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A novel hybrid global optimization algorithm having training strategy: hybrid Taguchi-vortex search algorithm

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Abstract: In this paper, a novel hybrid Taguchi-vortex search algorithm (HTVS) is proposed for solving global optimization problems. Taguchi orthogonal approximation and vortex search algorithm (VS) are hybridized in presenting method. In HTVS, orthogonal arrays in the Taguchi method are trained and obtained better solutions are used to find global optima in VS. Thus, HTVS has better relation between exploration and exploitation, and it exhibits more powerful approximation to find global optimum value. Proposed HTVS algorithm is applied to sixteen well-known benchmark optimization test functions with different dimensions. The results are compared with the Taguchi orthogonal array approximation (TOAA), vortex search algorithm, grey wolf optimizer (GWO), sine cosine algorithm (SCA), moth-flame optimization algorithm (MFO), whale optimization algorithm (WOA) and salp swarm algorithm (SSA). In order to compare the effectiveness of HTVS statistically, Wilcoxon signed-rank test (WSRT) is used in this study. Furthermore, HTVS is applied to two different real engineering problems having some constraints (tension/compression spring design and pressure vessel design). All obtained results suggested that HTVS can find optimal or very close to optimal results. Moreover, it has good computational ability and fast convergence behavior as well.

Key words: Hybrid Taguchi-vortex search algorithm, Taguchi orthogonal arrays, vortex search algorithm, global optimization, engineering design problems with constraints

1. Introduction

Global optimization techniques have been very important in engineering applications such as electrical, mechanical engineering and also robotic etc. In the globalizing and modernizing world, engineering systems and their problems have become more complex. To solve complicated problems, many researchers have searched and developed a lot of metaheuristic optimization methods in the literature.

Metaheuristic algorithms mostly gained inspiration from the nature. If these are wanted to be categorized, they can be considered in three main groups. First group can be classified as population based. The interactions of individuals in the community with each other are modeled in population based algorithms. These algorithms have different search strategies, for example hunting, seeking food etc. [1]. Grey wolf optimizer (GWO) [2], particle swarm optimization (PSO) [3], salp swarm algorithm (SSA) [4], krill herd algorithm (KH) [5], whale optimization algorithm (WOA) [6], artificial bee colony (ABC) [7] are some of developed algorithms in this

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group. Second group is classified as physical action based. While developing these algorithms, nature and physical events are taken into account and modeled. Gravitational search algorithm (GSA) [8], big bang-big crunch algorithm (BBBC) [9], water wave optimization (WWO) [10], black hole (BH) [11] are some of second group algorithms. Third group can be classified as evolution based. Genetic algorithm (GA) [12] may be well known and most popular algorithm of this group. Apart from GA, differential evolution (DE) [13] and biogeography based optimizer (BBO) [14] are other algorithms in this group. Mathematical based analytical methods are classified as fourth group. Dynamic programming [15] and others [16–19] can be categorized in this group. Artificial intelligence based techiques can be classified as fifth group. These methods such as artificial neural network [20] and artificial immune system [21] etc. are applied to different problems.

Metaheuristic optimization algorithms have exhibited good exploration and good exploitation. However, the convergence performances and systematic search states of these algorithms may be insufficient. Additionally, balance of exploration-exploitation may be disrupted for complicated problems. In such cases, these algorithms can be plugged into local optimum points instead of global optimum points. For this reason, different metaheuristic algorithms have been combined with each other or different reinforcement techniques are added to metaheuristic algorithms. Thus, various advantages of algorithms are combined and their various disadvantages are eliminated. Opposition based learning (OBL) and adaptive differential evolution (ADE) were combined and partial opposition based learning-adaptive differential evolution (POBL-ADE) was developed in [22], genetic algorithm and big bang-big crunch were hybridized and hybrid genetic algorithm big bang-big crunch algorithm (HGAB3C) was developed in [23], sine cosine algorithm (SCA) and multiorthogonal search strategy (MOSS) were hybridized and multiorthogonal sine cosine algorithm (MOSCA) was developed in [24], particle swarm optimization and grey wolf optimizer were hybridized and hybrid particle swarm optimization-grey wolf optimizer (HPSOGWO) was developed in [25], mean variance mapping optimization was combined with swarm intelligence (MVMOSH) in [26], self-adaptive search equation-based artificial bee colony (SSEABC) in [27] and others [28–30] are some hybridized and strengthened algorithms.

In this study, two different methods are combined. First is Taguchi orthogonal array approximation (TOAA) [32]. This method is an experimental method and based on orthogonal arrays (OAs). The biggest advantage of OAs is that they can obtain good solutions with less numerical operations. But this method is not guaranteed the best results. Second is vortex search algorithm[1]SA (2020). Vortex Search (VS) Algorithm for Numerical Optimization Problems: Matlab Code [online]. Website https://web.itu.edu.tr/ bdogan/VortexSearch/VS.htm [accessed 14 October 2020]. [33] and this algorithm can be thought in second group algorithms. VS has strong capability for numerical optimization problems and it needs to few user defined parameters. However, if the parameters are not selected properly, this algorithm can exhibit nonoptimal convergences. Additionally, if the problem to be solved is too complex, this algorithm can become trapped to local minimum values like other metaheuristic algorithms. For this reasons, HTVS has been developed to eliminate the disadvantages of both TOAA and VS methods and creates a more powerful and superior algorithm. Proposed HTVS algorithm shows better performance with lower initial candidate solutions and lower iteration number for all global optimization problems.

This paper is organized as follows: In Section 2, Taguchi orthogonal approximation, vortex search algorithm and proposed hybrid Taguchi-vortex search algorithm are explained. In Section 3, sixteen optimization test function are defined and comparative results are given. Furthermore, WSRT statistics that confirm the

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effectiveness of HTVS are proved. Moreover, the results obtained with HTVS are given for two different real engineering problems. The conclusion is given in Section 4.

2. Hybrid Taguchi–vortex search algorithm

In this section, hybridized Taguchi orthogonal array approach and vortex search algorithm is defined. After than proposed HTVS algorithm is explained.

2.1. Taguchi orthogonal arrays

The Taguchi orthogonal arrays approximation method was developed by Genichi Taguchi [31]. Orthogonal arrays offer many advantages. First, OAs have fractional factorial characteristics [32]. It means that desirable solutions can be obtained with fewer probability situation. For example, a set of ten parameters (considering that each parameter has 3 levels) problem, there are 3^{10} probability situations. However, with the use of OA, the probability situations are reduced to 27 [32]. Second, all possible states up to variable k are distributed equally in OAs [32]. Thus, the levels of these variables are analyzed equally. Finally, if some columns are removed from the OA, then the property of the OA is not disrupted [32]. In this way, instead of using too many columns, up to k columns can be used. An example of OA is shown in Table 1.

OAs can be symbolized as OA(N, k, s, t). In this form, N represents row, k represents column (also optimized parameters number), s represents level and t represents strengt of an OA.

In Table 1, s and t are selected 3 and 2, respectively. This means that, every parameter has three level (s=3) values (1, 2, 3) and selected any two column (t=2) have different double combinations as row for example (1,1), (1,2), (1,3), (2,1), (2,2), (2,3), (3,1), (3,2), (3,3) [32].

