INTELLIGENT CONTROL & TRACKING

OF A PARABOLIC TROUGH SOLAR COLLECTOR

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Abstract:

Tracking is particularly important in solar energy collection systems that operate under concentrated sunlight. The aim of the research project is to test the solar-to-thermal energy efficiency of a tracking line-focus parabolic trough solar collector (PTSC). This is determined by measuring the temperature rise of water as it flows through the receiver of the collector when it is properly focused. The thermal efficiency of a PTSC is a function of intercept factor, which in turn depends on the accuracy with which the collector follows the sun. Accurate control of the collector is therefore crucial to the maximising of a PTSC's thermal efficiency. Given the varying demands of different operating regimes required for proper operation of the solar collector, different modes of control will form an integral part of the project to optimise tracking accuracy and thereby thermal efficiency as well.

Keywords: Fuzzy Logic, Programmable Logic Control, Solar Energy

1. INTRODUCTION

Three modes of control will offer the option to position the PTSC (parabolic trough solar collector). Tracking is particularly important in solar energy collection systems that operate under concentrated sunlight. The aim of the research project is to test the solar-to-thermal energy efficiency of a tracking line-focus parabolic trough solar collector (PTSC). Accurate control of the collector is therefore crucial to the maximising of a PTSC's thermal efficiency.

The energy efficiency will be determined by measuring the temperature rise of water as it flows through the receiver of the collector when it is properly focused. The thermal efficiency of a PTSC is a function of intercept factor, which in turn depends on the accuracy with which the collector follows the sun. Given the varying demands of different operating regimes required for proper operation of the solar collector, different modes of control will form an integral part of the project to optimise tracking accuracy and thereby thermal efficiency as well.

The optical efficiency of the collector is a function of five factors namely mirror surface reflectance, glass envelope transmittance, heat collection element absorptions, incidence-angle modifier and intercept factor:

$$\eta_o = f(\rho, \tau, \alpha, K, \gamma)$$

The specific relationship for normal incidence conditions (K = 1) is as follows:

$$\eta_o = [\tau \alpha \rho] \gamma$$

The factors within the square brackets are physical properties specific to the materials used to construct the collector and are constants. The intercept factor γ, which is constant for changes in beam irradiance and working fluid temperature, is a function of collector geometric parameters as well as error parameters. These errors arise during the construction and operation of a parabolic trough and include among others:

- Misalignment of the receiver
- Misalignment of the reflector
- Tracking errors
- Parabolic profile errors
- Sun image width error

Since the optical efficiency is a function of γ, which is a function of tracking error, the tracking error directly affects thermal efficiency. In order to maximise the thermal efficiency of the collector, it is therefore necessary to reduce the tracking error by as much as possible which means ensuring that the collector tracking and control system keeps the parabolic surface pointing accurately towards the solar disc at all times. The main components of the tracking and control system are indicated in table 1.

Table 1: Components of system

COMPONENT	FUNCTION
S7-300 PLC	Stores control algorithm
Step7	Software control platform
ComLS7	Profibus communication
FuzzyControl++	Knowledge based control
Pentium PC	Programming device
MPI connector	Interfaces PC to PLC
AC Drive	Controls motor speed
Incremental Encoder	Detects rotary motion
Pyrheliometer	Direct beam radiation
Pyranometer	Diffuse radiation
Anemometer	Wind Speed

2. FIXED RATE CONTROL

Given that the sun's apparent speed of rotation across the sky is 0,25°/min, most solar tracking systems use an intermittent drive methodology, where the drive system switches on and off at a calculated rate and interval to ensure that the collector remains pointed at the moving sun. The use of discrete time steps for following the sun's movement introduces small errors as the sun moves constantly and the trough stands still in between angular corrections. The starting point for determining how to structure the tracking motion is to define how large the allowable tracking misalignment error may become before corrective action is taken.

