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Stiffness Optimization Design of a Light Space Manipulator

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***Abstract* -A light space manipulator is essential for space activities, the stiffness of such a light manipulator is a crucial problem. In this paper, a method of stiffness optimization is presented to improve the stiffness of a light space manipulator. First, the stiffness model is established, then, an optimization algorithm based on mass allocation is proposed. Finally, the effectiveness of our proposed method is confirmed by the experiments using our developed prototype of a six DOF manipulator.**

Index Terms - Space manipulator, Stiffness, Optimization

I. INTRODUCTION

Manipulators are playing a critical roll in space activities. A manipulator was used for module redocking on the MIR [1,2]. The SRMS [3-5] (Shuttle Remote Manipulator System), known as Canadarm, has performed perfectly for years since 1981. The SRMS has placed satellites into their orbit, repaired the Hubble Space Telescope, and was used as a mobile work platform for astronauts during space walks. The SRMS is 15.2 m in length and 410 Kg in weight. The diameter of the arm boom is 38 cm. The Space Station Remote Manipulator System (SSRMS) [6-9], known as Canadarm2, is playing a critical role in the external maintenance and operations of the International Space Station. The length of SSRMS is 17.6 m and the weight is 1,800 Kg.

The above mentioned manipulators are large and heavy. On the other hand, a light space manipulator is essential for some space activities, for example, monitoring the docking of two spacecraft and taking photography of some specified areas on the spacecraft. If the space manipulator is installed on the surface of spacecraft, the outline should be limited in the narrow space between the spacecraft and the fairing of carrier rocket. So the manipulator should be compact and light. For example, the length should be less than 3 m and the weight should be less than 30 Kg.

Stiffness is a crucial problem for the light space manipulator. High stiffness can significantly reduce coupled vibration and dynamic load during launching. The accuracy and dynamic response are also influenced by stiffness. But it is very difficult to construct a high stiffness space manipulator with the limited mass since high stiffness manipulator usually requires high expenditure on mass and volume.

An optimum mass allocation can significantly improve the combined stiffness of a light space manipulator since the combined stiffness is determined by the component stiffness which is mainly determined by the component mass.

In this paper, we proposed a stiffness optimization design method based on mass allocation. The organization of this paper is as follows: In Section 2, we provide the general description of the light space manipulator. In Section 3, the stiffness model of the light space manipulator is established, and the relation between deflection and mass is presented. In Section 4, the optimization algorithm is proposed based on the Lagrange Multiplier Method, the optimum mass allocation is calculated, and the least deflection is evaluated. In section 5, the results of optimization are analyzed, and then the material and optimum dimension is proposed. In Section 6, a prototype of a 6 DOF manipulator is presented, and the optimum stiffness is measured.

II. DESCRIPTION OF THE LIGHT SPACE MANIPULATOR

The light space manipulator has six degrees of freedom and consists of a shoulder, elbow and wrist separated by an upper and a lower arm. There are six joints according to the six degrees of freedom: shoulder raw joint, shoulder pitch joint, elbow pitch joint, wrist pitch joint, wrist yaw joint, wrist roll joint, as shown in Fig 1.

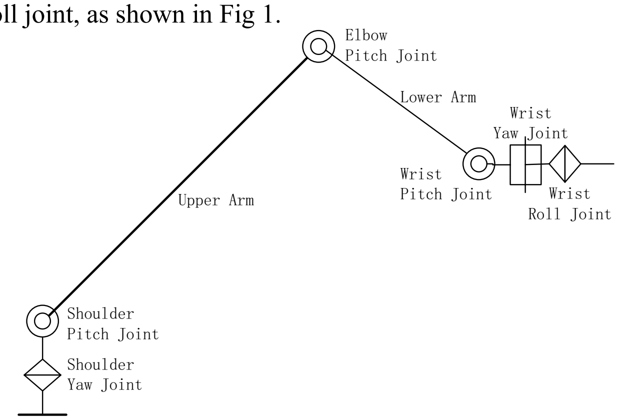

Fig1 Six degrees of freedom in the manipulator

Three different types of joint with similar architecture were employed: shoulder joint, elbow joint, and wrist joint. Each joint is driven by a harmonic gear reducer.

