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# SOLVING THE LOST IN SPACE PROBLEM WITH STAR TRACKER SENSOR USING GENERALIZED EXTREMAL OPTIMIZATION (GEO)

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**Abstract**: In this work, preliminary results of a study to determine the efficacy of using the Generalized Extremal Optimization algorithm (GEO) for star pattern identification for the lost in space problem, are presented. The results of the simulations are presented in graphics and tables which show the identifications and the algorithm performance.

**Keywords:** Star Tracker Sensor, Generalized Extremal Optimization (GEO), Spacecraft Attitude.

## 1. INTRODUCTION

The lost in space problem, consist in determine the spacecraft vehicle axis orientations in relationship to the inertial coordinates system without any other information. It is very important for the success of the space mission, because the correct determination of this orientation supply the correct spacecraft attitude to the control system.

In this work, this problem is solved using just information of the stars coordinates observed by the field of view (FOV) of a star tracker sensor attached to the spacecraft.

This sensor determine their attitude comparing the stars coordinates observed by their FOV and the stars coordinates presented in a catalogue stored in the on board memory. This comparison is performed by star patterns algorithms which search in the catalogue similar patterns to the FOV observation.

The evolutionary algorithm GEO is used in this work for realize this identification using an optimization approach, by minimizing an objective function which computes the discrepancy between the stars in the sensor´s FOV with the ones in candidate FOVs in the catalogue.

The simulations are divided in two different sets, where in the first set is used a plan catalogue with randomly distributed stars and in the second set is used a real catalogue with stars in spherical coordinates.

In the second set, with the stars observed by the FOV sensors and the stars identified by the algorithm in the catalogue, is possible calculates the spacecraft attitude using an attitude determination algorithm. In this work is used singular value decomposition (SVD) [1] to determine the attitude.

## 2. STAR TRACKER SENSOR

The star tracker sensor is an attitude determination sensor that is being largely used in space missions because their accuracy in calculate it.

These sensors, of a more general way, can be divided in two classes [2].

In the first class the star tracker sensors are called not autonomous, where these sensors just inform to the control system of the spacecraft the coordinates of the stars observed by their FOV, the identification of the stars in catalogue and the determination of the attitude is not make by the sensor [2].

In the second class, these sensors are able to identify the stars observed by their FOV and calculate their attitude independently [2].

The star tracker sensors of the second class are the ones addressed in this work.

### *2.1. Autonomous Star Tracker Operation*

In a concise form we can describe the autonomous star tracker operation in four steps [2].

- First step: Image acquisition of the stars by the FOV sensor.
- Second step: mapping of the stars observed in the matrix of the FOV sensor.
- Third step: recognition of the stars observed by the sensor FOV in the star catalogue stored in the sensor’s on board memory by the star pattern algorithm.
- Fourth step: Spacecraft attitude determination.

These four steps can by better observed in the figure 1[2].

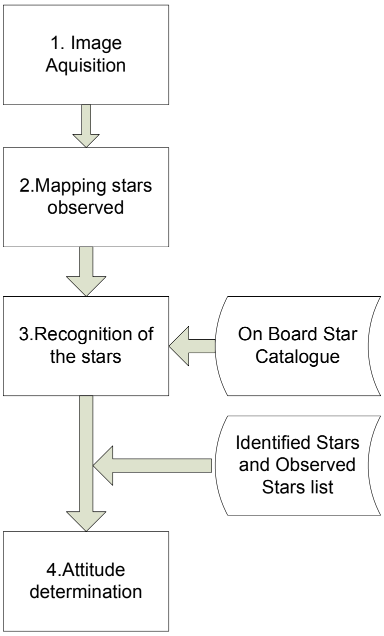

**Fig. 1. Autonomous Star Tracker Operation**

There is not yet a definitive solution for the star pattern identification problem, in the literature there are many approaches and algorithms proposed, in this work is proposed the use of a new evolutionary algorithm to solve this problem.

## 3. GENERALIZED EXTREMAL OPTIMIZATION (GEO)

The Generalized Extremal Optimization algorithm (GEO), is a new evolutionary algorithm proposed by De Sousa [3] [4], this algorithm is easy to implementation and can be applied in anyone optimization problem.

In this algorithm a sequence of species represented by a string of bits creates a population, to each species (bit) is attributed a fitness which define what species are more adapted after mutate (flipped bit). The design variables are encoded in the string of bits as show in figure 2[3] [4].

