Analysis and Optimization of Three Degree of Freedom Cylindrical Robotic Arm for Drilling Application

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Abstract
In this research, three DOF robotic arm using stepper motors has been designed and utilized for the drilling application of a mild steel plate and then simulation is done to visualize the robot motion. This robotic arm is control by an Aurdino AT Mega 2560 Microcontroller. The microcontroller is used to generate PWM signals which are applied to stepper motors for achieving the desired rotation. Each stepper has a different specification. The main advantage of controlling the stepper motors with PWM signals is that it can be programmed to have an initial position and to rotate with an exact degree withrespect to the requirements.
Optimization techniques are used to optimize the route of drilling for multi point holes on an object such as Branch and Bound, Genetic algorithm, Simulated Annealing. A mathematical approach is also formulated for the optimum sequence of drilling and this sequence is compared to Branch and Bound, GA andSA then conclusion is presented. Time taken to follow the sequence is also determined with these techniques and finally compared by the time taken using mathematical formulated technique.
Keywords: Mathematical approach, Branch and Bound, Genetic Algorithm and Simulated Annealing.V

1. Introduction and Literature review

In most of the industries, conventional radial drilling machine is used for drilling and much research has been done in this field to increase the productivity and reduce the operatingtime. Ali Baig et al. [1] works on conversion of conventional drilling machine into automatic machine using pneumatic devices which consists double acting cylinder, direction control valve, flow control valve, relay unit, filter regulator etc. Using this machine results to operation time is less, output is more and less human intervention. Abueejela et al. [2] designed of PLC based drilling machine which is automated. This machine increases the efficiency of the small drilling machine. Gurumukh Das et al. [3] determine the cuttingforces by artificial neural network model. Mild steel, aluminum, copper, brass and cast iron materials are used for experimentation. It has application in tool wear monitoring and choiceof tools for operation.

A lot of research has been done in the field of robotic arm for different operation such as drilling, welding, loading/ unloading, cutting etc. There are different robotic arm for such operation such as cylindrical, articulated and scara etc. Kruthika,K et al. [4] developed aarticulated robotic arm which has five degree of freedom. This robotic arm is controlled by arduino mega 2560 and graphical user interface is used to control the actuators. Forward and inverse kinematics is used for kinematic modeling. It has potentiometer attached at its elbow and shoulder joint to detect the position and force sensor attached at its gripper. Hussain et al.[5] designed a serial robotic arm which has three degree of freedom. D-H representation and euler- largrange is used for kinematic and dynamic analysis. Trajectory planning is alsoperformed. Design and simulation is done on CAD software and roboanalyzer. Barai et al.[6] works on active teaching method in which a meticulous task is performed for one time in learning phase then robot recorded the action during the task with the help of algorithm.

Neuro-fuzzy approach developed a controller which record the actions and converted into motion codes. This robotic arm is used for repetitive jobs. Huang et al. [7] designed a five degree of freedom human mimicking robotic arm and using forward and inverse kinematics to get a kinematic solution of robotic arm. C sharp is the programming for control and interfacing of human and machine. MATLAB is used for matrix solution of motor control. Urrea et al. [8] designed a SCARA manipulator which has six degree of freedom. Aim of design this manipulator to studying and testing

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of various control techniques. They developeda PC controller software has less complexity in design, excellent results and allow best functioning of complete system and this software is same as electronic interface. Karem et al. [9] developed a three degree of freedom SCARA manipulator for welding. Inverse kinematics is used for select the desired path and MATLAB for draw the path. PLC is used asa controller which conquers the complexity and drawback of traditional controller. Torres et al. [10] works on optimal control of cylindrical robotic arm for trajectory tracking. Thecontroller used the Riccati equation and quadratic regulator method which is well thought-out as adaptive function. Akkas et al. [11] designed a five degree of freedom drilling robotic arm and kinematics analysis is performed. This drilling robotic arm especially used in assembly lines and this is controlled by the computer so that operation is performed with less error and less time. Zhu et al. [12] works on offline programming of robotic arm which can drill in aerospace. Numerical optimization and bilinear interpolation is used for solving functional redundancy and correcting the hole position respectively. Garnier et al. [13] works on modeling of robotic arm which can drill. For modeling, recognize the interface between the drilling process and elasto- staic manners of robot, positioning evolution of robot and drilling configuration which results to identify the drilling parameters and improve accuracy of drilling operation. Weinberg et al. [14]designed a robotic planetary drilling system which includes drill bit, drill sub, power module, non- rotating steering unit and communication module. Specific energy tactic, geometric constraint analysis and forward kinematics is used to choose the range of operation parameters, choose the permissible dimension of curved path and derivation of gear bearing kinematics respectively.