III. STIFFNESS MODEL

The main structure of the light space manipulator is arm and joint. Joint model and arm model are established, and the combined deflection of the light space manipulator is calculated.

A. Arm Model

The external force on arm include: axial force F_a, radial force F_r, axial torque M_a, radial torque M_r, as shown in Fig. 2.

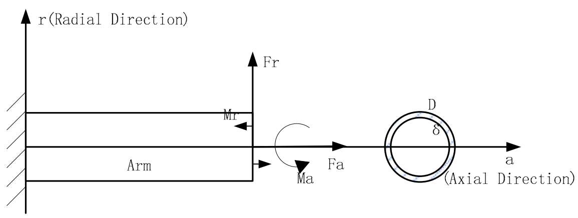

Fig2. External force on arm

The length of the arm is l, the density is ρ. The section of the arm is a torus, the diameter of the torus is D, and the thickness of the torus is in direct proportion to D, as in (1).

$$\delta = K_\delta D \tag{1}$$

The arm's mass is in direct proportion to D^2, as in (2).

$$m = \rho K_A l D^2 \qquad K_A = \pi K_\delta (1 - K_\delta) \tag{2}$$

The inertia moment of arm's section is in direct proportion to D^4 and m^2 as in (3).

$$I = \frac{1 - 2K_\delta + 2K_\delta^2}{8\pi\rho^2 (K_\delta - K_\delta^2) l^2} m^2 = K_I \left(\frac{m}{\rho l}\right)^2 \qquad K_I = \frac{1 - 2K_\delta + 2K_\delta^2}{8\pi (K_\delta - K_\delta^2)} \tag{3}$$

The deflection of arm is r, as in (4).

$$r = \frac{\rho^2 l^4}{K_I E m^2}\left(\frac{1}{3}F_r l + \frac{1}{2} M_r\right) \tag{4}$$

The deflection angle is θ, as in (5).

$$\theta = \frac{\rho^2 l^3}{K_I E m^2}\left(\frac{1}{2}F_r l + M_r\right) \tag{5}$$

The torsion deformation is γ, as in (6).

$$\gamma = \frac{(1+\mu)\rho^2 l^3}{K_I E m^2} M_a \tag{6}$$

The deflection and deformation are in inverse proportion to m^2.

The arm's deformation in axial direction is a, as in (7).

$$a = \frac{\rho}{E} \cdot \frac{l^2}{m} \cdot F_a \tag{7}$$

In the situation of F_a=F_r, the ratio of deformation caused by F_a to F_r is α / γ, as in (8)

$$\frac{a}{r} = \frac{3\left(D^2 + (D - 2K_\delta D)^2\right)}{16 l^2} < \frac{3}{8}\left(\frac{D}{l}\right)^2 \tag{8}$$

The length of the arms is bigger than the treble diameter, as in (9).

$$if\,(l > 3D), then \left(\frac{a}{r} < \frac{1}{24}\right) \tag{9}$$

If F_a is equivalent to F_r, the axial deformation can be ignored.

B. Joint Model

The external force on joint include: axial force F_a, radial force F_r, axial torque M_a, radial torque M_r, as shown in Fig. 3.

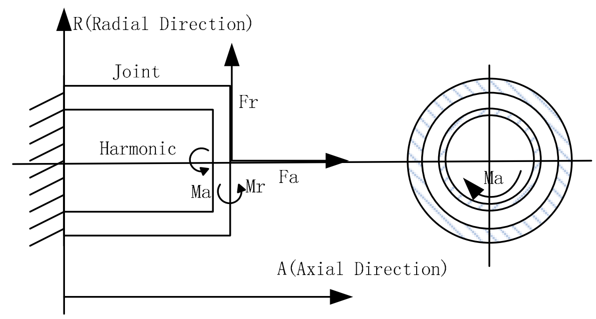

Fig3. External force on joint

The axial force F_a, radial force F_r, radial torque M_r are applied on the joint's bearing, and axial torque M_a is applied on the harmonic gear reducer. The joint bearing is much more rigid than the harmonic gear, therefore the joint's stiffness is mainly decided by the harmonic gear.

