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Study on performance of serial-robot manipulator based on spatial and structural parameters

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ABSTRACT

The performance of serial-robot manipulator is an important restrictive condition for the effective working of the robot. The study, in the first place, produced a discussion on the manipulator's structure and had it divided into waist joint, shoulder joint, elbow shoulder, wrist-pitching joint, and wrist-drawing joint, 5 joints in all. In the third part are the analysis on the kinematics principles of serial-robot manipulators, the discussion on the simplified manipulator motion model and the kinematics analysis on manipulators. And the following part is the detailed analysis on the workspace calculation of serial-robot manipulators, which is an important part in the study. In this part, firstly Monte Carlo method is introduced and then the stimulation analysis on the workspace of the manipulator. The fifth part is the detailed discussion on the area calculation of the manipulator by means of self adaptive mesh modeling, which is the core of the study. In this part, the volume calculation of workspace consists of 8 steps, outsourcing construction, spatial subgrid partition, redundant subgrid elimination, boundary spatial subgrid location, second subgrid partition, redundant boundary spatial subgrid elimination, space volume calculation and space volume modification. Lastly, the paper gave simple analysis on the influence on worksapce of manipulator based on various parameters. The research method is rigorous and effective, which can be referred to by relevant researchers.

KEYWORDS

Spatial parameters; Structural parameters; Serial robot; Manipulator; Workspace.

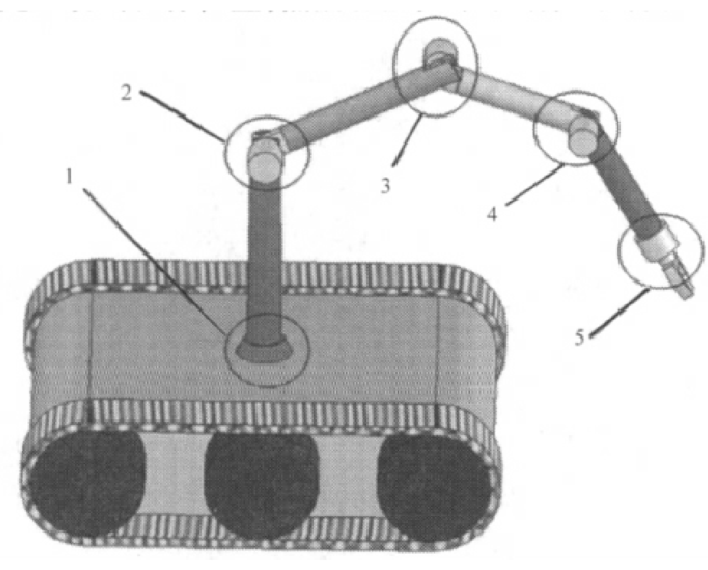
INTRODUCTION

With the development of technology, the application of robots has gradually become a reality and also very necessary in some fields. Serial robot is one category of production robots that can perform monotonous and complicated tasks. Nowadays, serial robots have been successfully applied in fruit-picking, vegetable planting and partial flow production line. The flexibility, accuracy and endurance of the manipulator are very fatal in finishing the designated tasks, thus the qualified research on the manipulator is required in the serial robot design. At present, the main method adopted in study of the manipulator is spatial structure method. This method equals the manipulator as a set which contains a plurality of points. And each point is required to precisely receive orders and the performance by the rules.

Implementation of Spatial structure method can do the calculation through 3 methods, graphic method, analytical method and numerical method. Graphic method is visible but its application is too narrow to describe the manipulator of some 3D robots. Analytical method can precisely cover and express the points and space but it is not visible enough. And the calculation process is very complicated, thus it is often used in the design of the manipulator with less 3 joints. The core thought of numerical method is to divide the manipulator into multiple workspaces which are both independent of each other and connected through interfaces. Therefore, the numerical method is not only simple but also easy to take a variety of combinations. As a result it can be used to design the robots with complex joint points and also can adopted to combine multiple simple manipulators, which functions different combinations of different robots and different manipulators. The paper will study on the serial-robot manipulator through numerical method based on spatial parameter and structural parameter. Besides, in the process of study the envelope theory will be used in the optimization on curved surface and precision of the manipulator. In conclusion, this research method is efficient, accurate and convenient, and the calculated working parameters can be referred to in relevant studies.