2. Design of components

The drawing of the mild steel workpiece with 9 holes is made in Solid Works 2014 as shown in fig 1.

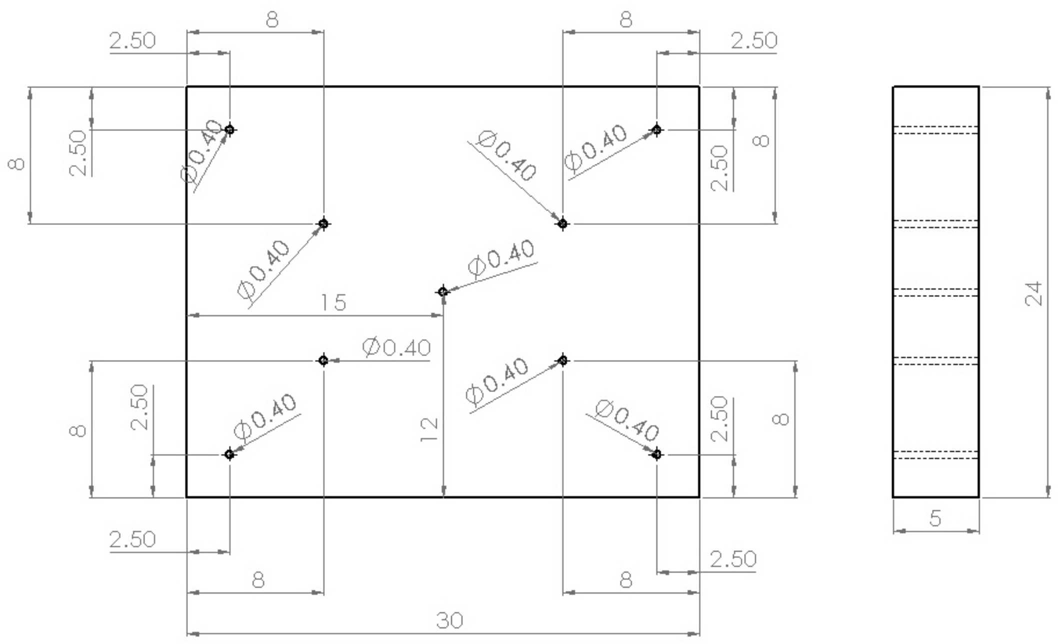

Fig.1 Design of Work Object

3.Optimization techniques for drilling

The motive to apply these techniques are to identify the best sequence to drill the plate with less time. After applying the following techniques for optimum sequence, different sequence has been obtained for the shorter time period for drilling operation. Details of the sequence of hole are described in this section. The results from all the techniques are compared with formulated mathematical approach.

Branch and Bound
Simulated annealing
Genetic Algorithm
Formulated Mathematical approach

3.1 Branch and Bound:

Branch and Bound is a mathematical optimization technique. The algorithm depends on efficient estimation of the lower and upper bounds of the branches. Table 1 shows the Travelling salesman problem matrix (TSP). X and Y are the coordinators of holes.

Table 1 TSP matrix

POINT	X	Y	1	2	3	4	5	6	7	8	9
1	12.50	12.50	-	19.00	7.78	14.58	15.70	20.26	23.72	25.00	31.40
2	12.50	31.50	19.00	-	14.58	7.78	15.70	23.72	20.26	31.40	25.00
3	18.00	18.00	7.78	14.58	-	8.00	8.06	14.00	16.12	20.26	23.72
4	18.00	26.00	14.58	7.78	8.00	-	8.06	16.12	14.00	23.72	20.26
5	25.00	22.00	15.70	15.70	8.06	8.06	-	8.06	8.06	15.70	15.70
6	32.00	18.00	20.26	23.72	14.00	16.12	8.06	-	8.00	7.78	14.58
7	32.00	26.00	23.72	20.26	16.12	14.00	8.06	8.00	-	14.58	7.78
8	37.50	12.50	25.00	31.40	20.26	23.72	15.70	7.78	14.58	-	19.00
9	37.50	31.50	31.40	25.00	23.72	20.26	15.70	14.58	7.78	19.00	-

The Objective function of Branch and Bound is to minimize the total distance travelled which is given by

Min $\sum\sum d_{ij}X_{ij}$ for $j = 1$ to n subject to

$\sum X_{ij} = 1$ for all i for $i = 1$ to n subject to

$\sum X_{ij} = 1$ for all j

$X_{ij} = 0, 1$

Lower Bound = Sum of the row minima in TSP table which shown in previous chapter.Where d_{ij} is the distance travelled between holes and X_{ij} is decision variable.

h is the height from the base of work piece.
Base motor 1 rotates angle θ
L is the distance covered by rotation.

$$d_{ij} = \sqrt{(x_{i} - x_{j})^2 + (y_{i} - y_{j})^2}$$

Where x and y is the drilling point coordinates.

