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Diversified-Intensified Current Search Algorithm and Its Application to Optimal State-Feedback Controller Design for Tractor Active Suspension System

***Abstract**. This paper proposes the novel metaheuristic search algorithm named the diversified-intensified current search (DICuS) and its application to design the optimal state-feedback controller for the tractor active suspension system. The proposed DICuS is based on the intensified current search (ICuS) initiated from the electrical current flowing through the electric networks. The random number drawn from the uniform distribution and the automatically-adjusted search radius mechanism are conducted to improve the search performance and ease of use. The DICuS is tested against ten selected standard multimodal benchmark functions for minimization. Results obtained by the DICuS will be compared with those obtained by the ICuS. As simulation results, the proposed DICuS is much more efficient for function minimization than the ICuS, significantly. Then, the DICuS is applied to design the optimal state-feedback controller for the tractor active suspension system based on the modern optimization. From results, it was found that the DICuS can successfully provide the optimal state-feedback controller for the tractor active suspension system. By comparison, the tractor active suspension system controlled by the state-feedback controller designed by the LFICuS algorithm yields very satisfactory response with smaller oscillation and faster regulating time than that designed by the pole-placement method.*

Streszczenie.** W artykule zaproponowano nowatorski algorytm wyszukiwania metaheurystycznego, nazwany zróżnicowanym, zintensyfikowanym wyszukiwaniem prądowym (DICuS) i jego zastosowanie do zaprojektowania optymalnego sterownika ze sprzężeniem zwrotnym stanu dla aktywnego układu zawieszenia ciągnika. Proponowany DICuS opiera się na zintensyfikowanym przeszukiwaniu prądu (ICuS) inicjowanym na podstawie prądu elektrycznego przepływającego przez sieci elektryczne. Losowa liczba losowana z rozkładu równomiernego i mechanizm automatycznie dopasowywany promienia wyszukiwania są przeprowadzane w celu poprawy wydajności wyszukiwania i łatwości użytkowania. DICuS jest testowany pod kątem dziesięciu wybranych standardowych multimodalnych funkcji wzorcowych w celu minimalizacji. Wyniki uzyskane przez DICuS zostaną porównane z wynikami uzyskanymi przez ICuS. Jak wynika z symulacji, proponowany DICuS jest znacznie skuteczniejszy w minimalizacji funkcji niż ICuS, znacznie. Następnie DICuS jest stosowany do zaprojektowania optymalnego sterownika ze sprzężeniem zwrotnym dla aktywnego układu zawieszenia ciągnika w oparciu o nowoczesną optymalizację. Na podstawie wyników stwierdzono, że DICuS może z powodzeniem zapewnić optymalny sterownik sprzężenia zwrotnego stanu dla aktywnego układu zawieszenia ciągnika. Dla porównania, układ aktywnego zawieszenia ciągnika, sterowany przez sterownik ze sprzężeniem zwrotnym, zaprojektowany przez algorytm LFICuS, daje bardzo zadowalającą odpowiedź przy mniejszych oscylacjach i szybszym czasie regulacji niż projektowany metodą przestawiania biegunów.* (Zróżnicowany, zintensyfikowany algorytm wyszukiwania prądu i jego zastosowanie w optymalnej konstrukcji sterownika ze sprzężeniem zwrotnym dla aktywnego układu zawieszenia ciągnika***)

Keywords: Diversified-intensified current search, State-feedback controller, Tractor active suspension system, Modern optimization.
Słowa kluczowe: wykrywanie prądu, ciągnik z aktywnym układem zwieszenia.

Introduction

Nowadays, metaheuristic optimization techniques have played the important role to solve various real-world engineering optimization problems [1, 2, 3]. Following the literatures, the current search (CuS) is one of the most interesting metaheuristic algorithms firstly proposed in 2012 [4]. The CuS algorithm mimics the principle of an electric current flowing behavior in the electric circuits and networks. It utilizes the deterministic process for generating the feasible solutions in all search iterations. The CuS performed superior search performance to the genetic algorithm (GA), tabu search (TS) and particle swarm optimization (PSO) [4]. Also, it was successfully applied to control problems [5] and filter design problems [6].

In 2014, the intensified current search (ICuS) was consecutively proposed to improve the search performance of the CuS [7]. The ICuS algorithm consists of the memory list (ML), the adaptive radius (AR) and the adaptive neighborhood (AN) mechanisms. The ML is used to store the ranked initial solutions at the beginning of search process, record the solutions found along each search direction, and contain all local solutions found at the end of each search direction. The ML is also applied to escape the local entrapments caused by local optima. The AR and AN mechanisms are together conducted to speed up the search process. It utilizes the random drawn from the uniform distribution for generating the feasible solutions. The ICuS was successfully applied to many control engineering problems including single-objective and multi-objective optimization problems [7-10].