THE STRUCTURE OF THE MANIPULATOR

As shown in Figure 1, the serial-robot manipulator in the study contains 5 joints, wrist-drawing joint, wrist-pitching joint, elbow joint, shoulder joint, waist joint. The joints with different working divisions are able to perform multiple tasks through various combinations. Generally speaking, the front 2 joints ensure the performance accuracy through the adjustment in small amplitude, while the 3 joints closer to the body are functioning to raise the manipulator to certain height and pose it at one particular angle. Thus, the precise grasp of target object by the manipulator requires the good cooperation between the joints. The movement of each joint is independent of each other, however all the joints are the control of the central control system, which means the joints not only can perform individually but also avoid the movement disorders of whole manipulator.



1-waist joint, 2-shoulder joint, 3-elbow joint, 4-wrist-pitching joint, 5-wrist-drawing joint

Figure 1 : Serial-robot manipulator structure

THE KINEMATICS ANALYSIS ON SERIAL-ROBOT MANIPULATORS

In the field of robot research, the moving scope of the manipulator is a vital index to evaluate the quality of the robot. In the case of serial robot, its moving scope is determined by its working space. The length of the manipulator defined the reachable spherical space in which the manipulator can theoretically perform the task. However, limited by the joint kinematic singularities, the manipulator end can only operate in certain limited space of the spherical space where is the efficient workspace for the manipulator. In order to expand the efficient workspace of the mechanical arm as far as possible, the suitable adjustments on the size and rotation angle range of each joint are required, so as to ensure the manipulator's flexibility and expand its working range.

The simplified movement model of manipulators

The manipulator in the study has 5 joints, which means its DOF (degree of freedom) is 5. The working range of end-joint is the efficient working range of the manipulator and the end-joint is both supported and controlled by the other joints. Therefore, the study has laid constraints on all parameters of the joints to ensure the coordination and consistency of the manipulator.

(1) Constraints on rotation angle

Since the joints are connected to each other, they are inevitably constrained by the connecting part during rotation, which further constrains the rotation angle range. That is to say, the joint rotation angle is inevitably to be constrained and the full-rotation joint is both hardly to actualize and unnecessary in a manipulator. As shown in TABLE 1, the constraints on rotation angle of each joint are different. The waist joint possesses the biggest rotation angle range, while the wrist-pitching joint possesses the smallest rotation angle range. It is obvious that the rotation ranges of joints are gradually shrinking from the machine body to the manipulator end.

TABLE 1 : The rotation angle range of each joint

joint rotation angle	joint rotation range (radian)
elbow-pitching joint	[0,90]
elbow joint	[-160,0]
shoulder joint	[-80,75]
waist joint	[-180,180]

Constraints on the length

Although the longer is the length of the manipulator, the bigger is the reachable space of it, an overlong joint or manipulator, on one hand can increase the weigh-bearing of the robot to affect its flexibility, on another hand can also increase the possibility that it is constrained by environment thus to make the working in certain environment hard to operate. In all, the length of each joint can not be prolonged infinitely.

(2) The kinematics analysis on manipulator

According to the mechanical kinematics principles, the moving direction and moving posture of each joint and posture are to be influenced by other joints in the system. Since the end-joint directly perform the tasks, its moving information is very important. In order to master the relevant information of the end-joint, the calculation on the parameters of the 4 front-joints is needed. As shown in Figure 2, the study uses the D2H method to describe the parameters of each joint and the relationship between them. And the parameters of each joint are all listed in TABLE.2.