While determining the level values, initial solution of problem x_i=1 may be chosen as midpoint of upper limit and lower limit. This midpoint is selected as center of level value. For example, if s=3, this point is equal to level 2. The other level values are determined by adding or subtracting LD_i (level difference) to level 2 [32]. LD is found from Equation 1 [32]:

$$LD_{i=1} = \frac{maximum\ limit - minimum\ limit}{level + 1} \tag{1}$$

Here; i is iteration number (i=1, 2, 3, ...), x is candidate solution, *maximum* and *minimum limits* are boundary of problem. After defining of parameter level values, all probability situations are tried and results are calculated as in [32]. Optimal level values are found for every parameters and chosen center level values for next iterations. Every iteration LD value is decreased by reduced rate coefficient *(RR)* and this equation is given as follows [32]:

$$LD_{i+1} = LD_i \times RR \tag{2}$$

This period is maintained until the finish conditions are met. This criteria is defined below [32]:

$$\frac{LD_i}{LD_{i=1}} < target\ error\ value \tag{3}$$

Table 1. An orthogonal array OA (27,10,3,2).

Probability situation	Parameters									
	1	2	3	4	5	6	7	8	9	10
1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	3	2
5	1	2	2	2	2	2	2	3	1	3
6	1	2	2	2	3	3	3	1	2	1
7	1	3	3	3	1	1	1	3	2	3
8	1	3	3	3	2	2	2	1	3	1
9	1	3	3	3	3	3	3	2	1	2
10	2	1	2	3	1	2	3	1	1	2
11	2	1	2	3	2	3	1	2	2	3
12	2	1	2	3	3	1	2	3	3	1
13	2	2	3	1	1	2	3	2	3	3
14	2	2	3	1	2	3	1	3	1	1
15	2	2	3	1	3	1	2	1	2	2
16	2	3	1	2	1	2	3	3	2	1
17	2	3	1	2	2	3	1	1	3	2
18	2	3	1	2	3	1	2	2	1	3
19	3	1	3	2	1	3	2	1	1	3
20	3	1	3	2	2	1	3	2	2	1
21	3	1	3	2	3	2	1	3	3	2
22	3	2	1	3	1	3	2	2	3	1
23	3	2	1	3	2	1	3	3	1	2
24	3	2	1	3	3	2	1	1	2	3
25	3	3	2	1	1	3	2	3	2	2
26	3	3	2	1	2	1	3	1	3	3
27	3	3	2	1	3	2	1	2	1	1

2.2. VS algorithm

This algorithm was developed based on the sample shape of the mixed liquids by Doğan and Ölmez [33]. This algorithm resembles nested circles in a 2D space when viewed from above [33]. The working system of the algorithm is depicted in Figure 1. In this figure, green point represents circle center, blue point represents best candidate solution and red points represent candidate solutions. The best solution in outer circle is memorized and it is placed to the center of the next inner circle for the next iteration.

The center of outermost circle (μ_0) is:

$$\mu_0 = \frac{maximum\ limit + minimum\ limit}{2} \tag{4}$$

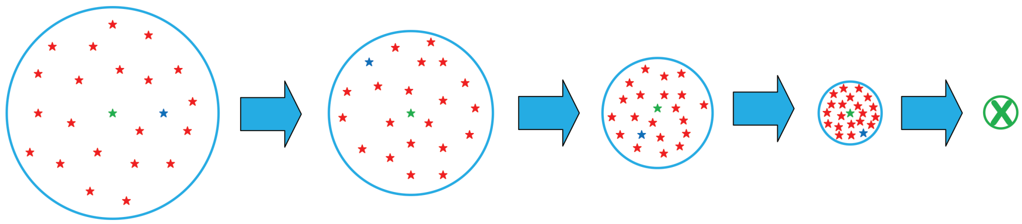

Figure 1. Systematic running of VS algorithm.

The radius of this circle (σ_0) is:

$$\sigma_0 = \frac{max(maximum\ limit) - min(minimum\ limit)}{2} \tag{5}$$

Every candidate solutions boundaries are checked in every iteration. If they are not within boundaries, they are relocated into the boundaries using following equation [33]:

$$cs_k = minimum\ limit + (maximum\ limit - minimum\ limit) \times rand \tag{6}$$

In here, k represents number of candidate solutions and rand is a random variable interval 0 and 1. Radius of circles (r_i) are decreased every iteration with inverse gamma function *(gammaincinv)* [33]:

$$r_i = \sigma_0 \times \frac{1}{x} \times gammaincinv(x, a_i) \tag{7}$$

In here a is shape parameter and x is constant value. a_i is reduced every iteration and given in as follows [33]:

$$a_i = a_0 - \frac{i}{MaxItr} \tag{8}$$

In here, i and *MaxItr* represent iteration number and maximum iteration respectively. For contained all search area, a_0 is chosen 0 [33].

2.3. Proposed HTVS algorithm

The proposed hybrid Taguchi-vortex search (HTVS) algorithm is formed by hybridizing with Taguchi orthogonal array approximation and vortex search algorithm. Orthogonal arrays may be preferred in population initialization stage [34]. OAs drastically reduce the number of probability situation during the process and therefore better results are achieved with fewer operations. Randomly generated initial candidate solutions are scattered using TOAA. Thus, TOAA is used in training of generating a candidate solution in proposed algorithm. Each candidate solution is distributed at certain equal intervals in the search space with TOAA. Thus, exploration phase of HTVS is enhanced. These candidate solutions are evaluated according to the probability situations of OA and therefore reinforced candidate solutions are found. These redefined and improved candidate solutions are used in VS algorithm. Thus, exploitation phase and the convergence behaviour of HTVS are enhanced with good approximation features of VS. Thanks to these improvements, much better results can be obtained from HTVS using fewer solutions and less iterations. Moreover, since the trained parameters are used in the VS during the entire iteration period, optimal or very close to optimal results are achieved with a fast convergence in HTVS.

The process of the HTVS algorithm is simply listed below:

(a) Randomly generated initial design parameters are scattered using TOAA,

(b) Probability situations are evaluated,

(c) Trained new design parameters are generated,

(d) These parameters are used in VS,

(e) Updating the parameters for next iterations.

Step1: initializing of HTVS Necessary definitions are made for using in the problem and algorithm such as problem boundaries, dimension, iteration number, reduce rate etc. The desired OA is constituted according to the problem dimensions. If the problem dimension is lower than OA columns, OA columns are selected as many as problem dimension. Thus, the number of OA columns are synchronized with the problem dimension. After than, candidate solutions are formed and controlled whether they are within limits.

Step2: training of OA Every level value is determined for each candidate solution. These level values are associated with OA. Objective values of probability situations in OA are calculated. Optimal level values are determined for every parameters. These values are chosen as best values for training of OA. After than, the level difference is decreased by reduce rate coefficient and this process is continued until it reaches the target error value. Thus, candidate solutions are improved.

Figure 2 shows an example of the training of OA. In this example, OA (9,4,3,2) is chosen to make it easier to understand. Red points show the candidate solution being trained. Other hollow points indicate the placement of this candidate solution in the OA. The optimum levels of the parameters are determined by controlling the entire probability situation in the OA. These determined levels are analyzed again with trained OA and an improved candidate solution is found.