The section of the harmonic flexspline is a torus, and the diameter is D. For the harmonic flexspline, the thickness δ and length l are in direct proportion to D, as in (10).

$$\delta = k_\delta D, \quad l = k_l D \tag{10}$$

The joint's mass is in direct proportion to D^3, as in (12).

$$m = k_m D^3 \tag{12}$$

The inertia moment of harmonic flexspline section is in direct proportion to D^4, as in (13).

$$I = \frac{\pi k_\delta}{4} D^4 \tag{13}$$

The torsion deformation of the harmonic gear reducer is φ, as in (14).

$$\phi = \frac{4(\mu + 1) K_l K_m}{\pi K_\delta E m} \cdot M_a \tag{14}$$

The torsion deformation is in inverse proportion to the joint's mass.

C. Combined Deflection

In the environment of microgravity, the force and torque applied on the light manipulator is caused by the inertia of the load. The external force on the light space manipulator is $\{F_x, F_y, F_z, M_x, M_y, M_z\}$, As shown in Fig. 4.

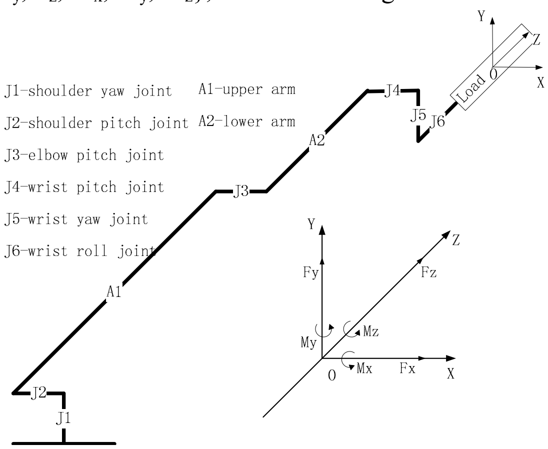

Fig4. External force on the light space manipulator

The length of upper arm is l_{A1}, the length of lower arm is l_{A2}, the distance between the centroid of the load and the manipulator's end is l_{load}. The load mass is m_{load}, the load acceleration is $\{a_x, a_y, a_z, \varepsilon_x, \varepsilon_y, \varepsilon_z\}$, limited by a_{max} and ε_{max}, as in (15).

$$\sqrt{a_x^2+a_y^2+a_z^2} \le a_{\max}, \sqrt{\varepsilon_x^2+\varepsilon_y^2+\varepsilon_z^2} \le \varepsilon_{\max} \tag{15}$$

The deflection of the manipulator is supreme when the light space manipulator is fully expanding and driving the load in maximal acceleration. In the situation of fully expanding, the deflection is supreme when the force and torque are applied on the y direction, as in (16).

$$a_y = a_{\max}, \ \varepsilon_y = \varepsilon_{\max} \tag{16}$$

When the deflection is ultimate, the light space manipulator is fully expanding, and the load is in maximal acceleration in y direction.

The torque applied on the shoulder pitch joint is M_{J2}, as in (17).

$$M_{J2} = m_{load}a_{\max}\left(l_{A1}+l_{A2}+l_{load}\right)+I_{load}\varepsilon_{\max} \tag{17}$$

The torque applied on the elbow pitch joint is M_{J3}, as in (18).

$$M_{J3} = m_{load}a_{\max}\left(l_{A2}+l_{load}\right)+I_{load}\varepsilon_{\max} \tag{18}$$

The torque applied on the elbow pitch joint is M_{J4}, as in (19).

$$M_{J4} = m_{load}a_{\max}l_{load}+I_{load}\varepsilon_{\max} \tag{19}$$

The force applied on the upper arm and lower arm is F_{max}, as in (20).

$$F_{\max} = m_{load}a_{\max} \tag{20}$$

The ultimate deflection of the light space manipulator is shown in Fig. 5.

