ratio by using well-known sun tracking systems. Training and sensitizing our students to these new technologies requires first to design didactical equipment: Thus, we present the design and modelling of a two axis small scale tracking system. A mixed SPICE circuit, including geometrical, optical, electronic linear and non-linear aspects is built as well as a 3 dimensions VRML virtual animated modelling. Electronic design is presented and validated. This small scale system is now used for practical lessons and projects in our institute.

Key words: Sun tracking, Mixed SPICE modelling, Analogue design, Sustainable development

1. Introduction

1.1 Context of the study

Within the framework of sustainable development concept, a functional and realistic small scale eco-friendly house, built in genuine materials has been designed. The building (with true materials) of the small scale house itself was detailed in [1]. It required more than 1500 hours of work. The model is now used:

- To perform thermal measurements, thermal modelling, insulator efficiency comparison,
- To make demonstration of power generation and saving capacities
- To support practical lessons and electronic student's projects,
- And more generally, to sensitize students to sustainable development.

In order to make the house model as realists as possible, several systems and their electronic control circuits were designed and included:
- LED low power lighting for the terrace and the house, powered by a roof solar panel and battery cells.
- Hydrogen fuel stack to provider "air conditioned" system (fresh air flow under the house like a scaled Canadian well),
- A rotating solar dish to simulate sun cooking,
- A modular solar tower,
- An "in door" electrical heater and temperature control circuit

And more recently, a sun tracking system for a small solar panel (9cm x 5cm) has been added in the garden. Figure 1 shows a picture of the finished modular scale model (1/20 scale).

Figure 1: View of small scale house and surroundings.

This paper focuses on this last system. In particular, we present the modelling and design of the small scale 2 axis solar tracking system.
This updated version is an enhanced evolution of the previous design which was working only on azimuth axis as already presented in [2].

1.2 General solar tracking interest

Industrial sophisticated systems are generally controlled by processor board [3]. The position of the sun is known from astronomical data, all over the year and then tabulated. The solar panel position follows the programmed law on two axes. The sun ray optical diffraction and refraction through atmosphere are also taken into account. Such real solar tracking system can

increase the electricity production of a solar panel up to 27 % for a double axis tracker and 23 % for a single axis tracker. In France, only a few didactical tools already exist [4], [5], [6] to illustrate these systems principles, but they do not really fit the scope of our electronic department. So, we present here a specific design which matches our scientific needs and pedagogical goal since it must be integrated in our wider project shown on figure 1.

2. Tracking circuit

2.1 Generalities
Here, the proposed circuit is obviously greatly simplified compared to a true tracking system [3]. It is a sensor based tracker of which its complexity is enough important to require a strong modelling and design strategy.

2.2 Tracking system principles and schematic
As our "eco-friendly house" is used for in-door demonstration, a small halogen spot light, supposed isotropic, "replaces" the sun.
The design is based on a robust but simple system with two servomotors for rotating the panel in the two directions. The sun tracking principle is shown in Figure 4.
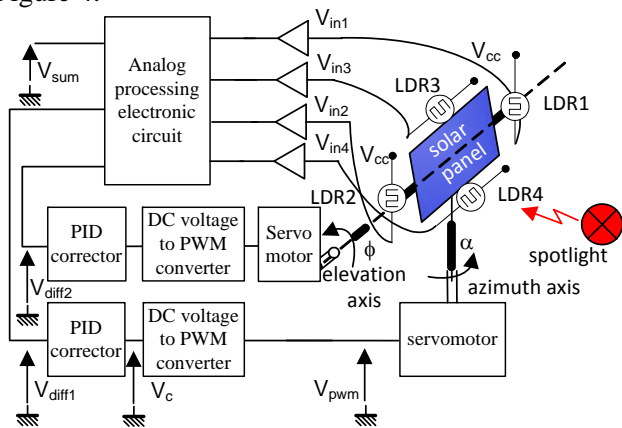

Figure 4: Sun tracking system block diagram

We use the same feed-back control loop principle on the two axis (elevation ϕ and azimuth α). Explanation is thus given for azimuth control and can be transposed to the elevation axis:
Two light dependant resistors sensors LDR1 and LDR2, located on left and right side of the panel receive the "sun" light. The received light intensities are converted into two voltages DC values V_{in1} and V_{in2}. Then, an electronic circuit makes the difference

"left minus right", $V_{diff} = V_{in1}-V_{in2}$. When the solar panel is perfectly align in "spot light" direction, the received left and right lights flux L1 and L2, are equal. The voltage difference V_{diff} signals is null. When it is not aligned, one of the two LDR receives more flux than the other. V_{diff} becomes positive or negative. And the feed-back loop moves the servo motor into the right direction in order to cancel V_{diff} (Cf. figure 5).
According to hobbyist standards, the rotation angles of the servomotors are proportional to the pulse width V_{pwm} (1ms to 2ms for a 180° range) of a periodic (T=50ms) control signal. Thus, the resulting voltage V_{diff} being a DC voltage, it needs to be converted from DC to PWM by a simple electronic circuit.
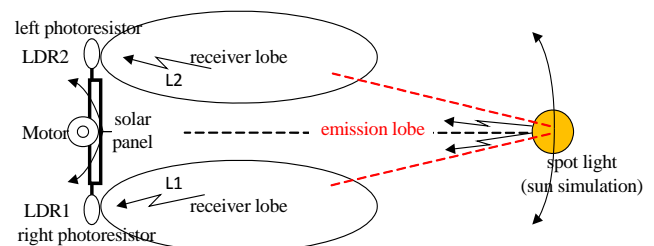

Figure 5: Solar panel alignment

2.3 Modelling interest
The principle explained in §2.3 (based on a differential structure) is well known since a long time; Similar applications using infrared or ultrasonic sensors instead of LDR are described in [7], [8], [9], [10]. Thus, a kind of "intuitive" electronic design can be directly done without a preliminary high level theoretical approach, by experimented designers.
However, for a fine understanding of parameters impact (i.e. spotlight distance, matching and non linearity of LDR sensors, mechanical behaviour of servomotor etc.), a system modelling is mandatory.

