Research Article

Design and development of vibratory cultivator using optimization algorithms

N. R. N. V. Gowripathi Rao[1] · Himanshu Chaudhary[1] · A. K. Sharma[2]

Abstract
Tillage system design is one of the important areas of interest for farming community. Oscillatory tillage is one such area which reduces the draft consumption and plays a crucial role to farmers during soil manipulation process. The paper deals to design a vibratory mechanism to provide a continuous motion to the tillage tool for following a particular path adopted from the literature through proper synthesis theory and procedure. A four bar mechanism is designed through proper synthesis procedure to identify the dimensions. Analytical and optimal synthesis method is followed during the design process. Optimization algorithms such as hybrid teaching–learning particle swarm optimization based algorithm (HTLPSO), teaching–learning based algorithm, and particle swarm optimization is used to find the values of the design variables. MATLAB is the software used for the synthesis and analysis process. It is observed in the study that designed four mechanism follows the required path for vibratory tillage operation. The results attained through optimization algorithm in HTLPSO performed better for the required path than other nature-inspired algorithms. Also the developed vibratory cultivator performed better in the field trials.

Keywords Soil · Vibratory tillage · Four bar mechanism · Optimization algorithms

1 Introduction

Since ancient age agricultural soil plays an important role and crop yield significantly improves when there is less soil resistance along with adequate mixing of the soil aggregates. The process of soil behaviour is called tillage. Several agricultural studies have concluded that design and development of effective tillage system can contribute in providing desired soil behaviour with less force and energy consumption [1]. The contribution can be seen by upgraded tractors and machineries, which serves as a gateway for productive farming. Due to high power requirements the farmer's economy is impacted. There is a need to design and develop a cost-effective and energy-efficient machineries that contributes in reducing the number of passes during tillage operation [2–4]. According to some studies, soil degradation is reported due to excessive use of heavy agricultural machineries in farm operations [5]. To solve this problem, improved tillage systems contribute in efficient working. Although tillage operations contributes 40% of the total agricultural mechanization scenario, still there is a need to work in this area [6]. Nowadays, active tools play an important role in agricultural tillage system and work efficiently as compared to passive tools [7]. There are many misconceptions regarding the active tillage tools that it will be not effective and causes structural difficulties. This is because of the lack of propagation of knowledge regarding the machine and lack of experience concerning their adaptability in agriculture.

The usage of heavy machineries in tillage operation soil compaction is occurring and contributing a negative

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effect on the plant growth and development [8–10]. High requirement of drawbar force and the additional weights in the tractor causes the soil for poor aeration, lower water infiltration, and draining rates. During this process, the soil is susceptible to formation of hard pans below the normal soil depths [11]. Another researcher studied that a 2–5 cm thick pan is formed in sandy soil mostly after a few runs by the tillage machine [12]. Fields are performed subsoiling operation to break the hardpan for the next crop and improve the drainage [13]. Thus the main area of concern of research is to use low draft implements which can reduce the soil compaction and contribute in farmer's economy for preparing the field with minimum expense [14]. To overcome this problem, it is a well-established fact that oscillation of tillage equipment can contribute in less draft and drawbar power requirements [15]. Previous studies [16–18] in oscillatory tillage reported that there is a reduction of draft force requirement when longitudinal or vertical vibrators are introduced. Due to high draft requirements by soil engaging tool such as blade, tine or share different studies verified by researchers [19–21] concluded that oscillatory or vibratory tillage produces better soil breakup and reduced draft. Although the power requirement may increase according to [22, 23], but the reduction of draft can be compensated on the basis of increased power requirement because the total energy input per unit mass is smaller than non-vibrating tillage operation and secondary action in the soil is minimized [21].

There have been several studies reported on the effect of oscillation angle, frequency, forward speed, amplitude on draft and power requirements by cutting tool and optimum setting are also proposed for efficient operation [24–26]. Thus the application of vibration in tillage tool can provide better soil pulverization, soil crumbling efficiency, reduced draft requirements, and soil resistance. Different researchers have reported and compared with the rigid tillage implements in terms of performance and efficiency [27]. The researchers quoted that there is a significant reduction in the draft of about 50–60% by using active vibratory tools [28, 29]. Efficient use of tractor PTO in oscillatory tillage equipment is 90–95% [15]. Some researchers have quoted an increase in power consumption by 30–35% [30].

Thus to provide an oscillating motion to the cutting tool, there is a need for a mechanism to be given to the system and is provided through tractor's power take-off shaft. The total oscillating unit had a flywheel, gearbox and a chain sprocket arrangement which gives the motion to the crankshaft unit driving the two tines through connecting rods. The eccentricity of the crankshaft provides the varied amplitude at the cutting tool tip and frequency is adjusted through tractor PTO and chain sprocket arrangement. The angle is varied by changing the tine arrangement [1]. The oscillations through the eccentric shaft assembled to the cutting blade to move forward and reverse direction is provided by [18] in the study. Through crankshaft eccentricities different amplitude are varied, and power is provided through tractor spiral bevel gears and tractor PTO. Tool oscillation through the crankshaft, connecting rod, and toggle crank mechanism is provided through the study by [28]. Rotation of the PTO shaft is transmitted to the crankshaft. Simple harmonic motion through a slider crank mechanism to impart oscillation to the tillage tool is also studies by [5]. Two different mechanisms, one is the oscillation to the shank through the double crank-rocker mechanism. The first mechanism consisted of an eccentric cylinder and connecting rod, which changed the direction of the motion from PTO axle to the second crank-rocker mechanism. Shank oscillation is provided through one complete PTO axle rotation which resulted in two complete shank oscillations. Another mechanism is eccentric crank and rocker mechanism as studied by [15]. A crank rocker mechanism is provided to the power tiller operated oscillatory tillage implement which is studied by [31]. A crank-rocker mechanism is designed for vibrator system design, and used bionics for subsoiler development by [32]. Designing a mechanism synthesis plays an important process in machine design. A detailed discussion on the synthesis of the mechanism is explained below in the section as follows.

1.1 Synthesis of mechanisms

Kinematic synthesis plays an important role to design a mechanism for the particular path, motion, etc. [33]. There are three categories in the kinematic synthesis and are categorized according to the task such as path generation, motion generation (rigid body guidance), and function generation problem. In path generation, we are concerned only about a particular trajectory that a mechanism should trace. But in the case of motion generation, we are worried about the entire coupler movement that is its path and angular orientation. Function generation deals with an output which is dependent on input link [34]. Mechanism design for vibratory tillage operation is through analytical and optimal synthesis, and tractor velocity for agricultural tillage operation was considered during the design 3–5 kmph.

There are two methods for linkage synthesis one is precision point method and optimal synthesis. The following methods are used frequently by different researchers [35, 36]. Nature-inspired algorithms are used to solve different path synthesis problems. Kinematic synthesis of linkages involves problem formulation as an objective function, constraint formulation, and an algorithm to solve the objective function which yields to identify proper design variables. The objective function most commonly used is the Euclidian distance formula, which is the distance between the generated and the desired path. There are standard algorithms to solve the path generation problem such as artificial bee colony (ABC) [37], Whale optimization algorithm (WOA) [38], genetic algorithm (GA) [39], particle swarm optimization (PSO) [40, 41], etc. many other algorithms. Genetic Algorithm and Particle Swarm requires a proper tuning of parameters. Another algorithm teaching learning based (TLBO) is a parameter less algorithm which uses the philosophy of teaching and learning based concept [42]. There are some improved algorithms [43–45] proposed recently by named as Modified Particle Search Algorithm and Hybrid teaching–learning based algorithm proposed by [46] combination of TLBO and PSO to solve and identify the design variables for the problem. For any algorithm, there are two phases one is exploration and exploitation. The algorithm should balance both phases to get global solutions. The algorithm Hybrid Teaching Learning Particle Swarm Optimization (HTLPSO) have both the qualities which yield better results and used in our study. The following results encourage us to use HTLPSO algorithm in our study to design a mechanism through the path generation synthesis procedure. Optimal solutions are obtained to trace the path required for the tillage operation. HTLPSO have both qualities such as exploration and exploitation, which concludes with good results in our study. Thus a mechanism is designed for vibratory tillage application through analytical and optimization methods.