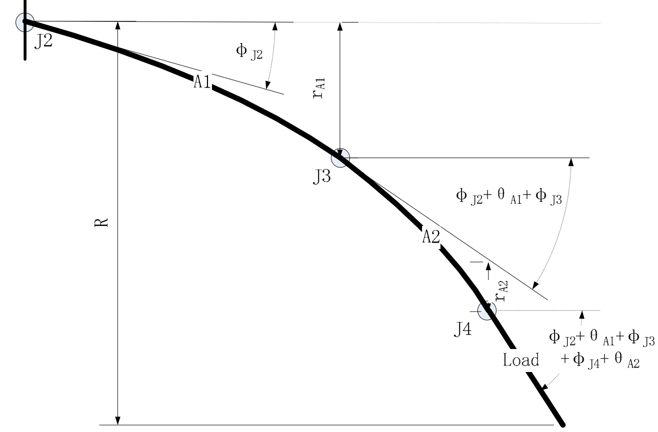

Fig5. The deflection of the light space manipulator

The torsion deformation of joints is φ_{J2}, φ_{J3}, φ_{J4}, as in (21), (22) and (23).

$$\phi_{J2} = \frac{4(\mu+1)K_lK_m}{\pi K_\delta E}\cdot\frac{\left(m_{load}a_{\max}\left(l_{A1}+l_{A2}+l_{load}\right)+I_{load}\varepsilon_{\max}\right)}{m_{J2}} \tag{21}$$

$$\phi_{J3} = \frac{4(\mu+1)K_lK_m}{\pi K_\delta E}\cdot\frac{\left(m_{load}a_{\max}\left(l_{A2}+l_{load}\right)+I_{load}\varepsilon_{\max}\right)}{m_{J3}} \tag{22}$$

$$\phi_{J4} = \frac{4(\mu+1)K_lK_m}{\pi K_\delta E}\cdot\frac{\left(m_{load}a_{\max}l_{load}+I_{load}\varepsilon_{\max}\right)}{m_{J4}} \tag{23}$$

The deflection of upper arm and lower arm is r_{A1} and r_{A2}, as in (24) and (25).

$$r_{A1} = \frac{\rho^2 l_{A1}^4}{K_l E m_{A1}^2}\left(\frac{1}{3}m_{load}a_{\max}l_{A1}+\frac{1}{2}\left(m_{load}a_{\max}\left(l_{A2}+l_{load}\right)+I_{load}\varepsilon_{\max}\right)\right) \tag{24}$$

$$r_{A2} = \frac{\rho^2 l_{A2}^4}{K_l E m_{A2}^2}\left(\frac{1}{3}m_{load}a_{\max}l_{A2}+\frac{1}{2}\left(m_{load}a_{\max}l_{load}+I_{load}\varepsilon_{\max}\right)\right) \tag{25}$$

The deflection angle of upper arm and lower arm is θ_{A1} and θ_{A2}, as in (26) and (27).

$$\theta_{A1} = \frac{\rho^2 l_{A1}^3}{K_l E m_{A1}^2}\left(\frac{1}{2}m_{load}a_{\max}l_{A1}+m_{load}a_{\max}\left(l_{A2}+l_{load}\right)+I_{load}\varepsilon_{\max}\right) \tag{26}$$

$$\theta_{A2} = \frac{\rho^2 l_{A2}^3}{K_l E m_{A2}^2}\left(\frac{1}{2}m_{load}a_{\max}l_{A1}+m_{load}a_{\max}l_{load}+I_{load}\varepsilon_{\max}\right) \tag{27}$$

The combined deflection of the light space manipulator is R, as in (28).

$$R = \phi_{J2}\left(l_{A1}+l_{A2}+l_{load}\right)+\left(\theta_{A1}+\phi_{J3}\right)\left(l_{A2}+l_{load}\right)+\left(\theta_{A2}+\phi_{J4}\right)l_{load}+r_{A1}+r_{A2} \tag{28}$$

