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Service robot passive safety impedance mechanism design and dynamics analysis

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Abstract. The wide application of service robot caused security problems between humans and robots. Through the theoretical analysis and mathematical formula based on the calculation. Designing a novel safe impedance joint mechanism consisting of an inclined link, a slider with rollers, and linear springs is proposed. Analysis the institutions of different friction between rollers and tilt links in the form of organization function at the same time. Using solidworks software to mechanism of 3D modeling, the design of two different partial CAM model, importing ADAMS software and analysis the function, Comparison between simulation data and experimental data consistency, for later used in robot mechanical arm to provide a theoretical basis.

Introduction

In recent years,with the constant development and widespread application of service robot, people hope that service robots can not only coexist with human in the environment, but also provide various services for human.However, there are still some security problems in human-computer interaction.Safety problem on interaction between service robots and people has become an more and more important issue to the development of the service robot .

In order to realize the harmonious human-computer interaction, many scholars have put forward an idea of elasticity security mechanism[2],and have carried on thorough researching and exploring. Currently the development of compliance can be divided into two type:active type and passive type. The mechanical arm based on compliant passive type is usually composed of mechanical elements,such as springs and flexible connecting rods.This type can provide appropriate responses in the way of its institutions,which also plays an important role of absorbing and slowing down external impacts.It also has the advantages of having a short reaction time and no damage to electronic components,so it can achieve a stable protection.Safety mechanical arm based on active type is formed by electronic components,such as sensors and control components.This method may cause a class of disadvantages of low response,loud noise,appearance of brake failure,and high cost of manufacturing.Comparing the two methods, the passive adaptation type does not need any sensors or brakes, so in dynamic collision it can provide a fast and stabile response.Aiming at the safety problem of dynamic collision,it is very necessary to design a mechanism,which has characteristics of the flexibility,rapid response,and tending to be an ideal security mechanism.

In order to achieve these ideal characteristics, foreign scholars have already done lots of related researches.For example,an MIA design of Waseda University in Japan,RCC institutions of the United States Northwestern University, etc. These mechanisms are security mechanisms based on the theory of passive compliant security.However,after testing we found that though the MIA mechanism has the advantages of simple and perfect linear model of control mode, considering the arm's weight and only 0.5kg of the bearing capacity at the end, its weight and volume of the adjustable system are indeed too large; RCC mechanism is still in the stage of theoretical research.By comparing the advantages and disadvantages of these institutions, this paper introduces a new design of the security mechanism which has a passive[3,4] concept. Moreover the mechanism has a small size, light weight and an ability of bearing heavier load.Meanwhile through the theoretical calculation and experimental verification,we proved whether the designed mechanism has safety performance.

The Establishment About Mechanism Model Of Impedance Institutions

Wedge mechanism can have a slowly sliding state when in a collision with a roller and play a buffer role against external impact force.By improving Wedge mechanism, this paper advances and designs a new passive safety resistant model [3].

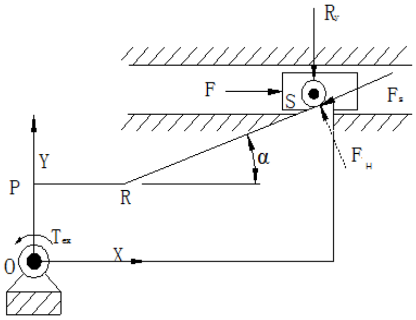

Fig. 1 The tilting mechanism with a slider

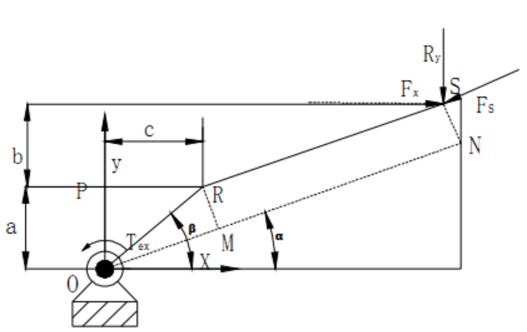

Fig. 2 The detailed analysis diagram of the inclined connection

Fig. 1 is a mechanism sketch about a tilting mechanism with a slider.In Fig. 2 we give a detailed graphical analysis on Fig. 1 in view of the force equilibrium equation at each point , and draw several equations. Equations are as follows:

