Optimal Design of a Novel Two-Branch Spray Painting Robot for Prescribed Process Space

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Abstract: Painting of roadside blocks manually is costly and time-consuming and can cause road accidents for workers. This paper is devoted to the optimum design of a novel two-branch robot utilized as spray painting mechanism for side and top of the roadside blocks simultaneously. Considering painting process conditions and the block displacement pattern which can change both height and lateral location along the road, clear that the process could be carried out properly by means of two nozzles. Two planar process spaces are evolved in favour of two-dimensional paths where nozzles track during the process. A conceptual architecture is formed considering the same movements that nozzles are actuated to compensate the blocks' horizontal displacements. One parallel and one serial manipulator of the robot structure a relation by common prismatic joint. Actuators are positioned close to the base of the truck so that dynamics of movable parts are to be improved logically. Due to the change in the height and lateral location of the blocks, position of joints be optimized in terms of stroke angle and process space could be best fitted into workspace, optimization problem is arisen and solved using Genetic algorithm (G.A.) which results in less angular stroke for lower nozzle and faster matching with block conditions. The optimized joint position and center of mass are far from the base, resulting in a large torque subjected to the base. To solve the problem, the joint position is shifted toward the base without a change in the optimum situation. Finally, results are studied and detailed further.

Keywords: Genetic Algorithm, Painting Robot, Workspace Optimization

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1 INTRODUCTION

These days, painting of roadside blocks is carried out slowly belonging to a staggering number of labours, costs and accidents as it causes traffic jam even for a long time. Actually, utilization of robot in dangerous areas such as roadways achieves both a reduction in the number of accidents and a rate of increase in labour efficiency. Therefore, designing a robot to paint roadside blocks seems essential. Nowadays, robot utilization clearly points out many features for industries. In fact, robots make a lot of works with remarkable features such as high speed [1], considerable accuracy [2], desire performance [3] and acceptable lower cost [4]. Therefore, almost all advanced industries like Medical and Surgical [5-6], Aerospace [7-8], Optics [9], Nano [10-11] and so on are benefited enormously from robots.

Robots have a major contribution to the construction industry. A wide range of practical applications such as automatic lane painting [12], pavement sign painting [13], automatic highway maintenance [14], Bridge crack inspection [15] and so on have been performed using robots but there has not been any work on designing and fabrication a robot to paint roadside blocks.

There are few studies in the field of road-related painting. Kotani et al. [16] proposed a method for finding and following a half-faded lane sign on pavement using image processing. Kotani et al. [17] built a prototype robot which could repaint a half-faded lane sign. Kochekali and Ravani [18] derived a path planning system for roadway sign stencilling using a robotic system. Lee et al. [19] introduced a design concept of the roadway sign painting robot system that consists of a wheeled mobile base and gantry robot on the base.

Shin et al. [20] designed and controlled a robot system for roadway sign painting automation. The selected robot was a gantry type with an airless paint spray system. Hong et al. [21] developed a robotic system for automating the pavement sign painting operations that consists of a gantry frame equipped with transverse drive rail and automatic paint spray system. Woo et al. [12] performed the pavement lane painting operations automatically using a novel robot structure design.

Image processing algorithms could recognize deteriorated lane signs and robot installed on a truck, performed repainting operations. Ali et al. [22] presented a new Wheeled Mobile Robot prototype for autonomous road marks painting. The platform of the robot comprises the differential drive, the measurement and vision, the processing and the painting units. Jali et al. [23] designed and developed a semi-automated road painting vehicle. A mobile platform with the automatic painting mechanism was mounted on an electric bicycle to produce the required paint pattern on the road.

As robots are developed to meet a wide spectrum of duties, quality criteria or optimization approaches, which shape robot behaviour, sound important. There can be found diverse criteria for a specific optimization problem, yet how well an approach works absolutely depends on the type and property of task performed by the robot. Each optimization approach provides a manipulator whose advantage differs from that of other approaches result. Consequently, one fundamental problem with whom designers are faced is to bold a proper approach or criterion for designs [24].