The combined deflection is the summation of joint's deformation R_J and arm's deflection R_A, as in (29)

$$R = R_J + R_A \tag{29}$$

The combined deflection caused by joints is R_J, as in (30)

$$R_J = \phi_{J2}(l_{A1}+l_{A2}+l_{load})+\phi_{J3}(l_{A2}+l_{load})+\phi_{J4}l_{load} = \frac{4(\mu+1)K_lK_m}{\pi K_\delta E}\left(\begin{array}{l} m_{load}a_{\max}\left(\frac{(l_{A1}+l_{A2}+l_{load})^2}{m_{J2}}+\frac{(l_{A2}+l_{load})^2}{m_{J3}}+\frac{l_{load}^2}{m_{J4}}\right)+ \\ I_{load}\varepsilon_{\max}\left(\frac{(l_{A1}+l_{A2}+l_{load})}{m_{J2}}+\frac{(l_{A2}+l_{load})}{m_{J3}}+\frac{l_{load}}{m_{J4}}\right)\end{array}\right) \tag{30}$$

The combined deflection caused by arms is R_A, as in (31).

$$R_A = r_{A1}+\theta_{A1}(l_{A2}+l_{load})+r_{A2}+\theta_{A2}l_{load} = \frac{\rho^2}{K_I E}\left(\begin{array}{l} m_{load}a_{\max}\left(\begin{array}{l}\dfrac{l_{A1}^3\left(\frac{l_{A1}^2}{3}+(l_{A1}+l_{A2}+l_{load})(l_{A2}+l_{load})\right)}{m_{A1}^2} \\ +\dfrac{l_{A2}^3\left(\frac{l_{A2}^2}{3}+\frac{(l_{A1}+l_{A2})l_{load}}{2}+l_{load}^2\right)}{m_{A2}^2}\end{array}\right)+ \\ I_{load}\varepsilon_{\max}\left(\dfrac{l_{A1}^3\left(\frac{l_{A1}}{2}+l_{A2}+l_{load}\right)}{m_{A1}^2}+\dfrac{l_{A2}^3\left(\frac{l_{A2}}{2}+l_{load}\right)}{m_{A2}^2}\right)\end{array}\right) \tag{31}$$

IV. Optimization

The constraint condition of optimization is the gross mass of the light space manipulator. The optimization result is the optimal proportion of joint or arm in the goose mass.

The first step is to optimize the joints and arms separately. The optimal mass proportion between joints and is evaluated, and the deflection of a certain gross joint mass with the optimal proportion is calculated. Then the optimal mass proportion between arms and the minimal deflection of a certain gross arms mass are also evaluated.

The second step is to get the best mass proportion between joint and arm. The minimal combined deflection of the light manipulator can be calculated.

A. Joints Optimization

If the summary of the joint's mass m_J is invariable, the deflection caused by the joints is decided by the proportion between joints.

A single shoulder joint's mass is m_s ($m_s = m_{J1} = m_{J2}$), an elbow joint's mass is m_e ($m_e = m_{J3}$), and a single wrist joint's mass is m_W ($m_W = m_{J4} = m_{J5} = m_{J6}$). The summary of joint's mass is m_J($m_J = 2m_S + m_E + 3m_W$).

The optimization of joint's mass allocation is to calculate the minimal value of R_J in the condition of $m_J = 2m_{J2}+m_{J3}+3m_{J4}$.

The Lagrange Multiplier Method is adopted to optimize the allocation of mass. An assistant function is constructed, as in (32).

$$F(m_{J2},m_{J3},m_{J4}) = R_J(m_{J2},m_{J3},m_{J4})+\lambda(2m_{J2}+m_{J3}+3m_{J4}-m_J) \tag{32}$$

Set:

$$\begin{cases} F'_{m_{J2}}(m_{J2},m_{J3},m_{J4})=0 \\ F'_{m_{J3}}(m_{J2},m_{J3},m_{J4})=0 \\ F'_{m_{J4}}(m_{J2},m_{J3},m_{J4})=0 \end{cases} \tag{33}$$

The optimal proportion of joint mass allocation can be evaluated, as in (34).

$$m_{J2}/m_{J3}/m_{J4} = m_S/m_E/m_W = \sqrt{\frac{m_{load}a_{\max}(l_{A1}+l_{A2}+l_{load})^2+I_{load}\varepsilon_{\max}(l_{A1}+l_{A2}+l_{load})}{2}} \Big/ \sqrt{m_{load}a_{\max}(l_{A2}+l_{load})^2+I_{load}\varepsilon_{\max}(l_{A2}+l_{load})} \Big/ \sqrt{\frac{m_{load}a_{\max}l_{load}{}^2+I_{load}\varepsilon_{\max}l_{load}}{3}} \tag{34}$$