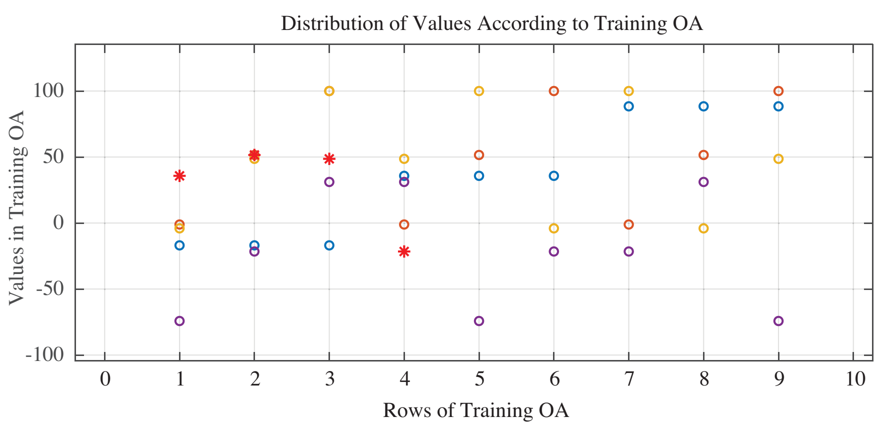

Figure 2. Illustration of training OA.

Step3: evaluation and iteration Improved candidate solutions are sent into the circle for evaluation. The best solution among them is determined as the best solution of the iteration. If the best solution of the iteration is better than the global best solution, the best solution of the iteration is selected as the global best solution and memorized. After than, this solution is shifted to the center of the next circle. Then the radius of the circle is reduced. All these processes are continued until the number of iterations is equal to defined maximum iteration number. Detailed steps of HTVS algorithm are delineated in Figure 3.

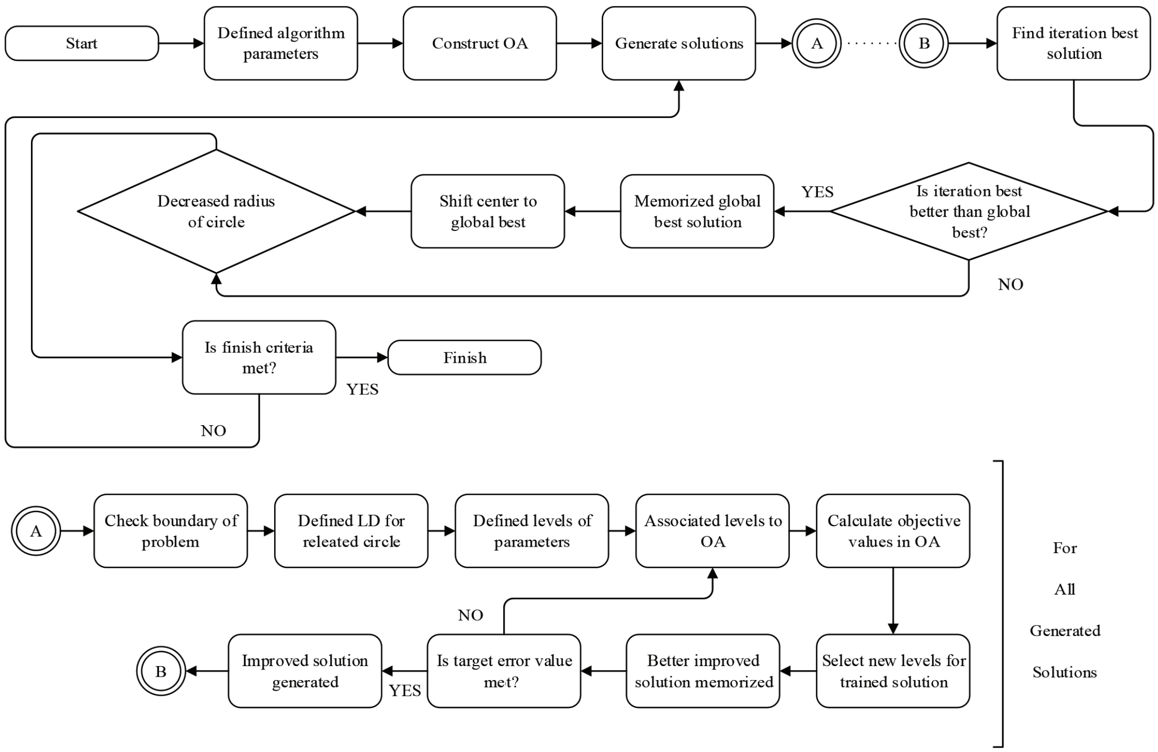

Figure 3. Flow diagram of HTVS.

Algorithm 1: Pseudo-code for HTVS Algorithm

Begin Procedure HTVS Algorithm
Set parameters;
Generate Orthogonal Array related with the problem dimension;
for *Up to maximum iteration* **do**
  Check solutions boundary;
  for *Each solutions* **do**
    Defined Level Difference;
    while *Target error value* **do**
      Designate solutions level;
      Correlate levels to Orthogonal Array;
      Evaluate probability situations;
      Describe optimal level values;
      Find improved new solutions;
    end
  end
  Determine iteration best;
  if *iteration best value* $<$ *global best value* **then**
    global best value = iteration best value;
  end
  Reduce radius;
end
End Procedure

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3. Experimental study

In this part, two different experiments have been carried out to examine the performance of optimization algorithms. The first experiment has been realized on benchmark functions (BFs), the second experiment on real engineering problems in the literature.

3.1. Experimental test 1

In this part, 16 BFs have been utilized to examine the performance and efficiency of the improved HTVS algorithm. BFs have been selected from [34]. Six optimization algorithms (GWO [2], SSA [4], WOA [6],VS [33], SCA [35] and MFO [36]) used in the literature have been utilized to affirm the validity and performance of the proposed HTVS algorithm.

3.1.1. Benchmark functions and algorithm settings

The BFs utilized in the first experiment are listed in Table 2. In this table, the limits of the variables used for each function, the equations used in the calculation, the type of the function and the size information are given. Additional information and parameters for Penalized, Penalized2 $u(x_i, 10, 100, 4)$ and Foxholes (a_{ij}) functions in Table 2 are as defined in [33]. If a function has a single optimum point in a certain range, it is called the unimodal function. If a function has many local optimum points, it is called a multimodal function. Separability is associated with the concept of mutual relationship between the variables of the function. Nonseparable functions cannot be expressed in this way because there is a relationship between variables. Optimizing nonseparable functions is harder than optimizing separable functions [37].

Table 2. Chosen BFs (n: ddimension, T: type, U: unimodal, M: multimodal, S: separable, N: nonseparable).