After applying this technique the optimum sequence is [1-3-5-4-2-6-8-9-7-1]. The number of steps required to complete the task is 46941.

Table 2 is showing the calculation for the number of steps by each motor for drilling 9 holes.

x & y are the coordinates of drill point in a Cartesian system.

Table 2 Calculation of Total no of steps by Branch and Bound optimum sequence

Points	X	Y	θ(deg)	θFinal-θInitial	Steps by motor 1	L(cm)	L Final-L Initial	Steps by motor 2	Total h(cm)	Steps by motor 3
1	12.5	12.5	90.00	90.00	50	0.73	0.73	183	44	11000
3	18	18	74.40	15.60	9	10.41	9.68	2419	12	3000
5	25	22	63.38	11.02	6	19.10	8.69	2173	12	3000
4	18	26	78.58	15.20	8	17.28	1.82	455	12	3000
2	12.5	31.5	90.00	11.42	6	19.73	2.45	613	12	3000
6	32	18	49.24	40.76	23	22.75	3.02	755	12	3000
8	37.5	12.5	36.84	12.40	7	25.73	2.98	745	12	3000
9	37.5	31.5	54.80	17.96	10	35.58	9.85	2463	12	3000
7	32	26	56.73	1.93	1	27.52	8.06	2015	12	3000
Total Steps					120			11821		35000

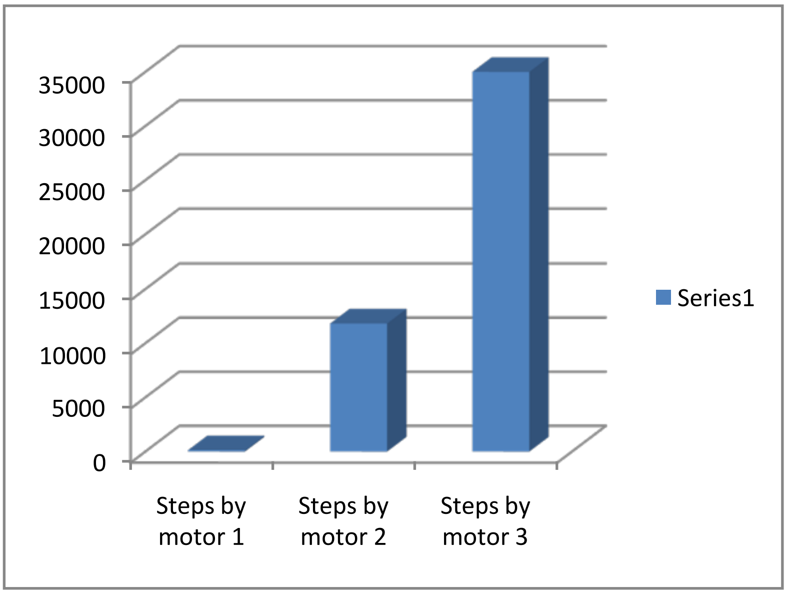

Figure 2 Number of steps by each motor according Branch and Bound

Figure 2 shows the graphical representation of number of steps by each motor. Figure shows the number of steps of motor 1 (120) is very less compared to other it means there is less effect of steps of motor 1 in sequence of drilling and steps of motor 3 (35000) is constant in any sequence, So it is focused to reduce the steps of motor 2 (11821). So, total number ofsteps for drilling 9 holes is 46941.

3.2 Simulated annealing:

SA is a stochastic or nontraditional optimization technique. It works very well for discrete optimization problem as well as for exceeding complex problem. Basic philosophy of SA is cooling process of molten metal through annealing. The Objective function of Simulated Annealing is to minimize the total distance travelled which is given by

Min $\sum\sum d_{ij}X_{ij}$ for j = 1 to n subject to

$\sum X_{ij} = 1$ for all i for i = 1 to n subject to

$\sum X_{ij} = 1$ for all j

X_{ij} = 0, 1.

Where d_{ij} is the distance travelled between holes and X_{ij} is decision variable.

$$d_{ij} = \sqrt{(x_{ss} - x_{jj})^2 + (y_{ss} - y_{jj})^2}$$

Where x and y is the drilling point coordinates.