Then the minimal deflection caused by joints can be calculated, as in (35).

$$R_J = \frac{4(\mu+1)K_lK_m}{\pi K_\delta E}\left(\begin{array}{l}\sqrt{2\left(\begin{array}{l}m_{load}a_{\max}(l_{A1}+l_{A2}+l_{load})^2+ \\ I_{load}\varepsilon_{\max}(l_{A1}+l_{A2}+l_{load})\end{array}\right)}+ \\ \sqrt{\begin{array}{l}m_{load}a_{\max}(l_{A2}+l_{load})^2+ \\ I_{load}\varepsilon_{\max}(l_{A2}+l_{load})\end{array}}+ \\ \sqrt{3\left(\begin{array}{l}m_{load}a_{\max}l_{load}{}^2+ \\ I_{load}\varepsilon_{\max}l_{load}\end{array}\right)}\end{array}\right)^2\frac{1}{m_J} \tag{35}$$

The coefficient of $1/m_J$ is K_J, as in (36).

$$K_J = \frac{4(\mu+1)K_lK_m}{\pi K_\delta E}\left(\begin{array}{l}\sqrt{2\left(\begin{array}{l}m_{load}a_{\max}(l_{A1}+l_{A2}+l_{load})^2+ \\ I_{load}\varepsilon_{\max}(l_{A1}+l_{A2}+l_{load})\end{array}\right)}+ \\ \sqrt{\begin{array}{l}m_{load}a_{\max}(l_{A2}+l_{load})^2+ \\ I_{load}\varepsilon_{\max}(l_{A2}+l_{load})\end{array}}+ \\ \sqrt{3\left(\begin{array}{l}m_{load}a_{\max}l_{load}{}^2+ \\ I_{load}\varepsilon_{\max}l_{load}\end{array}\right)}\end{array}\right)^2 \tag{36}$$

R_J can be denoted as (37)

$$R_J = K_J/m_J \tag{37}$$

The minimal deflection caused by joints is in reverse proportion to the joint's gross mass.

B. Arms Optimization

If the gross arm mass m_A is invariable, the deflection caused by the arms is decided by the mass allocation of arms. The optimization of arm's mass allocation is to calculate the minimal value of R_A in the condition of $m_A = m_{A1} + m_{A2}$.
The Lagrange assistant function is shown in (38).

$$F(m_{A1},m_{A2}) = R_A(m_{A1},m_{A2})+\lambda(m_{A1}+m_{A2}-m_A) \tag{38}$$

Set:

$$\begin{cases} F'_{m_{A1}}\left(m_{A1}, m_{A2}\right) = 0 \\ F'_{m_{A2}}\left(m_{A1}, m_{A2}\right) = 0 \end{cases} \tag{39}$$

The optimal proportion of joint mass allocation can be evaluated, as in (40).

$$\frac{m_{A1}}{m_{A2}} = \frac{l_{A1}}{l_{A2}} \frac{\sqrt[3]{m_{load} a_{\max}\left(\frac{l_{A1}^2}{3} + \left(l_{A1} + l_{A2} + l_{load}\right)\left(l_{A2} + l_{load}\right)\right) + I_{load}\varepsilon_{\max}\left(\frac{l_{A1}}{2} + l_{A2} + l_{load}\right)}}{\sqrt[3]{m_{load} a_{\max}\left(\frac{l_{A2}^2}{3} + \frac{\left(l_{A1} + l_{A2}\right)l_{load}}{2} + l_{load}^2\right) + I_{load}\varepsilon_{\max}\left(\frac{l_{A2}}{2} + l_{load}\right)}} \tag{40}$$

The minimal deflection caused by arms can be calculated, as in (41).

