نهمین کنگره ملی مهندسی ماشین‌های کشاورزی
(مکانیک بیوسیستم) و مکانیزاسیون
پردیس کشاورزی و منابع‌طبیعی دانشگاه تهران
۲ و ۳ اردیبهشت ۱۳۹٤ - کرج

Meta-heuristics to minimize the rolling resistance force of off-road vehicles

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Abstract

Synthesis of rolling resistance has been a great field of studying interest for the researchers of vehicle dynamics and a parameter to be minimized owing to its negative effects on vehicle efficiency. The application of a meta-heuristic evolutionary optimization method, imperialist competitive algorithm (ICA), for minimization of rolling resistance in a soil bin facility equipped with single-wheel tester is presented. Three parameters, namely, wheel load, tire inflation pressure and velocity are selected as optimization variables. When compared to conventional genetic algorithm (GA), new and popular particle swarm optimization (PSO) and hybridized GA-PSO, ICA can achieve optimum configuration with superior accuracy in less required computational time.

Keywords: Imperialist competitive algorithm; Genetic algorithm; Particle swarm optimization; Rolling resistance; Soil bin

Introduction

Soil and tire are subjected to consecutive deformations through wheel traversing over terrain, each of which, results in soil compaction and rolling resistance, respectively. The stability of soil, a substance of semi-infinite elastic-plastic medium behavior (Lamandè and Schjønning, 2011) is depending on acting mechanical loads on it. Soil loses its stability and gets irreversibly compacted if the load is great. Furthermore, tire deforms under the effect of applied load. The successive deformations cause tire to heat up and energy loss turns out that is known as rolling resistance in Terramechanics. Soil-wheel interactions are, however, the substantial contributor to occurrence of rolling resistance. Dissipated fuel due to mismanagement in the domain of agricultural tires due to mismanagement was reported to be about 575 million Liters per year in USA (Wulfsohn, 1987).Until now, many attempts have been made to predict rolling resistance theoretically (Komandi, 1999: Wong , 1984: Hetherington and Littleton, 1978: Pope, 1971: Kim and Shin, 1986) and empirically (Elwaleed et al., 2006: Kurjenluomar et al., 2009: Coutermarsh, 2007: Shoop et al., 2010: Çarman et al., 2002) amongst which the joint intention was rolling resistance prediction through various modeling approaches. However, population-based evolutionary optimization assessments are required for minimization of rolling resistance as a competent tool for dealing with nonlinear problems such as terrain-tire contact problem.

Many of meta-heuristic techniques inspired by natural phenomena are proposed. Genetic algorithm (GA) motivated by Darwin's theorem is the most prominent optimization method. GA is formed based on the endurance of fittest while its core ideology is constructed based on genetics and evolution behavior in biological reproductions (Holland, 1975). Another popular stochastic method is particle swarm optimization (PSO) based on bird flocking and fish schooling (Eberhart, 1995). PSO implements through initial populations (each called a particle) moving in search space. Each individual agent attempts to conquer the other particles and then evolution continues based on particle's and populations' experience for movement adjustment (Eberhart, 1995). There are also too many algorithms introduced for evolutionary optimization including but not limited to harmony search (HS), ant colony optimization (ACO), and bee colony optimization (BCO).

In this paper we furnished a novel method as a substitute to the mentioned meta-heuristic revolutionary optimization techniques for rolling resistance minimization known as Imperialistic Competitive Algorithm (ICA), first introduced by Atashpaz-Gargari and Lucas (Atashpaz-Gargari and Lucas, 2007) which in essence, is inspired by human's social-political evolution. This algorithm, similar to any evolutionary algorithm, commences with a random initial population (country). Each representative of an empire is a country so that the countries are divided into a colony and imperialist indicates that colonies jointly come together as the empires. Imperialistic competitions among the empires form the basis of ICA, during which, weak empires collapse and powerful ones take possession of their colonies to the level that optimal points are possessed by the most powerful imperialist.

