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## Dimensional Synthesis and Design of a Shoulder Joint for Fruit and Vegetable Harvesting Manipulator

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### ABSTRACT

In order to improve the performance of a novel shoulder joint for fruit and vegetable harvesting robot, parameter optimization was presented. On the basis of the Jacobian matrix of the parallel mechanism, the global dexterity index and driving performance index which met the workspace requirements and the constrained conditions were used as the optimal objective and the optimization model of the shoulder structure parameters was established. The ant colony algorithm was used to optimize the structure parameters of the mechanism, dimensional synthesis of the shoulder was carried out and the optimal scale parameter values were given. With the mechanism for the prototype, a shoulder joint of humanoid robot is designed. It has the advantages of compact structure, easy manufacturing, strong carrying capacity and lower motion inertia, etc.

**Key words:** Shoulder joint, performance index, dimensional synthesis, parameter optimization

### INTRODUCTION

Application of the picking robot has changed the traditional picking method and promoted the development of modern agriculture. It is the effective way to alleviate the lack of labor and improve the quality of labor productivity and operation (Zhao *et al.*, 2003; Chen and Guo, 2013; Song *et al.*, 2006). The shoulder joint is a key part of the fruit and vegetable picking robot. Reasonable structural design directly affects the performance of the picking robot (Wang *et al.*, 2011; Lu *et al.*, 2011; De-An *et al.*, 2011). In certain constraints, optimization functions are constructed based on performance evaluation indexes and operation performance of the mechanism can be improved in its workspace by optimizing the scale parameters, so the dimensional synthesis is one of the core contents for the mechanism design (Zhang *et al.*, 2010; Huang *et al.*, 2005; Liu *et al.*, 2006, 2007).

In this study, parameters of a spherical three DOF humanoid shoulder joint used for picking robot are optimized. In order to meet the requirements of design space and various constraints, the global dexterity index and driving performance index which meet the design work space requirements and the constrained conditions are used as the optimal objective and the optimization model of the shoulder structure design is established, ant colony algorithm is used to optimize the structure parameters of the mechanism. The optimum values of the scale parameters which make the global operating performance and driving performance index of the shoulder joint be optimal are derived.

**MATERIALS AND METHODS**

The schematic diagram of the shoulder joint is shown in Fig. 1. It consists of a fixed base, a mobile platform and three limbs which consist of a framed link and a connecting rod with identical structure. Each limb that consists of three revolute joints in series connects the fixed base to the mobile platform. All revolute axes of the mechanism intersect at one point O. The axes of three revolute joints connected with the fixed base are vertical to each other and the axes of three revolute joints connected with the mobile platform are vertical to each other and the revolute joint axes of framed links and connecting rods are vertical to each other too.

**Inverse kinematics modeling and Jacobian matrix:** Taking the enter point O as the origin of the system coordinates, as shown in Fig. 1, a fixed Cartesian frame O{X, Y, Z} connected with the fixed base and a moving Cartesian frame O{x, y, z} connected with the mobile platform are established, with the X, Y, Z axes in coincidence with U<sub>1</sub>, U<sub>2</sub>, U<sub>3</sub> axes and the x, y, z axes in coincidence with V<sub>1</sub>, V<sub>2</sub>, V<sub>3</sub> axes, respectively. In the initial posture, the fixed Cartesian frame is coincident with the moving Cartesian frame.

The mobile platform only can rotate round the fixed base, the transformation matrix between the motion coordinate and the fixed coordinate is given as follows:

$$R = R_{ZYX}(\alpha, \beta, \gamma) = \begin{bmatrix} \cos \alpha \cos \beta & \cos \alpha \sin \beta \sin \gamma - \sin \alpha \cos \gamma & \cos \alpha \sin \beta \cos \gamma + \sin \alpha \sin \gamma \\ \sin \alpha \cos \beta & \sin \alpha \sin \beta \sin \gamma + \cos \alpha \cos \gamma & \sin \alpha \sin \beta \cos \gamma - \cos \alpha \sin \gamma \\ -\sin \beta & \cos \beta \sin \gamma & \cos \beta \cos \gamma \end{bmatrix} \quad (1)$$

where,  $\alpha$ ,  $\beta$  and  $\gamma$  are the posture angles of the mobile platform.