Later, in 2021, the Lévy-flight intensified current search (LFICuS) was launched to improve the search performance of the ICuS in the large-space multimodal problems [11]. The LFICuS still employs the ML, AR and AN mechanisms as the ICuS, but the random process was changed to the Lévy-flight distribution. It was successfully conducted to optimized the PID controller of car active suspension system [11] and an azimuth position control system [12].

From studying the differences of CuS, ICuS and LFICuS algorithms, it was found that the ICuS is more efficient than the CuS in global solution finding, but the adjustment the AR and AN mechanisms to suit each problem remains complex for users. The LFICuS is more efficient than the ICuS in global solution finding of the large-space multimodal problems. However, setting the AR and AN mechanisms to suit each problem still remains complex for users. In addition, it also requires additional programming for generating the random with Lévy-flight distribution.

In this paper, the newest modified version of the ICuS named the diversified-intensified current search (DICuS) is proposed to increase the ease of use and improve the search performance of the ICuS. The proposed DICuS will use the random drawn from the uniform distribution for generating the feasible solutions, discard the AN mechanism and utilze the automatically-adjusted AR mechanism. The DICuS will be tested against ten selected standard multimodal benchmark functions and applied to design the optimal state-feedback controller for the tractor active suspension system based on the modern optimization approach.

Intensified current search (ICuS) algorithm

The ICuS algorithm [7] developed from the CuS [4] is based on the iteratively random search by using the random number drawn from the uniform distribution. The ICuS possesses the ML, AR and AN mechanisms. It can be described by the pseudo code as shown in Fig. 1, where $f(\boldsymbol{x})$ is the objective function, $\boldsymbol{x} = (x_1,\ldots,x_d)^T$ is the solution vector, Ω is the search space, Ψ is the low-level ML, Γ_k is the medium-level ML of the k^{th} search direction, Ξ is the high-level ML, j_{max} is the maximum allowance of the solution cycling, N is number of initial solutions (search directions), n is number of neighborhood members, R is the search radius, i and j are the counting variables, $\boldsymbol{X}_i$ are the initial solutions, $\boldsymbol{x}_0$ is the selected initial solution, $\boldsymbol{X}_{local}$ is the local solution, $\boldsymbol{X}_{global}$ is the global solution, $\boldsymbol{x}^*$ is the best solution in the current search iteration, ρ is the decreasing factor for the AR and AN mechanisms and TC is the termination criteria.

Initialized:
- Objective function $f(\boldsymbol{x})$, $\boldsymbol{x}=(x_1,\ldots,x_d)^T$,
- Search space Ω,
- Memory list ML (Ψ, Γ_k, and Ξ),
- Maximum allowance of solution cycling j_{max},
- Number of initial solutions N,
- Number of neighborhood members n,
- Search radius R = 10% of Ω, $i=j=k=1$.
- Uniformly random initial solution $\boldsymbol{X}_i$ within Ω.
- Evaluate $f(\boldsymbol{X}_i)$ then rank $\boldsymbol{X}_i$ and store in Ψ.
- Let $\boldsymbol{x}_0=\boldsymbol{X}_k$ as selected initial solution.
- $\boldsymbol{X}_{global}=\boldsymbol{X}_{local}=\boldsymbol{x}_0$.

while ($k<=N$ or termination criteria: TC);
  while ($j<=j_{max}$);
    Uniformly random $\boldsymbol{x}_i$ around $\boldsymbol{x}_0$ within R.
    Evaluate $f(\boldsymbol{x}_i)$ and set the best one as $\boldsymbol{x}^*$.
    if $f(\boldsymbol{x}^*)<f(\boldsymbol{x}_0)$;
      Keep $\boldsymbol{x}_0$ into Γ_k, update $\boldsymbol{x}_0=\boldsymbol{x}^*$ and set j=1.
    else
      Keep $\boldsymbol{x}^*$ into Γ_k and update $j=j+1$.
    end
    Activate AR mechanism by user.
    Invoke AN mechanism by user.
  end
  Update $\boldsymbol{X}_{local}=\boldsymbol{x}_0$.
  Keep $\boldsymbol{X}_{global}$ into Ξ.
  if $f(\boldsymbol{X}_{local})<f(\boldsymbol{X}_{global})$;
    Update $\boldsymbol{X}_{global}=\boldsymbol{X}_{local}$.
  end
  Update $k=k+1$ and set j=1.
  Let $\boldsymbol{x}_0=\boldsymbol{X}_k$ as selected initial solution.
end