Based on experimental results from parabolic trough collector systems of similar proportions to the collector in this project, Kalogirou (1996) reports good thermal efficiency results for a rotational tracking error not greater than 3,5 mrad (0,2°). Stine (1985) describes the magnitude of typical tracking sensor errors as approximately 2,0 mrad, though this does not appear to be based on test results from a single case. A tracking error less than 3,5 mrad is assumed to be sufficiently accurate. The nature of tracking sensor errors is best illustrated graphically in figure 1. The sun's position is shown as it "moves" across the sky, first from position A to B and then C. The parabolic trough is positioned to be perfectly aligned at position B. For position B the sun's rays will be reflected off the mirror surface and on to the focal point, in accordance with Snell's Law. The tolerable error is 3,5 mrad, or 0,2° either side of position B. This means the trough can be positioned ahead (west) of the sun (at A in the sketch) and left standing until the sun moves through a total of 7 mrad, or 0,401°, which would take 69,12 seconds. Once the sun moves into position C, the DTCS must once more rotate the trough west through 7 mrad to reposition for A.

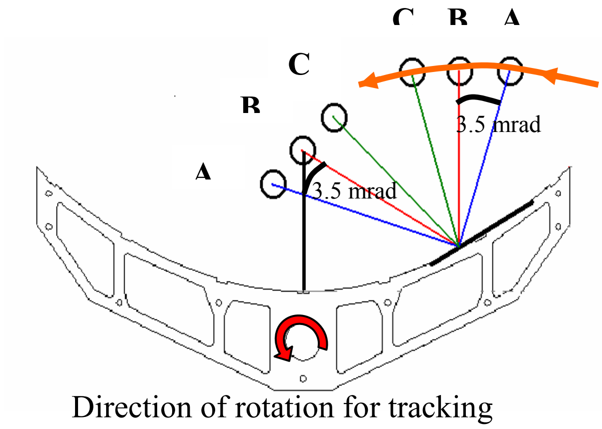

Figure 1: Trough misalignment due to movement of the sun at 0.25 degrees/minute.

The rotary encoder used in this project to provide feedback on the absolute angular position of the trough, has 2500 pulses per 360° of rotation, or 0,144° per pulse. A rotational movement of 0,007 rad, or 0,401° equates to 2,79 pulses. Since a discrete number of pulses must be used to position the trough, it is suggested that the trough corrections be made for 2 pulses, thus ensuring that the maximum allowable misalignment error is not exceeded. Working backwards, two pulses correspond to an angle of 0,288°, which gives a maximum angular tracking error of (0,5 x 0,00503 rad) = 2,513 mrad or 0,144°. This represents the angular distance between A and B, or between B and C in figure 1. Having determined the number of pulses to be used for each positioning step the behaviour of the Variable Speed Drive (VSD) must be defined. The VSD is capable of controlling motor drive speed from 685 rpm down to zero rpm, although for the sake of motor stability, speeds very near to zero are best avoided. At the same time, it is advisable to avoid a situation where the VSD has to switch on and off too quickly in order to cover each 0,288° step. The faster the trough rotates, the shorter the "on-time" of the VSD. VSD behaviour should therefore represent a compromise between these competing constraints. A reasonable "on-time" for the VSD-motor combination is 4 seconds. This would require a trough angular speed of 0,288°/4 = 0,072°/s. Working back through the drive train, the gearbox input speed, or VSD output speed, would therefore equal 33,336°/sec or 5,556 rpm. Since the sun moves at 0,25°/min or 0,004167°/s the time interval between corrective steps would be 69,12 seconds. The VSD should switch on for 4 seconds at 5,556 rpm every 69,12 seconds. This would rotate the trough through exactly two pulses on the encoder. Obviously, other combinations of rate and duration are possible to give the same overall result.

3. PSA CONTROL

The second mode of control calculates the position of the sun from the Plataforma Solar de Almeria (PSA) algorithm and positions the trough to keep pace. The trough is positioned in the North-South axis in order to track the sun in the East-West direction. The constants applied to the control algorithm are the longitude and latitude based on the geographical location of the trough and the variable will be the instantaneous universal time extracted from the processor of the controller. Feedback is provided by means of the incremental encoder for position detection, to compare the calculated position of the sun to the actual position of the trough. The software mathematical algorithm is configured in statement list using the Step7 architecture.