Function					
No.	Range	n	T	Name	Formulation
Fnc1	[-100, 100]	30	US	Sphere	$f(y) = \sum_{j=1}^{n}(y_j)^2$
Fnc2	[-10, 10]	30	UN	Schwefel 2.22	$f(y) = \sum_{j=1}^{n}\lvert y_j\rvert + \prod_{j=1}^{n}\lvert y_j\rvert$
Fnc3	[-100, 100]	30	UN	Schwefel 1.2	$f(y) = \sum_{j=1}^{n}(\sum_{k=1}^{j} y_k)^2$
Fnc4	[-30, 30]	30	UN	Rosenbrock	$f(y) = \sum_{j=1}^{n}[100(y_{j+1} - y_j^2)^2 + (y_j - 1)^2]$
Fnc5	[-100, 100]	30	US	Step	$f(y) = \sum_{j=1}^{n}(\lvert y_j + 0.5\rvert)^2$
Fnc6	[-1.28, 1.28]	30	US	Quartic	$f(y) = \sum_{j=1}^{n}(jy_j)^4 + random[0,1)$
Fnc7	[-500, 500]	30	MS	Schwefel	$f(y) = \sum_{j=1}^{n} -y_j \sin(\sqrt{y_j})$
Fnc8	[-5.12, 5.12]	30	MS	Rastrigin	$f(y) = \sum_{j=1}^{n}[(y_j)^2 - 10\cos(2\pi y_j) + 10]$
Fnc9	[-32, 32]	30	MN	Ackley	$f(y) = -20\exp\Big(-0.2\sqrt{\frac{1}{n}\sum_{j=1}^{n} y_j^2}\Big)$ $-\exp\Big(\frac{1}{n}\sum_{j=1}^{n}\cos(2\pi y_j)\Big) + 20 + \exp(1)$
Fnc10	[-600, 600]	30	MN	Griewank	$f(y) = \frac{1}{4000}\sum_{j=1}^{n}(y_j)^2 - \prod_{j=1}^{n}\cos(\frac{y_j}{\sqrt{j}}) + 1$
Fnc11	[-50, 50]	30	MN	Penalized	$f(y) = \frac{\pi}{n}\{10\sin(\pi z_1)^2 + \sum_{j=1}^{n-1}(z_j - 1)^2[1 + 10\sin(\pi z_{j+1})^2]\}$ $+\sum_{j=1}^{n} u(y_j, 10, 100, 4), z_j = 1 + \frac{1}{4}(y_j + 1)$
Fnc12	[-50, 50]	30	MN	Penalized2	$f(y) = 0.1\{\sin(\pi y_1)^2 + \sum_{j=1}^{n-1}(y_j - 1)^2[1 + \sin(3\pi y_{j+1})^2]$ $+(y_n - 1)^2[1 + \sin(2\pi y_n)^2]\} + \sum_{j=1}^{n} u(y_j, 10, 100, 4)$
Fnc13	[-65.536, 65.536]	2	MS	Foxholes	$f(y) = \Big[\frac{1}{500} + \sum_{k=1}^{25}\frac{1}{k+\sum_{j=1}^{2}(y_j - a_{jk})^6}\Big]$
Fnc14	[-5, 5]	2	MN	Six Hump Camel Back	$f(y) = 4y_1^2 - 2.1y_1^4 + \frac{1}{3}y_1^6 + y_1y_2 - 4y_2^2 + y_2^4$
Fnc15	[-5, 10]&[0, 15]	2	MS	Branin	$f(y) = \big(y_2 - \frac{5.1}{4\pi^2}y_1^2 + \frac{5}{\pi}y_1 - 6\big)^2 + 10(1 - \frac{1}{8\pi})\cos(y_1) + 10$
Fnc16	[-2, 2]	2	MN	GoldStein-Price	$f(y) = [1 + (y_1 + y_2 + 1)^2(19 - 14y_1 + 3y_1^2 - 14y_2$ $+6y_1y_2 + 3y_2^2)][30 + 3(2y_1 - 3y_2)^2(18 - 32y_1 + 12y_1^2$ $+48y_2 - 36y_1y_2 + 27y_2^2)]$

Population size has been determined as 50 and iteration number is 1000 for each compared algorithm. Thirty independent runs have been executed each test function. The best, worst, mean and standard deviation (SD) parameters have been obtained from these runs.

3.1.2. Statistical analysis

In the first experiment, proposed HTVS algorithm is compared to TOAA, VS, GWO, SCA, MFO, WOA and SSA algorithms. Statistical values of TOAA, VS and GWO are listed in Table 3. Also, statistical values of SCA, MFO, WOA and SSA are given in Table 4. It can be clearly seen that from this table, HTVS algorithm obtained better mean value and lower standard deviation value in other comparison functions except Fnc1, Fnc2 and Fnc4. Mean and standard deviation (SD) values can be used as an indicator about the robustness of the algorithm. By examining the best and worst values, an idea about the quality of the optimization algorithm can be obtained [34]. Although these values provide a rough idea, pairwise statistical test is often used for a stronger comparison. Therefore, WSRT has been chosen to perform a pairwise statistical test. HTVS and other selected algorithms have been run different 30 times for each function. WSRT has been performed using the results obtained from this process. The obtained statistical pairwise results are illustrated in Table 5.

Table 3. Statistical results for 30 runs.

No.	Min.		HTVS	TOAA	VS	GWO
Fnc1	0	Mean	3.0368E-147	0	8.7754E-68	3.2601E-70
		SD	1.8419E-147	0	4.7513E-67	7.4302E-70
		Best	4.4734E-157	0	3.1944E-90	1.2881E-72
		Worst	7.0213E-147	0	2.6033E-66	3.9161E-69
Fnc2	0	Mean	5.8818E-74	0	2.7291E-36	3.9362E-41 7
		SD	1.9096E-74	0	1.3341E-35	5.8096E-41
		Best	1.7604E-74	0	3.0048E-47	3.7870E-42
		Worst	8.1700E-74	0	7.3306E-35	3.1475E-40
Fnc3	0	Mean	0	0	9.7719E+03	3.4143E+03
		SD	0	0	2.3343E+04	3.1775E+03
		Best	0	0	1.8897E-90	2.3814E+02
		Worst	0	0	8.2809E+04	3.1775E+03
Fnc4	0	Mean	12.409	3758.975	1.5679E-33	26.4631
		SD	10.4425	3758.975	2.0959E-33	0.8077 5
		Best	7.6498E-31	3758.975	0	25.1885
		Worst	21.9412	3758.975	4.2762E-33	28.51
Fnc5	0	Mean	0	0	0	0.3583
		SD	0	0	0	0.2907
		Best	0	0	0	9.3673E-06
		Worst	0	0	0	1.0043
Fnc6	0	Mean	8.8371E-07	0.08	1.6124E-04	4.1014E-04
		SD	8.5843E-07	0.064	1.5318E-04	2.1143E-04
		Best	7.8925E-08	6.5572E-04	1.7327E-05	6.6443E-05
		Worst	4.2453E-06	0.2567	5.3662E-04	0.0011

Table 3. (Continued).