When the mobile platform pose changes, the direction cosine U<sub>i</sub>, W<sub>i</sub> and V<sub>i</sub> of revolute joint of the i-th branch (i = 1, 2, 3) can be derived by:

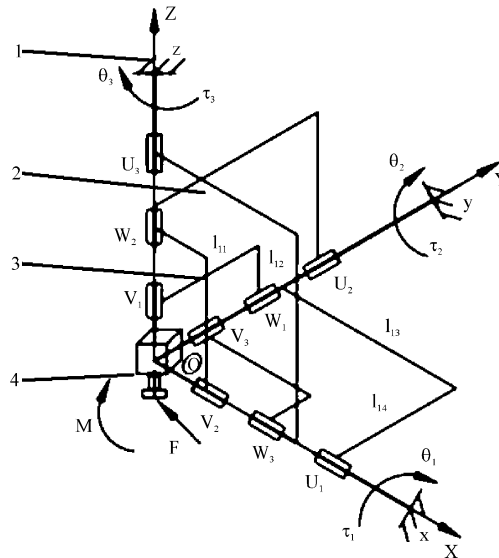


Fig. 1: Sketch map of a shoulder joint, 1: Fixed base, 2: Frame connecting rod, 3: Connecting rod and 4: Mobile platform

$$\begin{cases} \mathbf{U}_i = \mathbf{U}_o \\ \mathbf{V}_i = R\mathbf{V}_o \\ \mathbf{W}_i = |\mathbf{U}_i \times \mathbf{V}_i|^T (\mathbf{U}_i \times \mathbf{V}_i) \end{cases} \quad (2)$$

where,  $\mathbf{U}_{i0}$ ,  $\mathbf{W}_{i0}$  and  $\mathbf{V}_{i0}$  are the direction cosines of revolute joint of the  $i$ -th branch ( $i = 1, 2, 3$ ) when the mechanism is on the initial state.

Referring to Huang *et al.* (1999), the constraint equation for the mechanism can be written as follows:

$$\mathbf{W}_i \cdot \mathbf{V}_i = 0 \quad (3)$$

Solving constraint Eq. 3 and considering interference problems, singular configuration and motion smoothness of the mechanism, the solutions for the inverse kinematics can be derived by:

$$\begin{cases} \theta_1 = \arctan \frac{\sin \alpha \sin \beta \cos \gamma - \cos \alpha \sin \gamma}{\cos \beta \cos \gamma} \\ \theta_2 = -\arctan \frac{\sin \beta}{\cos \beta \cos \alpha} \\ \theta_3 = \arctan \frac{\cos \alpha \sin \beta \sin \gamma - \sin \alpha \cos \gamma}{\sin \alpha \sin \beta \sin \gamma + \cos \alpha \cos \gamma} \end{cases}$$

Differentiating the constraint Eq. 3 with respect to time, yields:

$$\dot{\boldsymbol{\psi}} = \mathbf{J}\dot{\boldsymbol{\theta}} \quad (4)$$

where,  $\boldsymbol{\theta} = (\theta_1 \theta_2 \theta_3)^T$  is the vector of actuated joint rates and  $\boldsymbol{\psi} = (\dot{\alpha} \dot{\beta} \dot{\gamma})^T$  is the vector of the output angular velocities of the mechanism and  $\mathbf{J}$  is the Jacobian matrix.

### Modeling for optimizing the mechanism parameters of the shoulder

**Design variables:** The size of the designed robot shoulder joint is consistent with the structural size of human body, then  $l_{13} = 150$  mm. According to the orthogonal structure of shoulder joint,  $l_{11} = l_{14}$ . The increase of the moving platform size will increase the inertia load, therefore it is unfavorable to high-speed movement of mechanism and can affect the movement spatial of the mechanism when the overall size is fixed. Then according to the assembly requirements, the minimum value for  $l_{12}$  is 60 mm. So, the performance of shoulder joint in the working space depends on  $l_{11}$  or  $l_{14}$ , the values of  $l_{11}$  and  $l_{14}$  are 70-140 mm.

**Dimensional constraints:** As shown in Fig. 1, for branch  $i$ -th,  $l_{12}$  is the vector of  $L_{12}$ ,  $l_{13}$  is the vector of  $L_{13}$ ,  $\theta_i$  ( $i = 1, 2, 3$ ) is the angle between connecting rod and framed link. The angle is derived by:

$$\cos \theta_i = \cos \frac{l_{12} \cdot l_{13}}{\|l_{12}\| \|l_{13}\|} \quad (i = 1, 2, 3) \quad (5)$$

where,  $\theta_i$  is 0 or  $\pi$ ,  $|J| = 0$ , this mechanism is in the singular state, then the constraint between the connecting rod and rod connected to the frame is:

$$0 < \theta_i < \pi \tag{6}$$

Mobile platform and the connecting rod of mechanism is wrapped in the rods connected to the frame, so there is mutual interference between the connecting rod and the rod connected to the frame. It is assumed that section of the rods is round and its diameter is  $d$ , the shortest distance between the same side of the connecting rod and the rod connected to the frame is set  $D_i$ , the constraint conditions that there are not interference between two rods is:

$$D_i > d \tag{7}$$

**Performance constraints:** Dexterity is an important index for evaluating the kinematic accuracy of the mechanism. Usually the inverse of the condition number of Jacobian matrix is used to characterize the mechanism dexterity, the following equation can be obtained by taking the spectral norm of matrix:

$$0 \leq \mu = \frac{1}{k_J} = \frac{\sigma_{\min}}{\sigma_{\max}} \leq 1 \tag{8}$$

where,  $\sigma_{\max}$  is the largest singular value of matrix  $J$  and  $\sigma_{\min}(J)$  is the smallest singular value of matrix  $J$ .

It can be observed that the value of  $\mu$  is larger, the motion precision is higher. Because the dexterity index is a function of the Jacobian matrix and the Jacobian matrix is not a constant matrix which depends on posture of the robot, so, the dexterity index is a local performance index. In order to evaluate the overall performance of robot, the global dexterity performance index is defined as:

$$\eta = \frac{\int_V \mu(J) dv}{\int_V dv} \tag{9}$$

where,  $V$  is the reachable work space of the mechanism.

It can be observed that  $\eta$  is the average value of the dexterity index in workspace which does not depend on the configuration of the mechanism and only relates to structural parameters. The larger value of  $\mu$ , the better dexterity.

Driving characteristics is an important index to measure the performance of parallel mechanisms. The analysis of driving characteristics for the parallel mechanisms is a necessary part of practical analysis. It aims to determine the driving force or torque through the transmission effect of robot joint and provides theoretical basis for the reasonable choice of the driver and the effective mechanism stiffness control.

It is assumed that all components of the shoulder are rigid components and the friction forces between revolute joints are not considered. Where  $\tau = (\tau_1 \ \tau_2 \ \tau_3)^T$  is defined the vector of driving matrix,  $F_g = (FM)^T$  is defined the generalized force of the mechanical ending which includes

forces and torques effecting on the mechanism, as shown in Fig. 1. Where  $F = (f_x \ f_y \ f_z)^T$ ,  $M = (m_x \ m_y \ m_z)^T = (m_{ox} \ m_{oy} \ m_{oz})^T + F \times r$ ,  $r$  is the vector of action point of generalized force to rotation center. Because the moving platform only can rotate relative to the fixed platform, the mechanism only has posture change and no change in position, the following equation (10) is obtained by the principle of virtual displacements (Craig, 2011):

$$M \bullet \delta \psi = \tau \bullet \delta \theta \tag{10}$$

where,  $\delta \psi = (\delta \alpha \ \delta \beta \ \delta \gamma)$  is virtual angle vector of end-effectors under the action of external force.  $\delta \theta = (\delta \theta_1 \ \delta \theta_2 \ \delta \theta_3)$  is the corresponding virtual angle vector of actuated joints.

The relationship between virtual angle vector  $\delta \psi = (\delta \alpha \ \delta \beta \ \delta \gamma)$  and  $\delta \theta = (\delta \theta_1 \ \delta \theta_2 \ \delta \theta_3)$  depends on the matrix which should meet Eq. 11:

$$\delta \psi = J \delta \theta \tag{11}$$

In view of Eq. 10 and 11, it can be derive that:

$$M = G \tau \tag{12}$$

where,  $G$  is defined as force Jacobian matrix of the mechanism.

$$G = (J^{-1})^T \tag{13}$$

In view of Eq. 12, the relationship between the input and output torque is determined by matrix  $G$ . When the robot is not in the singular pose,  $\text{rank}G = 3$ . According to matrix analysis theory, force Jacobian matrix  $G$  has singular value decomposition, then Eq. 13 can be written into:

$$G = U \Sigma V \tag{14}$$

Where:

$$\Sigma = \begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{bmatrix}$$

$U \in \mathbb{R}^{3 \times 3}$  and  $V \in \mathbb{R}^{3 \times 3}$  are orthogonal matrix, respectively,  $\sigma_i$  is singular value of matrix and  $\sigma_1 \geq \sigma_2 \geq \sigma_3$ , for  $i = 1, 2$  and  $3$ .