3. Tracking system modelling

3.1 One axis feed back loop modelling
Modelling requires a global approach. It is not easy because the whole system consists of several heterogeneous and non-linear parts. Among several modelling possibilities, (analytic calculus, MATLAB/SIMULINK software, SPICE…) we implemented hereafter, a called "mixed" SPICE modelling because it must take into account mechanical behaviour of servomotor, but also electronic behaviour (Electronic circuits, non linear sensors (LDR1 and LDR2), optical and geometrical aspects, due to the rotation of the spot light (simulating the sun).

In order to simplify the approach, the angle rotation range -i.e. 0° to 180° for the azimuth servomotor- is supposed covering exactly a sweep from East to West.

The first step is to draw a block diagram representing the global feed-back system as depicted on figure 6, where:
- L_1, L_2 represents the received light (in Lux) by LDR1 and LDR2 sensors,
- α_{ref} (main input of the feed-back system) is the sun azimuth position (0° to 180°),
- α is the angle given by the servo motor,
- α_e (equal to α_{ref} - α) is the error angle (cf. figure 7),
- "I" is the source light intensity. It can be seen as a secondary input which corresponds to fluctuation of source intensity (fog, sky partially cloudy, etc),
- Θ_0 is the angle defined as Θ_0 = arctg(l/2D), where l is the distance between sensors and D the distance to spotlight
- (D) Input represents local disturbances that can occur individually, on each LDR optical way. (LDR partially hidden by an object passing over, etc).
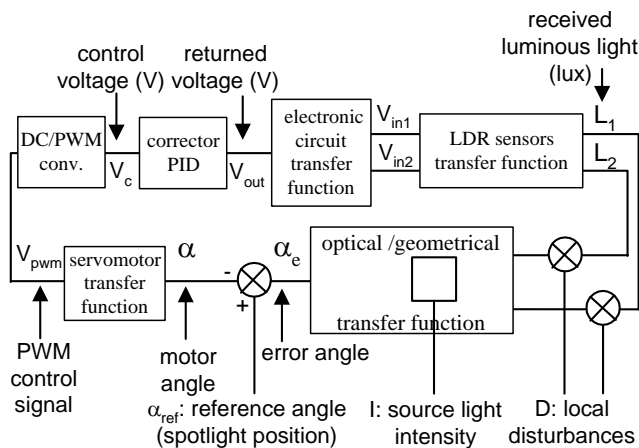

Figure 6: System identification

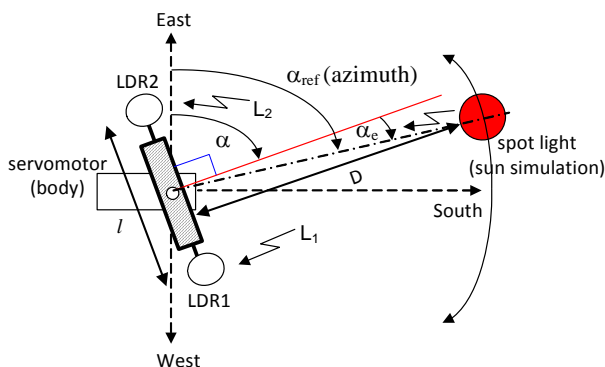The corresponding geometrical angles for azimuth axis are depicted in figure 7.

Figure 7: Azimuth geometrical angles (top view)

Feed back loop for the second rotation axis is exactly similar. And the two axis movements are obviously coupled to track the spot light. Thus, relation between elevation and azimuth must be known as explained in §3.2).

3.2 Sun position modelling

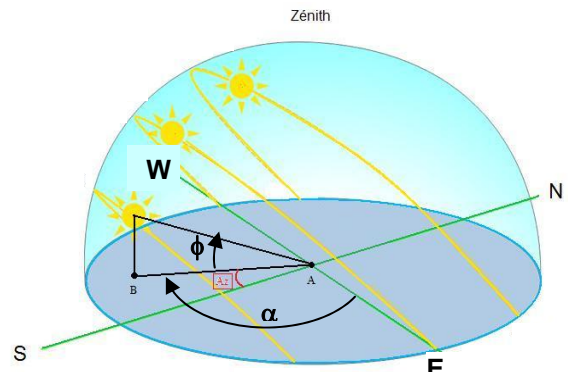Figure 8 shows a 3 D representation of two angles α and ϕ.