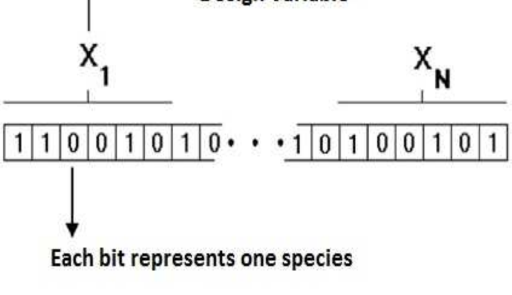

**Fig. 2. Design Variable encoded in a binary string**

The number (m) of the bits necessary for each design variable ($X_i$) to have a precision (p) can by calculate by equation 1[3] [4].

$$2^m \ge \left[\frac{X_{i\_\sup} - X_{i\_\inf}}{p} + 1\right] \qquad (1)$$

Where the $X_{i\_sup}$ and the $X_{i\_inf}$ are the higher and low design variables limits.

The values of the design variables encoded in real number can by calculated by equation 2 [3] [4].

$$X_i = X_{i\_\inf} + (X_{i\_\sup} - X_{i\_\inf}) \cdot \frac{X_{i\_b^{10}}}{2^m - 1} \qquad (2)$$

Where $X_{i\_b}{}^{10}$ is an integer number obtained from the transformation of the design variable $X_i$ in a decimal representation.

The implementation of the GEO algorithm are represented in figure 3 [5]:

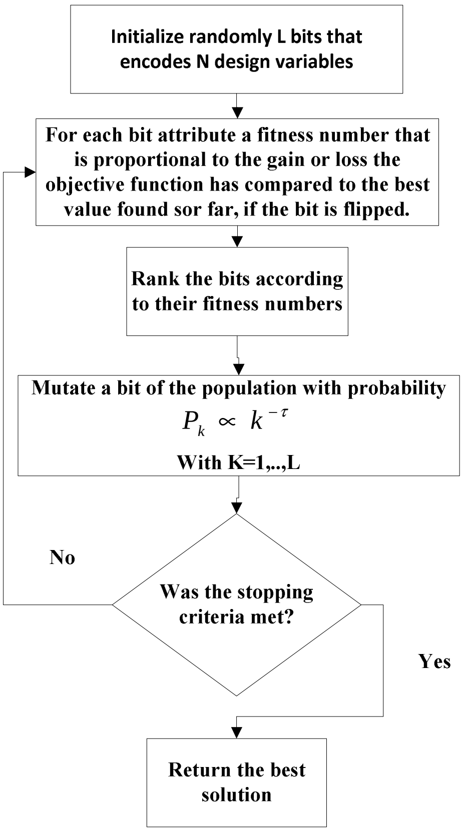
Initialize randomly L bits that encodes N design variables
For each bit attribute a fitness number that is proportional to the gain or loss the objective function has compared to the best value found sor far, if the bit is flipped.
Rank the bits according to their fitness numbers
Mutate a bit of the population with probability
$P_k \propto k^{-\tau}$
With K=1,..,L
Was the stopping criteria met?
No
Yes
Return the best solution

**Fig. 3. Canonical GEO flowchart**

The parameter $\tau$, is a adjustable parameter which determine how stochastic is the search. If the parameter $\tau$ is equal to zero the algorithm is completely stochastic.

With the objective to make the search more efficient in the GEO algorithm De Sousa [3] [4] proposed the $\text{GEO}_{\text{var.}}$

The change realized in $\text{GEO}_{\text{var}}$ does not modify the original GEO concept and just occur in the fact that now one bit of each design variable is mutated.

### *3.1. GEO*$_{real}$

With the purpose of the use a real codification for the representation of the design variables, Lopes [5] developed two versions of the GEO using real codification.

This codification avoids has to stipulate a precision for the algorithm.

The mutation in the design variables occur now using the equation 3 [5].

$$X'_i = X_i + N(0,\sigma) \cdot X_i \qquad (3)$$

Where the $N(0,\sigma)$ is a random number with zero mean and standard deviation $\sigma$.

Lopes also propose the $GEO_{real2}$ differing of the $GEO_{real1}$ in fact of the $GEO_{real2}$ realizes P changes in design variables with P different standard deviations. These standard deviations can be calculated with the equation 4 [5].

$$\sigma_{i+1} = \frac{\sigma_i}{2 \cdot i} \qquad (4)$$

With i = 1 to P.

