Optimal Helical Spring Design for a P-Pod Using Chaotic Backtrack Search Algorithm

Soyinka Olukunle Kolawole, Hakeem Adewale, Osueke Christian

Abstract— A critical component of the ejection mechanism in a P-Pod is the helical compression spring. The helical spring ensures safe ejection at moderate velocities and also prevent jamming of the satellite within the P-Pod. To perform this function, the helical spring requires adequate stored energy during the ejection process. In this paper the design of the helical spring considered the mean coil diameter *D*, the wire diameter *d* and the spring index *C*. as variables to be optimized within specified constraints. The optimization problem entails the maximization of the stored strain energy in the helical compression spring. Optimal solutions are found using the Chaotic Backtrack Search Algorithm (CBSA).

Index Terms— Backtrack search algorithm, helical spring, optimization, P-Pod, strain energy.

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1 INTRODUCTION

CubeSats are becoming increasingly popular due to the advantages it portends in space research and exploration. These satellites come under a general category known as Pico-satellites and a typical 1U CubeSat has a standard dimension of 100mm x 100mm x 100mm and weigh between 0.1kg - 1kg. These satellites have the advantage of low cost of manufacture hence are prime for experimental and research purposes. The deployable mechanism for launch of CubeSat called Poly-Pico Satellite Orbital Deployer (P-Pod) has received considerable scholarly attention. The standards that define the nominal dimensions, tolerances, acceptable materials, reference coordinate system of the P-Pod, and other general information are detailed in several articles [1], [2] and [3]. The P-Pod is critical to the success of the CubeSat program since it must interface experimental satellites to launch vehicles and mother satellites safely. Critical to the design of the P-Pod is the design of the helical spring used for unloading the satellites for deployment during launch. This paper considers the optimization of the spring design parameters using a variant of a heuristic algorithm called the Backtrack Search Algorithm (BSA) [4]. To do this an existing framework for P-Pod is considered for optimization. The purpose is to maximize the energy stored in the spring mechanism thus ensuring a smooth and easy deployment of the CubeSat during launch and to prevent jamming during the process. Further, the ejection velocity of the spring is determined to ensure it is within acceptable limits as specified in [1].

2 THE SPRING DESIGN.

The schematic of a plain compression helical spring with ground end is shown in figure 1 in its unloaded state.

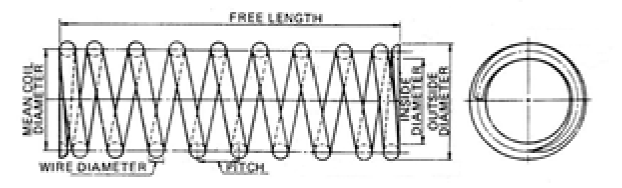

Fig. 1. Details of helical spring showing design parameters

Manufacturing of helical springs require a determination of the parameters of the spring such as the wire mean coil diameter *D*, wire diameter d and index *C*. Other parameters such as the total number of coils *Na*, free length lf also form important design parameters to be considered. Considering the functionality of the helical spring in a P-Pod the design intends to maximize the energy storage capacity of the spring, this is to ensure that the spring has adequate stored energy to eject the Nano satellites during launch. The boundary conditions for these parameters are moderated by several constraints in the design process. For the helical spring in our design the coil diameter and the free length are constrained by the geometric dimensions of the P-Pod. According to the automotive society of engineers [5], the ease of manufacturing the spring imposes a range on the value of index. Also, the use of the spring for static service recommends a range for *Na* [6]. The stability of the spring during usage to avoid buckling is constrained by a relationship between *D* and l_f [6]. These multiple design choices make it imperative for an optimal approach to solving the design problem as evident in [7], [8], [9] and [10].

3.1 Backtrack Search Algorithm

The helical spring to be designed should ensure that it has enough stored energy to jettison the CubeSat during launch. This requires the correct combination of the design parameters of the helical spring. To solve the attendant optimization problem, we rely on a variant of the numerical optimization technique called Backtrack Search Algorithm (BSA) [4]. BSA is an evolutionary algorithm for solving real-valued numerical optimization problems. The variant of the BSA that implements a chaotic map in place of the random number generator is discussed in [11]. In the following, the basic concepts of the algorithm are discussed.