Materials and Methods

All the experimentations were carried out in a long soil bin with the dimensions of 23 m length, 2 m width and 1 m depth and also a single-wheel tester mounted on a carriage (Mardani et al., 2010). A three-phase electromotor of 30hp was used to move a carriage equipped with the single-wheel tester through a chain system. In order to provide a desired level of velocity, an inverter was used. A Bongshin Model DBBP load cell with the capacity of 2000 kg, sensitivity of 0.1 kg and frequency of 50 Hz was located vertically between a power bolt and the wheel-tester. Four S-shape Bongshin Model DBBP load cells with 200 kg capacity were calibrated and then were placed at proper places horizontally in parallel pattern between carriage and single-wheel tester. These transducers were then interfaced to data acquisition system including Bongshin digital indicator BS7220 model connected to a port of RS232 Data Logger. The utilized tire was Good year 9.5L-14, 6 radial ply agricultural tractor tire. The system set up is shown in Fig. 1. The soil bin was filled with clay-loam soil as the predominant soil texture in Urmia, Iran. Tine, leveler and harrow were used to reverse soil bed to initial condition prior to each test run. Soil constituents and its properties are defined in Table 1.

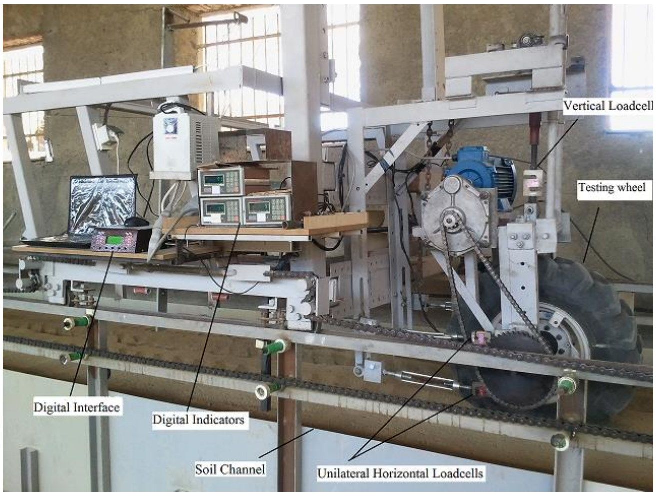

Figure 1- The soil bin facility setup and its equipments

Table 1- Soil constituents and its measured properties

Item	Value
Sand (%)	34.3
Silt (%)	22.2
Clay (%)	43.5
Bulk density (kg/m3)	2360
Frictional angle (°)	32
Cone Index (kPa)	700

This experiment was conducted with the different velocities of 0.7, 1.4, and 2 m/s at three inflation pressures of wheel at three levels of 100, 200, and 300 kPa and five different wheel loads of 1, 2, 3, 4, and 5 kN on wheel tester with three replications in a complete randomized block design. Summary of treatments being tested is shown in Table 2.

Table 2- Summary of experiment conducted

Independent Parameters			Dependent Parameter
Normal Load (kN)	Inflation Pressure (kPa)	Velocity (m/s)	
1	100	0.7	
2	200	1.4	Rolling Resistance
3	300	2	
4			
5			

Imperialist competitive algorithm

The optimization problem is described as to find the argument x with its optimum cost f(x) within the heuristic and meta-heuristic optimization algorithms. Imperialist Competitive algorithm (ICA) was first introduced by Atashpaz-Gargari and Lucas (2007) that has considerably been used in engineering applications. The objective in optimization is to reach the optimal value for the inputs. An array, which in genetic algorithm terminology is named ‘‘Chromosome’’ and in PSO ‘‘Particle’’, is generated in ICA known as country. The pseudo-code of this algorithm is described as follows.

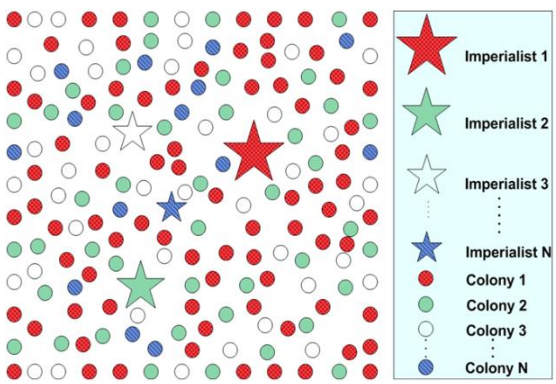

Figure 2- Movement of colonies toward their relevant imperialists -Gargari and Lucas (2007).