No.	Min.		HTVS	TOAA	VS	GWO
Fnc7	-12569.5	Mean	-1.2569E+04	-3686.29	-1.2569E+04	-6.3757E+03
		SD	2.5502E-12	-3686.29	1.8501E-12	8.6519E+02
		Best	-1.2569E+04	-3686.29	-1.2569E+04	-7.6185E+03
		Worst	-1.2569E+04	-3686.29	-1.2569E+04	-3.2684E+03
Fnc8	0	Mean	0	0	0	0.1504
		SD	0	0	0	0.8235
		Best	0	0	0	0
		Worst	0	0	0	4.5107
Fnc9	0	Mean	4.4409E-15	8.88E-16	8.8818E-16	1.3204E-14
		SD	0	8.88E-16	0	3.1959E-15
		Best	4.4409E-15	8.88E-16	8.8818E-16	7.9936E-15
		Worst	4.4409E-15	8.88E-16	8.8818E-16	2.2204E-14
Fnc10	0	Mean	0	2.82E-144	0	0.002
		SD	0	2.82E-144	0	0.0048
		Best	0	2.82E-144	0	0
		Worst	0	2.82E-144	0	0.0157
Fnc11	0	Mean	1.5705E-32	0.7519	1.5705E-32	0.0284
		SD	5.5674E-48	0.7519	5.5674E-48	0.0154
		Best	1.5705E-32	0.7519	1.5705E-32	0.0065
		Worst	1.5705E-32	0.7519	1.5705E-32	0.072
Fnc12	0	Mean	1.3498E-31	0.0443	1.3498E-31	0.3097
		SD	6.6809E-47	0.0443	6.6809E-47	0.1715
		Best	1.3498E-31	0.0443	1.3498E-31	2.1270E-05
		Worst	1.3498E-31	0.0443	1.3498E-31	0.7138
Fnc13	1	Mean	0.998	0.998604	0.9991	2.8953
		SD	1.1292E-16	0.998604	0.0054	3.2636
		Best	0.998	0.998604	0.998	0.998
		Worst	0.998	0.998604	1.0273	10.7632
Fnc14	-1.0316	Mean	-1.0316	-1.03163	-1.0035	-1.0316
		SD	6.7752E-16	-1.03163	0.0335	2.3754E-09
		Best	-1.0316	-1.03163	-1.0316	-1.0316
		Worst	-1.0316	-1.03163	-0.9108	-1.0316
Fnc15	0.398	Mean	0.3979	0.397887	0.4028	0.3979
		SD	0	0.397887	0.0093	4.4472E-05
		Best	0.3979	0.397887	0.3979	0.3979
		Worst	0.3979	0.397887	0.4472	0.3981

Table 3. (Continued).

No.	Min.		HTVS	TOAA	VS	GWO
Fnc16	3	Mean	3	99	3.4535	3
		SD	3.1939E-16	99	0.5875	2.1318E-06
		Best	3	99	3.0003	3
		Worst	3	99	5.6076	3

Table 4. Statistical results for 30 runs.

No.	Min.		SCA	MFO	WOA	SSA
Fnc1	0	Mean	3.0000E-03	2.0000E+03	1.2955E-173	8.8119E-09
		SD	5.5000E-03	4.0684E+03	0	1.8119E-09
		Best	1.0119E-07	2.2826E-06	1.1802E-187	6.1125E-09
		Worst	2.0600E-02	1.0000E+04	1.7212E-172	1.3440E-08
Fnc2	0	Mean	6.1720E-06	27.3334	2.1033E-108	0.5467
		SD	1.5267E-05	17.7983	1.0678E-107	0.7322
		Best	7.5984E-10	2.1225E-04	5.4601E-120	5.0879E-04
		Worst	7.6365E-05	70.0000	5.8555E-107	3.4807
Fnc3	0	Mean	3.4143E+03	1.6118E+04	1.0251E+04	35.2190
		SD	3.1775E+03	1.0657E+04	6.5943E+03	22.5824
		Best	2.3814E+02	273.8736	725.1963	9.2185
		Worst	1.2813E+04	4.5013E+04	2.7663E+04	106.1447
Fnc4	0	Mean	66.7187	1.2820E+04	26.5654	49.1718
		SD	80.2239	3.0839E+04	0.2899	45.3955
		Best	28.0344	7.3142	26.0486	19.9603
		Worst	327.5366	9.0081E+04	27.0279	200.2024
Fnc5	0	Mean	4.2785	1.3267E+03	0.0044	8.8659E-09
		SD	0.4562	4.3123E+03	0.0022	1.8151E-09
		Best	3.6326	2.6010E-06	8.9371E-04	5.6152E-09
		Worst	5.8445	1.9801E+04	0.0117	1.1868E-08
Fnc6	0	Mean	0.0264	3.8282	8.5780E-04	0.0585
		SD	0.0197	8.0671	9.1209E-04	0.0289
		Best	0.0046	0.0301	1.5986E-05	0.0183
		Worst	0.0731	40.3245	0.0040	0.1494
Fnc7	-12569.5	Mean 3	-3.9844E+03	- 8.6512E+03	-1.1384E+04	-7.4102E+03
		SD	2.7826E+02	861.1861	1.4685E+03	835.0389
		Best	-4.6838E+03	- 1.0571E+04	-1.2569E+04	-9.0163E+03
		Worst	-3.6256E+03	- 6.8511E+03	-8.2506E+03	-5.9019E+03

Table 4. (Continued).

No.	Min.		SCA	MFO	WOA	SSA
Fnc8	0	Mean	16.8594	137.2066	1.8948E-15	43.9440
		SD	20.7797	36.3597	1.0378E-14	13.4026
		Best	8.1685E-06	73.6266	0	19.8992
		Worst	72.3418	205.2448	5.6843E-14	76.6117
Fnc9	0	Mean	1.2487E+01	11.6837	3.0198E-15	1.6068
		SD	9.4183	8.4275	2.5721E-15	1.1970
		Best	3.5559E-04	6.7085E-04	8.8818E-16	1.9931E-05
		Worst	2.0311E+01	19.9630	7.9936E-15	3.6819
Fnc10	0	Mean	0.2481	18.0233	0.0026	0.0090
		SD	0.2188	36.6376	0.0143	0.0093
		Best	3.8536E-06	7.7973E-06	0	1.9672E-08
		Worst	0.5971	90.1836	0.0783	0.0344
Fnc11	0	Mean	1.6176	0.4448	0.0014	2.9985
		SD	2.877	1.2554	0.0029	2.1077
		Best	0.362	1.6537E-05	1.7603E-04	0.1086
		Worst	10.9041	6.7120	0.0149	9.8207
Fnc12	0	Mean	3.8187	1.3669E+07	0.0589	0.0069
		SD	4.1862	7.4867E+07	0.0706	0.0076
		Best	2.1981	2.4950E-05	0.0030	3.4119E-10
		Worst	19.1298	4.1006E+08	0.2875	0.0308
Fnc13	1	Mean	1.1965	1.6238	2.1729	1.0311
		SD	0.6054	1.4774	2.9739	0.1815
		Best	0.998	0.9980	0.9980	0.9980
		Worst	2.9821	5.9288	10.7632	1.9920
Fnc14	-1.0316	Mean	-1.0316	-1.0316	-1.0316	-1.0316
		SD	9.6489E-06	0	7.1907E-12	6.7921E-15
		Best	-1.0316	-1.0316	-1.0316	-1.0316
		Worst	-1.0317	-1.0316	-1.0316	-1.0316
Fnc15	0.398	Mean	0.399	0.3979	0.3979	0.3979
		SD	0.0015	1.1292E-16	2.0882E-07	1.2085E-14
		Best	0.3979	0.3979	0.3979	0.3979
		Worst	0.4036	0.3979	0.3979	0.3979
Fnc16	3	Mean	3	3.0000	3.0000	3.0000
		SD	1.9622E-05	2.5657E-15	2.9100E-06	6.9564E-14
		Best	3	3.0000	3.0000	3.0000
		Worst	3.0001	3.0000	3.0000	3.0000

Table 5. Wilcoxon signed-rank test results.