Figure 8: 3 D azimuth and elevation diagram

From the web site "sunearthtools.com" [11] used by solar equipment designers, one can obtain the sun position and path everywhere on earth in real time. For example Figure 9 gives the situation for Bordeaux Talence University the 21 of june 2017.
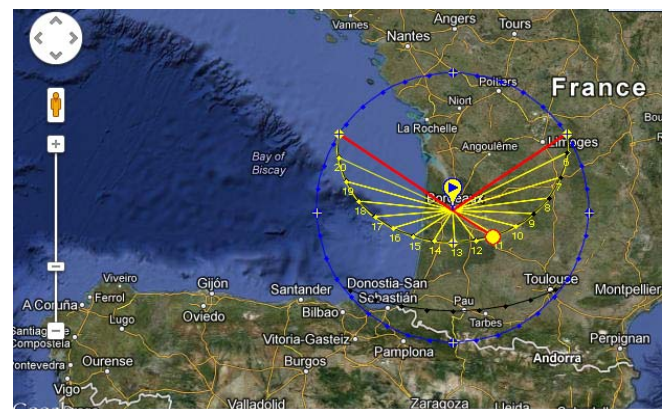

Figure 9: sun path over Bordeaux (hours and direction)

Figure 10 shows the corresponding sun elevation angle ϕ_{ref} vs. azimuth angle α_{ref}. The lower grey curve corresponds to winter solstice, and orange curve to summer solstice.
Horizontal scale: azimuth 0° to 360° (south <=>180°)
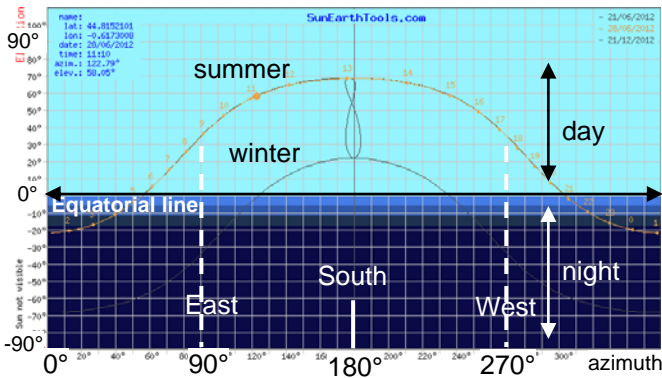Vertical scale: elevation -90° to +90°

Figure 10: Sun elevation vs. azimuth (in °), Bordeaux

Tabulated data corresponding to figure 10 are also available from Sunearthtools.com site. Thus, it is quite easy to extract a mathematical 2nd degree function to approximate theses curves on the interesting segment (i.e. East to West).
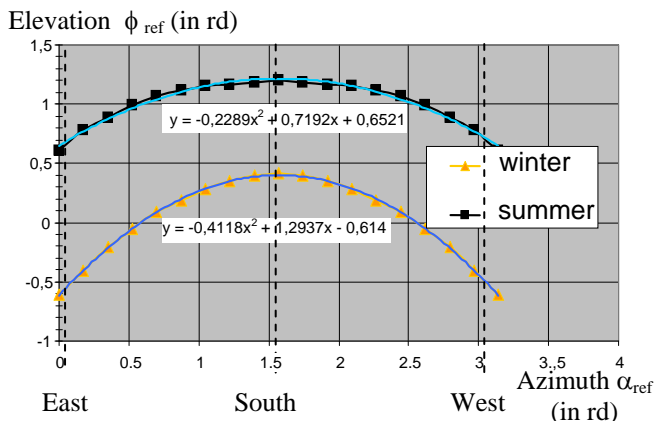

Figure 11: Elevation modelling in Bordeaux

Between summer and winter curves, we can extrapolate an average behaviour. We can write:

$$\phi_{ref} \# -0.3\alpha_{ref}^2 + 0.945\alpha_{ref} + 0.1 \quad (1) \text{ (angles in rd)}$$

3.3 Electronic circuits modelling

The main parts of electronics feed-back loop circuits (+5V voltage supply) have been previously modelled. In particular, static and dynamic behaviour of LDR has been experimentally characterised and then modelled by several equivalent Spice components.(non-linear block from "Analog Behaviour Modelling" -ABM-Spice library, linked source…) Details can be found in [2]. Analogue op amp subtraction circuit are directly included in Spice schematic as shown on figure 12.

3.4 Optical/Geometrical modelling

The mathematical transfer function "received light flux L_1 and L_2 (lux scale) on each LDR sensor versus incidence angle of the spotlight" must be also known:

each flux depends roughly on the cosines of incidence angle. Impacts of the distance D between sensors and the spot light as well as the distance l between LDR sensors on the same arm, are detailed in [2].

3.5 Modelling of servomotor

Any kind of hobbyist servo Hitec, Parallax, Futaba can be used, while their characteristics are similar.

Supply voltage is +5V. The control signal V_{pwm} is a PWM periodic signal: period 20ms, pulse width 1ms to 2ms for an rotation angle range of 180°. Maximum rotation speed is 60°/0.15s. Modelling has been extracted from practical test and characterisation. It includes internal feed-back loop, cut off frequency and angular speed saturation. Sampling effect caused by periodicity of the control signal was not taken into account while the operating frequency (movement of the spot light) is much lower compared to the control signal frequency. Details can also be found in [2].