Assume that the input torque is a unit vector, then:

$$\tau^T \tau = 1 \tag{15}$$

In view of Eq. 12 and 15, it can be derived that:

$$M^T U (\Sigma \Sigma^T)^{-1} U^T M = 1 \tag{16}$$

In view of Eq. 16, the values of output torque are located in space ellipsoid which is called the output torque transmission ellipsoid. The  $\sigma_i$  is diameter of the ellipsoid, for  $i = 1, 2$  and  $3$ . The values of output torque are located in space sphere when  $\sigma_1 = \sigma_2 = \sigma_3$ . In the workspace, the values of the force Jacobian matrix vary with the changing of posture of the mobile platform, output torques are also continually changing. The performance index of driving force transmission is defined as:

$$K_a = \sigma_3 \tag{17}$$

The value of  $K_M$  is larger, the output torque is larger and the driving performance of the shoulder mechanism is better. In the working space, the force Jacobian matrix  $G$  changes with the moving platform change,  $K_a$  also changes along with the mechanism configuration changes, so, it is a local performance index. In order to evaluate the overall performance of robot, the global driving performance index is defined as:

$$\zeta_a = \frac{\int_V k_a dv}{\int_V dv} \tag{18}$$

where,  $V$  is the reachable workspace of this mechanism.

The larger value of  $\zeta_a$ , the better driving performance of the shoulder mechanism.

**Objective function:** The global dexterity index and driving performance index are used as the optimal objective and the Multi-objective optimization model of shoulder structure design is established. The objective function of the system is defined as:

$$f(x) = \varepsilon(1/\eta) + (1-\varepsilon)(1/\zeta_a) \tag{19}$$

where,  $\varepsilon$  is the weighted coefficient of the dexterity,  $1-\varepsilon$  is the weighted coefficient of the driving performance. For different applications, the appropriate value of  $\varepsilon$  is selected, here  $\varepsilon = 0.5$ .

Dimensional synthesis of mechanism can be regarded as the satisfying inequality constraints of the constrained nonlinear programming problems, that is:

$$f(x) \rightarrow \min \tag{20}$$

## RESULTS AND DISCUSSION

### Parameter optimal design of the mechanism based on the ant colony algorithm

**Ant colony algorithm model:** Ant colony algorithm proposed by Dorigo *et al.* (1996) is a bionic algorithm that simulates the collective routing behavior of ants (Dorigo *et al.*, 1996, 2000; Bonabeau *et al.*, 2000). Because the algorithm has good ability of random search optimization, it has been widely used in the parameter optimization and mechanism design (Li *et al.*, 2011; Yang *et al.*, 2007).

Ant colony algorithm includes moving rule and pheromone updating rule. Let  $m$  individual worker ants, they locate in the  $m$  dividing points of the interval  $[a, b]$  at the beginning respectively, the transfer probability of ants is defined as:

$$P_{ij} = \frac{\tau_j^h \eta_{ij}^s}{\sum_{j=1}^m \tau_j^h \eta_{ij}^s} \quad (21)$$

where,  $P_{ij}$  is the probability that ants move from location  $i$  to  $j$ .  $\tau_j$  is the pheromone intensity between position  $i$  and position  $j$ .  $\eta_{ij}$  is the difference of the target function value,  $h$  is the weight of the pheromone concentration,  $s$  is the weight of the distance information.

After a moment of  $n$ , the ants complete a cycle, the pheromone update equation is:

$$\tau_{ij}(t+n) = \rho \tau_{ij}(t) + \Delta \tau_{ij}(t) \quad (22)$$

$$\Delta \tau_{ij}(t) = \sum_{k=1}^m \Delta \tau_{ij}^k(t) \quad (23)$$

$$\Delta \tau_{ij}^k = \frac{Q}{L_k} \quad (24)$$

where,  $\rho$  is the persistent characterization of the pheromone,  $\Delta \tau_{ij}$  is the pheromone increment of the path,  $Q$  is positive constant,  $0 < Q < 10000$ ,  $\Delta \tau_{ij}^k$  is the pheromone increment that is left in the path by the  $K$ -th ant,  $L_k$  which is defined  $L_k = f(x+r) - f(x)$  is the path length that the  $K$ -th ant walks in this cycle,  $r$  is step size in search. Thus solution of the optimization relies on the moving of ants to be derived constantly.