Many designers concern about workspace optimization since it improves access capabilities of robots [25-26], besides, workspace plays an important role in dexterity [27], control performing [28] and mechanism stiffness [29]. Gosselin and Guillot [30] performed optimization of planar manipulators by introducing a new algorithm so that workspace is very close to the prescribed workspace.

Laribi et al. [31] proposed a simple optimization method based on G.A. for DELTA robot to find the smallest workspace containing prescribed workspace and modifying joints position. Boudreau and Gosselin [32] utilized G.A. to a dimensional synthesis of a 3 degrees of freedom (DOFs) planar manipulator as it optimizes architectural parameters so that workspace contains prescribed workspace as good as possible.

Rao et al. [33] carried out the multi-dimensional synthesis of a 3 DOFs parallel manipulator including 3RPS joints. Zhen et al. [34] proposed a method to the dimensional synthesis of a spatial 6 DOFs parallel manipulator utilizing G.A. and artificial neural networks as an intelligent optimization tool. Wu et al. [35] optimized mass of a 3 DOFs spherical manipulator since the performance of both kinematic and dynamics are improved.

Rao et al. [36] determined architectural dimensions of the spatial 3-RPS manipulator by considering a prescribed range of spherical joints motion as the objective function for G.A. optimization. Workspace optimization of a spatial 3-RPS parallel manipulator was performed by using hybrid G.A. simplex method based on physic constraints [37].

In contrast to all the robotic systems used in previous works that have done road-related painting just in one dimension, in this study, a novel two-branch robot with two nozzles is designed as spray painting mechanism for side and top of the roadside blocks simultaneously that the lack of this kind of robot is felt in past work. Due to the change in the height and lateral location of the blocks, workspace and position of joints be optimized in terms of stroke angle and process space could be best fitted into the workspace. The optimization problem is solved using G.A. which results in less angular stroke for the lower nozzle and faster matching with block conditions.

2 CONCEPTUAL DESIGN OF MECHANISM

The process is carried out appropriately in case one nozzle sprays on the front surface and another nozzle sprays on the upper surface of cement blocks while a truck is moved almost parallel with blocks pattern in a certain distance. Moreover, the robot base is mounted to either left or right side of the truck's chassis. As long as height and position of blocks vary, mechanism compensates nozzles position accurately at a proper distance from corresponding surfaces. Figure 1 shows nozzles and block during the process. Variables h and w indicate desire width of spraying bands. The distances of each nozzle from surfaces are concluded by considering desired width and constant factor c depending on nozzle characteristics. This factor is considered equal to one in this study. Thus, distances of each nozzle from the corresponding surface is directly obtained equal to the desired width of spraying bands.

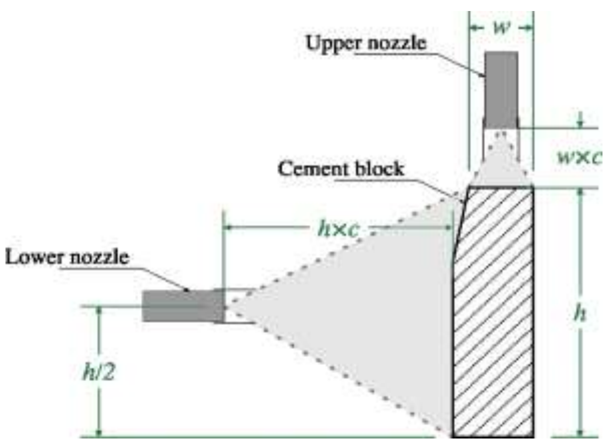


Fig. 1 Nozzles and block during the process.

Process spaces, which must be appropriately located within the robot workspaces, are comprised of regions where upper or lower nozzles may be traversed during the spraying process. Figure 2 shows lower nozzle process space including regions named 1, 2 and 3. Region 1 is defined where the lower nozzle compensates front surface displacements of blocks which are different in height.

Accordingly, region 2 is related to compensations for horizontal displacements of blocks pattern, and region 3 is a reachable and accessible area added to process space in order that the nozzle could be escaped from possible obstacles. Boundary lines are extended by 50 mm outward so that points of regions be fell far enough from robot workspace boundaries. Then, resulted space is considered as desire lower nozzle process space.