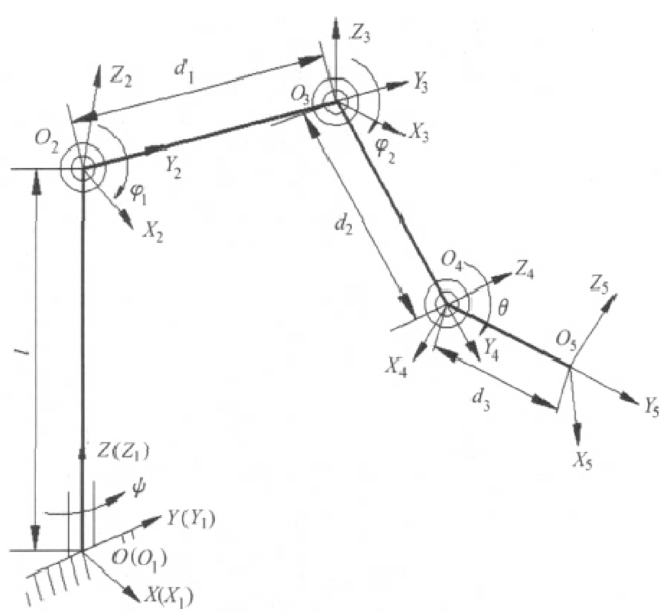


Figure 2 : Serial-robot manipulator components and their bar coordinates

TABLE2 : Each joint and linked bar work parameters

joint rotation angle	torsion angle ()	linked bar	linked bar length (mm)
waist joint	-90	l	400
elbow joint	-90	d1	320
shoulder joint	90	d2	250
wrist-pitching joint	0	d3	150

Note: 1, d_1, d_2 and d_3 stand for each linked bar marked in Figure 2

The movements by the end of manipulator execute the orders directly. The study calculated the moving indexes of the performer at the end of the manipulator according to Formula (1) as follow:

$$T_0^5 = T_0^1\ T_2^1\ T_3^2\ T_4^3\ T_5^4 = \begin{bmatrix} R & P \\ 0 & 1 \end{bmatrix} \tag{1}$$

In Formula (1), P represents the vector of end-performer relative to the based coordinate system, $P = \left[p_x\ p_y\ p_z \right]^T$. R represents the pose vector of end-performer relative to the based coordinate system.

According to Formula (1) and the data in TABLE.2, P can be worked out as follow:

$$P = \begin{bmatrix} -d_1 \cos\varphi_1 \sin\psi + d_2 \sin(\varphi_1 + \varphi_2)\sin\psi - d_3 \cos(\varphi_1 + \varphi_2 + \theta)\sin\psi \\ d_1 \cos\varphi_1 \cos\psi - d_2 \sin(\varphi_1 + \varphi_2)\cos\psi + d_3 \cos(\varphi_1 + \varphi_2 + \theta)\cos\psi \\ l - d1\sin\varphi_1 - d_2 \cos(\varphi_1 + \varphi_2) - d_3 \sin(\varphi_1 + \varphi_2 + \theta) \end{bmatrix}$$

THE WORKSPACE OF SERIAL-ROBOT MANIPULATORS

The calculation by Monte Carlo method

Monte Carlo method is a numerical method of which the core idea is to use random sampling to solve the mathematical problems, such as space calculation. Monte Carlo method is accessible to calculate the random data by computer and describe the results graphically. In this study, in order to calculate the manipulator's workspace, the data obtained in the random trials on the manipulator's working will be calculated based on Monte Carlo method. The steps of calculation are:

(1) input the reference coordinate into computer and calculate the position vector of the end-performer.

(2) calculate the random value of joint variables: After having obtained the random values (all in the interval [0,1])generated by random function $RAND\left(j\right)\left(j = 1, 2, \ldots n\right)$, further to get the random step with length of $\left(q_{\max} - q_{\text{mini}}\right) RAND\left(j\right)$. At the this point, the random values of joint variables can be worked out according to Formula (2):

$$q_i = q_{\text{mini}} + q_{\max} - q_{\text{mini}}{}^{RAND(j)} \tag{2}$$

In Formula (2), $q_{\max}$ and q_{mini} respectively represents the upper and lower limits of relevant joint variables; i represents the serial number of joint.

put the joint variables calculated in step2 into the kinematics equation to gee N (quantity of coordinate values) 3D (x,y,z) coordinate values of joint end and then to store the coordinate values respectively as Matrix X, Y, Z. All the coordinate values obtained in this step from every dimensions together reflect the manipulator's workspace, the more the values are, the higher the accuracy is.

(4)display the matrix produced in last step by drawing dots which form the cloud picture of workspace. The cloud picture will be used in the following stimulation analysis.