After applying this technique the optimum sequence is [1-3-4-5-2-7-8-6-9-1]. The number of steps required to complete the task is 46404.

Table 3 shows the calculation of the number of steps by each motor for drilling 9 holes.

Table 3 Calculation of Total no of steps by Simulated annealing optimum sequence

Points	x	Y	θ(deg)	θ_{Final}-$\theta_{Initial}$	Steps by motor 1	L(cm)	L Final-L Initial	Steps by motor 2	Total h(cm)	Steps by motor 3
1	12.5	12.5	90.00	90.00	50	0.73	0.73	183	44	11000
3	18	18	74.40	15.60	9	10.41	9.68	2419	12	3000
4	18	26	78.58	4.18	2	17.28	6.87	1718	12	3000
5	25	22	63.38	15.20	8	19.10	1.82	455	12	3000
2	12.5	31.5	90.00	26.62	15	19.73	0.63	158	12	3000
7	32	26	56.73	33.27	18	27.52	7.79	1948	12	3000
8	37.5	12.5	36.84	19.88	11	25.73	1.79	448	12	3000
6	32	18	49.24	12.40	7	22.75	2.98	745	12	3000
9	37.5	31.5	54.80	5.56	3	35.58	12.83	3208	12	3000
Total Steps					124			11280		35000

Figure 3 shows the graphical representation of number of steps by each motor. Figure shows the number of steps of motor 1 (124) is very less compared to other it means there is less effect of steps of motor 1 in sequence of drilling and steps of motor 3 (35000) is constant in any sequence, So focus is made on steps of motor 2 (11280). So, total number of steps for drilling 9 holes is 46404.

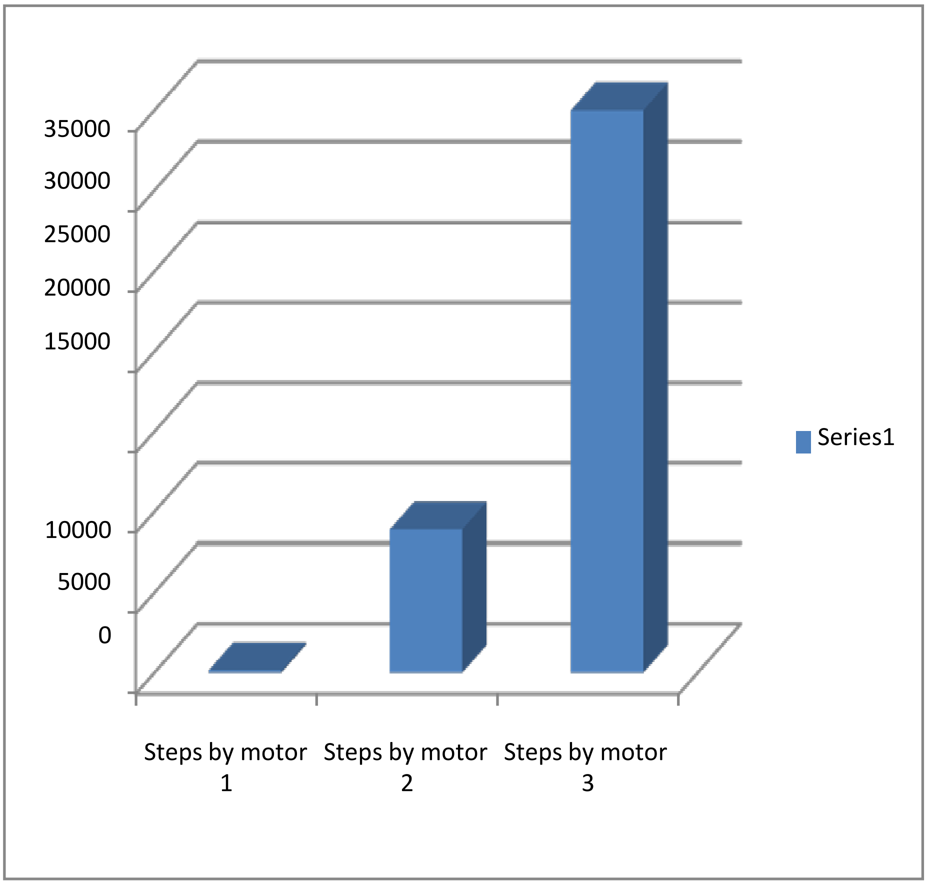

Figure 3 Number of steps by each motor according Simulated annealing

3.3 Genetic Algorithm:

GA is a search technique used in computer science to find approximate solutions of optimization problems. The genetic algorithms are more appropriately said to be an optimization technique based on natural evolution. They include the survival of the fittest idea algorithm. The Objective function of Genetic is to maximize the inverse of total distance travelled which is given by

Max $\sum\sum$ $(1/d_{ij})$ X_{ij} for j = 1 to n subject to

$\sum X_{ij} = 1$ for all i for i = 1 to n subject to

$\sum X_{ij} = 1$ for all j

$X_{ij} = 0, 1$.