Fig.1. Pseudo code of ICuS

Refering to Fig. 1, after initializing the objective function $f(\boldsymbol{x})$ and relevant search parameters, the ICuS begins the search process by randomly generating the initial solutions $\boldsymbol{X}_i$. Then, all $\boldsymbol{X}_i$ will be evaluated by the objective function $f(\boldsymbol{X}_i)$, ranked and stored in Ψ. After that, the k^{th} solution in Ψ is selected and set as the $\boldsymbol{x}_0 = \boldsymbol{X}_k$. $\boldsymbol{X}_{global} = \boldsymbol{X}_{local} = \boldsymbol{x}_0$ is also set. From this, the ICuS goes to the search iteration. If $k \leq N$ and $j \leq j_{max}$, the solutions $\boldsymbol{x}_i$ are randomly generated around $\boldsymbol{x}_0$ within R by the using the random number drawn from the uniform distribution. The initial value of R is fixed as equal 10% of the search space Ω. All $\boldsymbol{x}_i$ will be evaluated by the objective function $f(\boldsymbol{x}_i)$. The best solution among $\boldsymbol{x}_i$ will be set as $\boldsymbol{x}^*$. If $f(\boldsymbol{x}^*) < f(\boldsymbol{x}_0)$, keep $\boldsymbol{x}_0$ into Γ_k, update $\boldsymbol{x}_0 = \boldsymbol{x}^*$ and set j = 1, otherwise, keep $\boldsymbol{x}^*$ into Γ_k and update $j = j + 1$. The AR and AN mechanisms are then activated to reduce R and n, respectively. Then, $\boldsymbol{X}_{local}$ is updated by setting $\boldsymbol{X}_{local} = \boldsymbol{x}_0$. $\boldsymbol{X}_{global}$ is stored in Ξ. If $f(\boldsymbol{X}_{local}) < f(\boldsymbol{X}_{global})$, $\boldsymbol{X}_{global}$ will be updated by setting $\boldsymbol{X}_{global} = \boldsymbol{X}_{local}$. After that, update $k = k + 1$ and set j = 1 to proceed the next search direction. The ICuS algorithms will be iteratively proceeded until all significant local solutions are found and stored in Ξ. Then, one of the local solutions is the global solution.

Diversified-intensified current search (DICuS) algorithm

The proposed DICuS is developed from the ICuS based on the iteratively random search by using the random number drawn from the uniform distribution. The DICuS algorithm possessing the ML as the ICuS can be described by the pseudo code as shown in Fig. 2. In the DICuS, the AN mechanism in the ICuS is descarded to increase the intensification. The new AR mechanism is proposed to increase the ease of use as stated in (1), where R_i is the search radius at the i^{th} iteration, $R_0 = \Omega$ is the initial search radius and α is the decreasing factor. From (1), it can be seen that $R_0 = \Omega$ is set to increase the diversification. Once the search iteration is increased, R_i is exponentially-automatically decreased according to the defined α depending on the problems of interest as shown in Fig. 3.

Initialized:
- Objective function $f(\boldsymbol{x})$, $\boldsymbol{x}=(x_1,\ldots,x_d)^T$,
- Search space Ω,
- Memory list ML (Ψ, Γ_k, and Ξ),
- Maximum allowance of solution cycling j_{max},
- Number of initial solutions N,
- Number of neighborhood members n,
- Search radius R_0 = Ω (100% of Ω), $i=j=k=1$.
- Uniformly random initial solution $\boldsymbol{X}_i$ within Ω.
- Evaluate $f(\boldsymbol{X}_i)$ then rank $\boldsymbol{X}_i$ and store in Ψ.
- Let $\boldsymbol{x}_0=\boldsymbol{X}_k$ as selected initial solution.
- $\boldsymbol{X}_{global}=\boldsymbol{X}_{local}=\boldsymbol{x}_0$.

while ($k<=N$ or termination criteria: TC);
  while ($j<=j_{max}$);
    Uniformly random $\boldsymbol{x}_i$ around $\boldsymbol{x}_0$ within R.
    Evaluate $f(\boldsymbol{x}_i)$ and set the best one as $\boldsymbol{x}^*$.
    if $f(\boldsymbol{x}^*)<f(\boldsymbol{x}_0)$;
      Keep $\boldsymbol{x}_0$ into Γ_k, update $\boldsymbol{x}_0=\boldsymbol{x}^*$ and set j=1.
    else
      Keep $\boldsymbol{x}^*$ into Γ_k and update $j=j+1$.
    end
    Activate new AR mechanism in (1).
  end
  Update $\boldsymbol{X}_{local}=\boldsymbol{x}_0$.
  Keep $\boldsymbol{X}_{global}$ into Ξ.
  if $f(\boldsymbol{X}_{local})<f(\boldsymbol{X}_{global})$;
    Update $\boldsymbol{X}_{global}=\boldsymbol{X}_{local}$.
  end
  Update $k=k+1$ and set j=1.
  Let $\boldsymbol{x}_0=\boldsymbol{X}_k$ as selected initial solution.
end