3.2 Initialization Phase

In the initialization phase, the BSA generates two sets of population denoted *pop* and *Oldpop*; the Chaotic Backtrack Search Algorithm (CBSA) implements a chaotic map based on the expression in figure 2

```
Crand = rand();
kei = 4;
for i=1:N
    New_Crand = kei*Crand*(1-Crand);
      Crand = New_Crand;
   for j=1:D

      pop(i,j)= Crand*(up(j)-low(j))+low(j);
      Oldpop(i,j)= Crand*(up(j)-low(j))+low(j);

   end
end
```

Fig.2. Chaotic map implementation in CBSA

where i =1, 2 …., *N* , j = 1,2,…*D* . *N* represents the population size, D is the dimension of the problem and *pop(i,j)* is the target individual in the population. The function *Crand* is the chaotic map that replaces the random generator in the initialization phase. The purpose of the function is to reduce the possibility of the algorithm being trapped in local minima.

At the beginning of each iteration the algorithm performs a shuffling operation using an if-then conditional. The old population is redefined thus

$$if\ \ \alpha < \delta \text{ then } oldpop\ := \ pop \tag{1}$$

The parameters α and δ are random numbers. This operation shuffles members of the old population.

3.3 Mutation

This process generates the first set of the trial population called mutants via the expression

$$M\text{utant}= pop + F\left(Oldpop - pop\right) \tag{2}$$

F is a scale factor responsible for controlling the search direction matrix. An expression for evaluating *F* is given as

$$F = randn \tag{3}$$

3.4 Crossover

The final form of the trial population denoted (*T*) is generated in the crossover process. Initially, the value of *T* is equated to the population generated during the mutation process. Thus

$$T = \text{mutant} \tag{4}$$

The crossover has two distinct stages:

1. Initialization of a binary integer-valued matrix of size (*N*, *D*). This can be expressed as

$$map_{n,m},\ n \in \left\{1,2,3,...,N\right\}\ ,m \in \left(1,2,3,...,D\right) \tag{5}$$

2. Implementation of a strategy that defines the number of individuals in the population that mutates during the trials. This second stage can be done in two ways. First a mix rate can be specified to determine the number of individuals mutating in a trial or allow only one individual to mutate per trial

3.5 Selection II

In this phase, comparison is made between all the trial population and the initial population. The individuals in the trial population that have better fitness values replace the corresponding individuals in the initial population. Further, if the best individual in the initial population has fitness value better than obtained by CBSA in the trial population, it is taken as the global minimizer and the corresponding fitness value as the global minimum else the individual found by CBSA in the trial population is taken as the global minimum.

