Mono-axial tracking system for parabolic trough collector

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Abstract. Increased living standards in the developed countries lead to increased energy consumption. By using renewable energy, the fossil fuel consumption and greenhouse gas effect are reduced. The main source of renewable energy is the sun that can be used to produce the thermal energy or electric energy. The concentrating collectors are used to obtain both heat and electricity. The most common and used concentrating collectors are the parabolic trough collectors due to their advantages, such as: lower price, use of mono-axial tracking systems, simple maintenance. Parabolic trough collectors can have orientation around the N-S axis or E-W axis. In the case of N-S orientation, the angular stroke is higher than 120°, and in case of E-W orientation, the angular stroke that the tracking system has to ensure is less than 100°. The mechanisms used to orientate these collectors are using gears, cam or chain transmission. The paper presents a new type of mono-axial tracking system with linear actuators that has the advantages of assuring the required angular stroke, a high orientation accuracy and lower price.

1. Introduction

The 2017 reports inform that 70% of the energy was produced from renewable energy sources, but also that the amount of CO₂ emissions has risen by 1.4%, after three years of stagnation [1]. This increase is due to the cuts in fossil fuel prices, to the global economic growth (+ 3.7%), but also due to the reduced efforts to increase energy efficiency.

Worldwide, the new annual investments reached USD 279.8 billion at the end of 2017, 179 countries having as target the use of renewable energies, while 57 countries are targeting by 2020 to generate the whole amount of electric energy from renewable sources.

In 2017, 48% of the globally consumed energy was used for heating, 27% of it being produced from renewable energy (RE), 32% for transportation (3% from RE), and 20% for energy (25% from RE) (Figure 1).

![Figure 1. Renewable energy in the total energy consumption in 2017](image-url)
The main source of renewable energy is the sun. Solar energy can be used both to produce heat using solar collectors and to generate electricity by using solar panels or through thermal conversion by using concentrating collectors.

In the case of solar thermal systems, the temperature of the agent is approx. 60°C, while for concentrating collectors is over 100°C. A large amount of solar radiation should be captured to obtain temperatures of the thermal agent higher than 100°C. A way to capture more radiation is by using reflective surfaces that concentrate the solar radiation [2].

The main types of collectors that concentrate solar radiation are: trough-type parabolic collectors, dish-type collectors and central tower collectors [3]. The most used concentrating collectors are the trough type, due to the use of a tracking system, an easier maintenance and lower cost than the other two variants [1, 2]. Thus, to capture the solar radiation, the parabolic trough collectors are equipped with mono-axial tracking systems. These systems have to meet the following functional conditions: to provide a good orientation (the orientation error should be below 0.5°), to ensure a high rotation angle of the reflector, and a good stability of the whole structure and to allow the control of the reflector position under critical conditions (high wind speeds, etc.)

Two main variants of mono-axial tracking systems for trough-type parabolic collectors are on the market today: an E-W orientation system and a N-S orientation system. In the case of the E-W orientation, the angular stroke of the collector is up to 90°, being obtained by using either linkages or gears [4]. In the case of N-S tracking systems, the angular stroke that has to be achieved is higher than 100°. The mechanisms that can provide these angular strokes and which are found in the construction of the trough collectors are: cam mechanisms, gears and chain / belt transmissions [5].

The paper is proposing a new variant of tracking mechanism for the parabolic trough collectors. The linkage based system has the advantage of achieving large angular strokes and a lower price.

2. Conceptual design of the tracking system
The parabolic trough collectors consist of: reflector, receiver and a mono-axial tracking system. The operating temperature of these collectors is high due to the reflection of the solar radiation from the receiver to the reflector. In order to reflect the solar radiation, the reflector must follow the sun motion on the sky (see Figure 2).

The angles that determine the position of the sun on the sky and which the tracking system of the trough collector has to ensure are given by the following relations [2]:

\[
\alpha = \sin^{-1}(\sin \delta \sin \phi + \cos \delta \cos \phi \cos \omega) \tag{1}
\]

\[
\psi = (\text{sgn} \phi) \cos^{-1}\left(\frac{\sin \alpha \sin \phi - \sin \delta}{\cos \alpha \cos \phi}\right) \tag{2}
\]

where \( \alpha [^\circ] \) is the altitude angle (the angle between the sunray and the observer plane [6]), \( \psi [^\circ] \) is the azimuth angle (it is the compass direction from which the sunlight is coming [6]), \( \delta [^\circ] \) is the declination angle (the angle between the sunray and the equatorial plane [6]), \( \omega [^\circ] \) – the hour angle (the angle that describes the Earth’s rotation around its polar axis [6]) and \( \phi [^\circ] \) is the latitude angle (the angle that describes the observer’s position on the Earth [6]).

For Brasov (the latitude angle \( \phi = 45.583^\circ \)) and, for the four important days of the year (day no \( N = 82 \) - spring equinox, \( N = 172 \) - summer solstice, \( N = 266 \) - autumn equinox, and \( N = 355 \) - winter solstice) the altitude angle has the values presented in Figure 3, while the azimuth angle variation is illustrated in Figure 4, both depending on the solar hour.

