

超大惯量模拟方法在空间转位装置中的应用研究*

哈乐¹, 房立金¹, 徐志刚²

(1. 东北大学 机械工程与自动化学院, 辽宁 沈阳 110819; 2. 中国科学院 沈阳自动化研究所, 辽宁 沈阳 110016)

摘要:在空间对接地面实验中,为测试空间转位机构的工作性能,采用基于双轴惯量模拟理论设计一种新型空间转位实验装置,提出了利用惯量模拟增速机构模拟空间站的大惯量负载的方法。采用 Lagrange 法建立空间转位系统的动力学方程,通过分析转动关节惯量耦合参数确定转位装置结构;对空间转位装置中的转位机构与增速机构组成的双臂模型运动轨迹进行了唯一性证明;利用 SimMechanics 和 ADAMS 软件对转位装置进行了运动学仿真,仿真结果表明:系统能够实现利用小质量装置模拟空间站的大惯量负载的目标,在给定实验初始条件的情况下,转位装置能够很好地完成实验舱的转位和制动,说明该装置具有很好的创新性和应用性。

关键词:空间转位;惯量模拟;Lagrange 方程;动力学仿真

中图分类号:V416.8 **文献标识码:**A **文章编号:**1001-2354(2014)12-0021-05

空间站是由多个从地面发射的航天器在太空中组装而成的,大部分从地面发射的航天器都会选择与在轨飞行器在飞行方向进行前后对接,因为这种正向对接的方式要比侧向对接难度小得多。针对这种情况,就要求把先对接的航天器挪到侧向对接口,以便轴向对接口等待下一个航天器进行前后对接。因此,就需要利用空间转位机构来实现这一动作^[1-3]。在空间转位地面试验中,为了真实模拟转位机构在太空中承受的大惯量负载这一特殊情况,提出一种新型的空间转位实验装置设计方法,通过增加惯量模拟增速机构实现对转位机构关节的惯量加载,具有很好的创新性和实用性。

1 空间转位基本原理

如图 1 所示,空间转位装置利用捕获机构抓取被转移的实验舱从轴向对接口运动到侧向对接口,以便空间站能多次对接和实现舱体组装。

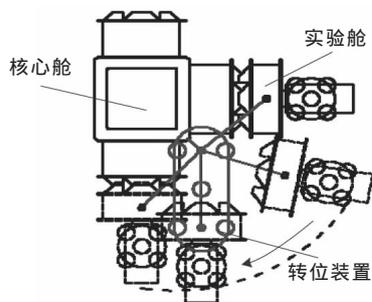


图 1 空间转位原理

2 空间转位装置结构

如图 2 所示,空间转位装置包括转位臂、肩关节、腕关节、捕获机构、惯量模拟增速机构和气足。转位机构的腕关节通过结构件固连在核心舱上,肩关节末端与捕获机构相连用于捕获实验舱,每个关节内部安装 2 个阻尼器用来实现转位制动。

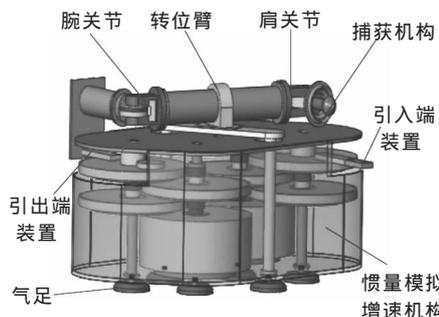


图 2 转位装置模型

在空间站中,实验舱作为展开科学研究的实际载体,安装有实验设备和空调器等控制装置,以及通信器材、电力供应装置等,具有很大的质量和惯量^[4]。为了在现有实验条件下尽可能模拟实验舱的全部质量和惯量,所以在转位装置设计时特别设计了惯量模拟单元,单元中的增速机构通过增速齿轮带动小惯量飞轮的方式来实现大负载惯量的等效模拟。整个装置采用气浮的方式进行重力平衡,能够最大程度地模拟太空失重环境。

* 收稿日期 2014-04-02, 修订日期 2014-07-13

基金项目 国家重点基础研究发展计划(973 计划)资助项目(2012CB026000)

作者简介 哈乐(1986—),男,回族,辽宁沈阳人,博士研究生,研究方向:机械电子工程,已发表论文 2 篇。

3 双轴惯量模拟原理

3.1 简化模型的建立

如图 3 所示,惯量模拟单元相当于一个新关节臂并联在转位臂的下面,一端和实验舱相连接,一端和核心舱相连接,单元的运动状态和转位臂完全一致,所不同的是单元内两组增速齿轮机构分别模拟了转位臂上两关节的惯量负载。这样,增速箱腕关节的传动轮系 1 和核心舱相固联,增速箱肩关节的传动轮系 2 和实验舱相固联。

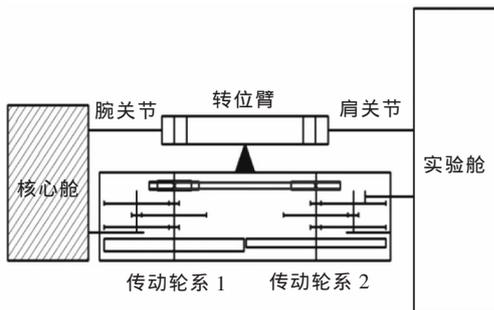


图 3 转位装置简化模型

如图 4 所示,惯量模拟单元的两个传动轴和转位臂的关节在铅垂方向的投影重合,这样就够成一边是固定基座,一边是平动的气浮体,中间连接两个独立的关节臂机构,两关节臂机构具有并联关系。 AE 左侧连接核心舱, BC 处为驱动关节, FG 处为从动关节, DH 处为关节臂与实验舱相连的两点。