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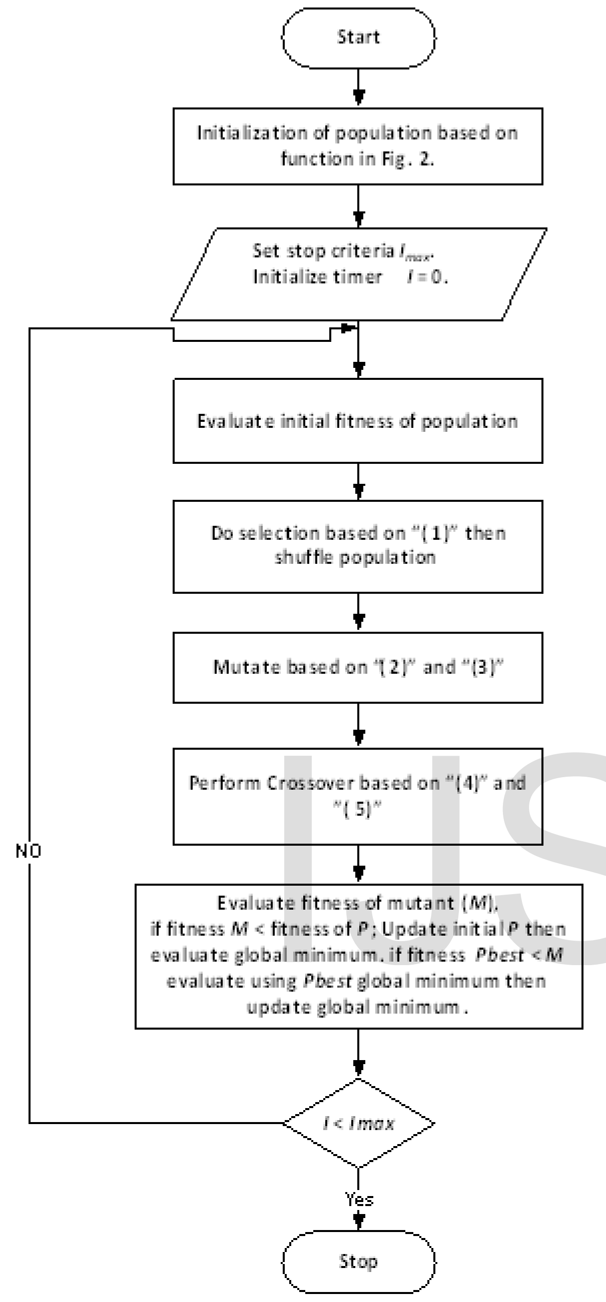

Fig. 3. Flowchart for optimization process of CBSA

4 PROBLEM DEFINITION

To design our spring for maximum energy storage we optimize a fitness function using the chaotic backtrack search algorithm. The fitness function is expressed

$$\Im_{\min} = \left(\frac{K}{d^2}\left(C^2 + 0.5\right)\right)^{-1} \tag{6}$$

where K is defined by the relationship

$$K = \frac{2P^2 N_a D}{G} \tag{7}$$

P is the force applied, G is the shear modulus of elasticity, Na, d, C and D retain their earlier definitions. According to [6], the maximum force is found from the relationship

$$P_{\max} = \frac{\pi d^3 \tau_{all}}{8DK_d} \tag{8}$$

and the allowable stress can be found from the relationship

$$\tau_{all} = 0.45 S_{ut} \tag{9}$$

The ultimate tensile strength is expressed as

$$S_{ut} = \frac{A_d}{d^m}, \tag{10}$$

where A_d and m are constants for a given range of wire diameter d. In "(8)" K_d is the transverse shear factor, obtained from the expression

$$K_d = \frac{C + 0.5}{C} \tag{11}$$

The optimization problem assumes a helical spring with uniform circular cross section made from music wire ASTM A226. Thus, the following constraints are imposed on the optimization problem to obtain the optimal design values

1) To ensure that the spring is not stressed beyond the allowable limit the range of wire diameter is defined as

$$0.1 \le d \le 6.5 \tag{12}$$

2) The ease of manufacturing the spring stipulates an acceptable range for the spring index given as

$$5.5 \le C \le 10 \tag{13}$$

3) The physical constraints imposed by the geometry of the P-Pod defines a maximum and minimum value for the mean coil diameter. This constraint is expressed as

$$40 \le D \le 56 \tag{14}$$

4) To avoid buckling, a constraint that defines the stability of the spring is also imposed and is expressed as

$$L_f < 2.63 \frac{D}{\alpha} \tag{15}$$

Further, the maximum deflection $\delta_{\max}$ of the spring is taken as half the solid length (lf) of the spring i.e.

$$\delta_{\max} = \frac{L_f}{2} \tag{16}$$

In the CBSA algorithm, the constraints C and d are the dimensions of the problem and the individual and trial population represents feasible solutions in the search space.

5 EXPERIMENTAL SIMULATION

The optimization algorithm assumes the following parameters. Initial trial population = 40, problem dimension = 2, number of iterations = 1000, mix rate = 1. The spring material is ASTM A228 leading to the following assumed parameters: G = 79.3 X 10^9Pa, A_m = 2.211X 10^9 Pa.mm, m = 0.145, $\alpha = 0.5$ [5].