The azimuth angle variation for different latitude angles is presented in Figure 6. The charts highlight that the azimuth angle varies from \( \pm 120^\circ \) for a latitude angle of 15° North to \( \pm 123.8^\circ \) for the latitude angle of 65°.

In order to concentrate the solar radiation, the reflector of the parabolic collector has to perform an angle whose values are between \( 240^\circ \)-\( 248^\circ \) (see Figure 5). As the solar radiation intensity is reduced in the mornings and evenings, it will be further considered that the collector orientation will begin at 8:00 and will end at 17:00, which will reduce the energy consumption required for orientation. During this period of time, the angular stroke the collector must achieve is \( \pm 90^\circ \) (see Figure 4).
To ensure this angular stroke, gears or linkages driven by two linear actuators can be used. These mechanisms allow a reduced orientation accuracy. The accuracy can be increased and a large angular stroke can be achieved by using the tracking system presented in Figure 6.

The mono-axial tracking system from Figure 6 is composed of: 1 – the collector base; 2 - lever that is solidar to the parabolic collector; 3, 4, 5 - linear actuators that provide a large angular stroke (higher than 180°) of the trough collector; 6 – parabolic trough collector.

The linear actuators 4 and 5, which are disposed triangularly and connected to the base through the revolute joints D and E, move the parabolic trough collector with a large angular stroke, but with a low accuracy [7]. The orientation accuracy is ensured by actuating the actuator 3.
**Kinematic analysis**

The tracking mechanism is presented in Figure 7 in structural scheme, being defined as a multibody system with a minimum number of bodies \( n_b = 5 \) bodies: 1 - fixed body; 2 - output body; 3,4,5 - other bodies. The number of driving constraints can be determined according to Eq. (3):

\[
M = S \cdot (n_b - 1) - \sum c_i = 3 \cdot (5 - 1) - 9 = 3
\]

where: \( S \) is the mechanism spaciality; \( n_b \) - number of bodies; \( c_i \) - number of geometrical constraints.

The type and number of geometrical constraints between each two bodies are presented in Table 1, while the geometrical models of the bodies are systematized in Table 2.

### Table 1. Geometrical constraints

| Bodies | Geometrical constraints | Place | \( \Sigma c_i \) |
|--------|-------------------------|-------|---------------|
| 1-2    | R                       | A     | 2             |
| 1-4    | RT                      | D     | 1             |
| 1-5    | RT                      | E     | 1             |
| 2-3    | RT                      | B     | 1             |
| 3-4    | R                       | C     | 2             |
| 3-5    | R                       | C     | 2             |

R - rotation, T – translation,

### Table 2. Geometry of bodies

**Body 1**

\[
x_{A_1} = 505.9 \text{ mm}; \quad y_{A_1} = 876.3 \text{ mm};
\]
\[
x_{D_1} = 0 \text{ mm}; \quad y_{D_1} = 0 \text{ mm};
\]
\[
x_{E_1} = 1011 \text{ mm}; \quad y_{E_1} = 0 \text{ mm};
\]

**Body 2**

\[
x_{B_2}^{(2)} = 0 \text{ mm}; \quad y_{B_2}^{(2)} = 0 \text{ mm};
\]
\[
x_{A_2}^{(2)} = 409.2 \text{ mm}; \quad y_{A_2}^{(2)} = 0 \text{ mm};
\]

**Body 3**

\[
x_{B_3}^{(3)} = 422 \text{ mm}; \quad y_{B_3}^{(3)} = 0 \text{ mm};
\]
\[
x_{C_3}^{(3)} = 0 \text{ mm}; \quad y_{C_3}^{(3)} = 0 \text{ mm};
\]
Table 2. Geometry of bodies (continuation)

| Body  | x₀, y₀, z₀ | x₁, y₁, z₁ | x₂, y₂, z₂ | x₃, y₃, z₃ | x₄, y₄, z₄ | x₅, y₅, z₅ |
|-------|------------|------------|------------|------------|------------|------------|
| 4     | 00 mm; 00 mm; 1288 mm; 00 mm; | y₄(4) = 0 mm; y₄(4) = 0 mm; | x₄(4) = 1288 mm; y₄(4) = 0 mm; |
| 5     | 00 mm; 00 mm; 1585 mm; 00 mm; | y₅(5) = 0 mm; y₅(5) = 0 mm; | x₅(5) = 1585 mm; y₅(5) = 0 mm; |