Fig.2. Pseudo code of DICuS

(1) $$R_i = R_0 e^{-\alpha i}, \quad 0 < \alpha < 1$$

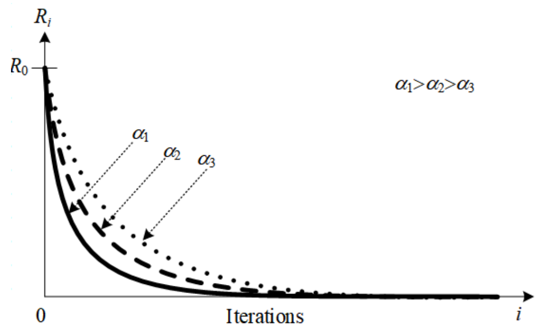


Fig.3. New AR mechanism

Performance evaluation

To evaluate its search performance, the proposed DICuS will be tested against ten selected standard multimodal benchmark functions for minimization [13, 14], including Griewank function (GF): f_1, Zirilli function (ZF): f_2, Bohachevsky function (BoF): f_3, Styblinski-Tang function (STF): f_4, Scahffer function (SfF): f_5, Alpine function (AF): f_6, Bird function (BdF): f_7, Cross-in-Tray function (CTF): f_8, Shubert function (ShF): f_9 and Rosenbrock function (RF): f_{10} as stated in (2) to (11), respectively, where (x^*, y^*) is the global minimum. For f_9 in (10), it posesess nine global minima [13, 14].

$$(2)\quad \begin{cases} f_1(x,y)=\dfrac{1}{4000}(x^2+y^2)-\cos(x)\cos\left(\dfrac{y}{\sqrt{2}}\right)+1, \\ f_1(x^*,y^*)=f_1(0,0)=0,\ -100\le x,\ y\le 100 \end{cases}$$

$$(3)\quad \begin{cases} f_2(x,y)=0.25x^4-0.5x^2+0.1x+0.5y^2, \\ f_2(x^*,y^*)=f_2(-10.0465,0)=-0.3523, \\ -10\le x,\ y\le 10 \end{cases}$$

$$(4)\quad \begin{cases} f_3(x,y)=x^2+2y^2-0.3\cos(3\pi x) \\ \qquad\qquad -0.4\cos(4\pi y)+0.7, \\ f_3(x^*,y^*)=f_3(0,0)=0, \\ -100\le x,\ y\le 100 \end{cases}$$

$$(5)\quad \begin{cases} f_4(x,y)=0.5[(x^4-16x^2+5x)+(y^4-16y^2+5y)], \\ f_4(x^*,y^*)=f_4(-2.9035,-2.9035)=-78.3320, \\ -5\le x,\ y\le 5 \end{cases}$$

$$(6)\quad \begin{cases} f_5(x,y)=0.5+\{(\cos^2[\sin(x^2-y^2)]-0.5)/ \\ \qquad\qquad [1+0.001(x^2+y^2)^2]\}, \\ f_5(x^*,y^*)=f_5(0,1.2531)=0.2926, \\ -100\le x,\ y\le 100 \end{cases}$$

$$(7)\quad \begin{cases} f_6(x,y)=|x\sin(x)+0.1x|+|y\sin(y)+0.1y|, \\ f_6(x^*,y^*)=f_6(0,0)=0, \\ -10\le x,\ y\le 10 \end{cases}$$

$$(8)\quad \begin{cases} f_7(x,y)=\sin(x)e^{[1-\cos(y)]^2} \\ \qquad\qquad +\cos(y)e^{[1-\sin(x)]^2} \\ \qquad\qquad\qquad +(x-y), \\ f_7(x^*,y^*)=f_7(4.7010,3.1529)= \\ \qquad\qquad f_7(-1.5821,-3.1302)=-106.7645, \\ -2\pi\le x,\ y\le 2\pi \end{cases}$$

$$(9)\quad \begin{cases} f_8(x,y)=-0.0001\left(\left|\sin(x)\sin(y)e^{\Delta}\right|+1\right)^{0.1}, \\ \Delta=|100-[(x^2+y^2)]^{0.5}/\pi|, \\ f_8(x^*,y^*)=f_8(1.3494,1.3494)=20.6261, \\ -10\le x,\ y\le 10 \end{cases}$$

$$(10)\quad \begin{cases} f_9(x,y)=\left(\displaystyle\sum_{i=1}^{5}\cos[(i+1)x+i]\right) \\ \qquad\qquad \times\left(\displaystyle\sum_{i=1}^{5}\cos[(i+1)y+i]\right), \\ f_9(x^*,y^*)=-186.7309, \\ -10\le x,\ y\le 10 \end{cases}$$

$$(11)\quad \begin{cases} f_{10}(x,y)=100(y-x^2)^2+(x-1)^2, \\ f_{10}(x^*,y^*)=f_{10}(1,1)=0, \\ -30\le x,\ y\le 30 \end{cases}$$

All selected benchmark functions are highly nonlinear and possess many local minima. Fig. 4 shows the 3D-surface of GF in (2) as an example.