6 RESULTS AND DISCUSSION

The result of the simulation is shown in fig 4. A total of 50 runs were performed and each run had 1000 iterations. The optimal solution is shown as a minimization of the inverse of the total strain energy over 1000 iterations.

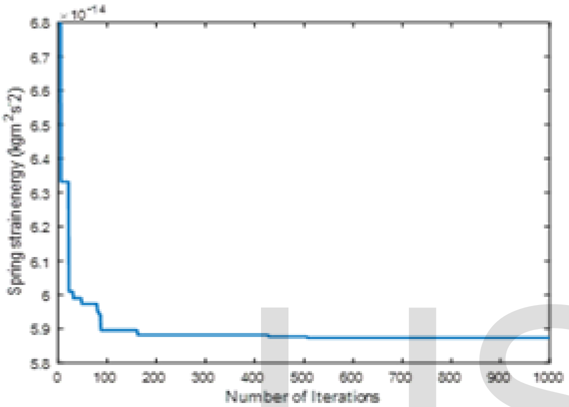

Fig. 4. Result of the minimization of the inverse of the spring strain energy using CBSA

The variation of the corresponding spring index C and wire diameter d is shown in figures 5 and 6 for the number of runs. The numerical values of the optimal design parameters obtained via CBSA are presented in Table 1.

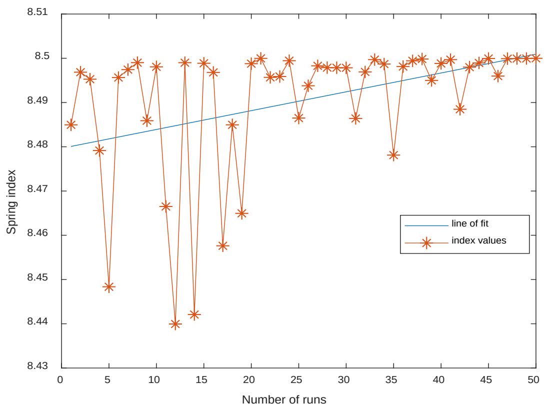

Fig. 5. Variation of spring index over 50 runs

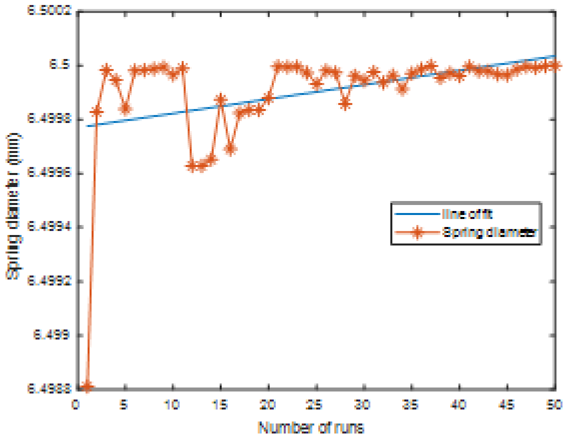

Fig. 6. Variation of spring diameter over 50 runs

TABLE 1
OPTIMAL PARAMETERS OBTAINED FROM CBSA

Fitness value	Spring index	Number of Coils	Wire diameter (mm)	Mean Coil Diameter (mm)
5.859296E-14	**8.496804**	**14**	**6.499999**	**55.229**

The optimal parameters obtained from CBSA are used as input for the design of the helical compression spring of the P-Pod. The result is modelled using a geometrical modelling software called SolidWorks; the performance of the helical spring under a static load that is equivalent to the weight of the CubeSat is further investigated and shown in fig.7, fig. 8, fig. 9, fig. 10, fig. 11 and fig. 12.