Formation of initial empires

In a problem of N_{var} dimensional the country is introduced as following.

$$\text{country}=\left[P_1,P_2,P_3,\ldots,P_{N_{\text{variable}}}\right] \tag{1}$$

The matrix of total countries is randomly formed as given.

$$Country = \begin{bmatrix} country_1 \\ country_2 \\ country_3 \\ . \\ . \\ . \\ country_N \end{bmatrix} = \begin{bmatrix} KP_1 & KI_1 & KD_1 \\ KP_2 & KI_2 & KD_2 \\ KP_3 & KI_3 & KD_3 \\ . & . & . \\ . & . & . \\ . & . & . \\ KP_N & KI_N & KD_N \end{bmatrix} \quad (2)$$

Each country's cost is defined by evaluation of the cost function f at variables $(P_1, P_2, P_3, \ldots, P_{N\,\mathrm{var}})$ to obtain the cost function as

$$\cos t_i = f(\text{country}) = f\left(P_1, P_2, P_3, \ldots, P_{N_{\text{variable}}}\right) \quad (3)$$

The initial countries are generated, $N_{country}$, to commence the algorithm. N_{imp} number of the best population, (i.e. countries with the lowest cost function values), are assigned as empires. N_{col} number of the remaining countries form the colonials each belong to an empire. The initial colonies are shared in proportion with each empire's power. To apportion the colonies, the normalized cost of imperialists is described as

$$C_n = \max_i \{c_i\} - c_n \quad (4)$$

Where c_n, $\max_i\{c_i\}$ and C_n are the cost of nth imperialist, the highest cost among imperialists and the normalized cost of imperialists, respectively. That is, the imperialist with the highest cost (weakest imperialist) denotes lower normalized cost. The relative normalized power of each imperialist, therefore, is defined by

$$P_n = \left| \frac{C_n}{\sum_{i=1}^{N_{imperialist}} C_i} \right| \quad (5)$$

Based on which, the colonies are allocated among the imperialists. From another standpoint, the normalized power of each empire is the amount of colonies run by that. Thus, the initial number of each imperialist's colonies is described by

$$N.C._n = \text{round}\{P_n . N_{col}\} \quad (6)$$

Where N. C.n is the number of initial colonies of an imperialist and Ncol is the total number of colonies and round is a function that yields the round number if it is approximate. Fig. shows the process of forming initial imperialists in which the powerful imperialists possess more colonies. Imperialist 1 is the most powerful among others that has possessed the highest number of colonies (see Fig.2).

Assimilation

The assimilation policy follows to take in their colonies on the basis of social-political characteristics such as religion, culture and language. This part of ICA is shown in Fig. 3.

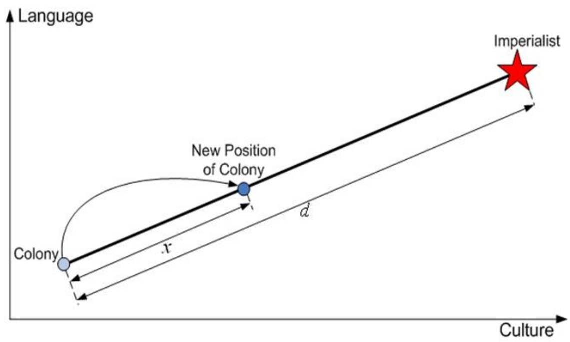

Figure 3- Moving colonies toward their corresponding imperialist in randomly deviated direction (Atashpaz-Gargari and Lucas, 2007)