Further, from the literature review, it is found that the oscillatory or vibratory mode of tillage tools has not been fully explored by experts and engineers. There is a need to work in this area to design and develop an efficient agricultural tillage machinery that can contribute in decreased draft reduction of the tillage tool. It is also found that maximum work is carried out on subsoiler equipment and no work is reported on the application of vibration in the cultivator tillage machine [47]. There are different active tillage implements available such as rotavator, power harrow, etc. They operate at a depth of around 12–15 cm, which satisfies the level of secondary tillage operation [48]. But the repetitive use of these implements the soil becomes compact and hard, which is not suitable for agricultural activities. The mechanism provided in different studies in vibratory tillage concept to make the tillage tool active was based on crop spacing, amplitude requirement, and are derived empirically. Proper synthesis procedure is not adopted for the mechanism design.

The main objective of the research work is to design and develop a vibratory cultivator which can efficiently perform both primary and secondary operation together. In Indian farming scenario, there is a need of combination tillage implements which can perform both primary and secondary tillage operations at a single instance in the field. In this paper, a procedural mechanism design is proposed through path generation synthesis techniques and applied on experimental trajectory selected from literature to design an oscillation system design. Mechanism design is through analytical and optimal synthesis method, which finds the best optimal solution and match the path of the tillage tool required. The proposed mechanism will definitely match the different phases of the soil cutting tool while operating in the field to complete the required task in the field during tillage operation. A small introduction on tool trajectory is explained below for understanding in the section.

1.2 Tool trajectory

Experimental tool trajectory, as explained by [1], concluded that there are four different important phases in one cycle of tillage tool. The following phases of tool trajectory are as follows: Cutting phase, backing off, catching up and end of the cycle, as shown in Fig. 1, and this is of 0.3 s. The cycle is repeated continuously to perform vibratory tillage operation. The sinusoidal path is obtained for the tool working in the soil.

Cutting phase The tool penetrates into the soil and cuts it known as cutting phase. This is the most important operation in the tillage system. The front side of the tillage tool remains active during the operation.

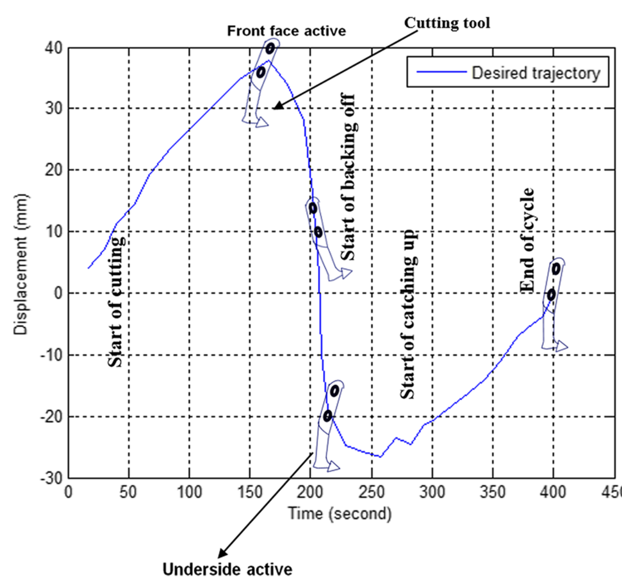


Fig. 1 Tool trajectory in the soil [1]

Backing off phase Tool gets disengaged from the soil, and the front face of the cutting tool becomes inactive, and the tool slowly reverts back to its original position.

Catching up and end of the cycle Tool moves until the uncut soil is reached and this phase is called catching up. After this, the cycle ends in tillage operation.

Thus to design a mechanism for the particular tool trajectory, a synthesis procedure is to be adopted from the literature. Path generation synthesis technique is performed for the tool trajectory. A detailed summary of the work done is explained below in the section.

2 Materials and methods

2.1 Plan of work

For designing the mechanism, a framework was adopted for the synthesis process. Figure 2 shows a detailed plan of work.

2.2 Precision point and optimal synthesis method for path generation problem

Kinematic synthesis is to identify the linkage dimensions for a specific objective [35]. There are several techniques, but among them, graphical and optimal methods are commonly used. Tool trajectory is explained below in Fig. 1. There are different phases according to [1] one is tool cutting, backing off and end of cycle phase. The following work consists of to design a mechanism for the tool cutting phase. Three positions for cutting phase are selected, as shown in Fig. 3 and synthesized to obtain the linkage dimensions of the mechanism, as shown in Fig. 4. A procedure is well defined by [33] to identify the dimensions for the three precision points through graphical synthesis procedure.

Optimal synthesis through path generation procedure consists of tracing the required path through optimization techniques. Six and thirteen precision points are selected for the cutting phase, and the required coupler position is matched with the precision points of the cutting phase selected from experimental trajectory through optimization technique as shown in Fig. 5.

Four bar linkage shown in Fig. 6 shows the various design parameters. Point P is the coupler point passing through the required path. Link 4 is defined as a ground

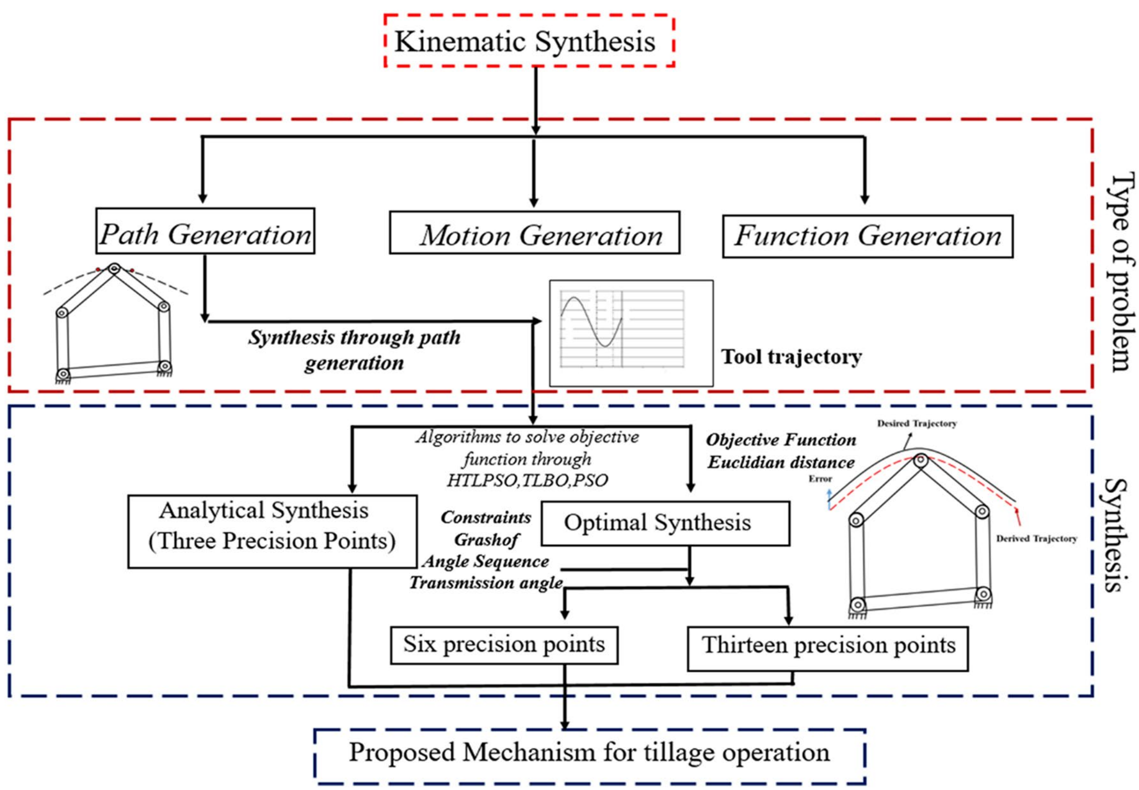


Fig. 2 Plan of work

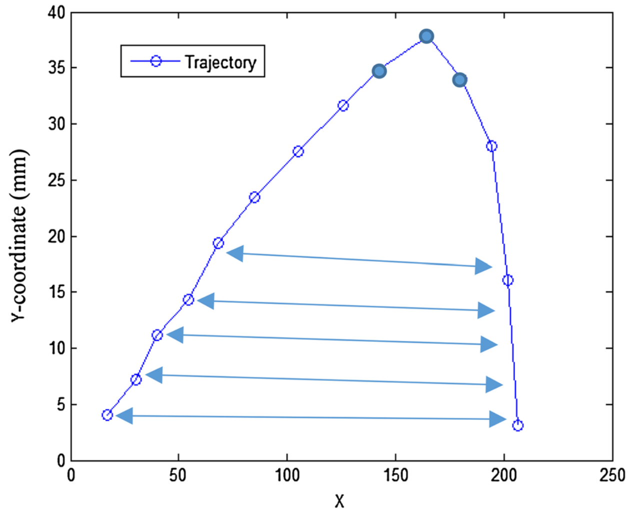


Fig. 3 Tool trajectory in cutting mode

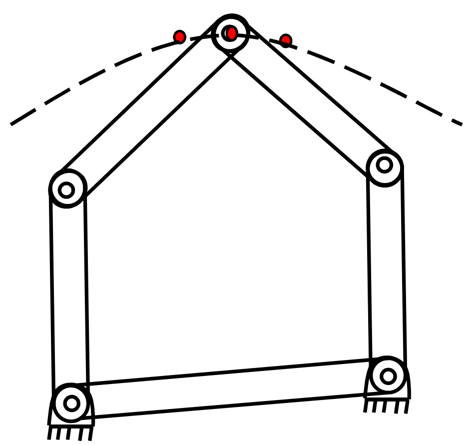


Fig. 4 Four bar mechanism passing through three position

link followed by link1 as crank. θ_2, θ_3, θ_4 are the angles measured with respect to axis X1. Link 4 is defined through orientation θ_0 with respect to X axis. Coupler position with respect to frame X1OaY1 is given by the following equations.