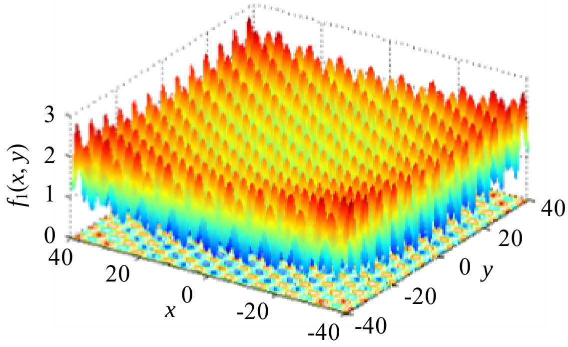


Fig.4.3D-surface of GF

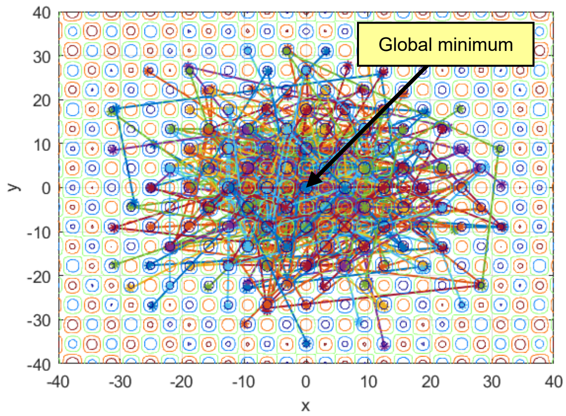
The proposed DICuS algorithm is coded by MATLAB version 2018b (License No.#40637337) run on Intel(R) Core(TM) i7–10750H CPU@2.60GHz, 16.0GB–RAM. Searching parameters of the DICuS are set from the preliminary studies with different ranges of parameters, i.e., number of neighborhood members n and the decreasing factor α. By varying n = 5, 6, 7, 8,...,40, and α = 0.01, 0.0125, 0.015, 0.0175,...,0.25, while the search directions N = 100 are fixed, it was found that the best parameters for most benchmark functions are: n = 10 to 30 and α = 0.0125 to 0.1. In this performance evaluation tests, n = 20 and α = 0.015 are set for all selected functions. Each search direction is terminated at 1000 iterations. 100-trial runs are conducted for each algorithm. For comparison with the ICuS, searching parameters of the ICuS are equivalently set as the same values to those of DICuS. The ICuS and DICuS algorithms will be terminated once two termination criteria (TC) are satisfied, i.e., (1) the function value are less than a given tolerance $\varepsilon \le 10^{-5}$ from the global minimum of each function or (2) the search meets the maximum search directions N_{max} = 5. The former criterion implies that the search is success, while the later means that the search is not success.

Table 1. Results of performance evaluation of ICuS and DICuS

Func-tions	ICuS	Proposed DICuS
GF	$2.99x10^4±2.25x10^4$(98%)	$2.52x10^4±1.5047x10^4$(100%)
ZF	$5.16x10^3±1.68x10^3$(100%)	$6.27x10^2±78.00$(100%)
BoF	$1.56x10^4±1.02x10^4$(96%)	$1.86x10^3±2.061x10^3$(100%)
STF	$2.16x10^4±1.38x10^4$(79%)	$7.45x10^2±82.00$(100%)
SfF	$1.10x10^4±5.06x10^3$(100%)	$1.84x10^3±3.453x10^3$(100%)
AF	$1.66x10^4±8.79x10^3$(100%)	$4.91x10^3±7.004x10^3$(100%)
BdF	$1.03x10^4±6.88x10^3$(100%)	$2.53x10^3±4.065x10^3$(100%)
CTF	$6.14x10^3±2.33x10^3$(100%)	$7.39x10^2±89.00$(100%)
ShF	$8.20x10^3±2.33x10^3$(100%)	$1.17x10^3±80.00$(100%)
RF	$1.04x10^4±8.80x10^3$(94%)	$8.05x10^3±1.357x10^3$(100%)

The obtained results are summarized in Table 1. Data in Table 1 are presented by the following format, i.e., AE±SD(SR%) [15], where AE is the average number (mean) of function evaluations, SD is the standard deviation and SR is the success rate. From Table 1, the proposed DICuS performs better performance for finding the global minima by SR = 100% for all selected benchmark functions with less AE and SD values than the ICuS. Fig. 5 shows the example of the DICuS's search results of global minimum finding of GF function (f_1). Results of other functions are omitted because they have a similar form to those of f_1 as shown in Fig. 5. The proposed DICuS algorithm will be extended to optimize the state-feedback controller for the tractor active suspension system as detailed in next sections.