The stimulation analysis on workspace of manipulators

In this part, the quantity of dots in joint end is to set as 80000, through which 80000 coordinate dots are to be produced. By means of the stimulation analysis on the serial-robot manipulator based on Monte Carlo method, the stimulation picture of workspace is to be conducted as Figure 3 as follow:

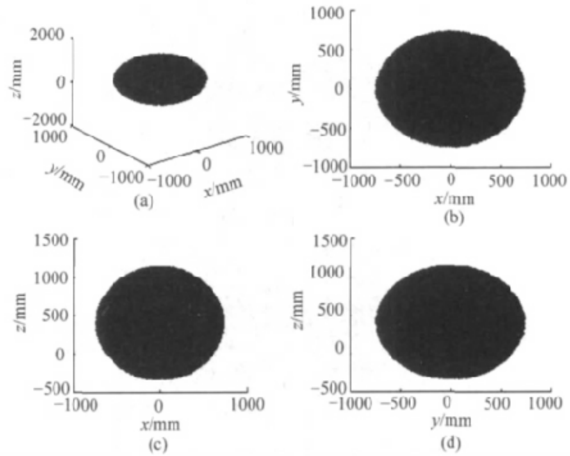


Figure 3 : The stimulation shape of workspace

Note: a, b, c, d, four parts in this figure respectively represent 3D working space of the end-performer, a is projection on plane (x,y) in 3D coordinates, a is projection on plane (x,z) in 3D coordinates, a is projection on plane (y,z) in 3D coordinates.

THE WORKSPACE VOLUME OF MANIPULATORS

There are many ways to calculate spatial volume mathematically, and the study adopted the adaptive mesh modeling. The calculation theory of adaptive mesh modeling: through matching the imaginative mesh of workspace with cloud picture, to remove the excess grids, and the volume of the grids left is the target volume of the calculation. The study calculates the workspace volume of the manipulator through following steps:

(1) Conduct outsourcing grid. According to the values of 3 coordinates (x, y, z)of the workspace dots in cloud picture in the 4th part $P=\left\{p_i \in R^3\right\}(i=1,2,...,m)$, the maximums and the minimums on the 3 coordinates in the workspace are all available. These extremes are the boundary of the imaginative grid to conduct. That way, the outsourcing grid of the cloud picture of dots is able to be conducted which shapes in cuboid, with a length: $a=x_{max}-x_{\min}$, $b=y_{\max}-y_{\min}$, $c=z_{\max}-z_{\min}$.

(2) Divide the outsourcing grid into spatial subgrids. To gift the grid analysis with certain precision needs to divide the outsourcing grid into umpty subgrids. If being divided into m segments, n segments, p segments orderly in the direction of x-axis, y-axis, z-axis, the outsourcing grid will be evenly cut into m ×n ×p cuboids of which each one is called spatial subgrids.

(3) Remove redundant subgrids. At this step, those subgrids without random dots will be removed, which is to make the outsourcing grid more concise and further to seek the effective boundary spatial subgrids for constructing convenient conditions.

(4) Find boundary spatial subgrids. Through subdivision of the spatial subgrids, those spatial subgrids without any random dots are removed again. Therefore, it is necessary to identify the boundary subgrids at this step.

First is the dimensional reduction on the subgrids. Adopting the method at step 2, the 3D spatial grid can be divided into p segments in the direction of one axis (the study picks z-axis), through which each layer will become a two-dimensional plane with a height h=z/p. At this point, the spatial grid has become 2D from 3D. In the same way, the dimensional reduction can also be realized by dividing the spatial subgrid into n layers in the direction of y-axis, m layers in the direction of x-axis. That way, the spatial grid has the highest 2D plane and the lowest 2D plane in the direction of each axis, and the union between them is the boundary spatial subgids to be found. As shown in Figure4, those are the boundary spatial subgrids on layer p.