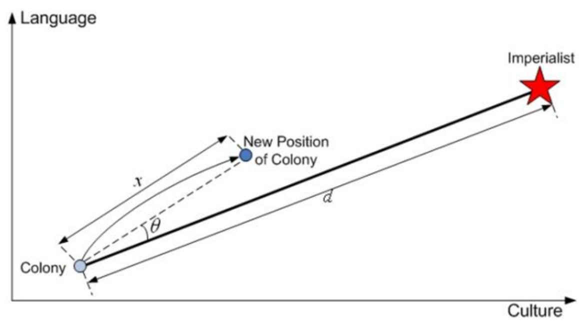

Figure 4- The actual movement of colonies toward their corresponding imperialist (Atashpaz-Gargari and Lucas, 2007)

As the result of assimilation, the colony moves by x unit in the direction of the imperialist to the new position of colony. Thus x is defined as

$$x \sim U(0,\beta \times d) \quad (7)$$

Where d is the distance between the colony and the imperialist, B is set between 1 and 2, however, β>1 moves toward the imperialist from both of the vectors.

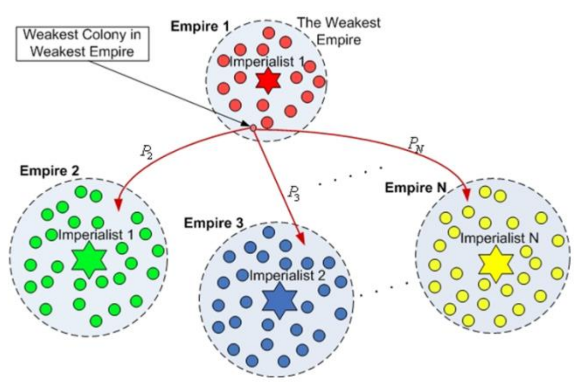

Figure 5- Imperialist competition: The more powerful empire is more likely to occupy the weakest colony of the

weakest empire (Atashpaz-Gargari and Lucas, 2007)

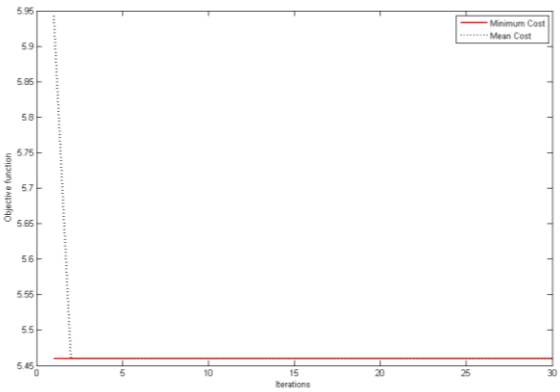

Figure 6- Mean and minimum cost of all imperialists versus iterations for rolling resistance

The absorption process, however, did not result in compliance with desires of imperialists. This implies that the real direction of movement toward the imperialist is not necessarily the shortest vector between the colony and the imperialist. These possible deviations in absorption are predicted in ICA by adding one random angle with uniform distribution, θ, to the direction of colony's movement as described by

$$\theta \sim (-\gamma,\gamma) \qquad (8)$$

Where γ can posses any random value, however, increased value causes more extensive searching around the imperialist and lower value causes the colony to move toward the imperialist closer to the connecting vector. In most of implementations, a θ value close to π/4 results in better convergence of colonies to the imperialist. The actual assimilation movement toward the imperialist is shown in Fig. 4.

Replacement of colony and imperialist

During the colony's movement toward the imperialist, it is possible that the colony can reach a lower cost function than imperialist. Then the imperialist and the colony would replace their positions. Thus, the algorithm continues with new colony and imperialist with the assimilation policy for newer colony and imperialist.

The total power of an empire

The total power of an empire equals with the power of an imperialist added with a certain percent of possessed colonies' power. Therefore the total cost of an empire is defined as

$$T.C._n = Cost(imperialist_n) + \xi\, mean\{Cost(\text{colonies of empire}_n)\} \qquad (9)$$

Where $T.C._n$ is the total cost of nth empire, and ξ is a positive value ranging between 0 and 1. Setting ξ to a small value results in equalization of costs for the empire and the imperialist, where a high ξ results the cost of empire to be highly affected by the colonies. ξ = 0.05 has given good results in most of implementations.