No		F1	F2	F3	F4	F5	F6	F7	F8
HTVS vs. VS	p-val.	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.00×10^{0}	1.73×10^{-6}	1.00×10^{0}	1.00×10^{0}
	h	1+	1+	1+	1-	0	1+	0	0
	Tp	0	0	0	465	0	0	0	0
	Tn	465	465	465	0	0	465	0	0
HTVS vs. TOAA	p-val.	1.73×10^{-6}	1.73×10^{-6}	1.00×10^{-0}	1.50×10^{-6}	1.00×10^{0}	1.73×10^{-6}	4.32×10^{-8}	1.00×10^{0}
	h	1-	1-	0	1+	0	1+	1+	0
	Tp	465	465	0	0	0	0	0	0
	Tn	0	0	0	465	0	465	465	0
HTVS vs. GWO	p-val.	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	2.50×10^{-1}
	h	1+	1+	1+	1+	1+	1+	1+	0
	Tp	0	0	0	0	0	0	0	0
	Tn	465	465	465	465	465	465	465	6
HTVS vs. SCA	p-val.	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}
	h	1+	1+	1+	1+	1+	1+	1+	1+
	Tp	0	0	0	0	0	0	0	0
	Tn	465	465	465	465	465	465	465	465
HTVS vs. MFO	p-val.	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	11.73×10^{-6}
	h	1+	1+	1+	1+	1+	1+	1+	1+
	Tp	0	0	0	0	0	0	0	0
	Tn	465	465	465	465	465	465	465	465
HTVS vs. WOA	p-val.	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.00×10^{0}
	h	1-	1-	1+	1+	1+	1+	1+	0
	Tp	465	465	0	0	0	0	0	0
	Tn	0	0	465	465	465	465	465	1
HTVS vs. SSA	p-val.	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}
	h	1+	1+	1+	1+	1+	1+	1+	1+
	Tp	0	0	0	0	0	0	0	0
	Tn	465	465	465	465	465	465	465	465

Table 5. (Continued).

No		F9	F10	F11	F12	F13	F14	F15	F16
HTVS vs. VS	p-val.	1.73×10^{-6}	1.00×10^{-0}	4.32×10^{-8}	1.00×10^{-0}	6.63×10^{7}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}
	h	1-	0	1+	0	1-	1+	1+	1+
	Tp	465	0	0	0	455	0	165	0
	Tn	0	0	465	0	1	465	300	465
HTVS vs. TOAA	p-val.	4.32×10^{-8}	4.32×10^{-8}	4.32×10^{-8}	4.32×10^{-8}	2.03×10^{-7}	1.00×10^{-0}	1.00×10^{0}	4.32×10^{-8}
	h	1-	1+	1+	1+	1-	0	0	1+
	Tp	465	0	0	0	459	0	0	0
	Tn	0	465	465	465	0	0	0	465
HTVS vs. GWO	p-val.	1.04×10^{-6}	6.25×10^{-2}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}
	h	1+	0	1+	1+	1-	1+	1-	1+
	Tp	0	0	0	0	374	0	464	0
	Tn	465	15	465	465	91	465	1	465
HTVS vs. SCA	p-val.	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}
	h	1+	1+	1+	1+	1-	1+	1-	1+
	Tp	0	0	0	0	459	0	294	0
	Tn	465	465	465	465	6	465	171	465
HTVS vs. MFO	p-val.	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.46×10^{-6}	1.00×10^{-0}	1.00×10^{0}	5.00×10^{-1}
	h	1+	1+	1+	1+	1-	0	0	0
	Tp	0	0	0	0	420	0	0	59
	Tn	465	465	465	465	21	0	0	0
HTVS vs. WOA	p-val.	1.56×10^{-4}	1.00×10^{-0}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	2.55×10^{-6}	1.73×10^{-6}	1.73×10^{-6}
	h	1-	0	1+	1+	1-	1-	1-	1+
	Tp	360	0	0	0	444	464	465	0
	Tn	10	1	465	465	21	0	0	465
HTVS vs. SSA	p-val.	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	1.73×10^{-6}	3.18×10^{-7}	2.00×10^{-3}	2.50×10^{-5}	1.69×10^{-6}
	h	1+	1+	1+	1+	1-	1-	1-	1-
	Tp	0	0	0	0	455	255	437	437
	Tn	465	465	465	465	1	0	0	28
	+/=/-	HTVS vs. VS 8/5/3	HTVS vs. TOAA 7/5/4	HTVS vs. GWO 12/2/2	HTVS vs. SCA 14/0/2	HTVS vs. MFO 12/3/1	HTVS vs. WOA 8/2/6	HTVS vs. SSA 12/0/4	

In the WSRT, it can be understood which of the two algorithms compared using the hypothesis test is superior. Two hypotheses can be determined as (H_0) and (H_1). The (H_0) hypothesis means that there is no difference between the compared pairs. Unlike (H_0), the (H_1) hypothesis means that there is a difference. In Table 5, when the h value is equal to 0, it is seen that there is no critical contrast between the compared two algorithms. When $h = 1$, a major difference is observed between the two compared algorithms. In addition, as $p - value$ which is the probability of observing a test statistic decreases, the similarity of the two algorithms decreases. In WSRT, statistical significance value is determined as $a = 0.05$. When $p-value$ used to determine whether algorithms have superiority to each other is less than a, it can be said that two compared algorithms are statistically distinctive from each other at 95% confidence level. In this table, 'h=1+' indicates situations where the zero hypothesis is refused and the HTVS performs statistically predominant in the WSRT at 95% significance level; 'h=1-' denotes states where the (H_0) is refused and the HTVS algorithm performed lower performance; and '$h = 0$' denotes states that are not critical contrast between the two algorithms. The nineteenth line and last line of Table 5 demonstrate the total number of three statistically major states ($+/=/-$) in the comparison between pairs. The $+$ sign demonstrates that the HTVS algorithm is superior to the compared algorithm, the $=$ sign demonstrates that the HTVS algorithm draws with the compared algorithm, the $-$ sign demonstrates that the HTVS algorithm is worse than the compared algorithm. In each comparison, the HVTS algorithm outperformed all the compared algorithms because the number of $+$ signs is greater than the $=$ and $-$ sign. The superiority of the HVTS algorithm is more dominant when it is compared to GWO, SCA, MFO, SSA algorithms and less dominant when it is compared to VS and WOA algorithms.

3.1.3. Convergence analysis

Convergence analysis has been performed to illustrated how the proposed HTVS algorithm converges to the solution. A total of 4 convergence graphics have been obtained from each function type (MS, US, MN, UN). The graphics have been drawn using information about average solutions 30 different runs for 1000 iterations. As seen in Figure 4, convergence graph is drawn for each function type. It has been viewed that the HTVS algorithm is more competitive than other algorithms. HTVS algorithm presents one convergence behavior while optimizing test functions. HTVS is generally very close to optimum value in the first few iterations.