$$Pxderived = r1 * cos(\theta_2) + lx * cos(\theta_3) - ly * sin\left(\theta_3\right) \quad (1)$$

$$Pyderived = r1 * sin(\theta_2) + lx * \sin(\theta_3) + ly * \cos\left(\theta_3\right) \quad (2)$$

The following Eqs. (1) and (2) are the coupler coordinates which need to be traced for our tillage trajectory. For n precision points to trace the required trajectory, our design vector will be, as following as shown in Eq. (3).

$$X = \left[r_1, r_2, r_3, r_4, ly, lx, \theta_2^1, \theta_2^2, \theta_2^3, \theta_2^4, \theta_2^n, \theta_0, Xo, Yo\right] \quad (3)$$

Where N is the no of precision points. θ_3 and θ_4 can be calculated through loop closure equations of four bar mechanism [34, 35, 46]. $r_1, r_2, r_3, r_4, ly, lx, Xo, Yo$ are in mm.

For any path generation problem, position error is considered and is defined by Euclidean distance formula. The following can be written as following in Eq. (4).

Objective function:

$$f(x) = \sum_{i=1}^{n} sqrt\left(Pxdesired^N - Pxderived^N\right)^2 + \left(Pydesired^N - Pxderived^N\right)^2 \quad (4)$$

where *Pxdesired*, *Pydesired* are the required points of the trajectory and *Pxderived*, *Pyderived* are the obtained points of the coupler. To achieve the precision points of the trajectory following constraints are applied in crank rocker mechanism.

Subject to:

1. *Grashof constraint*:

$$g_1(x) = r4 + r1 < r2 + r3 \qquad if \quad (r1 < r2 < r3 < r4) \quad (5)$$

Fig. 5 Desired and derived path to reach through four bar mechanism

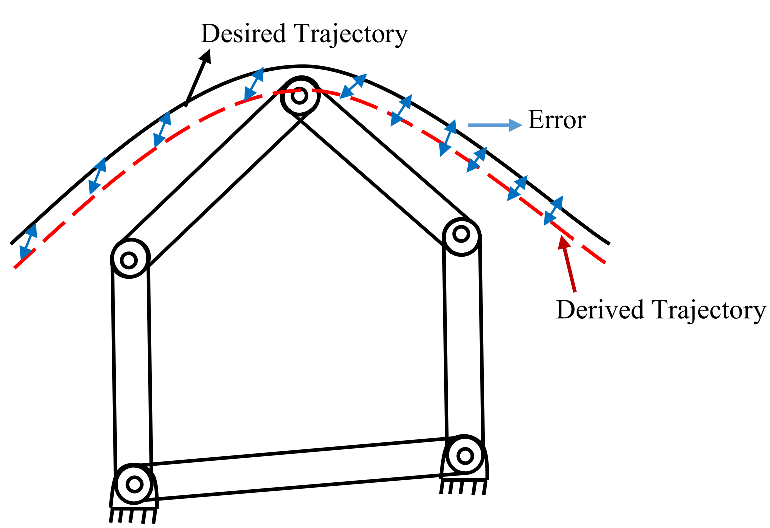
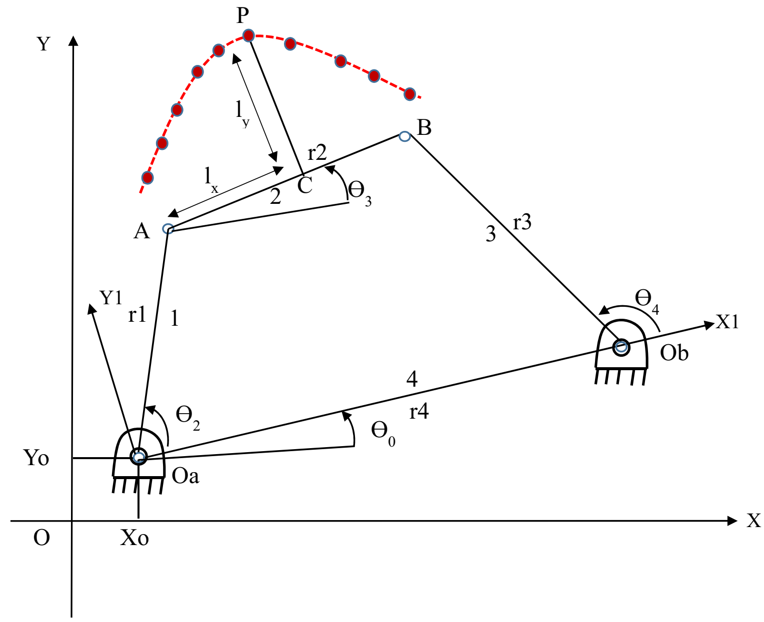


Fig. 6 Four bar mechanism and its notations [34, 35, 46]



2. *Angle sequence constraint*

$$g_2(x) = \theta_2^{N+1} - \theta_2^N < 0 \qquad (where\ N = 1, 2, 3 \ldots ..n) \tag{6}$$

3. *Transmission angle constraint (μ)*

$$\mu_{max} = \left[\left(r2^2 - (r4 + r1)^2 + c^2\right)/2 * r2 * r3\right] \quad (where\ r1, r2, r3, r4\ are\ the\ link\ dimensions) \tag{7}$$

$$\mu_{min} = \left[\left(r2^2 - (r4 - r1)^2 + c^2\right)/2 * r2 * r3\right]$$

$$\mu_{max} < \mu < \mu_{min}$$

4. *Lower and upper bound range of variables*

$$Li \le xi \le Ui \tag{8}$$

(where Li = lower bound and Ui = Upper bound, xi = design variables)

Thus the overall optimization problem defined by using Eqs. (4)–(8) is as follows:

Minimize:

$$f(x) = \sum_{i=1}^{n} sqrt\left(Pxdesired^N - Pxderived^N\right)^2 + \left(Pydesired^N - Pxderived^N\right)^2$$

Subject to:

$$g_1(x) = r4 + r1 < r2 + r3 \quad if \quad (r1 < r2 < r3 < r4)$$

$$g_2(x) = \theta_2^{N+1} - \theta_2^N < 0 \quad (where\ N = 1, 2, 3 \ldots ..n)$$

$$g_3(x) = \mu_{\max} < \mu < \mu_{\min} \quad (where\ Transmission\ angle = \mu)$$

$$Li \le xi \le Ui \quad (where\ Li = lower\ bound\ and\ Ui = Upper\ bound, \quad xi = design\ variables)$$

2.3 Nature inspired optimization algorithm

There are different algorithm techniques for solving the objective function to find the better optimal solutions for the particular path generation trajectory. So, in this section some of the nature inspired and hybrid algorithms are explained which are able to solve quickly, the objective function and yields better results. Two of the nature inspired algorithms such Particle swarm optimization (PSO), Teaching learning based algorithm (TLBO) is used in our problem for the path generation problem and one hybrid algorithm recently proposed which is a merger of TLBO and PSO and is known as Hybrid Teaching Learning based algorithm (HTLPSO) respectively.

2.3.1 Teaching learning based algorithm (TLBO)

Teaching learning algorithm is dependent on the efficient population based algorithm developed by the [49]. The teaching learning behaviour is mimicked the behaviour of teaching and learning ability in the classroom. The group of students consisted of students (learner) and is considered as population and the subjects offered to the student (learners) are the design variables. Results of students (learners) is similar to fitness value and the value of objective function represents the knowledge of the particular students. Teacher in the society is considered to be scholarly person in the society and this theory is followed in the TLBO algorithm. The process of TLBO is divided into two phases: the 'Teacher Phase' and the 'Learner Phase'. The following two phases is discussed in brief below in Fig. 7.