The realization process of ant colony algorithm is:

- Step 1:** Initialization. Let  $N$  be equal to 0 ( $N$  is the number of iterations or search times), the maximum number of iterations is set,  $\tau_j$  and  $\Delta \tau_{ij}$  are initialized
- Step 2:** All the ants are placed at the respective initial neighborhood, each ant moves or makes neighborhood search according to the probability
- Step 3:** The objective function of each ant calculated and the current optimal solution is recorded
- Step 4:** In accordance with the renewal equation, the neighborhood attraction intensity of the region is corrected
- Step 5:** Let  $N$  be equal to  $N+1$ , If  $N$  is less than a predetermined number of iterations, then the program goes to step 2
- Step 6:** The optimal solution is obtained

**Optimization design of the mechanism:** The ant colony algorithm is used to optimize the objective function, the parameter values are  $m = 30$ ,  $N_{max} = 60$ ,  $h = 1$ ,  $s = 1$ ,  $\rho = 0.7$  and  $Q = 100$ . The ranges of the posture angles which are obtained by solid works are  $\alpha \in [-30^\circ, 30^\circ]$ ,  $\beta \in [-30^\circ, 30^\circ]$  and  $\gamma \in [-30^\circ, 30^\circ]$ .

The results of the optimization are  $l_{11} = l_{14} = 90.3$  mm,  $l_{11} = l_{14} = 90$  mm is taken. In this case,  $\eta = 0.525$ ,  $\zeta_a = 0.679$ ,  $f(x) = 1.689$ .

Based on the above result and considering the processing and assembly technology, a shoulder joint is designed (Zhang *et al.*, 2010), as shown in Fig. 2, The technical parameters of the shoulder are listed in Table 1. The drivers and rods connected to the frame, rods connected to the frame and the connecting rod, the connecting rod and moving platform are connected by a revolute pair



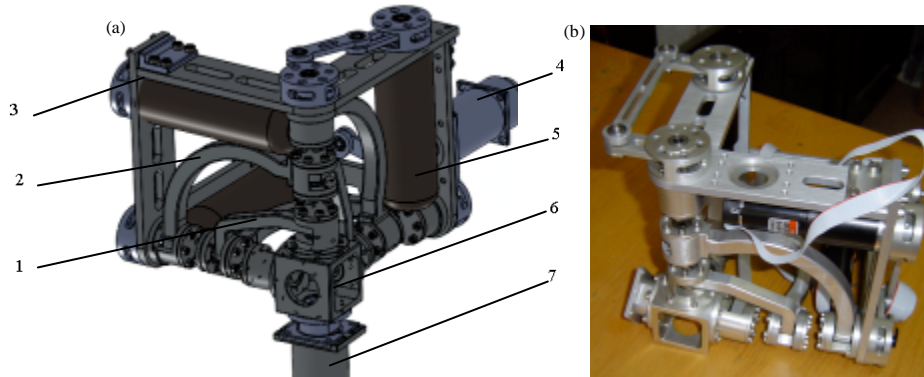


Fig. 2(a-b): Shoulder joint, (a) Shoulder joint model and (b) Shoulder joint prototype, 1: Connecting rod, 2: Frame link, 3: Frame, 4: Trunk connector, 5: Actuator, 6: Moving platform and 7: Big arm

Table 1: Technical parameters of shoulder

Name	Size/type
$l_1$ / (mm)	90
$l_2$ / (mm)	60
$l_3$ / (mm)	150
Motor model	MAXON 218012
Coupling model	MAXON 223085
Encoder type	MR TL 256-1024 CPT

respectively. All revolute axes of the mechanism intersect at one point. The axes of three revolute joints connected with the fixed base are vertical to each other and the axes of three revolute joints connected with the mobile platform are vertical to each other and the revolute joint axes of framed links and connecting rods are vertical to each other too. So, the shoulder joint parallel mechanism possesses advantages in terms of compact structure, easy processing and manufacturing. Moreover, the drivers are fixed on the fixed parts. This makes it possible that the moving components of the shoulder joint do not bear any loads of the driver. This enables large powerful drivers to drive relatively small structures. With respect to the series shoulder joint, the shoulder possesses the advantages of compact structure, bearing ability and low inertia.

## CONCLUSION

The global dexterity index and driving performance index which meet the design work space requirements and the constrained conditions are used as the optimal objective and the optimization model of shoulder structure design is established.

Ant colony algorithm is used to optimize the structure parameters of the mechanism, dimensional synthesis of the shoulder is carried out and the optimal scale parameter values are given. With the mechanism for the prototype, a shoulder joint of humanoid robot is designed. It has the advantages of compact structure, easy manufacturing, strong carrying capacity and lower motion inertia etc.

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