(a) Search movement over 100 trials



(b) Convergent rates over 100 trials

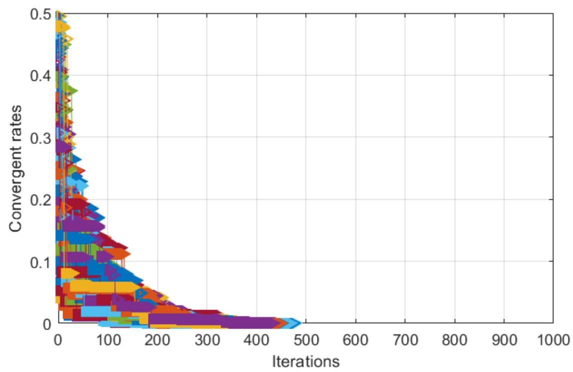


Fig.5. Results of minimum finding of GF by DICuS

Tractor active suspension model

Tractor active suspension system can be represented by the two-degree-of-freedom translation mechanical model [16, 17] as shown in Fig. 6, where M_1 is the tractor mass, M_2 is the suspension mass, x_s is the displacement of tractor body, x_w is the displacement of the suspension mass, k_1 and k_2 are the spring coefficients, and b_1 and b_2 are the damper coefficients, respectively. From Fig. 6, front and rear suspensions are lumped by one wheel and axle mounted to the quarter portion of the tractor body with the active spring-damper suspension. Based on the Newton's law and the modern control system, the tractor active suspension system with the full-state feedback controller can be formulated as expressed in (12) [17], where $[x_1, x_2, x_3, x_4, x_5]^T = [x_s, \dot{x}_s, y = (x_s - x_w), \dot{y}, \int y dt]^T$. The model in (12) shows that after the tractor tire is subjected to the road disturbance, the output $y = x_3 = (x_s - x_w)$ will ultimately reach to equilibrium point.

State-feedback controller design problem

In order to design the optimal state-feedback controller by the DICuS for the tractor active suspension system, the sum-squared error (SSE) between the input r (r = 0) and the output y is set as the objective function $f(\mathbf{K})$, $\mathbf{K} = [K_1, K_2, K_3, K_4, K_5]$, as stated in (13), where N_D is the number of data. The objective function $f(\mathbf{K})$ in (13) will be minimized by the DICuS according to their corresponding search spaces and predefined satisfactory responses set as the inequality constraints functions.

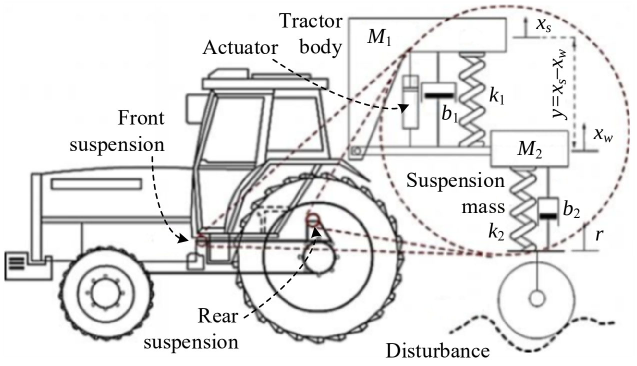


Fig.6. Two-degree-of-freedom model of tractor active suspension system [17]