As long as blocks height are equal, blocks displacements are compensated by the same horizontal movements of the upper and lower nozzle. This behaviour leads to embed one horizontal prismatic joint to move nozzles efficiently. On the contrary, when blocks are in different heights, except previous movements, the lower nozzle must be actuated in additional horizontal and vertical displacements simultaneously. These different behaviours of nozzles definitely clear that a separate manipulator consisting of revolute and prismatic joints should be comprised for proposed trajectories. Accordingly, one parallel structure can keep the lower nozzle efficiently into desire paths during the process. Parallel structures contribute to have an agile mechanism since moving parts and actuators can be positioned almost close to the base.

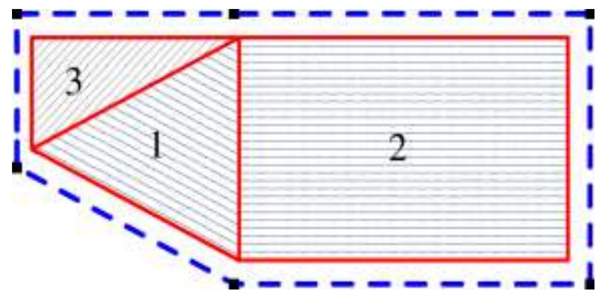


Fig. 2 Process space of the lower nozzle.

Process space of upper nozzle is fitted completely in workspace if a vertical prismatic joint perpendicular to the common horizontal prismatic joint is inserted that forms a serial manipulator separately. Figure 3 indicates the resulted conceptual design of the robot.

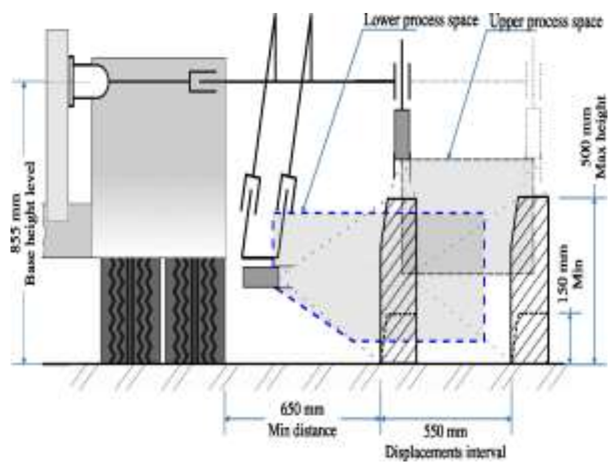


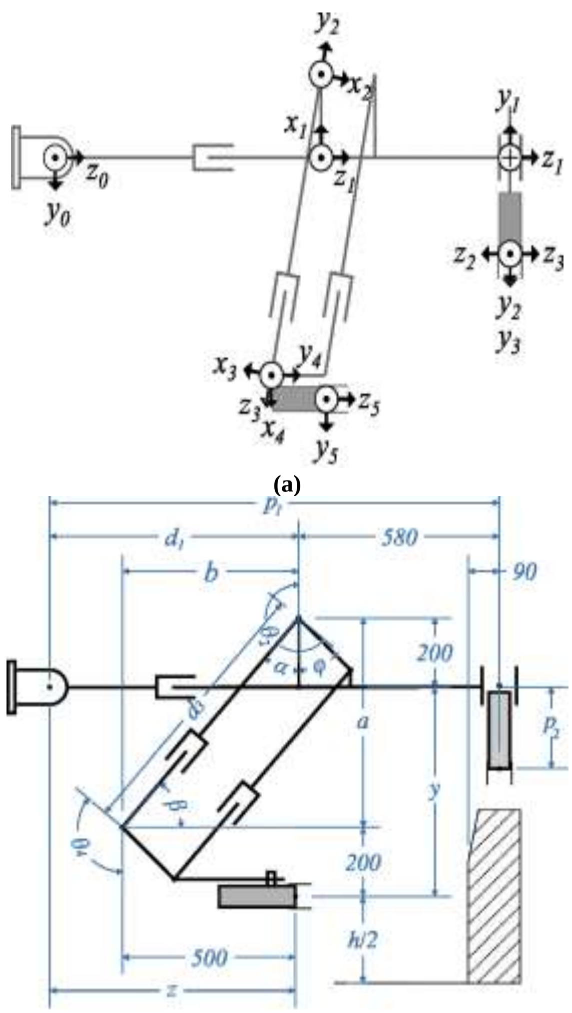
Fig. 3 Conceptual design of spray painting robot.