Where d_{ij} is the distance travelled between holes and X_{ij} is decision variable.

$$d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$$

Where x and y is the drilling point coordinates.

After applying this technique the optimum sequence is [8-6-7-9-5-4-2-3-1]. The number of steps required to complete the task is 55394.

Table 4 shows the calculation of the number of steps by each motor for drilling 9 holes.

Table 4 Calculation of total no of steps by Genetic optimum sequence

Points	x	Y	θ(deg)	θFinal-θInitial	Steps by motor 1	L(cm)	L Final-L Initial	Steps by motor 2	Total h(cm)	Steps by motor 3
8	37.5	12.5	36.84	36.84	20	25.73	25.73	6433	44	11000
6	32	18	49.24	12.40	7	22.75	2.98	745	12	3000
7	32	26	56.73	7.48	4	27.52	4.77	1192	12	3000
9	37.5	31.5	54.80	1.93	1	35.58	8.06	2015	12	3000
5	25	22	63.38	8.58	5	19.10	16.49	4121	12	3000
4	18	26	78.58	15.20	8	17.28	1.82	455	12	3000
2	12.5	31.5	90.00	11.42	6	19.73	2.45	613	12	3000
3	18	18	74.40	15.60	9	10.41	9.32	2331	12	3000
1	12.5	12.5	90.00	15.60	9	0.73	9.68	2419	12	3000
Total Steps					69			20324		35000

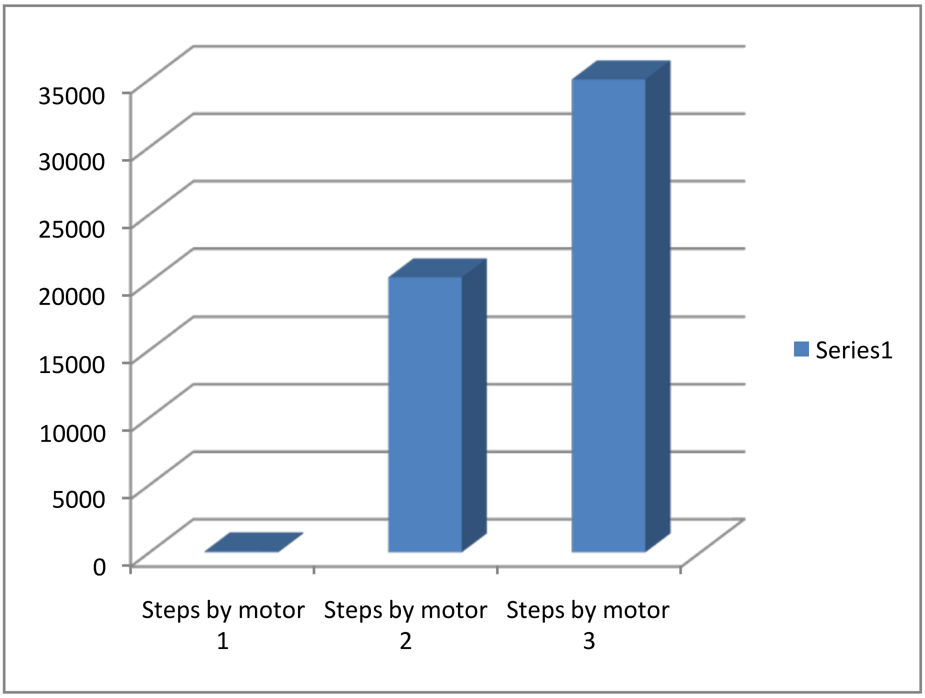

Figure 4 Number of steps by each motor according Genetic

Figure 4 shows the graphical representation of number of steps by each motor. Figure shows the number of steps of motor 1 (69) is very less compared to other it means there is less effect of steps of motor 1 in sequence of drilling and steps of motor 3 (35000) is constant in any sequence, So focus is on the steps of motor 2 (20324). So, total number of steps for drilling 9holes is 55394.