2.3.2 Teacher phase

Teacher is considered as one of the most learned and scholarly person. Teacher makes the learners learn if he is good in knowledge sharing. A learner who earns good grades are considered as teachers and result mean result of the class is improved if the teacher teaches it with quality and it also depends upon the quality of the learner also. The explorative tendency of the teaching phase is the grades obtained through all the learners is dependent on the course grade gained by the best learner who is teacher. The grades are exploited initial and final updated grades and the selection of the best grades along the course grades forms a new class.

Thus in the teacher phases both the qualities such as explorative and exploitative qualities are used and the new class formed is used as an initial population of the learner phase of the algorithm.

2.3.3 Learner phase

There are two ways of learning by a student: one is through teacher and other is by mutual interaction among the students that is learners in this case. New class formed by the teacher phase used both the methods such as explorative an exploitation. Thus the grades are improved once another learner secures better grades in the corresponding subject. Thus this process is followed similarly as in teacher phase as explained and a new class is formed and this comes to next iteration. Figure 7 shows a detailed algorithm of teaching learning based optimization method. Thus the following algorithm cycle completes one iteration.

2.4 Particle swarm optimization algorithm (PSO)

Particle swarm optimization was introduced by [50] in 1995. The algorithm is inspired by the behaviour of the birds, fish and insects. Main objective of the algorithm is to focus on simulating graphics rather than the unpredictable nature or behaviour of the bird flocks etc. The solutions

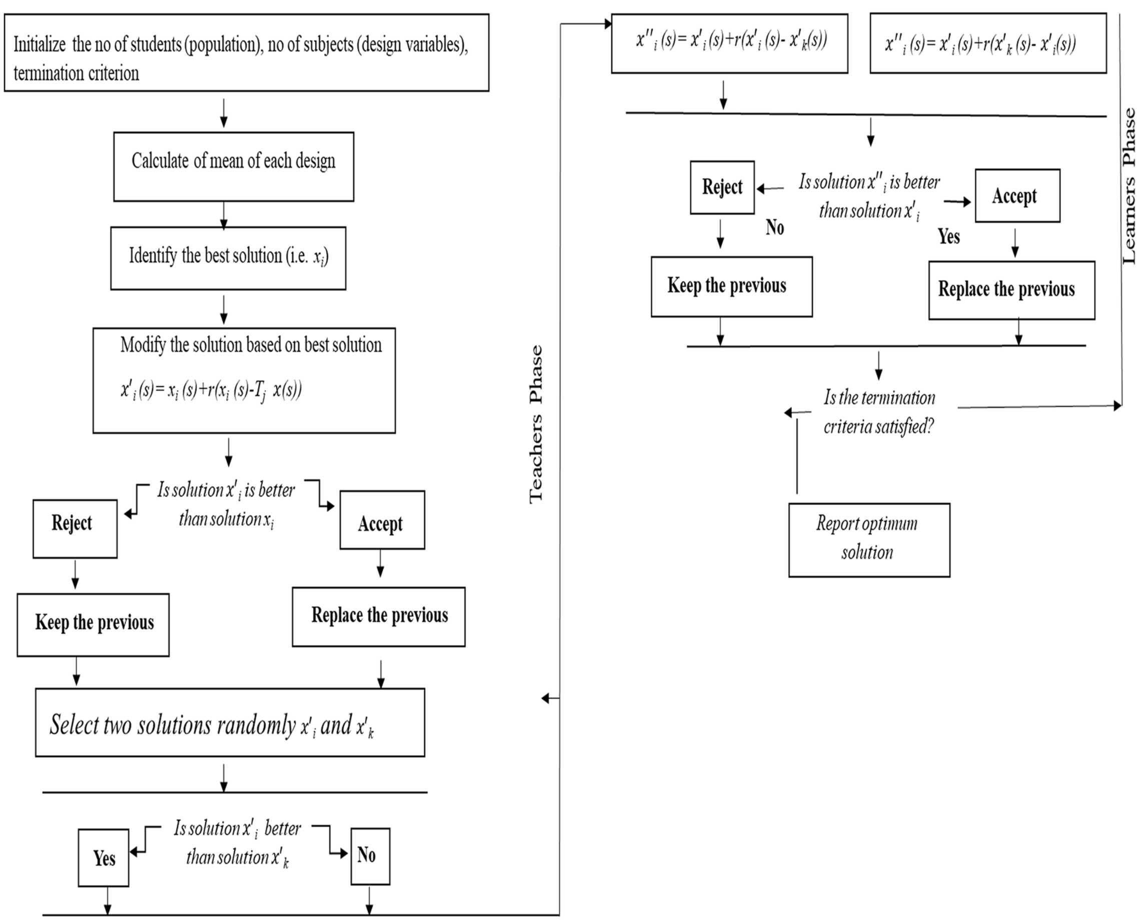


Fig. 7 Algorithm of teaching learning based algorithm (TLBO)

obtained are called particles. P^i_k is the best remembered individual particle position and P^g_k are the best remembered swarm position. C_1 and C_2 are the cognitive and social parameters. Thus the low and high values of the following constants allows the particles to flow far away from the target before being pulled back and abrupt movement towards or past the target respectively [51]. k_1 and k_2 are the random variables between 0 and 1 respectively, w is the constant inertia weight parameter. The algorithm PSO is shown in Fig. 8.

The algorithm proposed by [50] is as follows

x^i_k = Particle position
v^i_k = Particle velocity
P^i_k = Best remembered individual particle position
P^i_k = Best remembered swarm position
C_1 and C_2 = Cognitive and social parameters
k_1 and k_2 = Random numbers between 0 and 1
Position of individual particles updated as follows:

$$x^i_{k+1} = x^i_k + v^i_{k+1}$$

With velocity it is calculated as follows:

$$v^i_{k+1} = v^i_k + C_1 r_1 (P^i_k - x^i_k) + +C_2 r_2 (P^g_k - x^i_k)$$

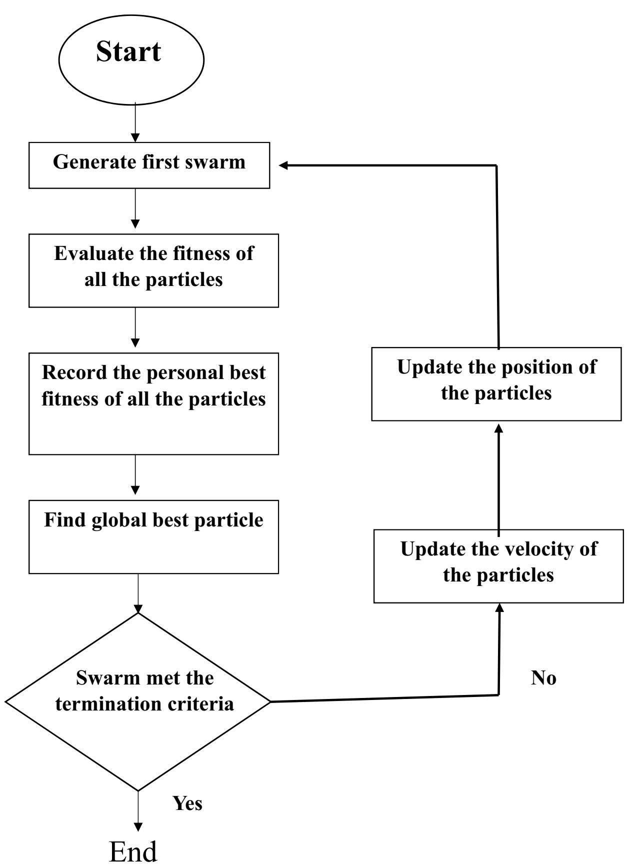


Fig. 8 Algorithm of particle swarm optimization (PSO)

2.5 Flow chart of hybrid teaching learning particle swarm optimization algorithm (HTLPSO)

HTLPSO algorithm technique [46] is used for solving our objective function to find the optimum solution in a lesser number of functional evaluations. Flow chart describes the HTLPSO technique in Fig. 9. HTLPSO is a hybrid teaching–learning based algorithm developed by mixing of TLBO and PSO algorithm together. The algorithm starts through the initialization of population. Thus the best half population is obtained through PSO and TLBO and merged together to get the best initial resulting population. The population is again given as an initial population in learners phase. Finally, after the learner's phase technique according to the termination criterion, the solution is obtained, and the algorithm stops.