Imperialistic competitions

Each empire unable to increase the power defeats by the others during the imperialistic competition and ends is gradual collapse of the empire. That is, the weak empires lose their colonies and the powerful empires possess these colonies. Thus, one colony (can be more) of the weakest empire is competed to be possessed by a powerful empire (not necessarily the most powerful empire). Fig. 5 shows this process clearly.

In Fig. 5, empire 1 is the weakest empire and one of its colonies is competed to be possessed by one of empires 2 to N. In order to model the competition among the empires, the probability of possessing each empire is defined which is in proportion with the total power of the empire. The normalized total cost of an empire is defined as

$$N.T.C._n = \max_i \{T.C._i\} - T.C._n \tag{10}$$

Where $T.C._n$ is the total cost of nth empire and $N.T.C._n$ is the normalized total cost. $T.C._n$ stands for the total cost of an empire where $N.T.C._n$ is the total power of an empire. Therefore, increase of $T.C._n$ has converse relation with $N.T.C._n$. Then the probability of possessing an empire (P_{pn}) is obtained by

$$P_n = \left| \frac{N.T.C._n}{\sum_{i=1}^{N_{imperialist}} N.T.C._i} \right| \tag{11}$$

The vector P is formed based on the (P_{pn}) to share the colonies among the empires.

$$P = \left[P_{P1}, P_{P2}, P_{P3}, \ldots, P_{PN_{imp}} \right] \tag{12}$$

P vector is $1 \times N_{imp}$ dimensional. Then R vector of 1×Nimp dimensional is formed. The arrays of R vector are random values with uniform distribution in the range of [0, 1].

$$R = \left[r_1, r_2, r_3, \ldots, r_{N_{imp}} \right] \tag{13}$$

$$r_1, r_2, r_3, \ldots, r_{N_{imp}} \sim U(0,1) \tag{14}$$

Then vector D is formed as following.

$$P = \left[P_{P1} - r_1, P_{P2} - r_2, P_{P3} - r_3, \ldots, P_{PN_{imp}} - r_{N_{imp}} \right] \tag{15}$$

The empire with the highest D vector index is the most powerful empire.

Collapse of weak empires

During the mentioned competitions, the empires lose their colonies to the more powerful ones. In ICA, there are conditions for collapse of an empire of them the most major one is to lose all the colonies.

Convergence

The algorithm continues to the point of reaching one of convergence conditions or reaching the described iterations. All empires gradually collapse and one empire stands as the most powerful empire and the countries are governed by a unique empire.

Development of the objective function

The core ideology of ICA or any evolutionary optimization is minimization of a described cost function (refer to 3. Imperialist competitive algorithm), as affected by input variables. Regarding this, rolling resistance obtained from experimentations is required to be described as a cost function to the ICA. Hence, we used multiple regression analysis using SPSS 19 to obtain a function in terms of wheel load, tire inflation pressure and velocity.

$$RR = 10W^2 + 3.2W - 0.37P - 25V + 153.56 \quad (16)$$

Where W is wheel load (kN), P is inflation pressure (kPa) and V is velocity (m/s). The statistical specifications of Eq. 16 are presented in Table 3. The adjusted-R square of the model was obtained 0.95.

Table 3- Analysis of variance (ANOVA) of multiple regression model for rolling resistance at three levels of velocity, three levels of tire inflation pressure and five levels of wheel load.

Source of variation	DF	Sum of squares	Mean square	F-value
Regression	3	417850.776	139283.592	178.468*
Residual	41	31998.033	780.440	
Total	44	449848.809		

* Significant at 0.05 probability level; DF, degree of freedom

Results and discussion

Defining the cost function of ICA by Eq. 16, country is simply described as a vector of input parameters.

$$Country = \begin{bmatrix} W_i \\ P_i \\ V_i \end{bmatrix} \quad (17)$$

Countries then compete internally to minimize their costs to become the imperialist and denote the optimum level of input variables, followed by the external competition among imperialists resulting in occupancy of the imperialists by the one with the lowest cost function. Results of optimization are shown in Table 4. Fig. 6 shows the minimum and mean cost of imperialists. Also, Fig. 6 shows that the imperialist with the lowest cost function could occupy the other imperialists after three iterations.