3.4 Formulated Mathematical approach

A mathematical approach has been formulated and in this approach function has to be minimized. As it is known that the distance covered by the drill tip for drilling at all the points is proportional to the total number of steps by stepper motor. So the total number of steps

$T_S = S_{m1} + S_{m2} + S_{m3}$

Where

S_{m1}= Total number of steps of motor 1S_{m2}= Total number of steps of motor 2S_{m3}= Total number of steps of motor 3

T_S will be min when either S_{m1} is min or S_{m2} is min.

Objective function

$(T_S)_1 = (S_{m1})_{min} + S_{m2} + S_{m3}$

$(T_S)_2 = S_{m1} + (S_{m2})_{min} + S_{m3}$

Where, $S_{m1} = (\theta / 1.8)$, $S_{m2} = [(Lx200) / 0.8]$ & $S_{m3} = (hx200) / 0.8$

After applying this technique the optimum sequence is [1-3-4-5-2-6-8-7-1]. The number of steps required to complete the task is 44051.

Table 5 shows the calculation of the number of steps by each motor for drilling 9 holes.

Table 5 Calculation of Total no of steps by Mathematical approach for optimizationoptimum sequence

Points	X	Y	$^{\theta}$(deg)	$^{\theta}$Final-$^{\theta}$Initial	Steps by motor 1	L(cm)	L Final-L Initial	Steps by motor 2	Total h(cm)	Steps by motor 3
1	12.5	12.5	90.00	90.00	50	0.73	0.73	183	44	11000
3	18	18	74.40	15.60	9	10.41	9.68	2419	12	3000
4	18	26	78.58	4.18	2	17.28	6.87	1718	12	3000
5	25	22	63.38	15.20	8	19.10	1.82	455	12	3000
2	12.5	31.5	90.00	26.62	15	19.73	0.63	158	12	3000
6	32	18	49.24	40.76	23	22.75	3.02	755	12	3000
8	37.5	12.5	36.84	12.40	7	25.73	2.98	745	12	3000
7	32	26	56.73	19.88	11	27.52	1.79	448	12	3000
9	37.5	31.5	54.80	54.80	30	35.58	8.06	2015	12	3000
Total Steps					155			8896		35000

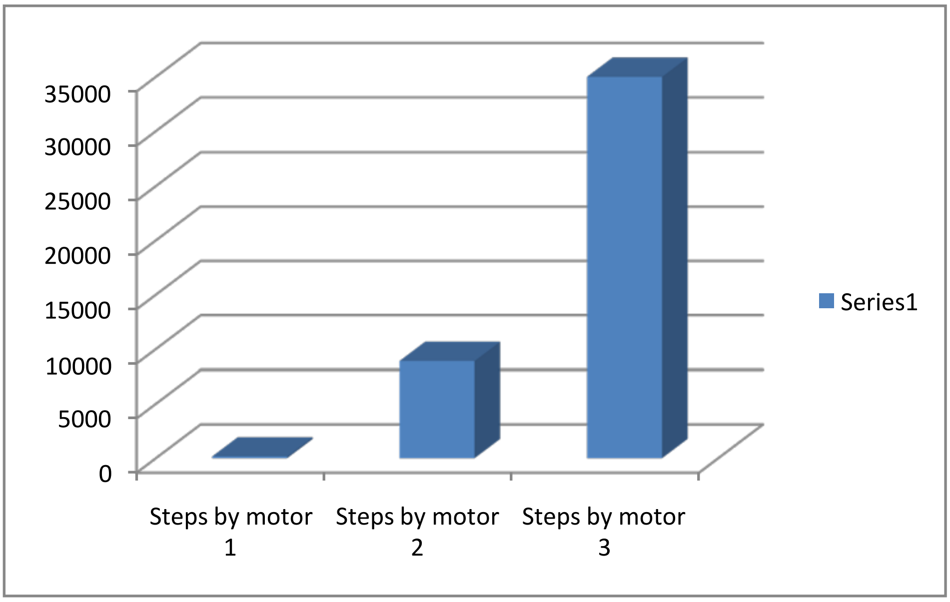

Figure 5 Number of steps by each motor according Mathematical approach foroptimization

Figure 5 shows the graphical representation of number of steps by each motor. Figure shows the number of steps of motor 1 (155) is very less compared to other it means there is less effect of steps of motor 1 in sequence of drilling and steps of motor 3 (35000) is constant in any sequence, So focus is on the steps of motor 2 (8896) which is very less compare to above optimization technique. So, total number of steps for drilling 9 holes is 44051 which is less compare to above technique.