As shown in "Fig. 4", Cartesian coordinate systems are defined and located on joints by using the Denavit-Hartenberg method. Reference coordinate system of the robot is positioned on the base whose height level is measurable every moment in the process (equal to 855 mm in this study). Dimensions of parts are specified in accordance with circumstance dimensions. The inverse kinematic model is derived by using the geometrical method in favour of nozzles planar movements as:

$$\begin{cases} d_1 = z - 2y + 1220 \\ \theta_2 = \pi + \tanh^{-1}\left(\frac{y}{-2y+1720}\right) \\ d_3 = \frac{y}{\sin\left(\tan^{-1}\left(\frac{y}{-2y+1720}\right)\right)} \\ \theta_4 = 2\pi - \theta_2 \end{cases} \tag{1}$$

Parameters of y and z indicate lower nozzle location in the reference coordinate system. a, b are distances and α, β, φ are angles between parts of the manipulator. Upper and lower nozzles location are related to each other. Thus, the inverse kinematic model of the upper manipulator is:

$$\begin{cases} p_1 = z - 2y + 1800 \\ p_2 = 2y - 975 \end{cases} \tag{2}$$



(a)

(b)

Fig. 4 (a): Cartesian reference and joints coordination systems and (b): Geometrical parameters in inverse kinematic.

3 OPTIMIZATION PROBLEM AND OBJECTIVE FUNCTION

Joints position play an important role as they modify stroke and position of each other, besides, joints parameters effect on total mass and mass dependent variables such as required force, torque and power. Therefore, it should be comprehended that how each joint effects on the workspace shape. In addition, some limitations such as keeping a logical distance between parts, positioning of joints neither so high nor low in comparison to the base, and preventing from the interference of manipulator's parts with truck's parts also associate with the positioning of joints.

Upper nozzle workspace is defined by movements of two perpendicular prismatic joints p_1 and p_2. This workspace is the same with related process space and it has an efficient shape inherently. On the contrary, lower nozzle workspace which is defined by movements of joints d_1, θ_2, d_3 and d_4 is shaped at a complicated form. Constraint $d_3 = d_4$, which keeps lower nozzle horizontally, helps to workspace be shaped more simple. Finally, the movement effect of three joints d_1, d_3 and θ_2 on workspace should be studied separately.

Accordingly, joints strokes $300 \text{ mm} < d_1 < 1700 \text{ mm}$, $\frac{3\pi}{2} - \frac{\pi}{6} \text{ rad} < \theta_2 < \frac{3\pi}{2} \text{ rad}$ and $600 \text{ mm} < d_3 < 1000 \text{ mm}$ are considered in correspondence with inverse kinematic relations and dimensions of manipulator parts as they are in a logical proportion with process space.

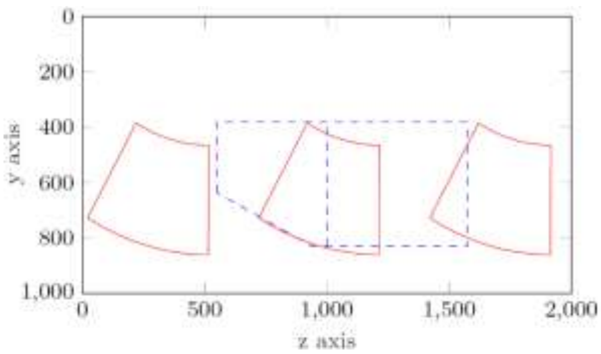
As shown in "Fig. 5a", the shapes obtained through the motion of joints θ_2 and d_3 via three different values of $d_1$that shows how that joint effects on the concluded workspace. In fact, it is realized that concluded shapes in three cases are the same; hence workspace area and parameter d_1 are related linearly. By motion of θ_2 and d_3, it shows separately that different values result in different shapes of workspace area. Thus, the relation of θ_2 and d_3 with workspace area are nonlinear ("Fig. 5b and 5c").