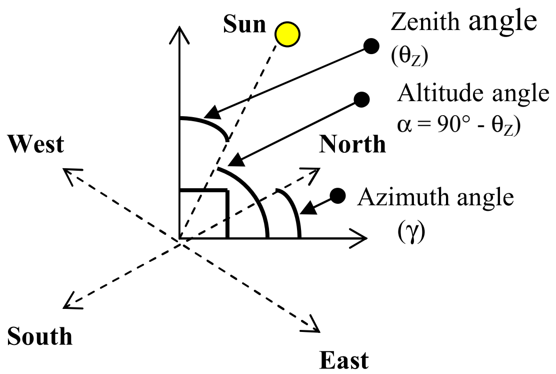

Figure 2: Location of Sun position

The location of the sun is determined by the following formulae with reference to figure 2 and appendix 1.

[1]… $jd =$
$[1461 \text{ X } \{y + 4800 (m - 14) / 12\}] /4 +$
$(367 \text{ X } [m - 2 - 12 \text{ X } \{(m - 14) / 12 \}]) /12 -$
$(3 \text{ X } [\{ y + 4900 + (m - 14) / 12 \} / 100])) /4$
$+ d - 32075 - 0.5 + hour / 24.0$

[2]… $n = jd - 2451545.0$

[3]… $\psi = 2.1429 - 0.0010394594 \text{ X } n$

[4]… $L = 4.8950630 + 0.017202791698 \text{ X } n$

[5]… $g = 6.2400600 + 0.0172019699 \text{ X } n$

[6]… $l = L + 0.03341607 \text{ X } \sin (g) + 0.00034894 \text{ X } \sin (2g) - 0.0001134 - 0.0000203 \text{ X } \sin (\psi)$

[7]… $ep = 0.4090928 - 6.2140 \text{ X } 10^{-9} \text{ X } n + 0.0000396 \text{ X } \cos (\psi)$

[8]… $ra = \tan^{-1} [\{ \cos (ep) \text{ X } \sin (l)\}/ \cos (l)]$

[9]… $\delta = \sin^{-1} \{ \sin (ep) \text{ X } \sin (l) \}$

[10]… $gmst = 6.6974243242 + 0.0657098283 \text{ X } (n) + hour$

[11]… $lmst = (gmst \text{ X } 15 + long) \text{ X } (\pi/180)$

[12]… $\omega = \text{lmst} - \text{ra}$

[13]… $\theta_z = \cos^{-1} [\cos(\Phi) \cos(\omega) \cos(\delta) + \sin(\delta) \sin(\Phi)]$

[14]… $\gamma = \tan^{-1} \left\{ \dfrac{-\sin(\omega)}{\tan(\delta)\cos(\Phi) - \sin(\Phi)\cos(\omega)} \right\}$

[15]… $Parallax = \dfrac{\underline{EarthMeanRadius}}{AstronomicalUnit} \text{ X } \sin(\theta_z)$

[16]… $\theta_t = \theta_{z\,+}\ Parallax$

[17]… $\rho = \tan^{-1} \left\{ \dfrac{\sin(\gamma)}{\tan(180/\pi) - \theta_t} \right\}$

The following software instructions in statement list make use of the actual time to solve the seventeen equations in order to locate the sun by means of the programmable logic controller:

```
CALL  "READ_CLK"
 RET_VAL:=#error
 CDT    :=#Act_time_date

CALL  "BCDtoDEC"
 BCD_byte :=LB5
 DEC_value:=#seconds_val

L     #seconds_val   //seconds from clock
DTR
L     3.600000e+003 //seconds to hours
/R
T     #sec_as_hours
CALL  "BCDtoDEC"
 BCD_byte :=LB4
 DEC_value:=#minute_val

L     #minute_val        // minutes from clock
DTR
L     6.000000e+001    //minutes to hours
/R
T     #min_as_hours
```

```
CALL  "BCDtoDEC"
 BCD_byte :=LB3
 DEC_value:=#Hour_val

L    #Hour_val            //hours from clock
DTR
L    #min_as_hours
+R
L    #sec_as_hours
+R
L    2.000000e+000        //hours to Universal
-R
T    #Universal_hours
```