3.5 Comparison between different Optimization techniques

Comparison is done between different optimization techniques for optimum sequence based on two following methods.

3.5.1 Comparison of number of steps by different Optimization techniques

The above four technique which is used to find the sequence of holes is compared according to total steps required for drilling 9 holes. Table 6 shows the number of steps by different motor and total number of steps for drilling 9 holes.

Table 6 Comparison of number of steps by different method

	Branch and Bound	Simulated annealing	Genetic	Mathematical approach for optimization
Steps by motor 1	120	124	69	155
Steps by motor 2	11821	11280	20324	8896
Steps by motor 3	35000	35000	35000	35000
Total No of Steps	46941	46404	55393	44051

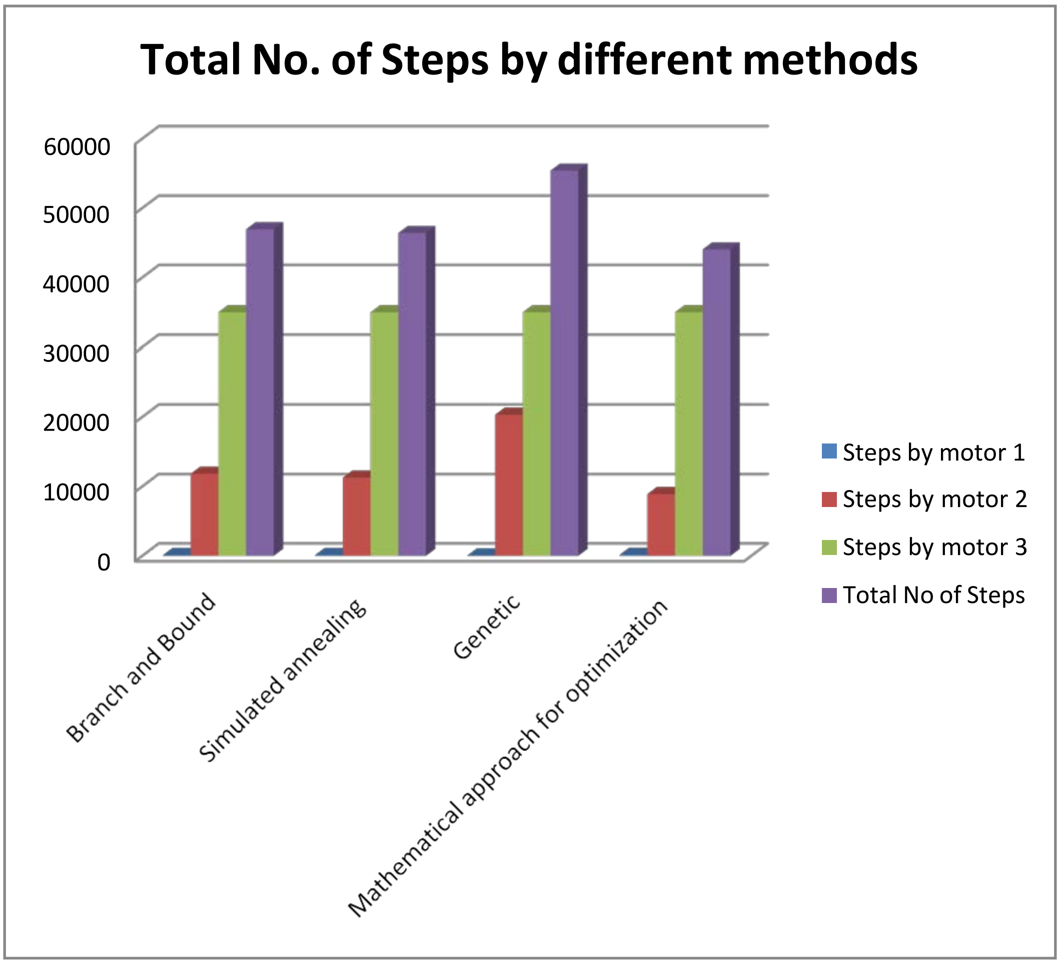

Figure 6 Comparison of number of steps by different method

Figure 6 shows the graphical representation of total number of steps by different technique. Figure shows the total number of steps is less in mathematical approach compare to otherthree optimization technique. So mathematical approach give the best sequence of drilling 9 holes. Total number of steps is calculated by different optimization techniques and concludes that the ascending order of number of steps is Formulated Mathematical Approach, SA,Branch and Bound and GA.

3.5.2 Comparison of time taken by different method for drilling

The above four technique which is used to find the sequence of holes is compared according to total time required for drilling 9 holes. Total time taken for drilling 9 holes is directly proportional to total number of steps.