$$R_A = \frac{\rho^2}{K_I E}\left(l_{A1}\sqrt[3]{m_{load}a_{\max}\left(\frac{l_{A1}^2}{3} + \left(l_{A1} + l_{A2} + l_{load}\right)\left(l_{A2} + l_{load}\right)\right) + I_{load}\varepsilon_{\max}\left(\frac{l_{A1}}{2} + l_{A2} + l_{load}\right)} + l_{A2}\sqrt[3]{m_{load}a_{\max}\left(\frac{l_{A2}^2}{3} + \frac{\left(l_{A1} + l_{A2}\right)l_{load}}{2} + l_{load}^2\right) + I_{load}\varepsilon_{\max}\left(\frac{l_{A2}}{2} + l_{load}\right)}\right)^3 \frac{1}{m_A^2} \tag{41}$$

The coefficient of $1/m_A^2$ is K_A, as in (42).

$$K_A = \frac{\rho^2}{K_I E}\left(l_{A1}\sqrt[3]{\left(m_{load}a_{\max}\left(\frac{l_{A1}^2}{3} + \left(l_{A1} + l_{A2} + l_{load}\right)\left(l_{A2} + l_{load}\right)\right) + I_{load}\varepsilon_{\max}\left(\frac{l_{A1}}{2} + l_{A2} + l_{load}\right)\right)} + l_{A2}\sqrt[3]{\left(m_{load}a_{\max}\left(\frac{l_{A2}^2}{3} + \frac{\left(l_{A1} + l_{A2}\right)l_{load}}{2} + l_{load}^2\right) + I_{load}\varepsilon_{\max}\left(\frac{l_{A2}}{2} + l_{load}\right)\right)}\right) \tag{42}$$

R_A can be denoted as (43)

$$R_A = K_A / m_A^2 \tag{43}$$

The minimal deflection caused by arms is in reverse proportion to the square of arm's gross mass.

C. Manipulator Optimization

The gross mass of the light space manipulator is invariable. In the situation of optimal arm mass allocation and optimal joint mass allocation, the combined deflection is decided by the mass proportion between joints and arms.

The combined deflection of the manipulator is R, as in (44).

$$R = R_J + R_A = \frac{K_J}{m_J} + \frac{K_A}{m_A^2} \tag{44}$$

The constraint condition is $m=m_J+m_A$.

The optimal proportion between m_J and m_A can be evaluated, as in (45)

$$\frac{m_J}{m_A} = \left(\sqrt[3]{\frac{K_J m}{4K_A} - \frac{1}{27} + \frac{K_J}{2K_A}\sqrt{\frac{m^2}{4} - \frac{2K_A m}{27K_J}}} + \sqrt[3]{\frac{K_J m}{4K_A} - \frac{1}{27} - \frac{K_J}{2K_A}\sqrt{\frac{m^2}{4} - \frac{2K_A m}{27K_J}}} - \frac{1}{3}\right) \tag{45}$$

V. Analysis

A. The Choice of Material

The deflection caused by joints is in direct proportion to K_I and K_m, and in reverse proportion to elastic modulus E and K_δ. The flexspline of harmonic gear reducer should be as short as possible and the thickness of flexspline should be enlarged. The material of harmonic gear reducer should be with high elastic modulus, and the others material of joints should be with low density.

The deflection caused by the arms is in direct proportion to the square of density, and in reverse proportion to elastic modulus E. The stiffness of the light space manipulator can be significantly improved by the reduction of density. The carbon fiber composite material is the best choice for the light space manipulator's arms.

In conclusion, the structure of the light manipulator should be made of the material with low density and high elastic modulus. The arms should be made up of carbon fiber composite material, and structure of joints should be made of aluminium magnesium alloy or titanium alloy.

B. Proportion between Joint's Diameter

When the external torque is zero, the proportion between joint's diameters is determined by the distance between joint and the load and is also determined by the joint's number of shoulder, elbow or wrist, as in (46).

$$D_S : D_E : D_W = \frac{\sqrt[3]{\left(l_{A1} + l_{A2} + l_{load}\right)}}{\sqrt[6]{2}} : \sqrt[3]{\left(l_{A2} + l_{load}\right)} : \frac{\sqrt[3]{l_{load}}}{\sqrt[6]{3}} \tag{46}$$

When the external force is zero, the proportion between joints diameter is smaller, as in (47).

$$D_S : D_E : D_W = \sqrt[6]{\frac{\left(l_{A1} + l_{A2} + l_{load}\right)}{2}} : \sqrt[6]{\left(l_{A2} + l_{load}\right)} : \sqrt[6]{\frac{l_{load}}{3}} \tag{47}$$

The proportions of two situations are similar. The force and torque is uncertain, the mean of two proportions is adopted.