3 Results and discussions

The section shows the results obtained through the synthesis procedure through the selection of different precision points. Three, six, and thirteen precision points were selected from the experimental trajectory, and synthesis procedure is performed to obtain the dimensions of four-bar mechanism. In three precision points, analytical synthesis procedure is performed to obtain the desired four-bar mechanism for the required tool trajectory and is as follows.

3.1 Three precision positions

Path generation synthesis requires precision points for synthesis. Three precision points for cutting phase were selected for synthesis procedure from the trajectory [1] and is shown in Fig. 10. The points selected are as follows.

Through graphical synthesis procedure mechanism, dimensions are obtained and simulated in MATLAB to observe whether the designed mechanism passes through the desired trajectory or not. Figure 8 is the actual trajectory through which the mechanism designed should pass through selected precision points. Three precision points were selected from the trajectory. The precision points selected are shown through red coloured circles in the Fig. 10. It is noted from Fig. 11 that coupler point of the mechanism passes through three precision points selected of the tool trajectory, which is cutting phase as discussed previously in the Sect. 1.3. This concludes that the designed four-bar mechanism will facilitate the tillage tool to follow the required path in the soil while working and are in agreement with the literature [1].

Fig. 9 Flow chart of hybrid teaching learning particle swarm algorithm (HTLPSO) [46]

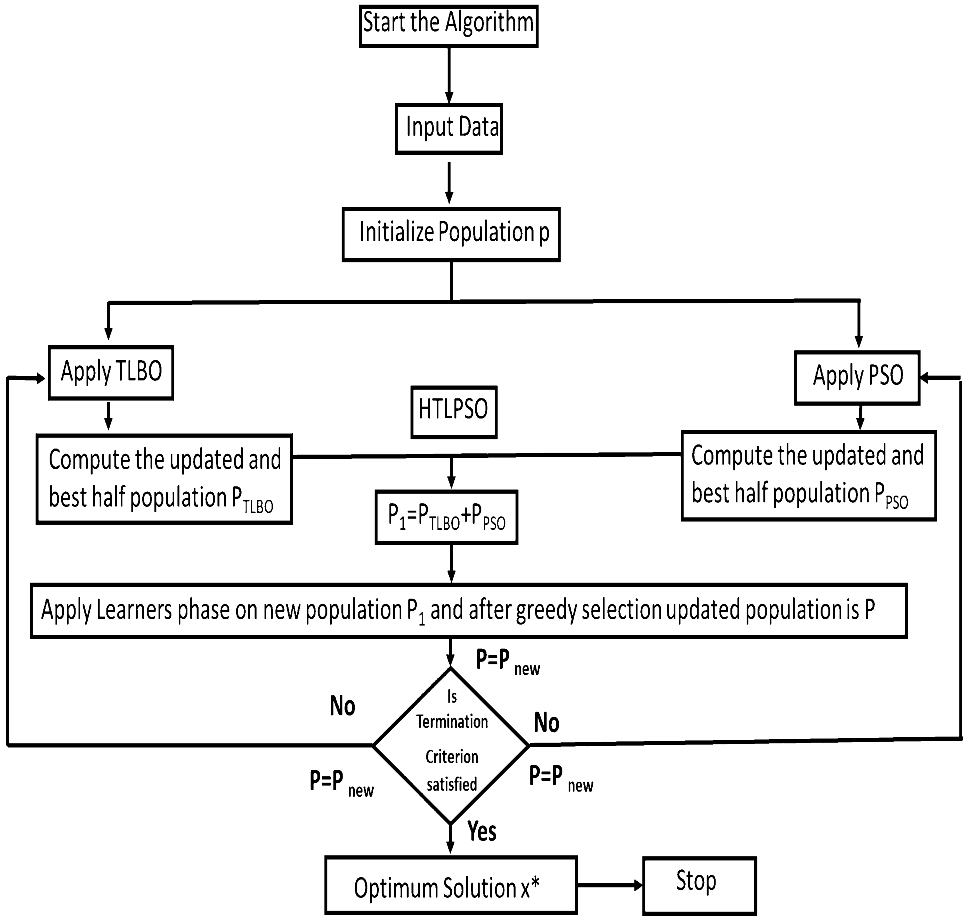
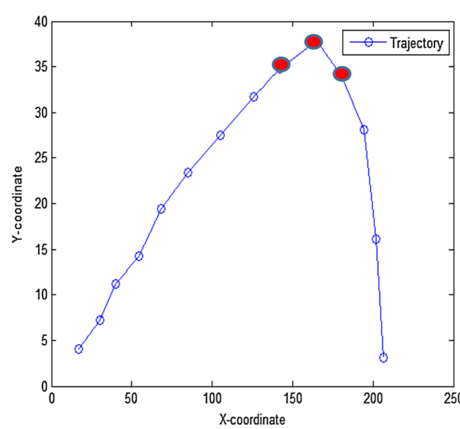


Fig. 10 Actual trajectory and prescribed points

Desired points (mm)	1	2	3
Pxd	141.741	165.179	180.804
Pyd	34.756	38.881	33.964



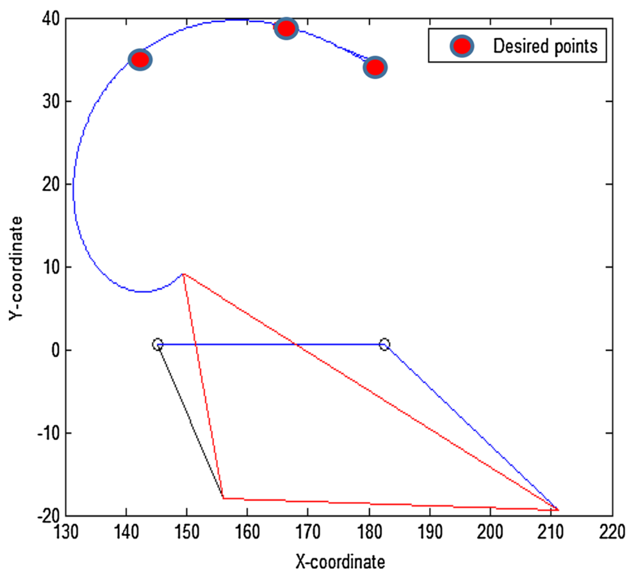


Fig. 11 Generated trajectory

3.2 Six precision points

Six precision points for cutting phase were selected as shown in Fig. 12 for synthesis procedure to be performed. The points selected from the trajectory are as follows and shown in Fig. 12 through red coloured circles. Precision points selected are of cutting phase as explained in tool trajectory. This phase, is of significance because the tool has to completely follow the path and cut the soil during operation.

An optimization algorithm is applied to the objective function such as Hybrid Teaching Learning Particle Swarm Optimization algorithm, Teaching learning based and particle swarm optimization technique to find the optimal solution through path generation synthesis procedure. Figure 13 shows the results of the desired and derived trajectory of the coupler point through different algorithms.

From Fig. 13, it is observed that the coupler point P of the four-bar mechanism, as mentioned in Fig. 6 passes through the required precision points selected from the experimental tool trajectory [1]. Desired and derived trajectory is shown in Fig. 13. The desired trajectory are the points selected from the experimental trajectory and derived is the obtained path of the coupler. It can be clearly seen from Fig. 13 that coupler point passes through all the precision points through the results obtained in HTLPSO and TLBO, respectively. But the error is found to be minimum in HTLPSO and can be seen form Table 2 as mentioned below. Table 1 gives the algorithm parameters for each algorithm.