Other modification in $GEO_{real2}$ is in the fact that now the mutation occur in all design variables similarly $GEO_{var}$.

The $GEO_{real2}$ is showed in figure 4 [5].

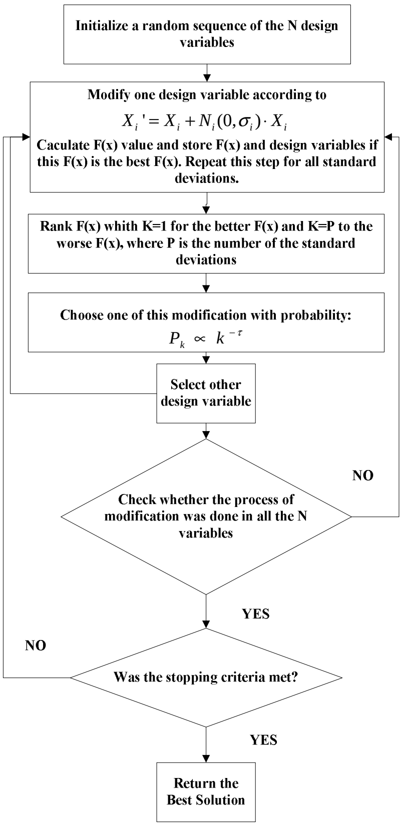
Initialize a random sequence of the N design variables
Modify one design variable according to
$X_i' = X_i + N_i(0,\sigma_i) \cdot X_i$
Caculate F(x) value and store F(x) and design variables if this F(x) is the best F(x). Repeat this step for all standard deviations.
Rank F(x) whith K=1 for the better F(x) and K=P to the worse F(x), where P is the number of the standard deviations
Choose one of this modification with probability:
$P_k \propto k^{-\tau}$
Select other design variable
NO
Check whether the process of modification was done in all the N variables
YES
NO
Was the stopping criteria met?
YES
Return the Best Solution

**Fig. 4. $GEO_{real2}$ flowchart**

In this work, the simulations uses the $GEO_{real2}$ for the star pattern identification.

## 4. STAR PATTERN INDENTIFICATION

The simulations are divided in two sets, in the first set was used a catalogue with 700 random points distributed in a plan with $X_{min}$ = -150, $X_{max}$ = 150 and $Y_{min}$ = -150, $Y_{max}$ = 150 simulating the stars in sky [6] as shown in figure 5.

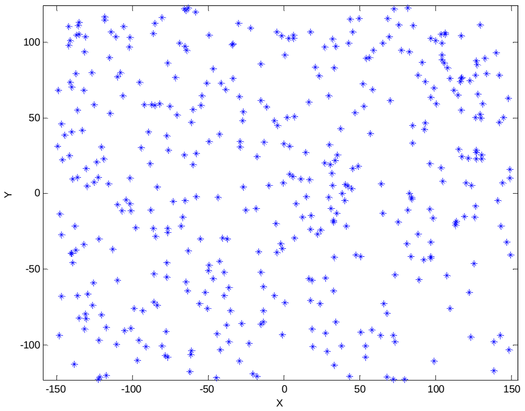

**Fig. 5. Random Stars in Flat Catalogue**

In this set of the simulation, the objective is to find the coordinates of the center of the FOV simulated and the stars presents in FOV.

For this, is simulated a FOV view in the random catalogue as shown in example in the figure 6.

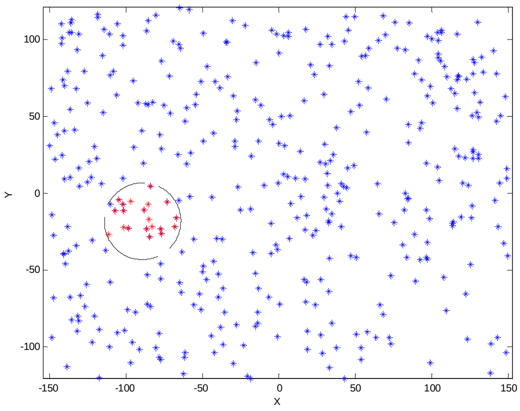

**Fig. 6. FOV simulated with coordinates X = -89 and Y = -18**

With the FOV simulated is make a vector with the distance between 20 stars closer to the FOV center and the same as shown in figure 7[7] and equation 5[7].