C. Proportion between Arm's Diameter

The proportion between arms diameter can be predigested when the external torque is zero, as in (48).

$$\frac{D_{A1}}{D_{A2}}=\sqrt{\frac{l_{A1}}{l_{A2}}}\cdot\sqrt[6]{\frac{\left(\frac{l_{A1}^2}{3}+\left(l_{A1}+l_{A2}+l_{load}\right)\left(l_{A2}+l_{load}\right)\right)}{\left(\frac{l_{A2}^2}{3}+\frac{\left(l_{A1}+l_{A2}\right)l_{load}}{2}+l_{load}^2\right)}} \tag{48}$$

When the external force is zero, the proportion between arms diameter is shown as (49).

$$\frac{D_{A1}}{D_{A2}}=\sqrt{\frac{l_{A1}}{l_{A2}}}\sqrt[6]{\frac{\left(\frac{l_{A1}}{2}+l_{A2}+l_{load}\right)}{\left(\frac{l_{A2}}{2}+l_{load}\right)}} \tag{49}$$

A mean proportion is adopted for the uncertainty of external force and torque.

D. Relation between Arm's Diameter and Joint's Diameter

The deflection caused by arms is in reversed proportion to the biquadratic of arm's diameter. The deflection caused by joints is in reversed proportion to the cube of joint's diameter. The combined deflection can be significantly reduced by increasing the arm's diameter. So the arm's diameter should be enlarged to ultimate.

The arm's diameter is equal to the flexspline's because of the limitation of the manipulator's structure. The upper arm's diameter is equal to the flexspline's diameter of shoulder joint. The optimal proportion between m_J and m_A is a method of validity check because it is hard to estimate K_m before manufacturing.

VI. EXPERIMENT

A light space manipulator with an optimum mass allocation is developed for a spacecraft, as shown in Fig. 6.

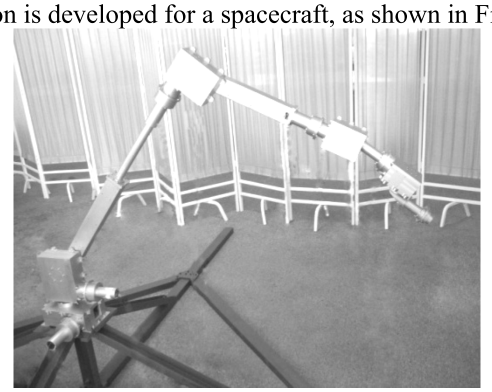

Fig6. The prototype of a light space manipulator

At a total weight of 20 Kg, the full length of this manipulator is 2.0 m, the length of upper arm is 1.0 m, and the lower arm is 0.6 m in length.

The optimum diameter's proportion between joints is 1.12/1.00/0.61 when the external torque is zero. And the optimum proportion is 1.00/1.00/0.72 when the external force is zero. The adopted proportion is 1.0/1.0/0.6.

The optimum diameter's proportion between two arms is 1.62 when the external torque is zero. And the optimum proportion is 1.47 when the external force is zero. The adopted proportion is 1.55.

The shoulder's harmonic and the upper arm share the same diameter.

Each joint consists of a harmonic gear reducer, a permanent magnet synchronous motor (PMSM), a precision resolver, a coarse resolver, a controller, and a motor driver.

The deflection is less than 0.4mm when the light space manipulator is fully expanding and a force of 80 N is applied on the centroid of load.

VII. CONCLUSION

The main results are follows.

- A method of stiffness optimization is presented, and the light space manipulator's stiffness can be improved by mean of optimum mass allocation.
- The combined deflection is composed of deflection caused by joints and deflection caused by arms, and the mass allocation of joints and arms can be optimized separately.
- The effectiveness is confirmed by the prototype of a light space manipulator.

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