Table 4- Results of optimization

Number of total countries	80
Number of initial imperialist countries	4
Number of iterations (epochs)	30
Revolution rate	0.3
Assimilation coefficient	2
Assimilation angle	0.5
Cost Function	RR

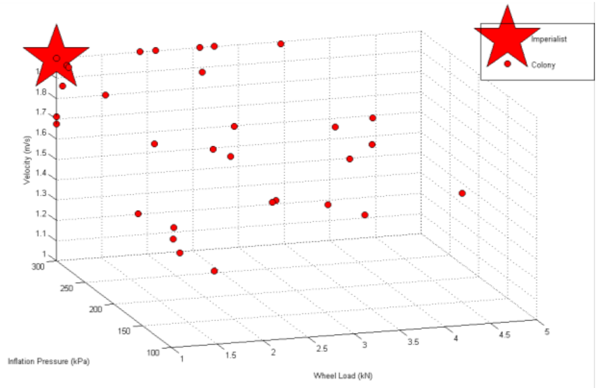

Figure 7- Occupancy of the weak imperialists by the imperialist with the lowest cost function in the search space including wheel load, inflation pressure and velocity.

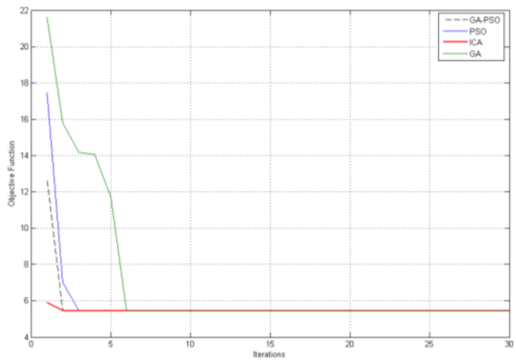

Figure 8- Convergence characteristics of ICA compared with PSO, GA and GA-PSO.

Fig. 7 shows that at wheel load of 1 kN, inflation pressure of 300 kPa and velocity of 2 m/s, the imperialist with the lowest cost function could possess other imperialists and form its empire and the including colonies (this is shown in ICA search space). Also optimization results showed that minimized rolling resistance of 5.46N (0.00546 kN) was obtained at wheel load of 1 kN, inflation pressure at 300 kP and velocity at 2 m/s. This also suggests that rolling resistance has direct relation with velocity and tire inflation pressure while has reverse relation with wheel load. That is, increase of wheel load, decrease of inflation pressure and decrease of velocity yields higher rolling resistance. Under same population and iteration size, ICA was compared to GA, PSO and hybridized GA-PSO (Fig. 8). These algorithms are simply used for the verification of ICA technique and the purpose of this study was not to evaluate the potential of GA and PSO.

Conclusions

Amongst the most well-known meta-heuristic techniques of genetic algorithm (GA), stochastic particle swarm optimization (PSO), ant colony optimization (ACO) and bee colony optimization (BCO), we selected GA, PSO and hybrid GA-PSO due to their documented abilities to compete with the recently introduced imperialist competitive algorithm (ICA) for minimization of wheel rolling resistance in a soil bin facility. The results divulged that ICA far succeeded in finding good results in a less iteration number compared to other evolutionary methods.

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استفاده از روشهای فرا ابتکاری برای مینیمم کردن مقاومت غلتشی ماشین های برون جاده ای

چکیده

در این مطالعه کاربرد روشهای فرا ابتکاری برای مینیمم کردن مقاومت غلتشی ماشین های برون جاده ای مانند روش ازدحام ذرات، رقابت استعماری و الگوریتم ژنتیک مورد بحث قرار گرفته است. سه پارامتر چرخ بار روی تایر، فشار باد تایر و سرعت حرکت به عنوان پارامترهای ورودی به سیستم داده شدند. نتایج نشان دادند که روش بهینه سازی رقابت استعماری در کمینه کردن مقدار نیروی مقاومت غلتشی نسبت به بقیه روش های مورد استفاده عملکرد بهتری دارد.

واژه‌های کلیدی: روش رقابت استعماری، بهینه سازی ازدحام ذرات، الگوریتم ژنتیک، مقاومت غلتشی، انباره خاک