Table 2 gives the design variables values obtained through different algorithms such as HTLPSO, TLBO, and PSO. The Euclidian distance formula is used as an objective function, and it is found that in HTLPSO solution in comparison to TLBO and PSO finds an optimal solution. The desired and derived trajectory are shown in Fig. 13, which shows that the results obtained through HTLPSO are better and in line with the previous works [46]. In fact, the coupler point P more efficiently traces the required path, as described in Fig. 13. The error in HTLPSO is found to be 5.48836 and in TLBO and PSO is 7.17443 and 48.80957 respectively. Moreover, TLBO results are also better, but concerning error and number of iterations, the least is found to be in HTLPSO as given in Table 1. The number of iterations is 200 in HTLPSO

Desired points (mm)	1	2	3	4	5	6
Pxd	16.741	68.080	126.116	165.179	202.009	206.473
Pyd	4.089	19.363	31.673	37.881	16.077	3.101

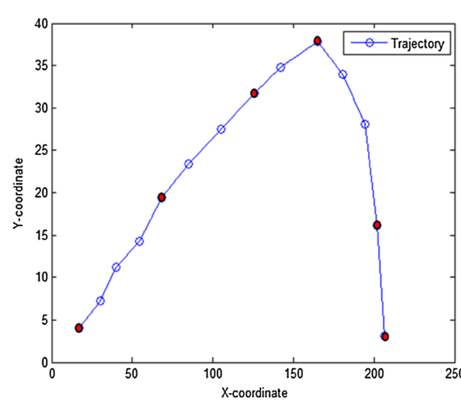


Fig. 12 Prescribed six precision point trajectory

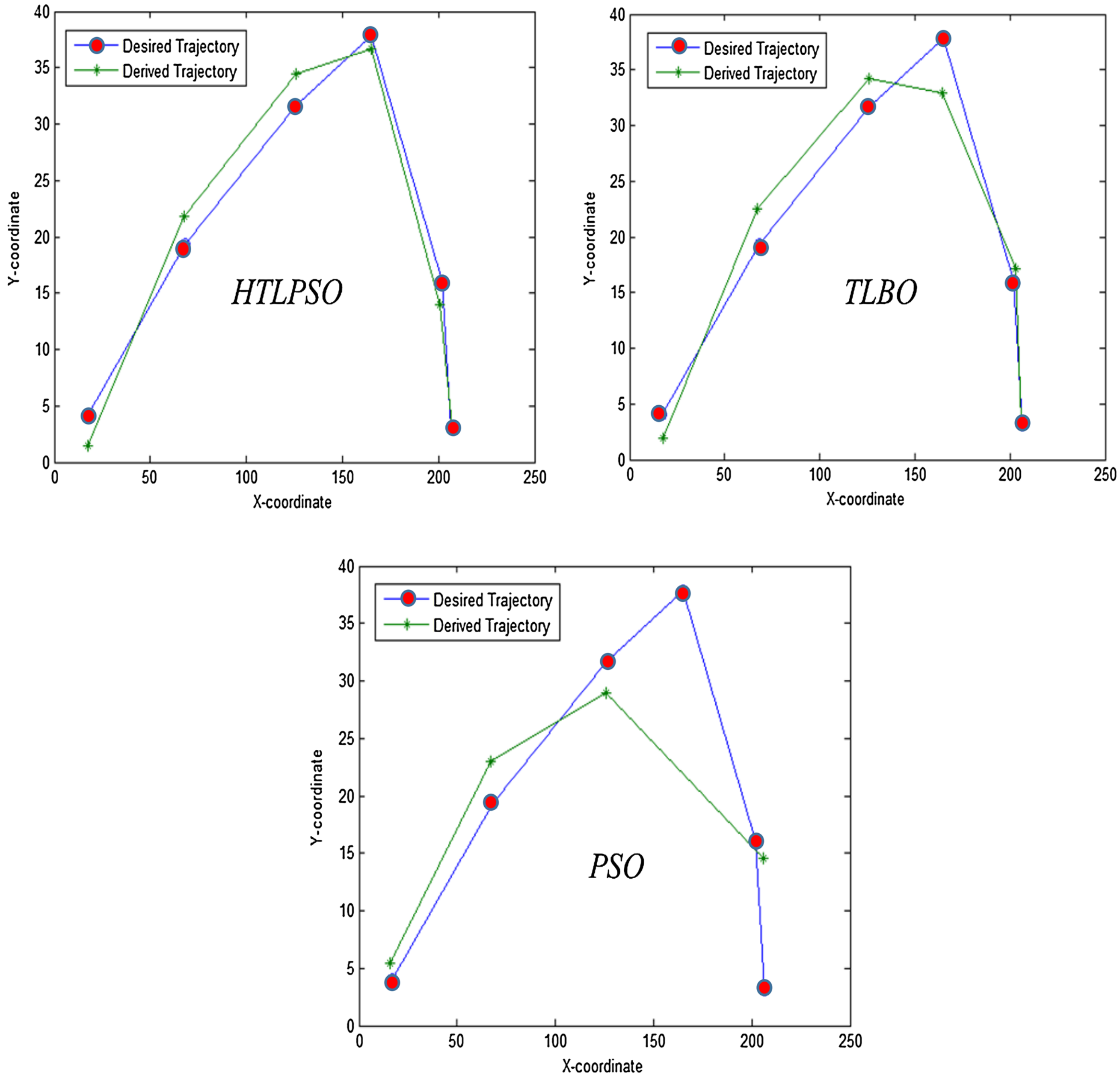


Fig. 13 Desired and derived trajectory

Table 1 Comparison of design variables results with different algorithms

Parameters	(PSO)	(TLBO)	(HTLPSO) (TLBO + PSO)
Population size	200	200	200
Design variables	15	15	15
Inertia weight maximum	0.9	Not applicable	0.9
Inertia weight minimum	0.4	Not applicable	0.4
C1 (acceleration factor)	2	Not applicable	2
C2 (acceleration factor)	2	Not applicable	2

while in TLBO and PSO it is found to be 2000 and 500 respectively. In HTLPSO number of iterations is found to be minimum among all the three algorithms. Convergence plot of three algorithms are shown in Fig. 14. The error calculated in PSO is found to be 48.8095 that is the distance, and the unit taken is mm. While evaluation, it is observed that the coupler point P is not able to reach the last precision point selected accurately and the last two points obtained of derive trajectory are clubbed with each other.

Table 2 Comparison of design variables results with different algorithms

Design variables	HTLPSO	TLBO	PSO
r_1	284.4183	255.8993	400.0000
r_2	254.3867	385.9992	400.0000
r_3	342.6088	399.9997	250.3673
r_4	312.4450	334.6795	250.0000
Ly	206.1237	333.7950	400.0000
Lx	35.3362	30.000	0
θ_2^1	3.6758	3.3528	3.6980
θ_2^2	3.4980	3.0629	3.5229
θ_2^3	3.3028	2.6559	3.3282
θ_2^4	3.1668	2.3039	6.2832
θ_2^5	2.6834	1.6649	6.2832
θ_2^6	2.5068	1.2088	0
θ_0	4.6753	4.4888	4.4592
Xo	137.5715	270.8318	184.7321
Yo	−40.0000	−40.0000	20.6917
Iterations	N = 200	N = 2000	N = 500
Error	5.48836	7.17443	48.80957

3.3 Six precision points (increasing points)

Six precision points increasing trajectory is selected for synthesis procedure, as shown in Fig. 15. The selected points are of cutting phase, and synthesis procedure is performed, as shown in Fig. 15. The selected points are shown through red coloured circles. Cutting phase points are selected for the synthesis process.

Optimization algorithm such as Hybrid Teaching Learning Particle Swarm Optimization algorithm, teaching–learning based algorithm is applied to the objective function to find the optimal solutions of design variables. Two algorithms were only selected to solve the objective function. Figure 16 shows the results of the desired and derived trajectory of the coupler point through different algorithms. From Fig. 16, it is observed that coupler point P (derived trajectory) traces exactly the desired trajectory. The error is found to be minimum in HTLPSO while minimizing the objective function that is error minimization function in this case by using both the algorithms.