$$
(12)\quad \begin{cases}
\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\end{bmatrix} = \left(\begin{bmatrix}
0 & 1 & 0 & 0 & 0\\
-\frac{b_1 b_2}{M_1 M_2} & 0 & \left(\frac{b_1^2}{M_1^2} + \frac{b_1^2}{M_1 M_2} + \frac{b_1 b_2}{M_1 M_2} - \frac{k_1}{M_1}\right) & -\frac{b_1}{M_1} & 0\\
\frac{b_2}{M_2} & 0 & \left(-\frac{b_1}{M_1} - \frac{b_1}{M_2} - \frac{b_2}{M_2}\right) & 1 & 0\\
\frac{k_2}{M_2} & 0 & \left(-\frac{k_1}{M_1} - \frac{k_1}{M_2} - \frac{k_2}{M_2}\right) & 0 & 0\\
0 & 0 & 1 & 0 & 0
\end{bmatrix} \right.\\
\qquad \left. - \begin{bmatrix}
0 & 0\\
\frac{1}{M_1} & \frac{b_1 b_2}{M_1 M_2}\\
0 & -\frac{b_2}{M_2}\\
\left(\frac{M_1 + M_2}{M_1 M_2}\right) & -\frac{k_2}{M_2}\\
0 & 0
\end{bmatrix} \begin{bmatrix}1\\ 0\end{bmatrix} \begin{bmatrix}K_1 & K_2 & K_3 & K_4 & K_5\end{bmatrix} \right) \begin{bmatrix}x_1\\ x_2\\ x_3\\ x_4\end{bmatrix}\\
\qquad + \begin{bmatrix}
0 & 0\\
\frac{1}{M_1} & \frac{b_1 b_2}{M_1 M_2}\\
0 & -\frac{b_2}{M_2}\\
\left(\frac{M_1 + M_2}{M_1 M_2}\right) & -\frac{k_2}{M_2}\\
0 & 0
\end{bmatrix} \begin{bmatrix}u\\ r\end{bmatrix}\\
y = \begin{bmatrix}0 & 0 & 1 & 0 & 0\end{bmatrix} \begin{bmatrix}x_1\\ x_2\\ x_3\\ x_4\end{bmatrix}
\end{cases}
$$

$$
(13)\quad \textbf{Minimize}\quad f(\mathbf{K}) = \sum_{i=1}^{N_D} [r_i - y_i]^2 = \sum_{i=1}^{N_D} [y_i]^2
$$

Results and discussions

From (12), the parameter values of Kubota M110X tractor [17] are conducted as follow, M_1 = 700 kg, M_2 = 90 kg, k_1 = 62,000 N/m, k_2 = 570,000 N/m, b_1 = 500 N.s/m and b_2 = 22,500 N.s/m. Some parameters of the tractor active suspension system can be approximately calculated by specific technique [18].

Referring to [17], the state-feedback controller for the tractor active suspension system was designed by the pole-placement method as stated in (14). Readers can find some details of the state-feedback controller and pole-placement method in [19-21].

$$
(14)\quad \mathbf{K}_{\text{pole-placement}} = [250\ \ 500\ \ 300\ \ 200\ \ 150]
$$

In this work, the DICuS algorithm coded by MATLAB version 2018b (License No.#40637337) run on Intel(R) Core(TM) i7–10750H CPU@2.60GHz, 16.0GB–RAM is applied to design the optimal state-feedback controller for the tractor active suspension system. The road disturbances were simulated by the step function representing the step road and the sinusoidal function representing the bumpy and pothole roads. The search parameters of the DICuS are set from the preliminary study, i.e., n = 25, α = 0.025, N = 100 and N_{max} = 5. Each search direction is terminated at 200 iterations. 50-trial runs are conducted to obtain the optimal values of gain $\mathbf{K}$ = [K_1, K_2, K_3, K_4, K_5]. The search spaces and predefined satisfactory responses are set from a priori study as the inequality constraints functions stated in (15), where M_p is the maximum overshoot, t_{reg} is the regulating time and e_{ss} is the steady-state error.

$$(15)\quad \begin{cases} \text{Subject to} \\ M_p \le 10.00\%,\ t_{reg} \le 5.00 \text{ sec}, \\ e_{ss} \le 0.01\%, 2{,}000 \le K_1 \le 4{,}000, \\ 2{,}000 \le K_2 \le 4{,}000,\ 2{,}000 \le K_3 \le 4{,}000, \\ 100 \le K_4 \le 500, 100 \le K_5 \le 500 \end{cases}$$

Once the search process is terminated over 50-trial runs, the state-feedback controller for the tractor active suspension system can be optimized by the DICuS as stated in (16). The convergent rates of the control objective minimization in (13) associated with the constraints functions in (15) by the DICuS are plotted in Fig. 7. From Fig. 7, it can be observed that the DICuS performs the effective search optimization over 50-trial runs with different initial solutions and rapidly converges to the optimal solutions with the average search time of 98.24 sec.