According to the linear relationship of parameter d_1 and the nonlinear relationship of parameters θ_2 and d_3 with workspace, an objective function is developed to minimize the workspace area of manipulator using G.A. method in order to find the position of joints that cover the process area. This function includes parameters of θ_2 and d_3 and it is independent of parameter d_1. As shown in "Fig. 6", objective function geometry is equivalent to area S as the center position O indicates the position of joint θ_2.

Analytical function of this geometry is written as below:

$$S = 0.5\Theta(R^2 - r^2) \tag{3}$$

Where R and r are maximum and minimum values of parameter d_3 and Θ equals to the angular rotation of θ_2. Minimization of S, which occurs in a certain situation, results in optimum values of both parameters θ_2 and d_3.



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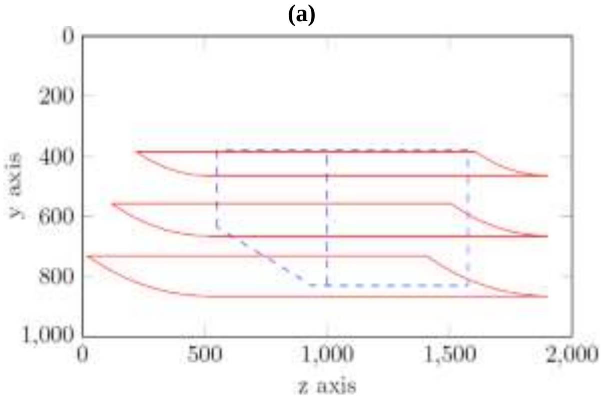

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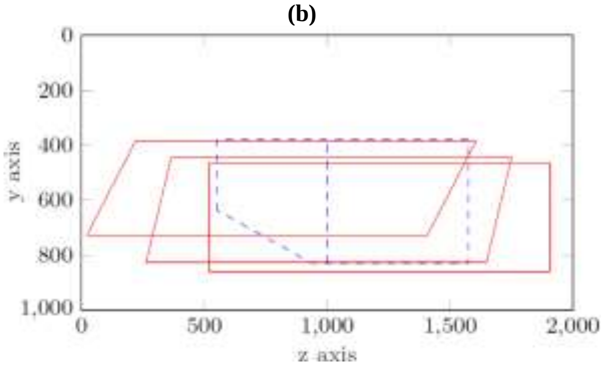


(c)

Fig. 5 (a): Effect of d_1 on workspace shape, (b): Effect of θ_2 on workspace shape and (c): Effect of d_3 on workspace shape.

Center position effectiveness could be comprehended when the variable d_3 joint to be drawn for different supposed center O. This approach is used to develop objective function as it is coded on software MATLAB to calculate the area of S. Accordingly, Intervals of radius and angle which cover the process space are defined and area S is concluded from their values using "Eq. (3)". Centers of O are distributed by algorithm among the desired region and those are considered as members of the first generation. Then, the algorithm evolves and evaluates members to find growing member values in the next generations. The Genetic algorithm is a technique which uses genetic evolution to solve problems. During execution, results are classified based on some specified approaches. Growing results are checked by inputs which are selected randomly. The Genetic algorithm as a classical optimization method is very successful to solve different problems such as linear and nonlinear problems.

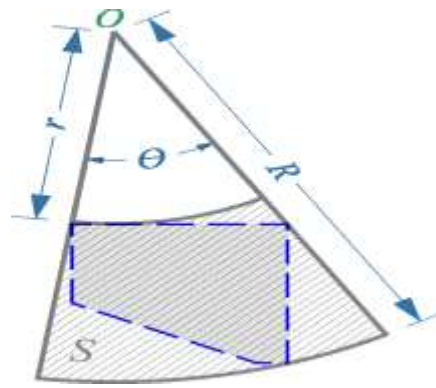


Fig. 6 Objective function geometry.