3.6 One axis solar tracking system modelling

The following figure 12 extracted from [2], gives the one axis equivalent ORCAD/SPICE schematic. It includes all sub blocks discussed in §3.3, 3.4, 3.5. Some minor adaptations have been done to make it usable for the two axis system.
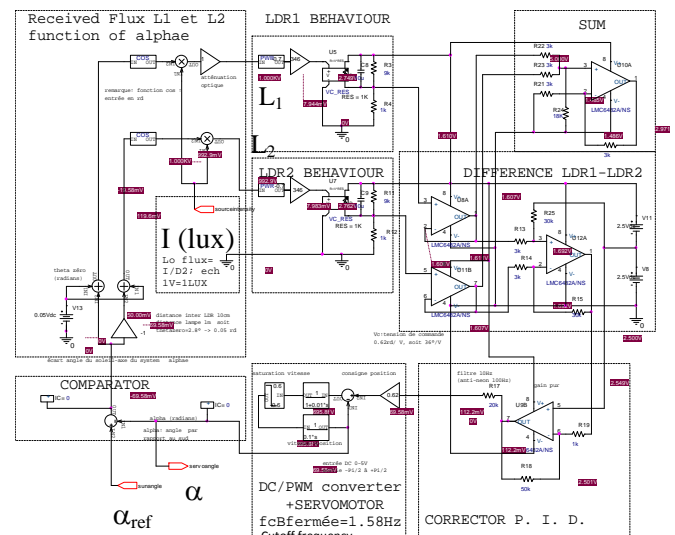

Figure 12: One axis tracking modelling

3.7 Two axis modelling

As the two axis works in the same way, the schematic given in figure 12, is converted into a SPICE sub circuit and duplicated. By associating them together, we obtain the full system: the first block will represent the azimuth movement and the second, the elevation movement. The two sub-circuits are linked by a Spice

element from ABM library) representing the equation (1) (cf. §3.2). Since SPICE stimuli are obviously in Volt and Amp, correspondence scales have been defined as follows:

1Vdc->1 Lux for light flux

1Vdc -> 1 rd for angles

Thus, "spotlight azimuth α_{ref} angle" input (0 to π) is represented by a Spice voltage ramp V1 stimuli from 0 to 3.14V. And a DC voltage source V3 represents the spot light intensity L. Outputs of each sub circuit represent azimuth and elevation angles given by the two servomotors (α and ϕ).

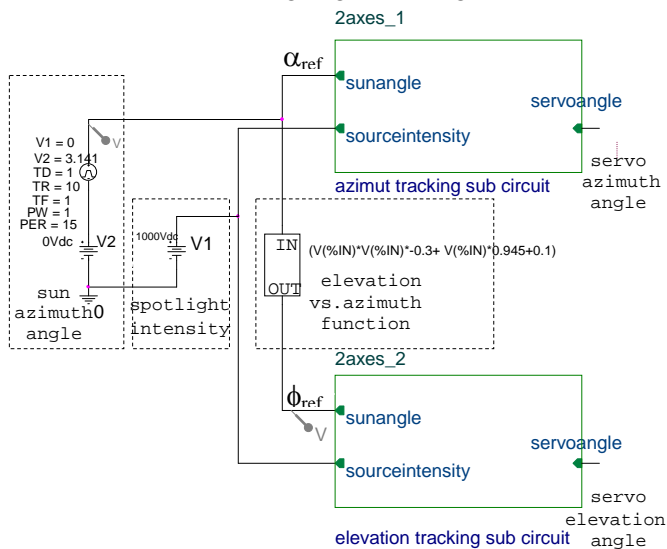Final two axis modelling is given in figure 13.

Figure 13: two axis solar tracking SPICE modelling

4. SPICE simulations

As SPICE simulates obviously in Volt and Amp, horizontal and vertical scales of the simulated response curves are converted (if necessary) in radians angles and Lux before display, for better understanding. We give the most significant simulation results in §4.1 and §4.2.

4.1 Open loop one axis simulations

Figure 14 shows the static behaviour in open loop on azimuth axis, when rotating the azimuth servomotor from East to West, while the spot light is locked in south position.

Upper curves shows L_1 and L_2 received lights flux on LDR1 and LDR2. L_1, L_2 reach their maximum values L_0 (here 1000 lux) when the spotlight is exactly in front of each (Respectively $\alpha_e = \pi/2+\Theta_o$ and $\alpha_e = \pi/2-\Theta_o$). And they tend toward 0 when α reaches $\pm$ 90° (Sunset or sunrise situation).

Lower curve shows the difference signal V_{diff} (as defined in figure 2), centered on Vsupply/2 (i.e. $V_{cc}/2=$ 2.5V). It looks like a classical "S" curve: when the light source is aligned, V_{diff} is centered on midpoint 2.5V. When the source light is shifted above LDR2, V_{diff} becomes greater than $V_{cc}/2$. When the source light is shifted above LDR1, V_{diff} becomes smaller than $V_{cc}/2$. V_{diff} is thus well suitable for feed back control. When α reaches 0 or 180° (Sunset or sunrise situation), L1 and L2 tend together toward to 0 (light ray parallel to the sensor's surface), thus V_{diff} return to Vcc/2.
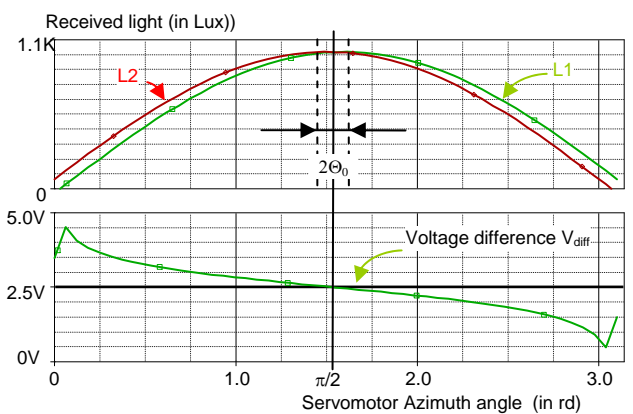

Figure 14: Open loop simulation (DC sweep)

4.2 Two axis closed loop simulations

4.2.1 Response to a full spot light rotation

A DC sweep is applied on spot light azimuth angle input α_{ref}, to simulate a full rotation from East to West. Figure 15 show the corresponding azimuth and elevation servomotor angle response.