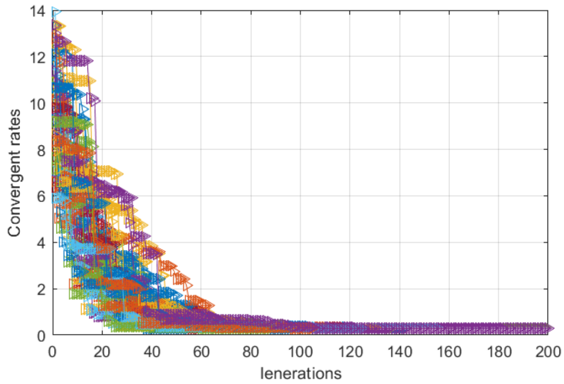


Fig.7. Convergent rates of state-feedback controller optimization by DICuS over 50 trials

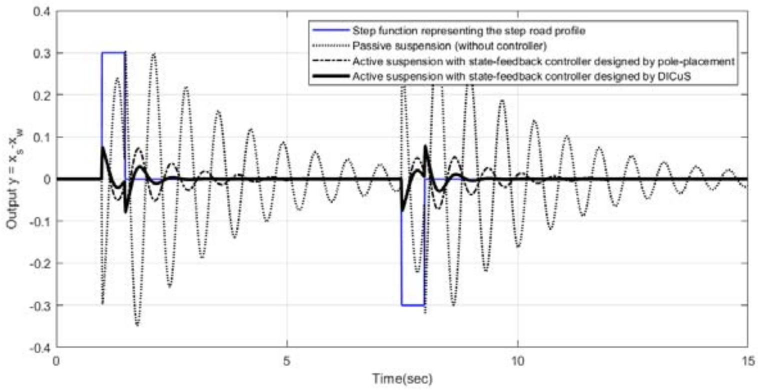


Fig.8. Step responses of tractor active suspension systems

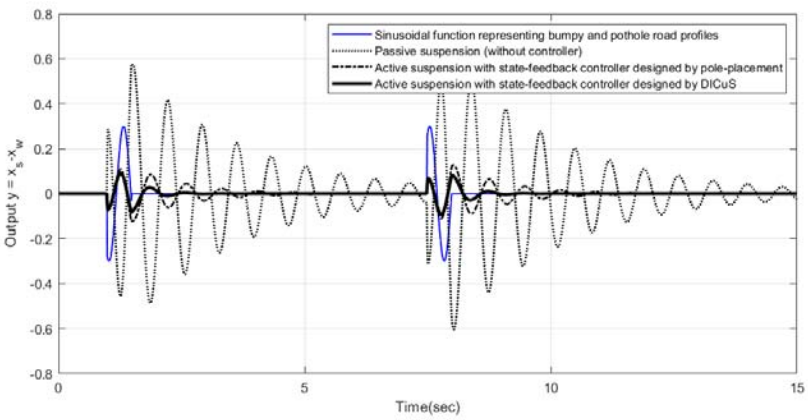


Fig.9. Sinusoidal responses of tractor active suspension systems

$$(16)\quad \mathbf{K}_{\text{DICuS}} = [3{,}752.56\ \ 3{,}601.83\ \ 3{,}195.14\ \ 127.22\ \ 274.31]$$

The step and sinusoidal responses of the tractor active suspension system without controller, with the state-feedback controller designed by the pole-placement method in (14) and with that designed by the DICuS algorithm in (16) are depicted in Fig. 8 and Fig. 9, respectively. All responses of the tractor active suspension systems are summarized in Table 2.

Table 2. Tractor active suspension system responses

Tractor suspension system	Step responses			Sinusoidal responses		
	M_p (%)	t_{req} (sec.)	e_{ss} (%)	M_p (%)	t_{req} (sec.)	e_{ss} (%)
Passive (without controller)	29.08	9.79	0.00	48.07	9.70	0.00
Active (pole-placement)	6.01	4.58	0.00	8.98	4.54	0.00
Active (DICuS)	2.42	2.21	0.00	7.61	2.03	0.00

From Fig. 8 – 9 and Table 2, it was found that the state-feedback controller designed by the DICuS can provide very satisfactory responses with smaller overshoot and oscillation and faster regulating time than the active suspension system designed by the pole-placement method and the passive suspension system, respectively.

Conclusions

In this paper, the diversified-intensified current search (DICuS) and its control problem application have been presented. The DICuS utilizes the random number drawn from the uniform distribution to generate the feasible solutions. In addition, the automatically-adjusted adaptive radius (AR) mechanism are proposed to improve the search performance and ease of use. The DICuS has been tested against ten standard benchmark functions to compare with the ICuS. Results shown that the DICuS is much more efficient than the ICuS. The DICuS has been applied to design the optimal state-feedback controller for the tractor active suspension system to compare with the pole-placement method. As results, the DICuS could completely optimize the state-feedback controller for the tractor active suspension system. By comparison, the tractor active suspension system controlled by the state-feedback controller designed by the DICuS could provide very satisfactory response with smaller oscillation and faster regulating time than that designed by the pole-placement method. For the future research, the DICuS will be extended to optimize other real-world control systems. Also, the parallel and hybrid DICuS algorithms will be developed.

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