Total time = (Total steps) / (200 x N) Where N = Speed of motor in rpm = 30 rpm

Table 7 shows the number of steps by different motor and total number of steps for drilling 9holes.

Table 7 Comparison of time taken by different method for drilling

	Branch and Bound(sec)	Simulated annealingsec)	Genetic(sec)	Mathematical approach for optimization(sec)
Time by motor 1	0.02	0.02	0.01	0.03
Time by motor 2	1.97	1.88	3.39	1.48
Time by motor 3	5.83	5.83	5.83	5.83
Total Time For Operation	7.82	7.73	9.23	7.34

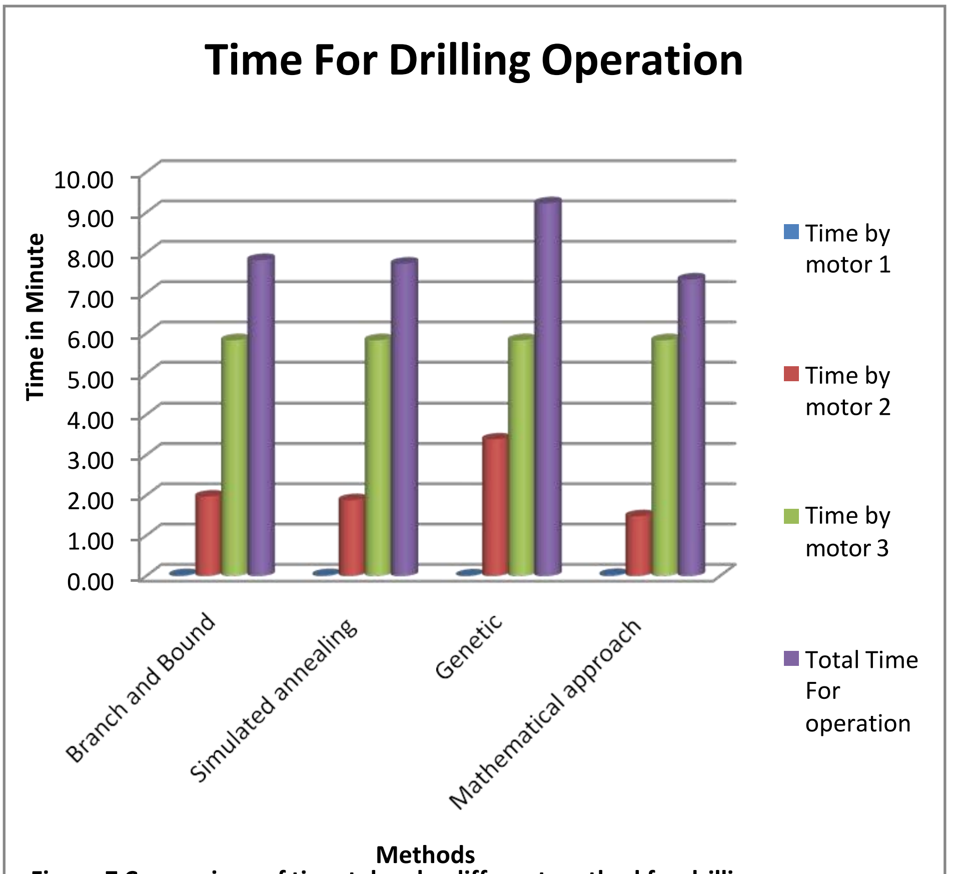

Figure 7 Comparison of time taken by different method for drilling

Figure 7 shows the graphical representation of total number of time by different technique. Figure shows the total time is less in mathematical approach compare to other three optimization technique. So, mathematical approach give the best sequence of drilling 9 holes. Total time is calculated by different optimization techniques and concludes that the ascending order of time is Formulated Mathematical Approach, SA, Branch and Bound and GA.

Conclusion

A cylindrical robotic arm has been used to drill 9 holes in a plate. Different optimization technique are used to find out the best sequence of drilling the 9 holes to reduce the drilling time on a mild steel object having dimension of 30cm x 25 cm x 40 cm. From the result, following conclusions have been drawn.

1. The optimum sequence of cylindrical robotic arm for drilling operation is [1-3-4-5-2-6-8-7-9] by using formulated mathematical optimization.
2. Total steps required for drilling 9 holes is to be minimizing using mathematical approach as compare to GA, SA and Branch and Bound.
3. Total time required for drilling 9 holes is to be minimizing using mathematical approach as compare to GA, SA and Branch and Bound.

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