Upper plot: spot light and servomotor elevation angles ϕ_e (green) and ϕ (red) vs. azimuth spotlight angle α_{ref}.

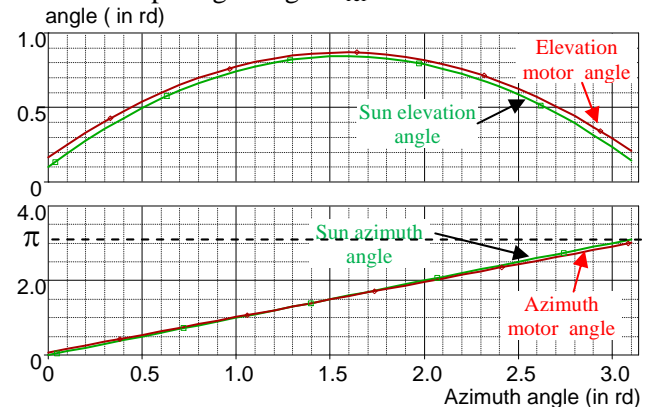Lower plot: spot light and servomotor azimuth angles vs. azimuth spot light angle α_{ref} .

Figure 15: Closed loop, DC sweep response

It shows a good tracking since error azimuth angle α_e and elevation angle remain close to zero (less than ±2.5°C) during all the simulated rotation. However, it must be mentioned that there is no integration correction in the feed-back loop circuits for stability reasons: thus, error is small but proportional to reference angle.

4.2.2 Response to light source intensity fluctuations

As the light source is located far from the LDR sensors, fluctuations of source intensity (input I) should normally affects identically the four LDRs. fluctuations can be considered like a parasitic common mode for the loop. However, it must be confirmed by running the following simulation: figure 16 shows the transient behaviour of the tracking system when submitted to a 20% fluctuations of the source (200 Lux around de 1000 Lux, square waveform, 10ms period which corresponds to flicker noise coming for example from artificial light (fluorescent neon tubes in the room at 100Hz).
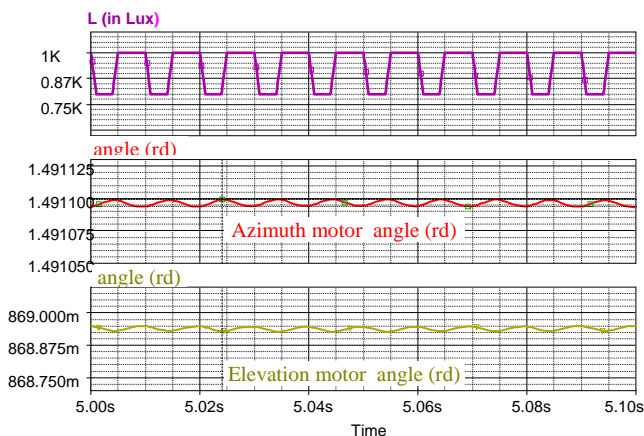

Figure 16: Closed loop response to fluctuation of source intensity (I input).

Fluctuations of azimuth and elevation angles α and φ are less than 0.1mrd. These parasitic variations are well rejected. That leads to an almost theoretical total insensitivity of the system while LDR sensors are perfectly matched. At this opposite, mismatching between the two LDR sensors could seriously affect the loop behaviour. Impacts and effects have been previously detailed in [12].

5. VRML 3D modelling

5.1 Interest of VRML modelling

Born in 1995, the Virtual Reality Modelling Language (VRML) aims to create and to animate any graphic objects. It was initially used for gaming and didactical applications. It is also the "hidden layer" in MATLAB software to run 3D simulation. Here, we use VRML [13] to visualize the tracking system movement in 3D image, to get a more realistic understanding of system behaviour than a set of curves. It is a complementary approach before the real electronic and mechanical design.

Main advantage of VRML is that it is freeware and it requires only an internet navigator such as Firefox and/or a "VRML viewer" like "orbisnap" for example.

5.2 Tracking system 3D VRML drawing

Here, we do not need sophisticated graphical CAD tools such as Solid Works, or Blender software because the quite easy shapes of our object. The system can be described using a classical text editor such as "wordpad" editor. Mechanical assembly is based on the association of simple objects such as "box", "cone" and "cylinder" to get a symbolic representation of the object.

As shown in figure 17, the body of the azimuth servomotor is the grey box; Solar panel is the dark blue rectangle and the two horizontal LDR sensors are represented by two small "cones" located at each extremity of the horizontal black mechanical arm. Elevation servomotor and vertical sensors are not
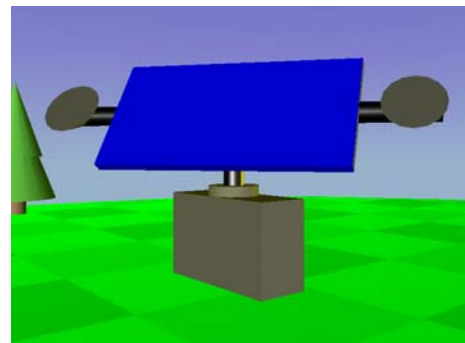
represented to make the drawing lighter.