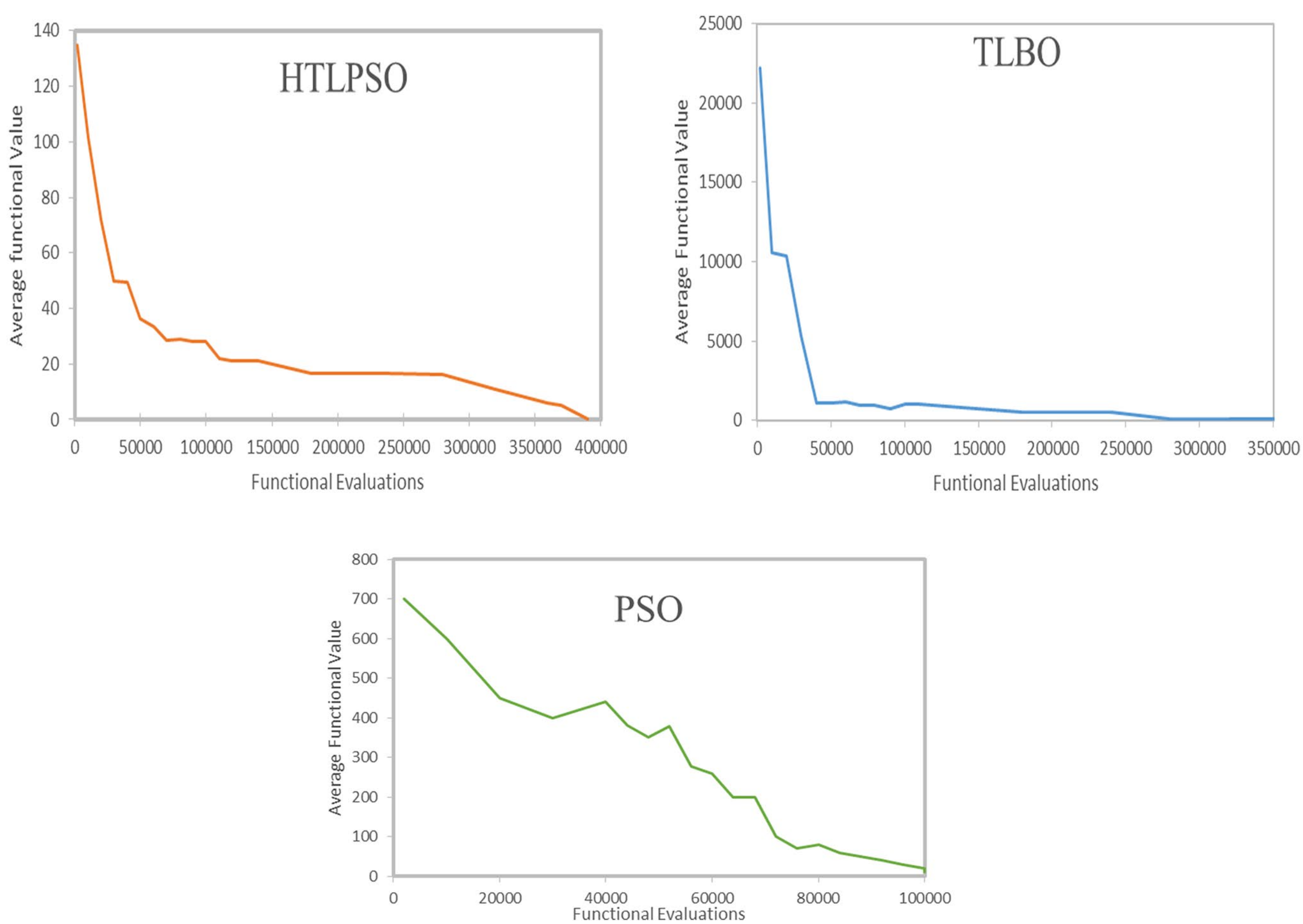


Fig. 14 Convergence plot of three algorithms

Fig. 15 Prescribed six precision point trajectory

Desired points (mm)	1	2	3	4	5	6
Pxd	16.741	40.179	68.080	104.911	141.741	165.179
Pyd	4.089	11.214	19.363	27.560	34.756	37.881

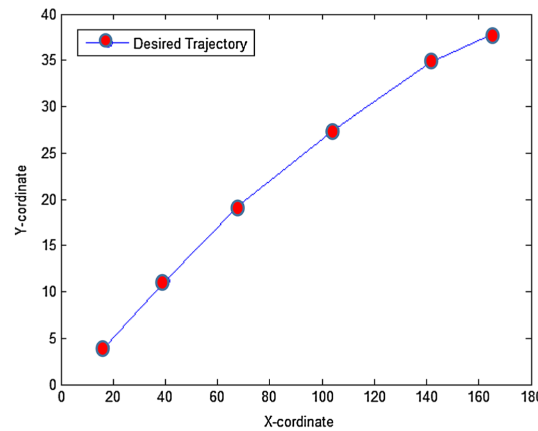


Table 3 gives the design variables values obtained through HTLPSO and TLBO. The desired and derived trajectory are shown in Fig. 16, which indicates that the results obtained through HTLPSO are better with minimum error. TLBO results also converge to the best solution, but regarding error and number of iterations, HTLPSO performed well and is in support of the previous work done [46]. The error in HTLPSO was found to be 0.73948, and in TLBO it is 0.82115, respectively. Moreover, TLBO results are also better, but concerning error and number of iterations, the least error was found to be in HTLPSO as given

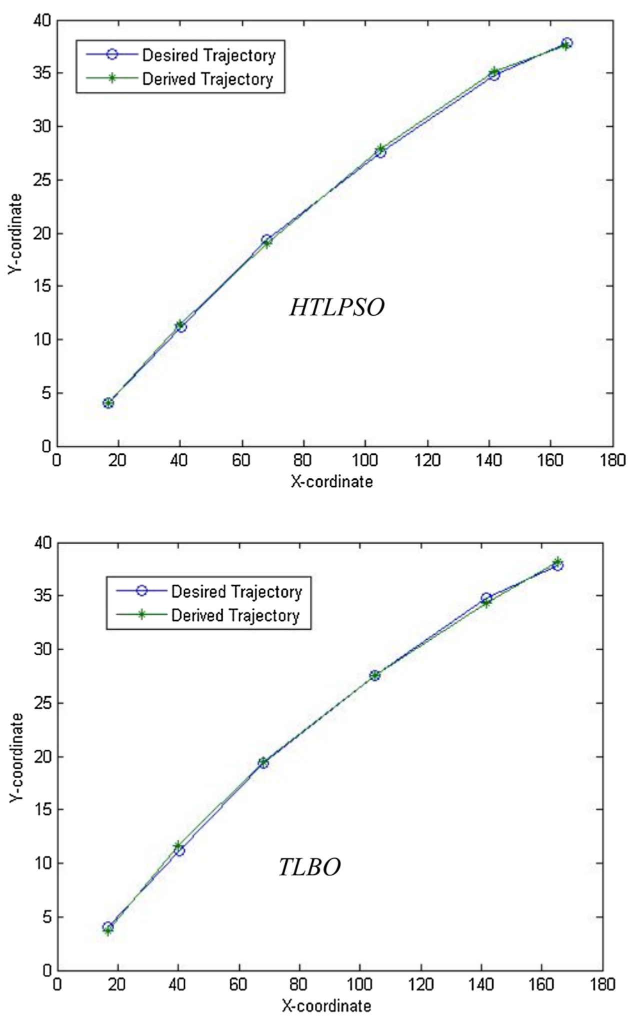


Fig. 16 Desired and derived trajectory

Table 3 Comparison of design variables results with different algorithms

Design variables	HTLPSO	TLBO
r_1	385.4400	251.7827
r_2	363.5701	267.2059
r_3	400.0000	375.0752
r_4	326.3298	302.5623
ly	377.1622	288.2807
lx	0	0
θ_2^1	2.9783	3.2730
θ_2^2	2.8205	3.1321
θ_2^3	2.5762	2.9415
θ_2^4	2.1316	2.6351
θ_2^5	1.6220	2.2332
θ_2^6	1.3477	1.9321
θ_0	4.7384	4.5288
Xo	131.8341	203.6208
Yo	−40.0000	−40.0000
Iterations	N = 100	N = 2000
Error	0.73948	0.821115

in Table 3. The number of iterations was found to be 100 in HTLPSO while in TLBO it was found to be 2000. In HTLPSO number of iterations was found to be minimum among another algorithm. Similar convergence plot are obtained for the following selected path. HTLPSO converged better than other algorithm.

3.4 Thirteen precision points

Thirteen precision points for cutting phase is selected for synthesis procedure and is shown in Fig. 17. More number of points are selected and synthesized because to confirm the behaviour of the tool in the soil during operation. The points selected from the trajectory are as follows and shown in Fig. 17 through red coloured circles.

The same process is applied, and optimization algorithms such as Hybrid teaching–learning based, and teaching–learning based algorithm were applied to the objective function to find the optimal solutions of design variables. The optimal results can be observed from Figs. 18 and 19. Figures 18 and 19 shows that the coupler point P (derived trajectory) traces exactly the desired trajectory. The error was found to be minimum while minimizing the objective function by using both the algorithms. Table 4 shows the values of the design variables, error, and the number of iterations of both the algorithms.