$$D_a = [R_1, R_2, \ldots, R_n] \qquad (5)$$

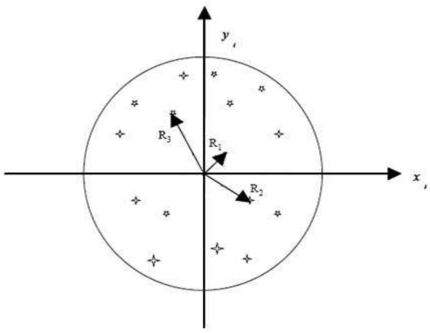

**Fig. 7. Distance between stars in FOV and FOV center**

Before the FOV simulation, the GEO algorithm starts the search. The design variables are the coordinates (X, Y) of the candidates FOV center.

Similarly is make a vector with stars of the candidates FOVs as shown in equation 6[7].

$$D_i = [R_{i1}, R_{i2}, ..., R_{in}] \qquad (6)$$

If the number of the stars in the FOV is less than 20, the vector is completed with zeros.

The GEO algorithm minimizes the objective function which calculates the discrepancy between the stars in the FOV simulated and the stars in candidate FOV. The objective function is calculated with equation 7 [7].

$$C_i = \sum_{k=1}^{n} \left| D_a[R_k] - D_i[R_k] \right| \qquad (7)$$

In the second simulations set is used a real catalogue with stars in spherical coordinates. For the simulation of the FOV is make a simulation of the spacecraft attitude and then verify the stars contained in FOV as shown in figure 8.

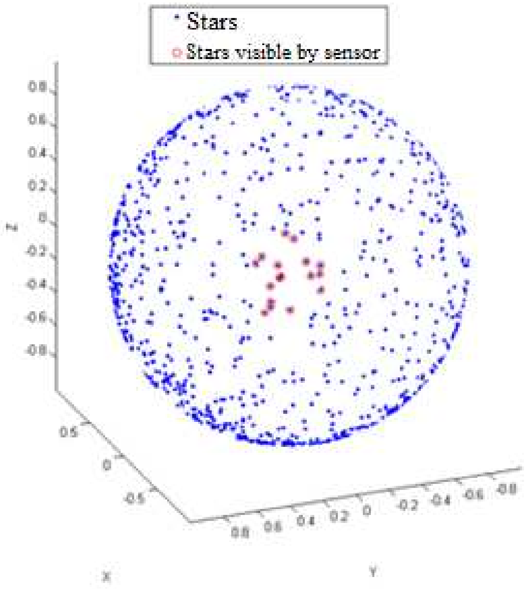

**Fig. 8. FOV Simulation with real catalogue**

The procedures of this set of simulations are similar to the first set, the difference is that the design variables are now right ascension ($\alpha$) and declination ($\delta$) which are transformed into (X, Y, Z) in the celestial sphere with the equations 8, 9 and 10:

$$X = \cos(\delta) \bullet \cos(\alpha) \qquad (8)$$

$$Y = \cos(\delta) \bullet sen(\alpha) \qquad (9)$$

$$Z = sen(\delta) \qquad (10)$$

Other modification is that the vector with the distance showed in equations 5 and 6, are transformed in vectors with angular distance between the stars and the FOV center.

The algorithm GEO$_{real2}$ minimizes the equation 7 and returns the stars observed by the FOV indentified in the catalogue.

With the stars observed by the FOV sensors and the stars identified by the algorithm in the catalogue, is possible calculates the spacecraft attitude using an attitude determination algorithm. In this work is used singular value decomposition (SVD) [1] to determine the attitude.

## 5. RESULTS

In the first simulations set, the FOV was simulate with 25 units of the radius and for each target coordinate was made a mean of the 50 runs.

The results are show in tables 1 to 3 and figures 9 to 11.

- Results with target coordinates (X = 0, Y = 0):

| | Mean Value | Mean Time for each execution (s) | Mean of evaluations of the objective function |
|---|---|---|---|
| Coordinate X | 0,047 | 30,3 | 4.130,3 |
| Coordinate Y | 0,009 | | |