Figure 17: VRML drawing of the tracking system

3D Description of the system represents only a few VRML text lines.

For example description of the spotlight (or sun) is given below. It is a simple sphere with some attributes such as appearance, colour, and initial position.

```
#VRML V2.0 utf8
#solartracking.wrl
#----------solar tracking
#-----------------solar description

    DEF SPOT Transform {
        translation 3 0 -20
        rotation 1 0 0 0
```

```
                   scale 1.0 1.0 1.0
       children [
         Shape {
           appearance Appearance {
             material Material {diffuseColor 1 1 0 }
           }
           geometry Sphere {   #sphere 1 m. radius  default value
           }
         }
       ]
     },
```

Table 1: VRML code example for sun or "spot light" description

5.3 Exporting SPICE simulation data into VRML file

Once the drawing of the system and surroundings done, the interest is to visualize the tracking movement according to predicting simulations. This can be done by exporting data from previous SPICE runs and including them after file conversion into the VRML description file. For that purpose, a transient simulation (time =0 to t_{max}) representing a full rotation from East to West is performed on the tracking system modelled (cf. figure 13). Simulation curves are saved as a multi voltage node points file *.dat. The file is then converted into a spreadsheet. Number of transient points is reduced to around 30 points equally spaced to minimize the file size (cf. table 1). This is enough to get a precise and fluid movement during the animation thank to VRML movement interpolator.

Time (s)	Normalized time	Sun azimuth (in rd)	Sun elevation (in rd)	Servo motor azimuth (in rd)	Servo Motor elevation (in rd)
t	t/t_{max}	α_{ref}	ϕ_{ref}	α	ϕ
0	0	$-\pi/2$	0	$-\pi/2$	0
…	…	…	…	...	…
t_i	t_i / t_{max}	$\alpha_{ref(i)}$	$\phi_{ref(i)}$	$\alpha_{(i)}$	$\phi_{(i)}$
…	…	…	…	…	…
t_{max}	1	$+\pi/2$	0	$\pi/2$	0

Table 2: spreadsheet organisation and contents

From the sun (or spotlight) azimuth and elevation angles α_{ref} and ϕ_{ref}, Cartesian coordinates x, y, z are calculated and converted to be compatible with the x, y, z reference axis used in VRML representation. The transformation is done as follows:

$$x = D. \sin(\alpha_{ref}). \cos(\phi_{ref})$$
$$y = D. \sin(\phi_{ref})$$
$$z = -D. \cos(\alpha_{ref}). \cos(\phi_{ref})$$

Angles given by SPICE simulation are converted to be compatible with origin and coordinates system used in VRML representation (cf. figure 18).
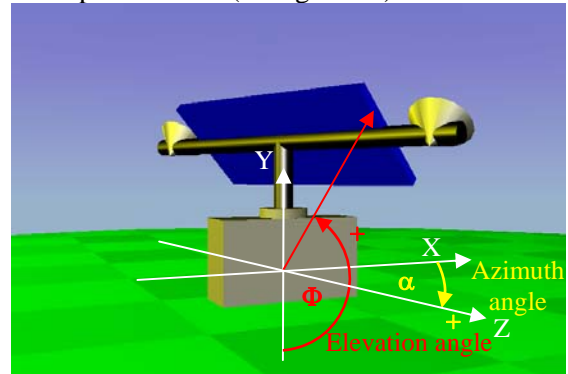

Figure 18: VRML axis and angles references

Finally, results are converted in a text format to be included as a table of values in the "*key value*" VRML instruction (see §5.4), into the VRML file created previously.

The full description of the animated system represents around 200 lines of VRML text.

Figure 19 summarizes the main steps of the data conversion process, to convert data from Spice simulation into VRML data.
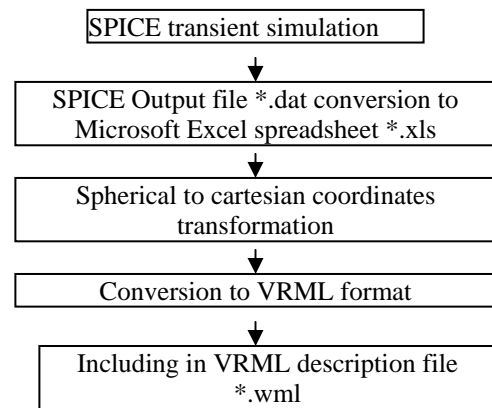

Figure 19: SPICE to VRML data conversion process

5.4 Running animation

Movements of the object in VRML are described as a combination of translation and rotation [14], [15].

Translations are defined as follows: for each normalized time instant t_i/t_{max}, the instantaneous corresponding 3D position x_i, y_i, z_i is given in a table with the syntax indicated below.

DEF course PositionInterpolator {
*   key   [t_o/t_{max},   ..., t_i/t_{max},   ..., 1]*

keyValue [x_o y_o z_0, ..., x_i y_i z_i, ...,x_n y_n z_n]}

Rotations are defined as follows: for each normalized time instant t_i/t_{max}, the instantaneous corresponding rotation axis x, y, z and rotation angle α (in rd) are specified in a table according to the syntax given below.