4. INTELLIGENT ALGORITHM

The third mode of control, a fuzzy logic controller, based on an intelligent control algorithm that is knowledge based will determine the output signal to the variable speed drive. This mode of control is different in that it is knowledge-based and three inputs are required to position the trough, viz. fluid inlet temperature, wind speed and the trough position. Three inputs, fluid temperature, wind speed and trough position, and one output, drive speed were defined. After naming the inputs and outputs the membership functions had to be defined, for each input and output. The trapezoid form was used for the inputs, in order to increase the number of corner points, for clear distinction of one function from the other. The output was inserted as singleton. The rules were then edited in the inference engine, in either the rule table or rule matrix form. Only the wind speed input and the drive output will be analysed under this section.

In order for the desired trough position to be maintained, it was dependent on certain plant and control variables. These variables had to be analysed at different values, within a specified band, in order to maintain the position at a desired value. The membership functions (procedural knowledge) for both, the inputs and outputs, were derived from the following plant variables, for the specified band:

- Wind speed
- Position of trough
- Fluid temperature
- Variable speed drive

The rules (declarative knowledge) for the intelligent system were derived from the following control variables, for the specified band:

- Data communication signal from anemometer
- Data communication signal from incremental encoder
- Data communication signal from the thermocouple
- Data communication signal to variable speed drive

Figure 3 represents the knowledge engineering process in a generic form.

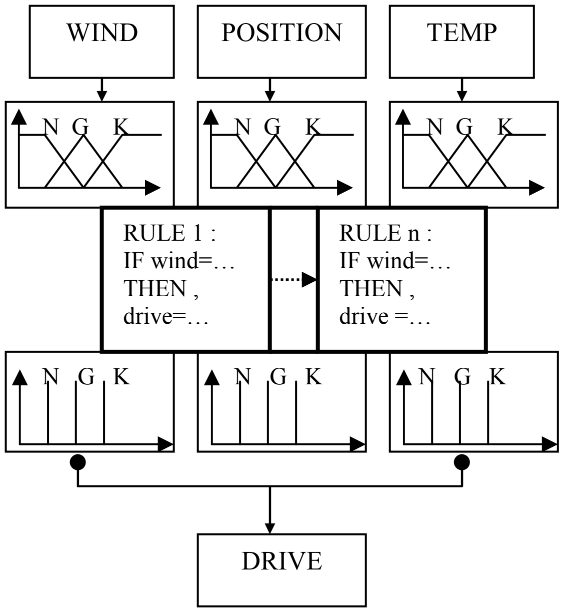

Figure 3: Generic structure of the 3-input, 1-output controller

Figure 4 and table 2 represents the edited input membership function in trapezoid form, for only fluid temperature. This facilitates fuzzification of a crisp value by scaling and mapping the input's domain, a linguistic variable, into an internal computer code. Figure 5 and table 3 represents the edited output membership function in singleton form, for the variable speed drive. This facilitates de-fuzzification of the internal computer code to a crisp value by scaling and mapping the output's domain.

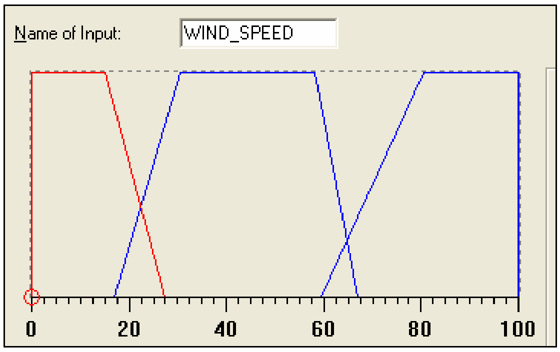

Figure 4: Edited Wind Speed (Graphical)

Table 2: Edited Wind Speed (Actual)

MEMB. FUNCT.	*PT 1*	*PT 2*	*PT 3*	*PT 4*
win_zer	0.0	0.0	15.0	27.5
win_med	16.9	30.6	58.1	66.9
win_max	59.4	80.6	100.0	100.0