Establish the force balance equations of x, y direction at the S point:

$$\begin{cases} F_x - F_s \cdot \cos\alpha - F \cdot \sin\alpha = 0 \\ R_Y + F_s \cdot \sin\alpha - F \cdot \cos\alpha = 0 \end{cases} \tag{1}$$

Among them：

$$\begin{cases} OR = \sqrt{a^2 + c^2} \\ OM = \cos(\beta - \alpha) \cdot OR \\ l = OM + MN \end{cases} \tag{2}$$

According to the torque balance equation：

$$T_{ex} = F \cdot l \tag{3}$$

l is the distance between the action point of force F and the origin .

Considering the above equations about the relationship between the torque T_{ex} and power F ,we get an equation that is as follows:

$$T_{ex} = \left(\sqrt{a^2 + c^2}\,\frac{\cos(\alpha - \beta)}{\sin\alpha} + \frac{b}{\sin^2\alpha}\right)(F - F_s\cos\alpha) \tag{4}$$

In the equation, the tilt angle α is an angle between inclined plane and horizontal surface, as the angle β is an angle between OR and the horizontal plane. The parameter a is the vertical height of the wedge improved mechanism, B is the height of the tilt, and C is the length of horizontal section of the wedge mechanism. The specific annotation is as shown in Fig. 2.

Since the spring provides elastic properties,the spring can be instead of the force F in Fig. 1 .The schematic diagram is as shown in Fig. 3:

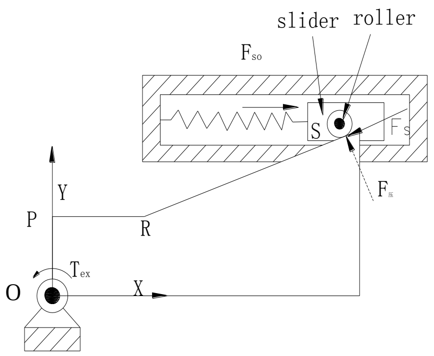

Fig. 3 A tilting mechanism with a spring and slider

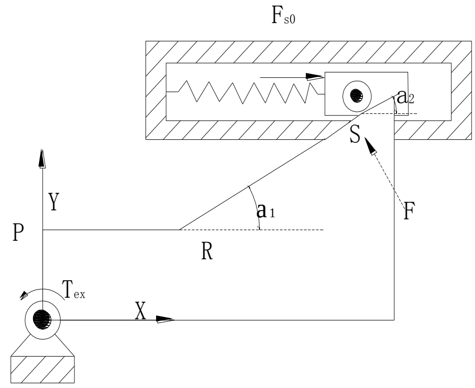

Fig. 4 Improved organization chart

In Fig. 3, when the role of external torque T_{ex} acts on the inclined connection mechanism, the inclined connection will rotate around O and contact the roller arranged on the slider ,which can be kept in a state of the static equilibrium by the resultant force acting on the sliding block along the X direction as shown in Fig. 3.

The linear equation of the spring force and displacement:

$$F = k \cdot s_0 \tag{5}$$

$$T_{ex} = (\sqrt{a^2 + c^2}\frac{\cos(\alpha - \beta)}{\sin\alpha} + \frac{b}{\sin^2\alpha})(ks_0 - F_s\cos\alpha) \tag{6}$$

k is the stiffness coefficient of spring, S_0 is the initial length of the spring, and F is the elastic restoring force of the spring .F_s= F_{Total} • f, F_{Total} is F and R_y's resultant force.F_{Total} is the resultant force of F and R_y.(Friction coefficient f of the collision respectively between aluminum alloys are 0.25 and 0.2;)

$$\frac{T_{ex}}{F} = (\sqrt{a^2 + c^2}\frac{\cos(\alpha - \beta)}{\sin\alpha} + \frac{b}{\sin^2\alpha})(1 - \frac{f}{\tan\alpha}) \tag{7}$$

According to these two kinds of friction, we calculate and analyze the Eq. 6 and Eq. 7 by using the software of Matlab, and moreover we draw the curves about the relation between the torque or force and the angle under the two different types of friction, which are shown as below, Fig. 4 and Fig. 5.