DEF rotcapt OrientationInterpolator {
*   key   [t_o/t_{max},   ..., t_i/T_{max},   ..., 1]*
keyValue [x y z $α_0$, ... , x_i y_i z_i $α_i$,..., x_n y_n z_n $α_n$]}

For example, a rotation of +π/2 around the Y axis will be specified with $x_i = 0$ $y_i = 1$ $z_i = 0$ $α_i = 1.57$.

The screen animation is not a "real time" process. The running time of the animation is specified as follows: Here, a sweep time of 20s from East to West is chosen for an easy and enough slow didactical animation. The "*Loop*" instruction allows repeating permanently the movement (simulation of daily rotations). Here, the "*ROUTE*" instruction makes the correspondence from time table towards the elevation table.

DEF temps TimeSensor {
*   cycleInterval 20*
*   loop TRUE}*

ROUTE temps.fraction_changed TO
elevationcapt.set_fraction

Figure 20 and 21, and 22 are captured image during the screen animation run with the "orbisnap" VRML viewer [16].
The yellow sphere represents the sun (or spotlight simulating the sun) moving in the sky from left to right (East to West).
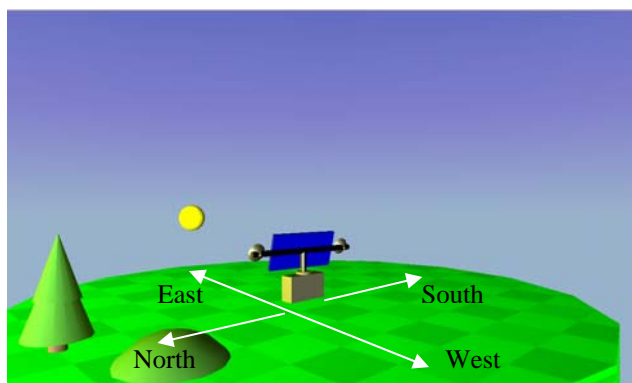

Figure 20: Captured image at the "sunrise"

On figure 20, we added manually the four main directions (North, South, East, and West) for better understanding.
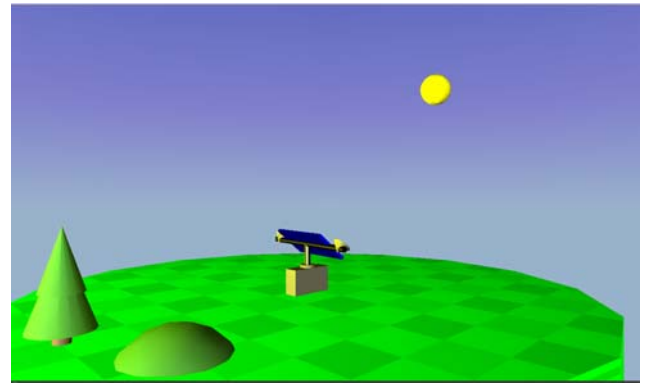

Figure 21: Captured image at the mid-day

By changing the viewpoint of the animation (cf. figure 23), we can display a more explicit angle of view (at midday for example).
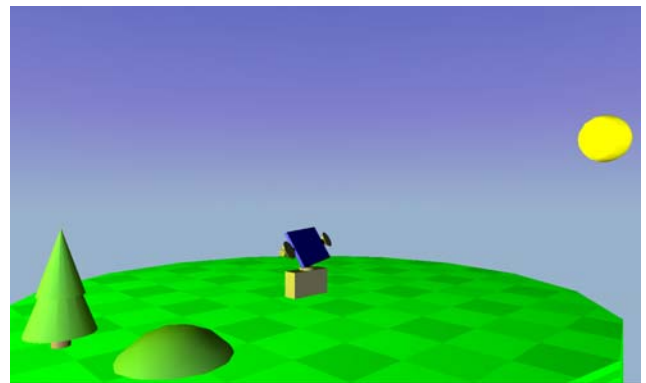

Figure 22: captured image at the "sunset"

Thus, it is possible to check that elevation movement is well reproduced by looking at the two LDR sensors axis "who are oriented towards the sun" (and not parallel to the floor like in sun rise or sun set situation.)
Once finished, the full scenario is captured and converted into an AVI video clip for portable demonstration uses with an open source freeware such as CAMSTUDIO for example and compressed into a animated GIF format and replay with any media player.
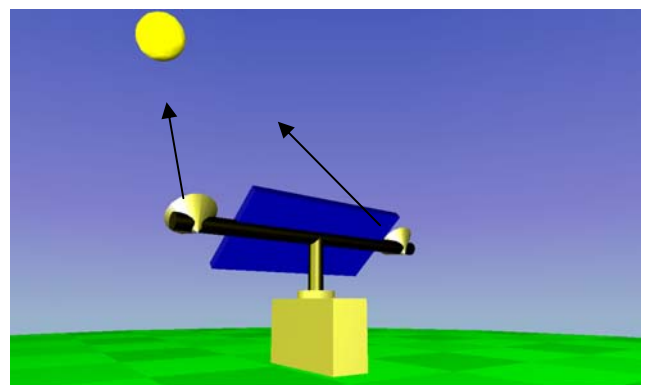

Figure 23: LDR sensor elevation at mid-day

6. Practical design

After modelling and 3D animation, the practical design in presented in Figure 24 and 25. Size of the small solar panel is 9cm x 5cm.