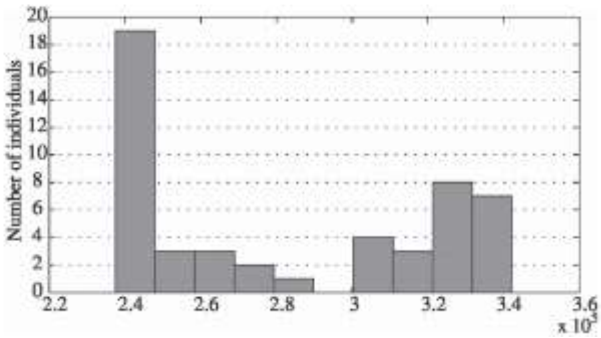
Centers of O must be selected from an acceptable region. Otherwise, they might not be suitable in terms of design and manufacture. It is in correspondence with total acceptable robot dimensions comprehended from conceptual design. This region is formed from 0 mm to 1200 mm for z and from -100 mm to 100 mm for y-axis in reference coordinate system. Other parameters type or value which is used to optimization, are shown in "Table 1".

Table 1 Parameters type or values for optimization

Option	Type or Value
Population type	Double vector
Population size	50
Creation function Initial	Feasible population
range	[-5; 0]
Scaling function	Rank
Selection function	Stochastic uniform
Elite count	5
Crossover fraction	0.8
Mutation function	Gaussian
Scale	0.1
Shrink	0.11
Crossover function	Scattered
Migration fraction	0.2
Migration interval	1

Since option items play an important role in calculation time and result in accuracy, they are justified first logically according to specifications of the objective function and then evolved by comparing obtained results among generations. While more population size leads to more calculation time, optimization is worked out through generation a dynamic and small population and choosing of proper parameters type. This is not the same in different sections of problems, but some trial adjustments contribute to select a proper population size to execute at an appropriate time.

Figure 7 indicates the first generation created randomly among acceptable region and last generation in rank order. Later chart features a logical conclusion in comparison to the former since their mean values have been decreased and the number of members having smaller values increased.



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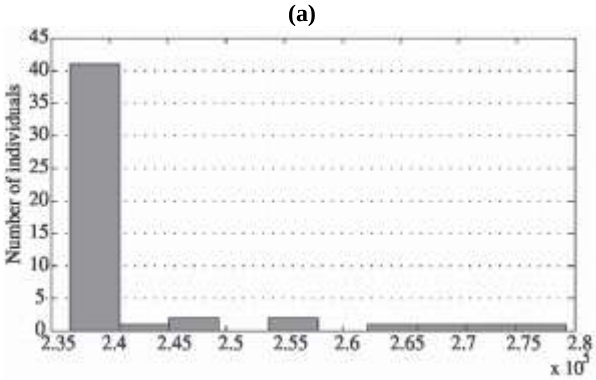
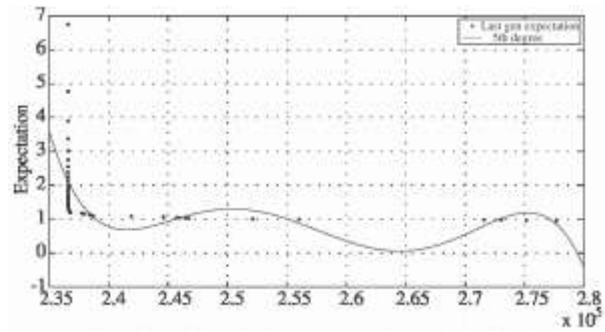


(b)

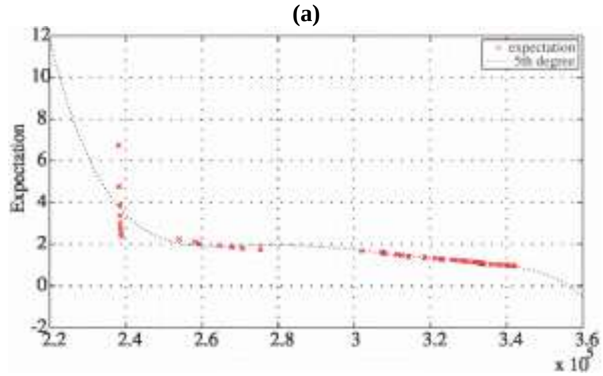
Fig. 7 Members of (a): First generation and (b): Last generation in rank order.