The 12 generalized coordinates \((x_{O2}, y_{O2}, \varphi_2; x_{O3}, y_{O3}, \varphi_3; x_{O4}, y_{O4}, \varphi_4; x_{O5}, y_{O5}, \varphi_5)\) from Table 2 can be obtained from the system of the position functions, consisting of 9 equations for the geometrical restrictions (Eq. 4...12) and 3 equations for the kinematic restrictions (Eq.13…15):

\[
1 - 2 \quad R \quad A_1 = A_2 \quad F_1: x_{A_1} - x_{O2} - x_{A_2}^{(2)} \cos \varphi_2 + y_{A_2}^{(2)} \sin \varphi_2 = 0 \quad (4)
\]

\[
F_2: y_{A_1} - y_{O2} - y_{A_2}^{(2)} \sin \varphi_2 - y_{A_2}^{(2)} \cos \varphi_2 = 0 \quad (5)
\]

\[
1 - 4 \quad RT \quad D_1 \quad F_3: x_{D_1} - x_{O4} - x_{D_4}^{(4)} \cos \varphi_4 + y_{D_4}^{(4)} \sin \varphi_4 \left( y_{O4} + x_{D_4}^{(4)} \sin \varphi_4 + y_{D_4}^{(4)} \cos \varphi_4 - y_{A_4} - x_{A_4}^{(4)} \sin \varphi_4 - y_{A_4}^{(4)} \cos \varphi_4 - y_{A_4}^{(4)} \cos \varphi_4 + y_{A_4}^{(4)} \sin \varphi_4 = 0 \quad (6)
\]

\[
1 - 5 \quad RT \quad E_1 \in E_5 \quad C_5 \quad F_4: x_{E_5} - x_{O5} - x_{E_5}^{(5)} \cos \varphi_5 + y_{E_5}^{(5)} \sin \varphi_5 \left( y_{O5} + x_{E_5}^{(5)} \sin \varphi_5 + y_{E_5}^{(5)} \cos \varphi_5 - y_{A_5} - x_{A_5}^{(5)} \sin \varphi_5 - y_{A_5}^{(5)} \cos \varphi_5 - y_{A_5}^{(5)} \cos \varphi_5 + y_{A_5}^{(5)} \sin \varphi_5 = 0 \quad (7)
\]

\[
2 - 3 \quad RT \quad B_2 \in B_3 \quad C_3 \quad F_5: x_{B_3} + x_{B_3}^{(3)} \cos \varphi_3 - y_{B_3}^{(3)} \sin \varphi_3 - x_{O4} - x_{B_3}^{(3)} \cos \varphi_3 + y_{B_3}^{(3)} \sin \varphi_3 \left( y_{O3} + x_{B_3}^{(3)} \sin \varphi_3 + y_{B_3}^{(3)} \cos \varphi_3 - y_{A_3} - x_{A_3}^{(3)} \sin \varphi_3 - y_{A_3}^{(3)} \cos \varphi_3 - y_{A_3}^{(3)} \cos \varphi_3 + y_{A_3}^{(3)} \sin \varphi_3 = 0 \quad (8)
\]

\[
3 - 4 \quad R \quad C_3 = C_4 \quad F_6: x_{C_4} + x_{C_4}^{(4)} \cos \varphi_4 - y_{C_4}^{(4)} \sin \varphi_4 - x_{O4} - x_{C_4}^{(4)} \cos \varphi_4 + y_{C_4}^{(4)} \sin \varphi_4 = 0 \quad (9)
\]
Equations (4) and (5) represent the geometrical constraint of R type from joint A, equation (6) - the geometrical restriction of RT type from joint D, equation (7) – the geometrical restriction of RT type from joint E, equation (8) – the geometrical restriction of RT type from joint B, equations (9) - (12) – the restrictions of R type from C, and equations (13)…(15) – the kinematic restrictions. The displacement function of the tracking mechanism (Figure 9) can be obtained by solving numerically the system (4)...(15) in Maple 5 software.

**Conclusions**

The proposed mono-axial tracking mechanism has the advantage of achieving a large angular stroke through the two actuators in a triangular arrangement, articulated to the base at their fixed ends. In order to ensure a smooth correction of the orientation and to increase the collector stroke, a third linear actuator, having its cylinder solidary to the trough collector, is used.

The variation of the angular stroke of the parabolic trough collector (Figure 9) and the strokes of the three linear actuators (Figure 10) can be obtained from the system of equations (4 ... 15) for the numerical data presented in Table 2, by using MAPLE 5 software.

The analysis of the mechanism dynamic behaviour can be performed based on the kinematic analysis of the tracking system.

**References**

[1] http://www.ren21.net/gsr-2018/ (last access on 20 of June)
[2] Visa I, Jaliu C, Duta A, Neagoe M, Comsit M, Moldovan M, Ciobanu D, Burduhos B, Saulescu R 2015 The Role of Mechanisms in Sustainable Energy System (Transilvania University Publishing House)
[3] Duffie A and Beckman W A 2006 Solar engineering of thermal processes (John Willey&Sons Inc.)
[4] Desai N B and Bandyopadhyay S Optimization of concentrating solar thermal power plant based on parabolic trough collector Journal of Clean Production 89 pp 262-271
[5] Mousazadeh H et. al. A review of principle and Sun tracking methods for maximizing solar systems output Renewable and Sustainable Energy Reviews 13 pp 1800-18018
[6] http://www.powerfromthesun.net/book.html (last access on May 15)
[7] Patent No. RO131808(A0): Highly Accurate Uniaxial Orientation Mechanism