The electronic design uses only COTS and cheap components. The four matched LDR sensors (VT90N2 series or equivalent) are inserted in a Wheatstone bridge. Output signals subtraction is done by rail to rail OP amps LMC6482, to have the widest dynamic voltage range. V_{diff} voltage is applied to the simple PID corrector to ensure the loop stability (adjustable gain+ low pass RC filter). The resulting voltage value, V_c, is processed by a microcontroller MC9S12C128 module to generate PWM control signals for servo. Actually, a simple DC to PWM voltage analogue circuit should be enough for this. But, we used this too much sophisticated module for getting extra data that could be transmitted to a distant computer. Board is powered by a classical LM7805 +5V regulator.
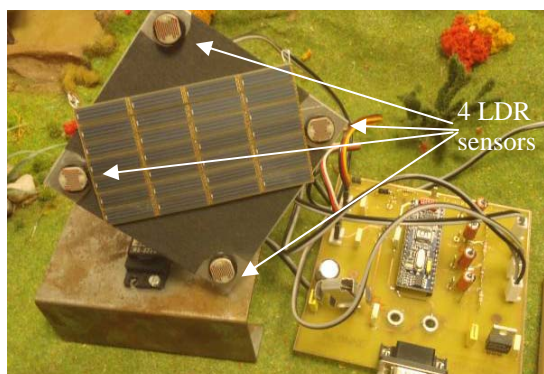

Figure 24: small scale solar tracking system (front side view)

Figure 25: small scale solar tracking system (back side view)

7. Experiment

7.1 Static open loop measurement

An open loop characterisation was performed on azimuth axis [2] mainly to identify the unknown servomotor transfer function (no manufacturer data). First cut-off frequency occurs at 1.58 Hz and confirms the servo parameters value used for simulations.

7.2 Visual test

Visual tests show that tracking feed back loop works correctly on the two axes. The system was validated under various conditions (light source distance and intensity). A correct matching between global SPICE modelling, predicting simulations and experimental behaviour is observed.

Finally, a small video clip was recorded to register the system behaviour (snapshot figure 26).
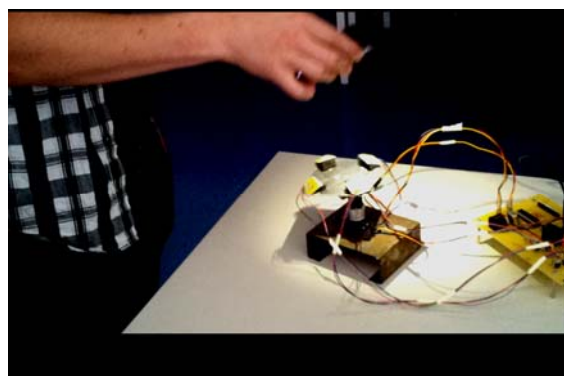

Figure 26 : In door Test with mobilephone lamp

7.3 Effect of local disturbance

A small shutter (simulating an objet passing over) was placed above only one of the two LDRs, to simulate a dissymmetric local disturbance on D input as defined in figure 6 (optical attenuation, small "cloud" and so on). Servomotor first deviates severely, and then comes back to the initial position as soon as the shutter is removed.

To check the behaviour the feed back loop, in extreme conditions, a second "non realistic" test was done: moving very suddenly the spot light out of the visual field of the LDR sensors. System turns towards the mechanical stop of the servomotor, stops and waits in this position until the spotlight comes again into the visual field of sensors.

7.4 Complementary tests

It is not easy to get quantitative data from the previous practical tests. In particular, the measurement of angular accuracy requires some extra accessories on the test bench (for examples fine needles to point more

precisely the azimuth and elevation directions). Secondly, despite the very positive results obtained by simulation, servomotor oscillates slightly because of the not perfect LDR matching and the inherent flicker at 100Hz coming from ceiling fluorescent light during indoor experimentation. So, a stop band filter will be added in the loop.

8. Comments

The Spice modelling gives satisfaction for predicting and analyzing the main performances of the small scale solar tracking system. Pros and cons are listed below:

Main advantages of the SPICE modelling are:
- Fast understanding of the solar tracking system global behaviour,
- Electrical modelling suitable for people who do not have specific optical, geometrical knowledge,
- Fast simulations,
- Modelling "enough but not too much complex" for didactical uses.

However, there are obviously aspects which can be improved:
- Approximations have obviously been done to build the modelling: we cannot be specialists of electronic circuits, optic and astronomy at the same time. Thus, accuracy of the modelling is certainly limited; it can be used only for a quick analysis. Refining some modelling blocks is always possible.
- Till now, this is not a parametric modelling: Each parameter must be changed manually if necessary.

Finally, the 3D VRML animation reflects accurately the tracking movement simulated with SPICE, but it obviously does not give quantitative data of error angles and feed-back loop accuracy.

9. Conclusion

An equivalent modelling of a small scale two axis solar tracking system was presented. Mixed Spice modelling predicts the correct tendencies and order of magnitude over the full rotation range. The experimental tests performed on the small scale system confirmed the modelling validity. In addition a 3 Dimensions VRML graphical animated modelling was presented. It was not mandatory but it is a more expressive and funny way (rather than a set of 2D

curves) to check and visualize the correct movement of the tracking system.

This solar tracking item is now installed in the garden of our small scale house modelling. Other accessories are going to be designed and will be integrated in the near future, to complete the Sustainable Development didactical platform.

Lastly, after some adaptations, the presented study is now used as training and application exercises during the electronic feed-back lessons and student's projects.

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