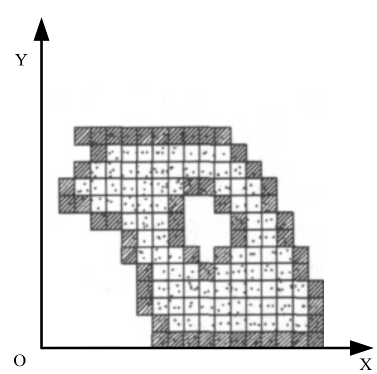
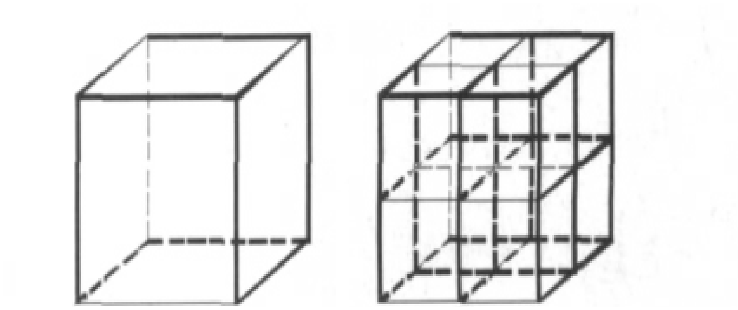


Figure 4 : Schematic Diagram of Boundary Subgrids

Subdivide the boundary spatial subgrids. To divide the boundary spatial subgrids calculated at last step into same segmentation, as shown in Figure 5.



(a) (b)

Figure 5 : Schematic Diagram of Boundary Subgrids Subdivision
Note: the left part is before subdivision, the right part is after subdivision

(6) Remove redundant boundary spatial subgrids. That is to say, to remove the boundary spatial subgrids without random dots, which reduces the calculation and also makes drawing more clear.

(7) Calculate spatial volume. After several former steps, the volume of subgrids left can be calculated through the following formula as the spatial volume:

$$V = n_s V_i + \sum_{j=1}^{r} n_j V_j \tag{4}$$

In the formula, n_s represents the quantity of spatial subgrids, v_i represents the volume of each spatial subgrid, r represents the number of times of the division on boundary grids, n_j and v_j orderly represents the quantity of boundary spatial subgrids and volume of individual boundary spatial subgrid after j-times subdivisions and removings.

(8) Modify spatial volume. In order to test the reliability of the calculated spatial volume, firstly add 1000 random dots one time, then repeat step (6), step (7), after this compare the repeatedly calculated spatial volume to the first-time result. If the deviation is within 2%, the modification will be stopped to pick the last-time result, which means the calculated spatial volume is reliable.

The adaptive mesh modeling in the study can efficiently remove the redundant subgrids thus to the accuracy of the final spatial volume, however, what's worth noting is the finally-calculated spatial volume is not the actual volume of the workspace of the manipulator but an approximation. Although the existing error cannot be eliminated in the actual design of the serial-robot manipulators, it is still possible to control the error by controlling the random dots according the requirements on accuracy.

In accordance with the above steps, the final workspace volume of the study subject-the end-effector will be calculated which is $1.2899 \times 10^9 mm^3$. The quantity of random dots in this workspace is 80000; this space contains 26 layers of which each one is a 2-dimensional cuboid as a phalanx 26×26.

EFFECTS ON WORKSPACE OF MANIPULATOR BY SERIAL ROBOT'S EVERY PARAMETERS

Effects on manipulator's workspace volume by bar length

On the condition that other parameters remain unchanged, as shown in Figure 6, the change of L does not cause change on the workspace, however, the change on length of d_1, d_2 and d_3 does. In terms of the inclination, d_3 has the most prominent influence on the workspace volume, followed by d_2.

Effects on workspace volume by joint rotation angle

Providing that other parameters remain unchanged, as shown in Figure 7, Figure 8, Figure 9 and Figure 10, the changes on workspace volume caused by the changes on the rotation angles of waist joint, shoulder joint, elbow joint, wrist-pitching joint are not completely the same, but their rotation-angle changes all make the workspace volume change in the same direction: when rotation angle range is widen, the workspace volume of manipulator also increases, which provides an instruction on the design of manipulator: With the given working environment and mechanical performance, the expansion on the manipulator's workspace can be done through increasing the rotation angles range of every joints individually or multiply.