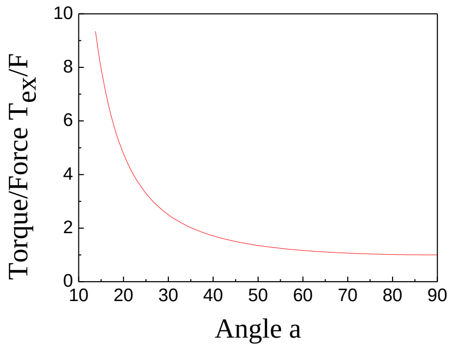

Fig. 5 The curve about the relation between torque or force and angle under the rolling friction

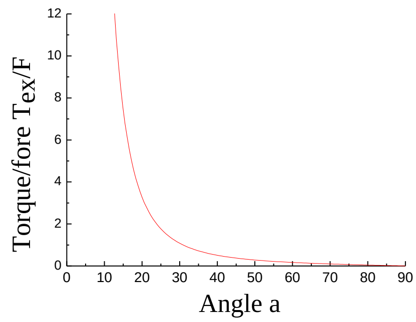

Fig. 6 The curve about the relationship between torque or force and angle under the sliding friction

By comparing Fig. 5 and Fig. 6, we found that under the condition of a smaller angle, sliding friction force can produce a larger torque than the rolling one. Therefore we tend to choose the sliding friction.

Through the analysis we found that as the tilt angle increases, the critical torque will decrease,which affects the position precision of the mechanism.So we have improved upon the organization chart (Fig.4). Using two inclined contacting surfaces of different angles can cause a much larger torque when there is a small inclination angle. When the rotation occurs, it will enter the second inclined plane, and stiffness of the mechanism will suddenly drop so as to alleviate the impact of the external force.

After theoretical calculating and analyzing,designing the following new institutions as shown in Fig. 7:

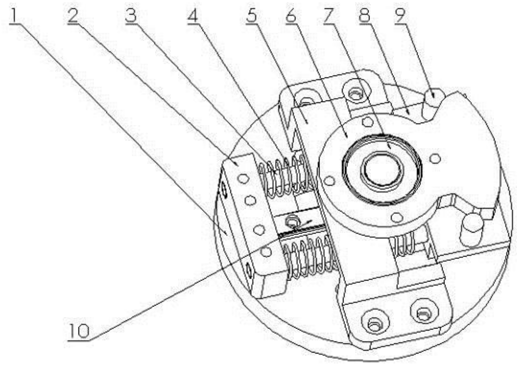

Fig. 7 Sketch of the Impedance mechanism
1- base, 2- mounting bracket, 3- rod, 4- spring, 5-support, 6- cam, 7- deep groove ball bearings, 8-block, 9- roller , 10-guide rail

The operational principles: Cam 6 is connected with the external part. When subjected to external shocks, cam 6 will begin to rotate, and drive roller 9 and block 8 to slide along guide rod 3, which compresses the spring 4.

According To Dynamics Modeling Of Contacting Collision Between The Cam And Roller

In the design of new institutions, impact contact will conduct instantaneous deformation between the cam and roller. Before the collision, system dynamic equations can be expressed as:

$$\begin{cases} M\ddot{q} + Kq + \phi_q^T = Q + F_g \\ \phi(q,t) = 0 \end{cases} \tag{8}$$

In the equations, q is the array of the generalized coordinates, F_g is the array of generalized force about the contact force F which is relative to the msem coordinates q; M, K, ϕ_q and Q respectively is generalized mass matrix, stiffness matrix, Jacobian matrix of the constraint equations $\phi(q,t)=0$, generalized speed quadratic term and generalized force matrix of the multi-body system; λ is the array of the Lagrange multiplier.