Table 4 gives the design variables values obtained through HTLPSO and TLBO. Similarly, as explained in

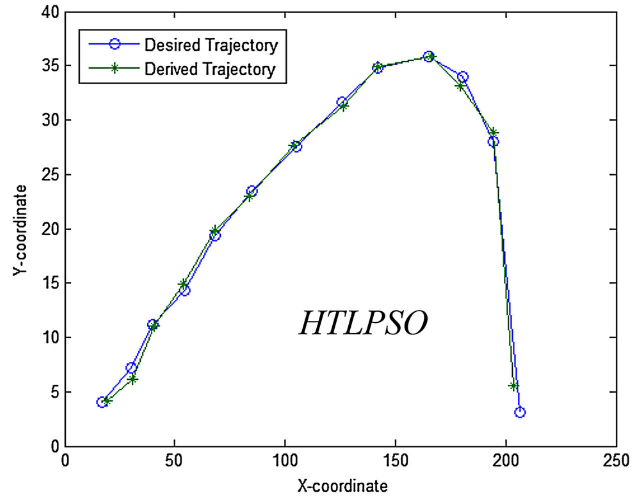


Fig. 18 Derived and desired trajectory (HTLPSO)

Desired points (mm)	1	2	3	4	5	6	7	8	9	10	11	12	13
Pxd	16.74	30.134	40.179	54.688	68.080	84.821	104.911	126.116	141.171	165.179	180.804	194.196	206.4
Pyd	4.089	7.161	11.214	14.292	19.363	23.452	27.560	31.673	34.756	35.881	33.964	28.036	3.101

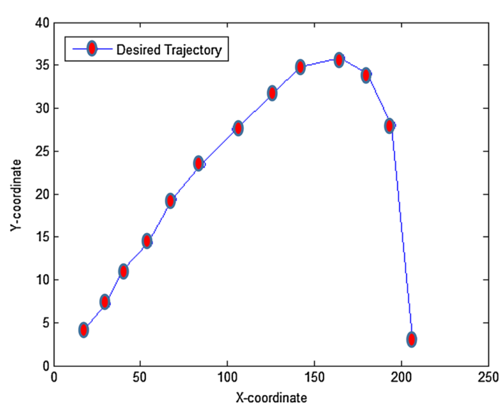


Fig. 17 Prescribed thirteen precision point trajectory

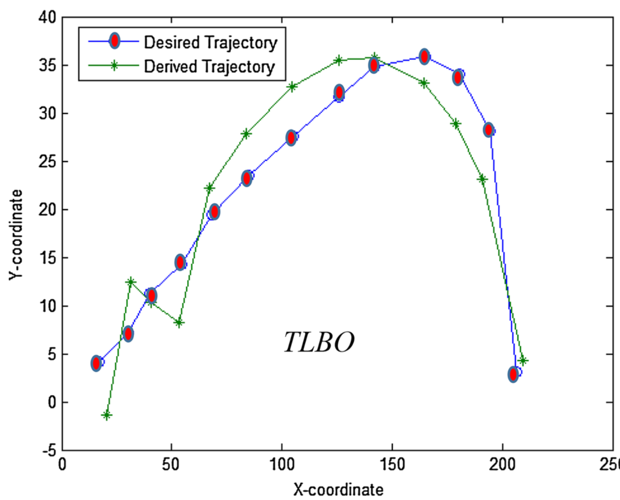


Fig. 19 Derived and desired trajectory (TLBO)

Table 4 Comparison of design variables results with different algorithms

Design variables	HTLPSO	TLBO
r_1	292.4320	373.5936
r_2	396.9918	276.4977
r_3	399.9972	390.051
r_4	341.6846	274.6354
ly	320.4930	220.0172
lx	134.6287	302.6541
θ_2^1	3.8748	0.8979
θ_2^2	0.4242	0.8630
θ_2^3	3.7732	0.8318
θ_2^4	0.5234	4.1711
θ_2^5	3.6404	0.7525
θ_2^6	3.5541	4.0824
θ_2^7	3.4448	0.6644
θ_2^8	3.3221	3.9627
θ_2^9	3.2216	3.9179
θ_2^{10}	3.0642	3.8490
θ_2^{11}	2.9434	3.8036
θ_2^{12}	2.8168	3.7615
θ_2^{13}	2.4926	0.4963
θ_0	4.3029	4.0183
Xo	252.3070	112.0486
Yo	39.9979	29.8383
Iterations	N = 200	N = 2000
Error	3.29645	13.65389

previous sections, HTLPSO converged to a better solution as compared to TLBO algorithm [46]. Figures 18 and 19 concluded that the coupler point traces the required trajectory accurately with minimum error. The Euclidean distance formula is used as an objective function, and it is found that in HTLPSO solution in comparison to TLBO yields to better result to trace the tool path. The desired and derived trajectory are shown in Figs. 18 and 19, which shows that the results obtained through HTLPSO are better and are in line with the previous studies [46]. In fact, the coupler point P efficiently traces the required path as described earlier. The error in HTLPSO is found to be 3.29645, and in TLBO, it is 13.65389, respectively. The number of iterations is found to be 200 in HTLPSO while in TLBO it is found to be 2000. HTLPSO number of iterations is found to be minimum as compared to TLBO. Similar convergence plot are obtained for the following selected path.

There are well-established techniques for two, three, four, and five precision synthesis technique. But for more than five precision points there is an optimal method to solve. Six and thirteen precision points were selected for optimal synthesis because to make trace the cutting tool more accurately for all the precision points selected. Other than this, no specific reason was there.

4 Development and experimental validation

The developed vibratory cultivator, as shown in Fig. 20 is validated through comparative field performance with the passive cultivator. Field evaluation is carried out, and comparative study is done to find the conclusion in performance with passive tillage system.

The experimentation of the developed vibratory cultivator is evaluated in sandy soil, and the average moisture content of the field is found to be around 5–12%. The speed of the tractor while operating in the field is kept around 3–4 kmph and rated engine rpm at 1500 rpm respectively. Tractor selected is (Mahindra Arjun Novo-57 hp). The main performance parameters of the machine are reported to be efficient and good. The reduction in draft consumption as measured with the dynamometer attached with the lower and top link of the three-point hitch system of the tractor and it is found to be decreased by 23% as comparison with passive tillage cultivator. Fuel consumption also improved significantly as 2.02–3 l/h measured through sensors. The average depth is observed

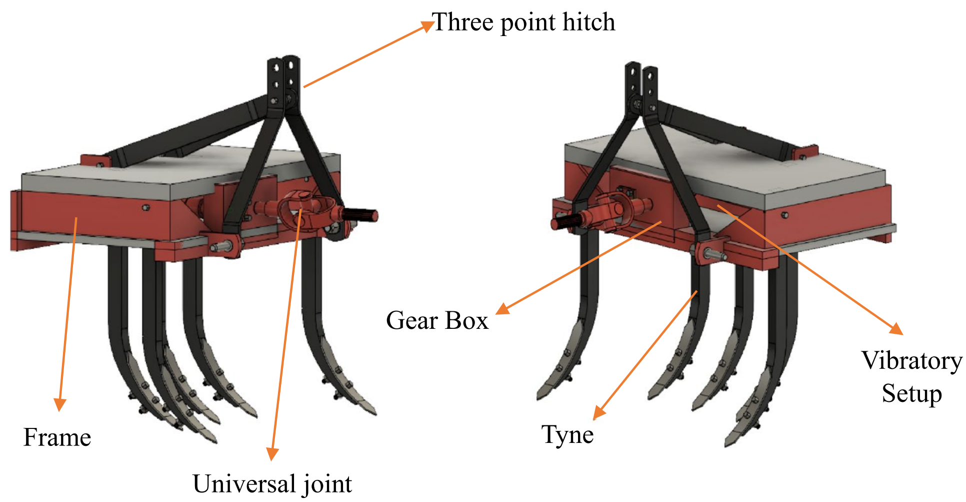


Fig. 20 Developed vibratory tillage machine

Fig. 21 Soil condition before and after vibratory tillage operation

to be around 15–25 cm, and soil pulverization also improved significantly as shown in Fig. 21.

5 Conclusion

The paper proposes a four bar mechanism dimensions for a particular tool experimental using a hybrid teaching learning based algorithm. Mechanism designed is used for the particular concept vibratory tillage operation which traces the four important phases in the oscillatory or tillage operation such as cutting, tool catching up, backing off and end of cycle. All the cycles are followed by the mechanism designed through optimization algorithms which are in agreement with the literature [1]. It is observed that results obtained though HTLPSO is better and the dimensions of the mechanism obtained in optimal synthesis procedure with less number of iterations and error traced the required trajectory precisely. The results are in agreement with the studies [46]. Using the dimensions obtained through the synthesis process, the machine has been fabricated and compared with the passive tillage cultivator system. There is a reduction of draft force by 23% as compared with passive tillage cultivator. Fuel consumption also improved significantly by 2.02–3 l/h as compared to the passive cultivator. The average depth is also observed to be around 15–25 cm, and soil pulverization also improved significantly.

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Compliance with ethical standards

Conflict of interest The author(s) declare that they have no conflict of interest.

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