3.2. Experimental test 2 (real engineering problems)

In this part, tension/compression spring design (T/CSD) and pressure vessel design (PVD) problems have been solved with proposed HTVS algorithm. HTVS has been run with population sizes 20 and 500 iterations in two problems. The performance and applicability of the proposed HTVS algorithm has been compared with the solutions of other algorithms in the literature. The results of the compared algorithms have been taken directly from the literature. As a result of the comparison, the feasibility of the HTVS algorithm has been confirmed.The setting parameters of the algorithms have been found from the studies in the literature and have been expressed in Appendix section.

3.2.1. Tension/compression spring design

The constrained design problem shown in Figure 5 has been solved and the minimum weight of the tension/compression spring has been tried to be found [38, 42]. The optimum design should provide restrictions on shear stress, ripple frequency and deviation. Three design parameters are wire diameter (d), average coil diameter (D), and active coil number (N).

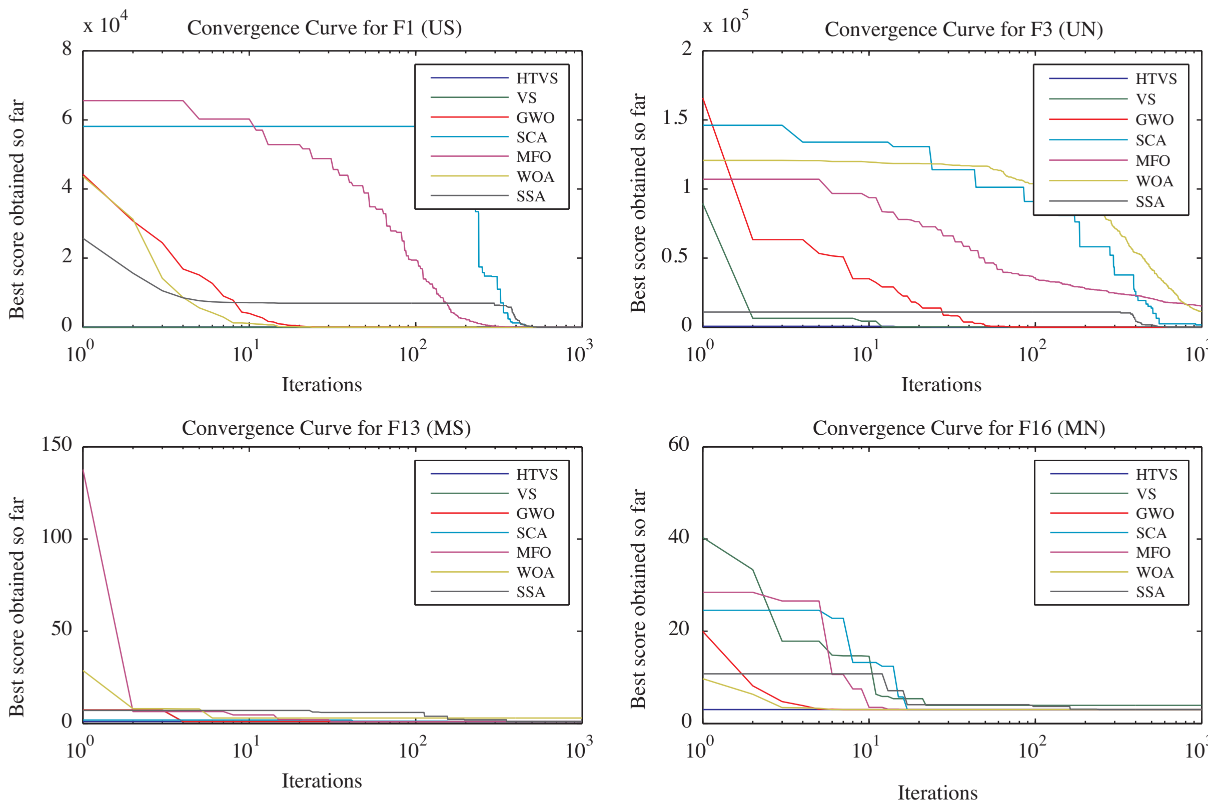

Figure 4. Convergence curve.

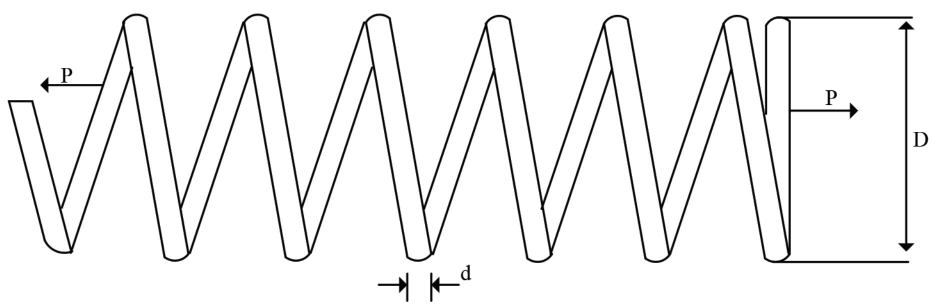

Figure 5. Schematic of T/CSD problem [38, 42].

The equations of constrained design problem are defined as follows [38, 42]:

Consider $Y = [y_1\ y_2\ y_3] = [d\ D\ N]$

Minimize $f(Y) = (y_3\ +\ 2)y_2 y_1^2$

Subject to $h_1(Y) = 1\ -\ \frac{y_2^3 y_3}{71785 y_1^4}\ \leq\ 0$

$$h_2(Y) = \frac{4y_2^2 - y_1 y_2}{12566(y_2 y_1^3 - y_1^4)}\ +\ \frac{1}{5108 y_1^2}\ -\ 1\ \leq\ 0$$

$$h_3(Y) = 1\ -\ \frac{140.45 y_1}{y_2^2 y_3}\ \leq\ 0$$

$$h_4(Y) = \frac{y_1\ +\ y_2}{1.5}\ -\ 1\ \leq\ 0$$

where $0.05 \leq y_1 \leq 2.00,\ 0.25 \leq y_2 \leq 1.30,\ 2.00 \leq y_3 \leq 15.00$

The results obtained with HTVS algorithm are compared with various techniques applied to this design problem in the literature. Founded values and comparative cost are shown in Table 6 and it shows that the optimum cost parameter obtained with the proposed HTVS algorithm is the same as the optimum cost value obtained with the HEAA and WCA algorithm in the literature. The optimum cost value found with the proposed HTVS, WCA and the HEAA algorithm is better than the optimum cost values found by other algorithms in Table 6. It is also worth noting here that although optimum costs value found by proposed HTVS, HEAA and WCA are equal, the obtained optimal design parameters are different. Therefore, HTVS finds a new optimal design for this problem. Also, the proposed HTVS algorithm shows that it can compete with other algorithms in the literature with the optimal cost result for the T/CSD design problem.

Table 6. Experimental results for T/CSD problem.

Algorithms	Optimum parameters			Optimum cost
	d	D	N	
HTVS	0.05176	0.35845	11.18786	0.012665
WOA [6]	0.05127	0.34521	12.00402	0.01267
HEAA [39]	0.05168	0.35672	11.28829	0.012665
CPSO [40]	0.05172	0.35764	11.24454	0.012674
WCA [41]	0.05168	0.35637	11.30922	0.012665
GA [42]	0.05148	0.35166	11.63220	0.012704
AIS-GA [43]	0.051660	0.35603	11.32955	0.012666
CDE [44]	0.05160	0.35471	11.41083	0.012670

3.2.2. Pressure vessel design

The main purpose of this section is to optimize the overall cost function of PVD problem under the different constraints. PVD schematic is illustrated in Figure 6 [38, 42]. Whereas the head is semispherical in shape, both ends of the container are covered. It has four design parameter: the thickness (T_s), the thickness of the head (T_h), the inner radius (R), the length, regardless of the head (L).