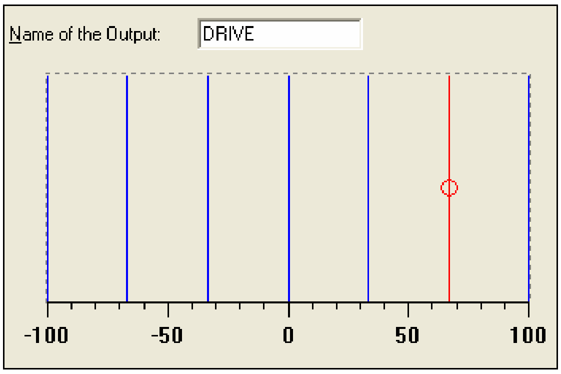

Figure 5: Edited Drive Speed (Graphical)

Table 3: Edited Drive Speed (Actual)

MEMB. FUNCT.	*VALUE*
rev_fas	-100.0
rev_med	-66.7
rev_slo	-33.3
stop	0.0
fwd_slo	+33.3
fwd_med	+66.7
fwd_fas	+100.0

Figure 6 represents only the rules assigned to the wind speed and fluid temperature for the variable speed drive to position the trough, out of the fifteen rules for the system as indicated in table3. The system can be configured up to two hundred rules in total. The facts and rules (declarative knowledge) are represented separately from decision-making algorithms (procedural knowledge). The rule at top left as in figure 6 state that IF the WIND_SPEED is win_zer and FLUID_TEMP is cold THEN DRIVE = rev_fas.

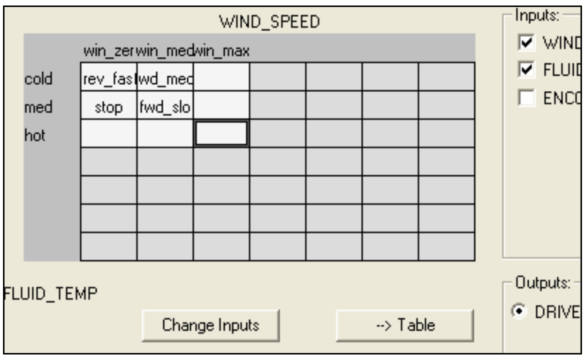

Figure 6: Rules for Speed and Temperature

Table 4: Assigned Rules

Rule No.	Wind Speed	Fluid Temp	Encoder	Drive
1	win_zer	cold	enc_neg	rev_fas
2	win_med	med	enc_zer	rev_med
3	win_max	hot	enc_pos	stop
4	win_max	hot	enc_pos	stop
5	win_max	hot	enc_pos	fwd_slo
6	win_med	med	enc_neg	fwd_slo
7	win_med	cold	enc_zer	fwd_med
8	win_max	hot	enc_pos	fwd_fas
9	win_med	cold	enc_pos	stop
10	win_med	cold	enc_neg	fwd_med
11	win_med	hot	enc_zer	fwd_slo
12	win_zer	med	enc_pos	fwd_med
13	win_med	cold	enc_pos	fwd_fas
14	win_zer	med	enc_zer	fwd_slo
15	win_zer	med	enc_neg	stop