Scale function helps that close differences between members get increased properly. Figure 8 shows the scale factors devoted to the first and last generation members by the algorithm. Scale factors devoted to the higher rank members are bigger and it reaches about 7 while other members have scale factors beginning from 2 and declines to about 1. Moreover, the possibility of existence for members with bigger factors are more probable, yet it doesn't cause to omit lower rank members immediately. From one generation to next, an evolving kind process is used to select higher rank members toward optimum value, and lower rank members might be omitted naturally. For a member with an objective function value 2.8e5 mm^2 that was devoted scale factor 2 at first, the factor is reduced to 1, while total members rank has been evolved and the number of members with higher values been increased.

Scale function devotes non-closing factors to members although their values are close to each other. In fact, scale function considers factors based on ranks not values. Higher ranks members are parent of next generation's members and algorithm involves their characteristics absolutely, so survivals are in proportion to their scale factor value.



(a)

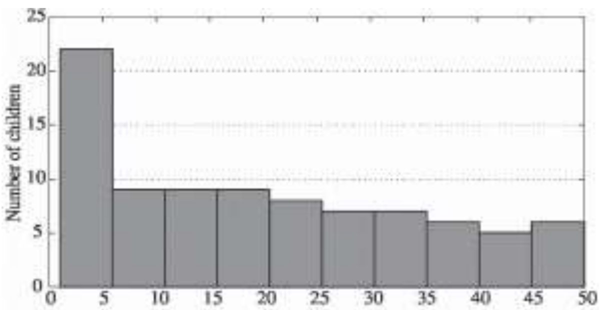


(b)

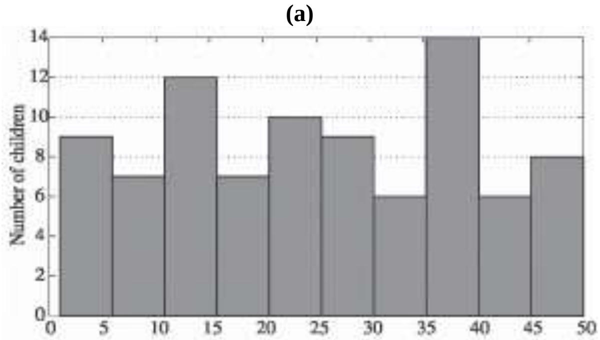
Fig. 8 (a): Scale factor devoted to the first generation and (b): Scale factor devoted to the last generation.

Selection function contributes more appropriate parents who their characteristics are involved. Figure 9 shows the selection function values for the first and last generations. Because the members in the first generation are distributed randomly, children numbers are more related to the number of members about a particular value, and it is even led to higher rank members often have fewer children numbers in comparison to lower ones. In the last generation, about 5 members with higher ranks are considered to have 22 children, so the chance for the existence of their characteristics are better absolutely.

Furthermore, selection function makes a considerable difference for existence, although the member's grade does not have significant difference. As shown, it is provided an almost equal chance of existence between the first five members and the other 45 members. In fact, the first 5 members have nine-to-one better chance so it clears obviously the effectiveness of selection function through evolving path. Parameter values study provides valuable insight for algorithm utilization and option justification. Figure 10 shows some benefit information in a chart. The chart includes the best, worst and mean values in all generations. From each generation to next, higher ranks members or lower objective function values are evolved with a low declining slope in spite of the fact that variations amplitude of higher values is high and unpredictable.



(a)



(b)

Fig. 9 (a): Children numbers of the first generation and (b): Children numbers of the last generation.