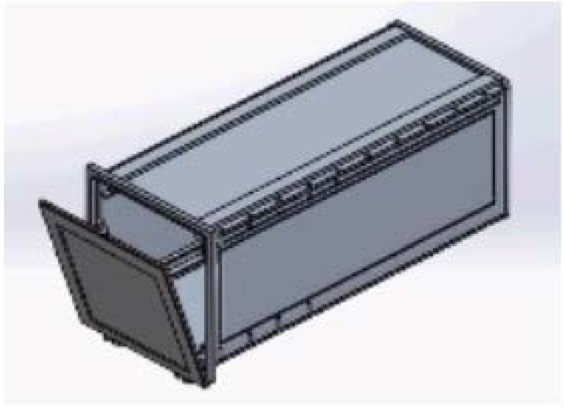

Fig. 7. P-pod at the opening stage

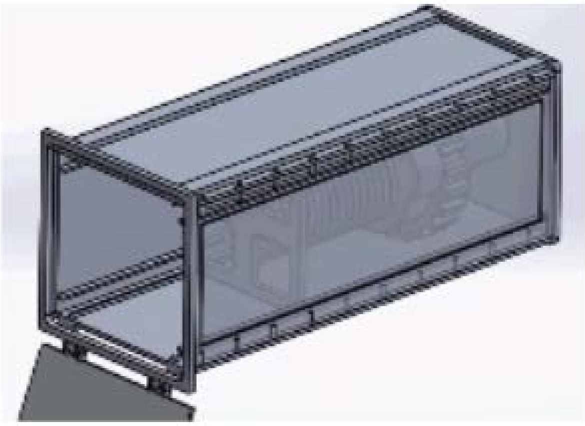

Fig. 8. P-pod at t=0 showing spring position

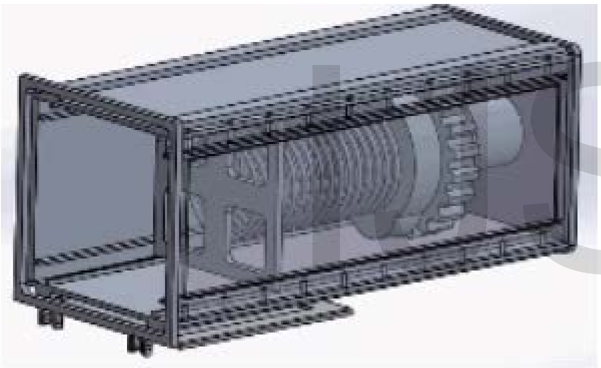

Fig. 9. Ejection process showing spring position at t=0.015

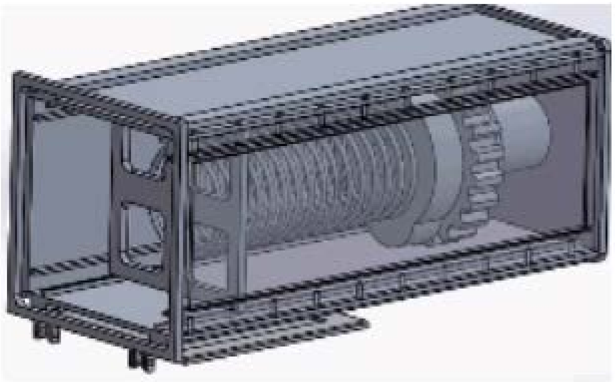

Fig.10. Ejection process showing spring position at t=0.020

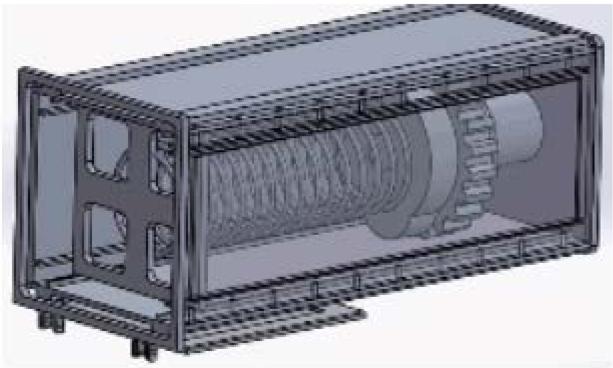

Fig.11. Ejection process showing spring position at t=0.024

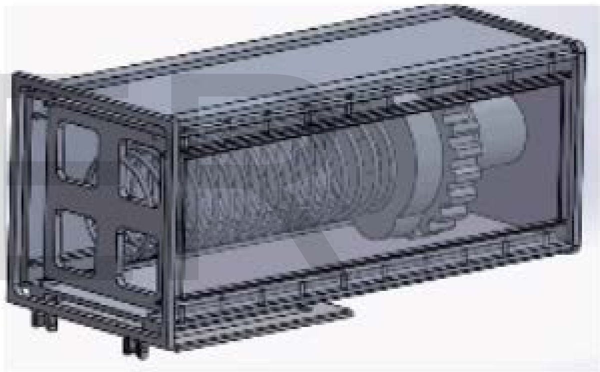

Fig. 12. Full deployment at t=0.03s

The performance of the helical spring during the ejection of the satellite in terms of the elongation of the spring and the velocity at the specified time instance is shown in figs. 13 and fig. 14.

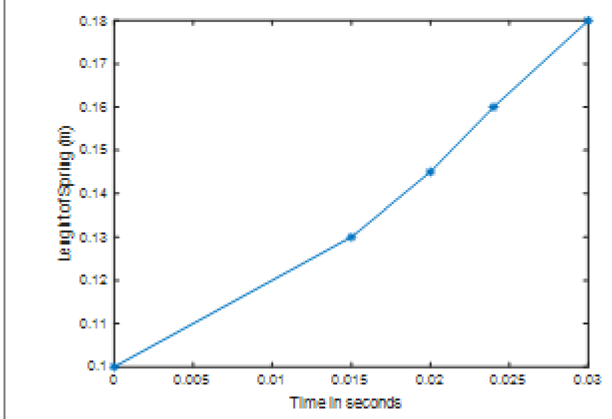

Fig. 13. Displacement-Time graph for spring

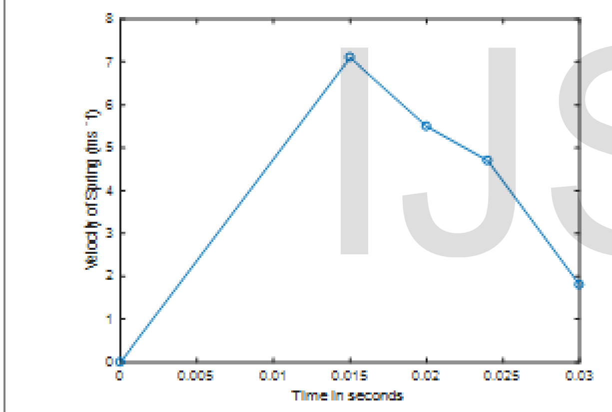

Fig. 14. Spring velocity during ejection

Figures 6 and 7 indicate an overall increase in the values of *C* and *d* as the strain energy is maximized over the number of runs. This can be seen from the line of fitness in the plots. The fluctuations in the values of *C* and *d* can be expected since the parameters are quadratic in nature in "(6)". The graph in Fig. 13 indicate an elongation of the spring length between t=0 and t=0.015, this is accompanied with a gradual increase in the velocity of the spring to a maximum value of 7 m/s as indicated in fig. 14. The elongation of the spring gradually reduces between t=0.02 and t=0.03 in fig. 13 with a reduction in the corresponding velocity. Finally, the ejection velocity of the CubeSat is at 1.8m/s and the corresponding spring length is 180mm; this is consistent with the results in [1] that stipulates a maximum ejection velocity of 2 m/s to avoid collision of the spring coils during ejection.

7 CONCLUSION

The results obtained show the feasibility of the method in solving optimal parameter determination for the design of the helical compression spring used in a P-Pod; in particular, this study has focused on optimizing the strain energy of the helical spring since this is the main operational consideration for ejection of the CubeSat. Additionally, the method can be used in solving optimization problems in mechanical engineering design.

ACKNOWLEDGMENT

The authors wish to thank the National Space Research and Development Agency, Nigeria, The Federal University of Technology Minna, Nigeria and The LandMark University Omu – Aran Nigeria for their support.

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