**Tab. 1. Results with (X=0, Y=0)**

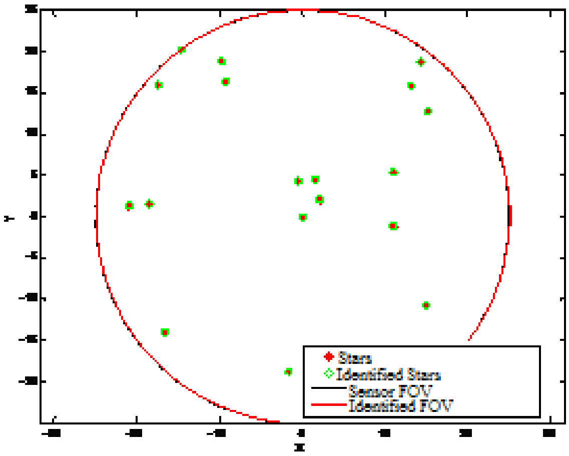

**Fig. 9. Graphical Results with (X=0, Y=0)**

- Results with target coordinates (X = 40, Y = 75):

| | Mean Value | Mean Time for each execution (s) | Mean of evaluations of the objective function |
|---|---|---|---|
| Coordinate X | 39,85 | 59,18 | 6.721,78 |
| Coordinate Y | 75,08 | | |

**Tab. 2. Results with (X=40, Y=75)**

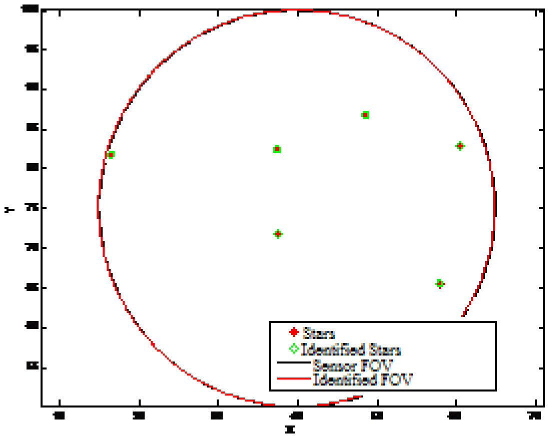

**Fig. 10. Graphical Results with (X=40, Y=75)**

- Results with target coordinates (X = -89, Y = -18):

| | Mean Value | Mean Time for each execution (s) | Mean of evaluations of the objective function |
|---|---|---|---|
| Coordinate X | -89,01 | 151,42 | 25.435 |
| Coordinate Y | -17,97 | | |

**Tab. 3. Results with (X=-89, Y=-18)**

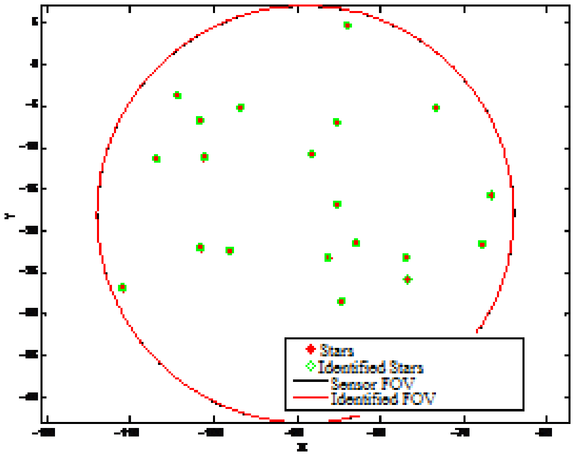

**Fig. 11. Graphical Results with (X=-89, Y=-18)**

In the second simulation set, was simulated the sensor with the characteristics showed in table 4.

| | |
|---|---|
| Field of view | 25,5º x 25,5º |
| Precision | ≈ 10 arcsec (3σ) |
| Visual Magnitude | Between 0 e 5 |
| Number of Rastreable stars | 16 |
| Output | Triaxial Attitude |

**Tab. 4. Sensor Configuration**

The results of this simulation set was obtained realizing 50 runs with random spacecraft attitudes. These results are showed in table 5.

| | **Star Pattern with GEO** |
|---|---|
| Mean Time for each execution (s) | 34,94 s |
| Wrong identifications | 0 |
| Not identified | 0 |
| Standard deviation in X (°) | $2{,}5 . 10^{-4}$ |
| Standard deviation in Y (°) | $2{,}39 . 10^{-4}$ |
| Standard deviation in Z (°) | 0.002 |

**Tab. 5. Results with real catalogue**

## 6. CONCLUSIONS

The results show that the $GEO_{real}$ is able to identify the stars observed by the FOV sensor.

In the future work shall be done a study to reduce the mean of identification time and realize the comparison of efficiency between the proposed approach and a frequently used approach in this problem.

## 7. ACKNOWLEDGMENT

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