Considering that the collision body has a speed "step" and energy loss before and after the collision, basing on generalized impulse and momentum theorem we obtain the generalized impulse of the system reaction and the system velocity mutation. Assuming that the collision between the two body is rigid, the collision occurs in a very short time zone $t_i^- < t < t_i^+$,and the system configuration is unchanged before and after collision time zone [t_i^-, t_i^+], which means the generalized coordinates of the system is not changed $q(t_i^-) = q(t_i^+)$, dynamic equations of the system can be obtained :

$$\begin{bmatrix} M & \phi & H^T \\ \phi_q & 0 & 0 \\ H & 0 & 0 \end{bmatrix} \begin{Bmatrix} \Delta\dot{q} \\ P^{\lambda} \\ P \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ \phi \end{Bmatrix} \tag{9}$$

In the equations, $\Delta \dot{q}$ is a generalized velocity increment array; P^{λ} is a generalized impulse array of constraint counterforce $P^{\lambda} = \lim_{\Delta \to 0} \int_{t_i^-}^{t_i^+} \lambda dt$;P is a generalized impulse array of the generalized force. $P^{\lambda} = \lim_{\Delta \to 0} \int_{t_i^-}^{t_i^+} F(t)dt$; $F(t)$ is a collision force for clearance; $H = \dfrac{\partial S}{\partial q}$, $S = (q,t)$ is the distance array between the collision points; $\phi = -(1+e)H\dot{q}(t_i^-)$.

At present, to the kinematic analysis of mechanism, although we only consider the influence of the sliding friction between the clearance joints and ignore the effect of rolling friction torque and rotational friction torque, it is feasible for most engineering problems in the allowed error range.

Simulation Analysis

Through establishing the mathematical equations and deducing the theories on the above institutions, this paper designed a new type of passive compliance mechanism, using a 3D Modeling Software Solidworks to establish the three-dimensional model. The parameters of radius is 35mm. Import the simplified geometric file of the solid model into ADAMS, and edit properties and properties of composition elements of the component, including colors, locations, names, material properties and other information. According to different α_2 degrees, we set two parameters, then on the basis of which we design and do the dynamic simulation.

$a = 10\text{mm}, b = 5\text{mm}, c = 15\text{mm}, \alpha_1 = 50°$, $\alpha_2 = 13°$, $\beta = 34°; \alpha_2 = 25^{\circ}, \beta = 34^{\circ}$.

Definitions of Parameters . In ADAMS,we set the parameters of the 3D model ,material is defined as 7075 (density 2810kg/m^3),added the torque $T_{ex} = 7.5N \cdot \text{m}$, defined parameters of the spring : spring coefficient $\text{k} = 3\text{k}N/\text{m}$, damping coefficient $c = 1.2E - 004N \cdot \text{s}/\text{m}$, increased the contact force between the cam and roller,and set the friction (here is the sliding friction force).

Adding The Constraints. We added motion pairs, contact forces and friction forces in each link. Then after the above settings, we analyzed the simulation results in the ADAMS, which told the spring force required in the moment of a deflection of the mechanism and at the same time got the changing curves when there were forces acting on the spring.The curves are shown in Fig. 8 and Fig. 9:

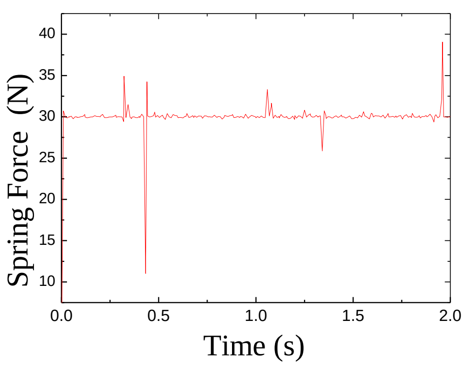

Fig. 8 The curve of the spring force and the time when the angle is 25 °

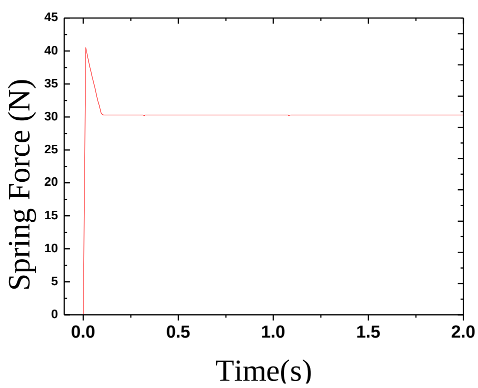

Fig. 9 The curve of the spring force and the time when the angle is 13 °

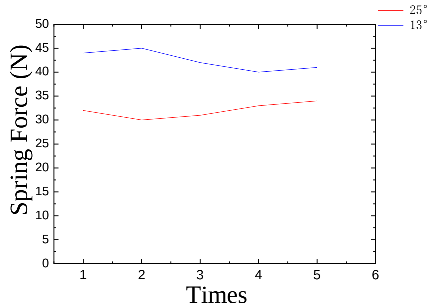

Fig. 10 A plotting graph of the experimental data

By putting the experimental data into equation (4),we can obtain the results shown in table 1:

Table 1 Experimental data of the Prototype

Operating condition	Theoretical value	Experiment value				
	Force （N）					
		1	2	3	4	5
25°	30	32	30	31	35	34
13°	43	44	45	42	39	41

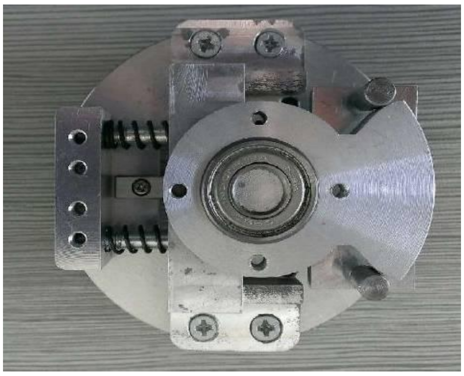

Fig. 11 Actual mode of the prototype

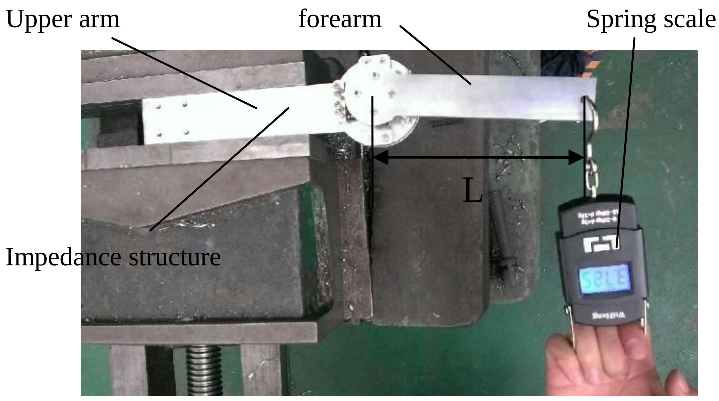

Fig. 12 Test pattern of the experiment

The distance L between action point of the testing force and rotating shaft is 180mm.Through the critical value on static balance of security mechanism tested by the spring, comparison about the curves achieved by the experimental data and analyzing the simulation data, the theoretical value is very close to the simulation value; Besides we found when the institution is 13°, the experimental value is closer to simulation value, and the mechanism has a certain stability to the external reaction.

Conclusions

Through the safety performance analysis of security mechanism design, we can conclude : First the mechanism can make a rapid response so that mitigate the impact force when it is subjected to external impact force;Then the critical spring force values obtained by simulation are in a good agreement with the experimental measured data; Also experiment showed that the changing of tilt angle would have a greater influence on institutional safety, which can provide a theoretical basis for later new model applied in the service robot arm.

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