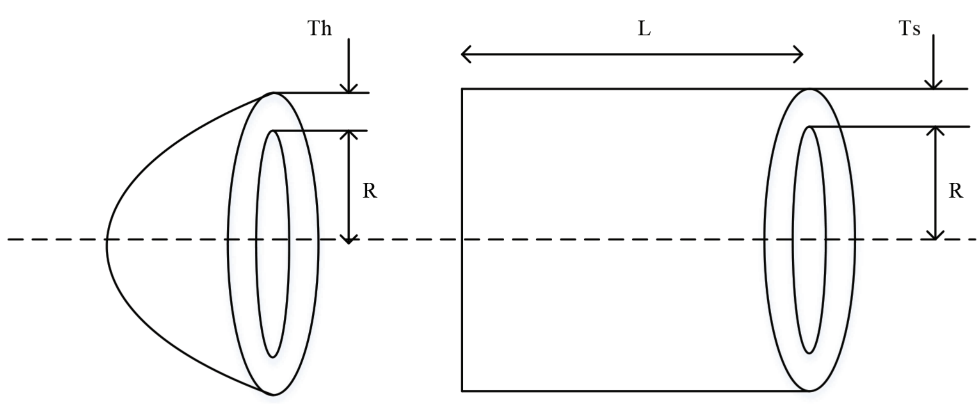

Figure 6. Schematic of PVD problem [38, 42].

The equations and constraints of this problem can be written as follows [38, 42]:

Consider $Y = [y_1, y_2, y_3, y_4] = [T_s, T_h, R, L]$

Minimize $f(Y) = 0.6224y_1y_3y_4 + 1.7781y_2y_3^2 + 3.1661y_1^2y_4 + 19.84y_1^2y_3$

Subject to $h_1(Y) = -y_1 + 0.0193y_3 \leq 0$

$h_2(Y) = -y_2 + 0.00954y_3 \leq 0$

$h_3(Y) = -\pi y_3^2 y_4 - \frac{4}{3}\pi y_3^3 + 1296000 \leq 0$

$h_4(Y) = y_4 - 240.0 \leq 0$

where $0 \leq y_1 \leq 99,\ 0 \leq y_2 \leq 99, 10 \leq y_3 \leq 200, 10 \leq y_4 \leq 200 - 240^*$.

There are some studies in the literature with a maximum y_4 value of 200 [6, 40, 42] and 240 [47]. The results obtained in both cases are given in Table 7. Also, results where y_4 is a maximum of 240 are marked with $*$. This problem is frequently used by researchers in optimization applications. According to this table, HTVS algorithm has found better optimum cost than other algorithms. Setting parameters of compared algorithms are given in Table 8.

Table 7. Experimental results for PVD problem.

Algorithms	Optimum parameters				Optimum cost
	T_s	T_h	R	L	
HTVS	0.7828	0.3869	40.5575	196.7148	5893.2314
WOA [6]	0.81250	0.43750	42.09826	176.63899	6059.7410
CPSO [40]	0.8125	0.4375	42.091266	176.7465	6061.0777
GA [42]	0.8125	0.4345	40.3239	200.00	6288.7445
CDE [44]	0.81250	0.43750	42.09841	176.63769	6059.7340
DELC [45]	0.8125	0.4375	42.09844	176.63659	6059.7143
G-QPSO [46]	0.8125	0.4375	42.0984	176.6372	6059.7208
HTVS*	0.7455	0.3685	38.62635	224.9935	5831.7849
BGRA* [47]	0.75	0.375	38.8601	221.36547	5850.383061
IHSA*[48]	0.75	0.375	38.86010	221.36553	5850.38363
DSO*[49]	0.75	0.375	38.86010	221.36547	5850.38309

4. Conclusion

In this article, vortex search, a single-solution based metaheuristic algorithm, is explored and adjusted by means of the orthogonal array concept. Taguchi orthogonal approximation and VS algorithm are hybridized in proposed hybrid Taguchi-vortex search algorithm. Thus, more powerful and more reliable HTVS is developed.

In this paper, two experiments to examine the success of the HTVS algorithm in solving optimization problems are presented. In the first experiment, the proposed method has been applied on 16 benchmark functions and performance comparison with TOAA, VS, GWO, SCA, MFO, WOA, and SSA algorithms. The success of HTVS in solving numerical optimization problems has been expressed using the Wilcoxon signed-rank test. In the second experiment, two real engineering problems with constraints (i.e. design of a tension/compression spring and design of a pressure vessel) have been solved to learn more about the proposed algorithm. When analyzed all obtained results, HTVS is extremely competitive with the other optimization algorithms used in this study.

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Appendix

Table 8. Setting parameters of compared algorithms.

Algorithms	Parameters	Values
WOA for T/CSD[6]	Search agents	10
	Iteration number	500
WOA for PVD[6]	Search agents	20
	Iteration number	500
HEAA[39]	N	60
	Q_1, Q_2	200, 60
	Simplex crossover parameters	10, 5, 10
	Fitness function evaluations	200,000
CPSO[40]	Size of swarms M_1, M_2	50, 20
	Number of generations G_1, G_2	25, 8
	Acceleration coefficients c_1, c_2	2, 2
	Maximum particles position $w_{1,max}$, $w_{2,max}$	1000, 1000
	Minimum particles position$w_{1,min}$, $w_{2,min}$	0, 0
WCA[41]	N_{total}	50
	N_{sr}	8
	d_{max}	1-03
GA[42]	$populationsize_1$	60
	$populationsize_2$	30
	$G_{max}1$	25
	$G_{max}2$	20
AIS-GA[43]	Population size	20
	Binary gray code	50 bits
	Crossover probability	1
	Mutation ratio	0.02
	Elitism	2
	Maximum iteration	20
	Cumber of clones	3
	Critical distance	10%
CDE[44]	M_1, M_2	32, 8
	G_1, G_2	10, 10
	F_1, F_2	0.6, 0.8
	CR_1 , CR_2	0.2, 0.1
DELC[45]	Decision variable n	4
	Population size N	80
	Level parameter	0.1
	Total number of function evaluation TNFE	30,000
G-QPSO[46]	Population size	20
	Iteration number	400

Table 8. (Continued).

Algorithms	Parameters	Values
BGRA[47]	Population size	200
	Iteration number	2000
	level with *sr*	0.6
	count with *r*	0.1
IHSA[48]	Harmony memory considering rate	0.95
	Pitch adjusting rate PAR_{max}, PAR_{min}	0.99, 0.45
	Harmony memory size	6
	Arbitrary distance bandwidth bw_{min}, bw_{max}	5e-4, 0.05
	NI (stopping criterion)	200,000
DSO[49]	Population size	40
	Forward probability	0.8
	Forward coefficient	1
	Backward coefficient	10
	Genetic mutation probability	0.01
	Iteration number	1000