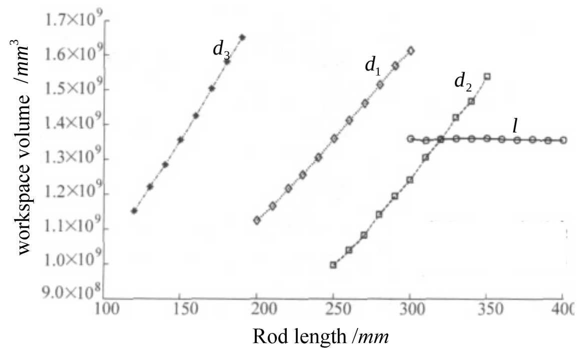


Figure 6 : Effects on workspace volume by the length of linked bar

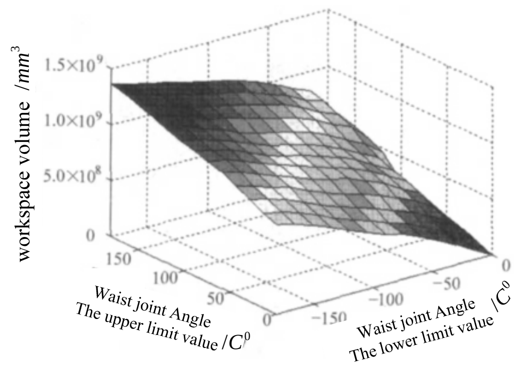


Figure 7 : Effects on workspace volume by rotation angle range of waist joint

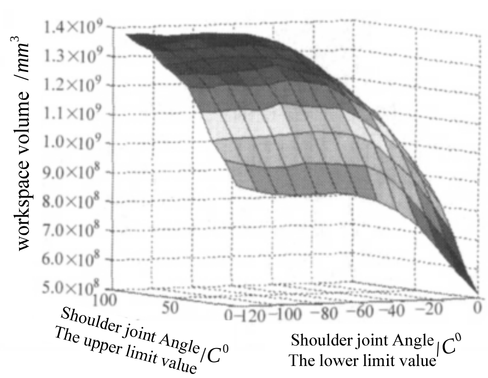


Figure 8 : Effects on workspace volume by rotation angle range of shoulder joint

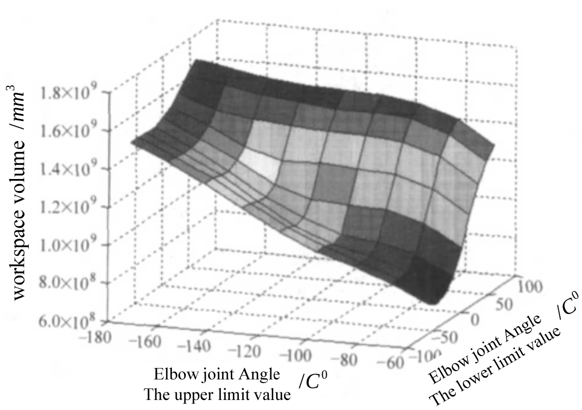


Figure 9 : Effects on workspace volume by rotation angle range of elbow joint

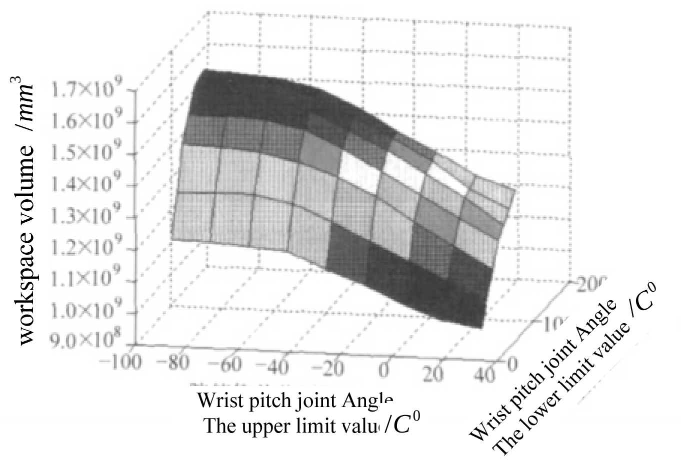


Figure 10 : Effects on workspace volume by rotation angle range of wrist-pitching joint

CONCLUSION

The serial robot can replace humans in the field of high-repeatability and easily-tiring works, which thus possesses a broad application range. In the design of the serial robot, the efficient workspace range determines the function of the robot to a large extent. Therefore, the accurate analysis on the issue of workspace is necessarily required to ensure set objectives are finally met. The study has discussed the workspace of serial-robot manipulator and simply analyzed the effects each parameter has on the workspace, which has the positive significance on the reference for the practical design of serial robot.

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