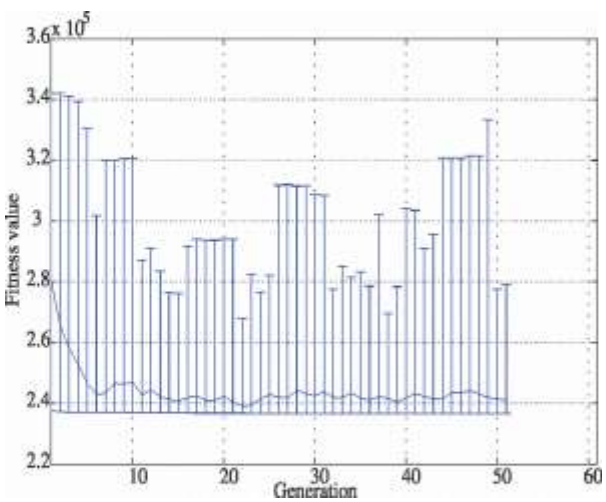
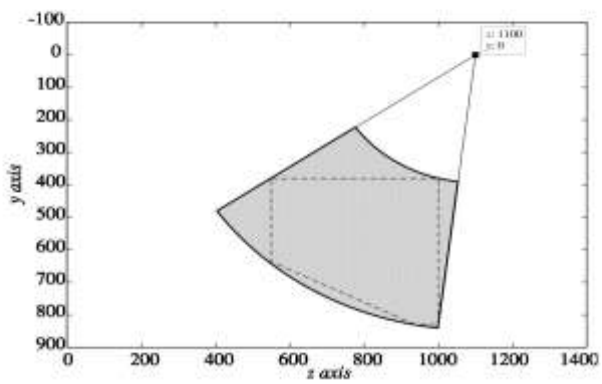


Fig. 10 Best worst and mean values of generations.

This is because of crossover and mutation functions. Crossover function plays a basic role in optimization as it combines chromosomes randomly, so it would generate low value children from low value parents. Even though parents might have low scale factor and chance of existence, it may lead to creating children which have even lower objective function values. Mutation function diverges local optimum areas in order that algorithm may search a broader space. Therefore, it may even create low value children after it makes small random changes. In some generations, mean values have low variations while higher values are varied highly indicating that some points which have low rank are going backward although optimization is in progress normally.

Finally, the algorithm is stopped after 51 generations since one of the termination criteria has been satisfied. This occurred when the average of changing in objective function value is less than the predefined value, or the algorithm advances slowly. In fact, it indicates that the optimum point with acceptable accuracy has been conducted. The optimum value of objective function 236598.86 mm^2 is concluded by the algorithm. This value is in correspond to point *O* placed as [0, -0.59, 1094.71] from the center of reference coordinate system. "Fig. 11a" shows joint position close to the optimum point.



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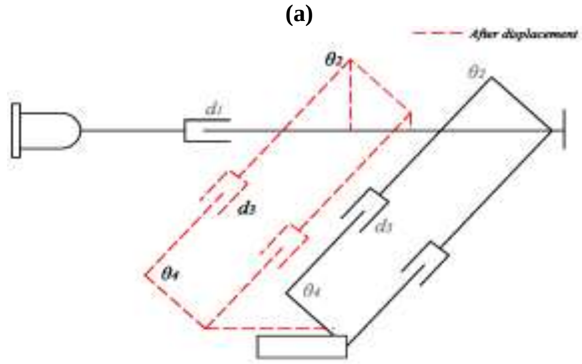

(b)

Fig. 11 (a): Final joint position after optimization and (b): Optimum position after displacement.

Although that point is concluded as the optimum position of *O*, it is not an acceptable point from the design angle of view since it is both close to the upper nozzle position and far from the base. It causes to the center of mass of robot be placed far from the base, where it leads to increasing the moment subjected to the base. Hence, at the first look, more strengthen parts are to be considered and the total mass of the robot is to be increased. After all, it is not desirable to leave optimum situations, nor is the center of the robot mass placed far from the base. Hence, the position of the joint is shifted toward the center of the robot and the lower nozzle attachment is replaced with a link so that joint displacement can be compensated without a change in the optimum situation. Figure 11b shows that changes as non-continues lines form a closed chain parallel manipulator so that the robot can be compacted easily when it is not at work.

4 CONCLUSIONS

By considering the limitations over mechanism and process, a conceptual design was formed as a serial manipulator for the upper nozzle and a parallel manipulator for the lower nozzle. Coordinate systems was defined and placed on joints using the Denavit-Hartenberg method. For the upper nozzle, it was cleared that workspace contains the process space with an optimum situation. For the lower nozzle, the effectiveness of joints on workspace shape was studied and objective function was defined for optimization. Joints' position of parallel manipulator wa optimized using the Genetic algorithm. Then, Evolution progress of optimization was studied and detailed. Modifications were directed so that the algorithm may obtain the conclusion at an appropriate time.

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