5. ANALYSIS OF RULE BASE

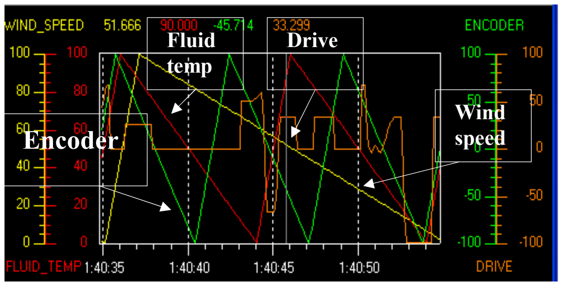

Figure 7: 2-Dimensional analysis of Rule Base

In order to clearly analyze all input signals the wind speed input signal was set for 1 cycle per screen, 10% aspect ratio, 1% phase angle, the fluid temperature input signal was set for 2 cycles per screen, 20% aspect ratio, 2% phase angle and the encoder input signal was set for 3 cycles per screen, 30% aspect ratio, 3% phase angle as indicated on figure 7. These adjustments made it possible to clearly allow all three inputs to be visible at all times on the screen when analysing the simulated signals. It was not necessary to adjust the output signal as the membership functions were configured as singletons and there was just a single output signal. Figure 7 represents the debugging stage that clearly indicates the point of analysis at the vertical solid line, where the active rule 11 was verified in the software. The signal to the variable speed drive is maintained at 33.3% although the input variables varied. Rule 11 states that IF wind speed is between 16.9-to-66.9 AND fluid temperature is between 54.4-to-100 AND encoder is between –71.3-to-43.8, THEN the variable speed drive must adjust to 33.3. All values are assigned as a percentage of the operating range. In comparison to the actual assigned rule it can clearly be seen that the process will not be subjected to unwanted fluctuations and that rule 11 is active for this condition from the configured algorithm.

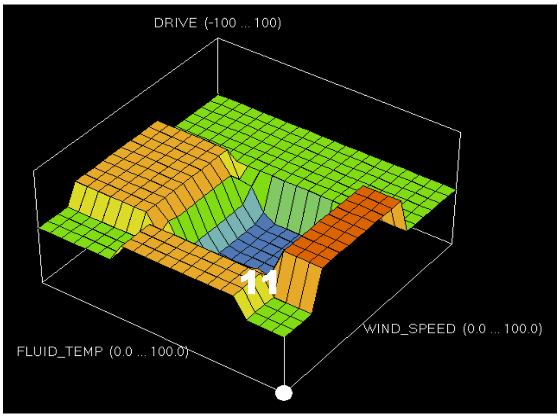

Figure 8: 3-Dimensional analysis of Rule Base

The number 11 indicated on Figure 8 indicates that rule 11 is active in this region of the X-Y-Z axis. It can be seen that when the wind speed is *win_med* (the second membership function from the X-axis), and the fluid temperature is *hot* (the third membership function from the Y-axis), the drive is *fwd_slo* (the fifth membership function from the Z-axis. All the configured rules can be verified from Figure 8 in the same way.

Along the X-axis is input one, wind speed. The three areas on the 3-dimensional representation that are parallel to the X-axis, is representative of the three input membership functions that were assigned for the wind speed. The adjoining areas that are slanted are the areas of the membership functions that overlap each other. Similarly, the fluid temperature and the drive signals can be analysed.

CONCLUSION

Most solar tracking and control systems function in open loop mode. In the fixed rate control mode the variable speed drive is programmed to rotate the trough at a constant rate based on the movement of the sun. In the PSA control mode an algorithm is defined by means of mathematical formulae, generating a variable data signal to the drive based on the position of the sun on the X, Y, Z axis. In both these modes position feedback is not necessary but will be used for reference purposes and not necessarily for actual control. However, in the fuzzy control mode the position detection, wind speed and the fluid circulation temperature will be essential to determine the position of the trough. The degree of offset with respect to the solar radiation onto the receiver tube needs to be analysed in terms of solar-thermal efficiency.

APPENDIX 1

jd:	Julian Day
m:	Month {required from the PLC}
y:	Year {required from the PLC}
d:	Day {required from the PLC}
hour:	Hour in Universal Time {required from the PLC}
n:	The difference between current Julian Day and Julian Day 2451545.0 (01-01- 2000)
L:	Mean longitude of the Sun
g:	Mean anomaly of the Sun
l:	Ecliptic longitude of the Sun
ep:	Obliquity of the ecliptic
ra:	Right ascension
δ:	Declination
gmst:	Greenwich mean sidereal time
lmst:	Local mean sidereal time
long:	Geographical longitude
Φ:	Geographical latitude
ω:	Hour angle
θ_z:	Zenith distance
γ:	Solar azimuth
ρ:	Actual position of Sun (+ve indicates East of verticle)

EarthMeanRadius = 6371.01 km
AstronomicalUnit = 149597890 km

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