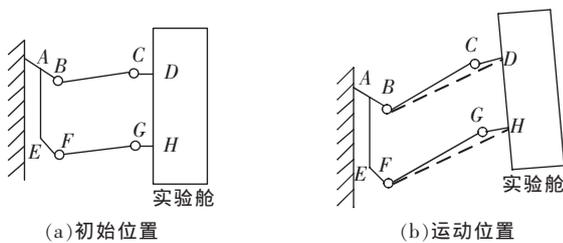


图 4 转位装置运动简图

3.2 动轨迹唯一性证明

为了保证机构具有确定的运动,机构的原动件数目应等于机构的自由度数目。如图 4 所示,转位运动一共分为 3 种工况:仅关节 B 转动,仅关节 C 转动,关节 B 和 C 同时转动。

当仅关节 B 或 C 转动时,机构的活动构件数 $n=2$, F 或 G 处为虚约束,则机构的自由度:

$$F=3n-2P_L-P_h-F'=3\times 2-2\times 2-0-1=1 \quad (1)$$

当关节 B 和 C 同时转动时,机构的活动构件数 $n=4$, F 和 G 处为虚约束,则机构的自由度:

$$F=3n-2P_L-P_h-F'=3\times 4-2\times 4-0-2=2 \quad (2)$$

由机构在上述 3 种工况下的运动分析可知,机构的原动件数目等于机构的自由度数目,所以机构的运动轨迹唯一确定。

3.3 动力学方程的建立

转位机构关节在转动过程中,关节和转位臂同时受到负载的作用,实验舱的质量对肩关节和腕关节的旋转轴的惯量会发生变化,需同时对两个传动轴的惯量耦合效应进行考虑。由于整个系统的结构较为复杂,这里采用 Lagrange 法^[5-8]对系统进行动力学分析,通过求出转位关节的惯量耦合参数来验证装置的合理性。

如图 5 所示,设腕关节为 K_1 ,肩关节为 K_2 ,实验舱捕获点为 K_3 。转臂 K_1K_2 和 K_2K_3 的长度、质量分别为 L_{11} , m_{11} , L_{12} , m_{12} ; 关节 K_2 与实验舱几何中心 O 在运动平面内投影长度 K_2O 为 L_{2M} ; 实验舱质量为 M , 转动惯量为 J_M ; 引入端装置质量为 m_{22} , 长度为 L_{22} , 转动惯量为 J_{22} 。

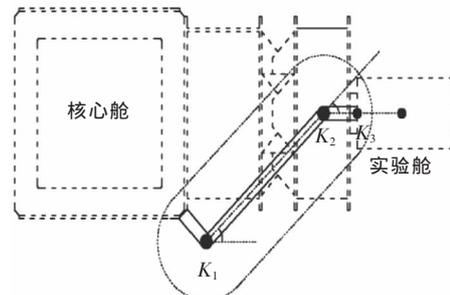
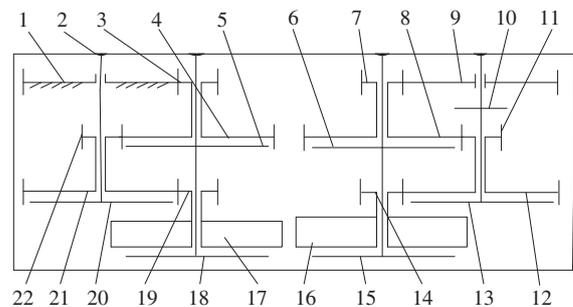


图 5 转位装置布局图

如图 6 所示,齿轮 1、齿轮 3(3') 为太阳轮,箱体为行星架。



1 齿轮 1; 2 箱体; 3 齿轮 2; 4 齿轮 5; 气浮轴承 1; 6 气浮轴承 5; 7 齿轮 6; 8 齿轮 6'; 9 齿轮 5; 10 气浮轴承 4; 11 齿轮 7; 12 齿轮; 13 气浮轴承 6; 14 齿轮 8; 15 气浮轴承 7; 16 飞轮 2; 17 飞轮 1; 18 气浮轴承 3; 19 齿轮 4; 20 气浮轴承 2; 21 齿轮 3'; 22 齿轮 3

图 6 增速机构结构示意图

在转位过程中,实验舱模拟件通过输入端装置将运动传递给齿轮 5 及箱体,齿轮 5 通过齿轮啮合将运动依次传递到齿轮 6(6')、齿轮 7(7')、齿轮 8、飞轮 2; 而箱体将运动传递给左侧的周转轮系,最后传递到飞

轮 1,从而实现转动惯量的模拟。设 z_i 为齿轮 i 的齿数, $i=1\sim 8$; $z_{i'}$ 为齿轮 i' 的齿数, $i'=2,3,6,7$; ω_i 为齿轮 i 的角速度, $i=1,4,5,8$; ω_H 为行星架角速度。齿轮 i 和 i' 的质量和转动惯量分别为 $m_{z_i}, m_{z_{i'}}, J_{z_i}, J_{z_{i'}}$; 传动轮系 1 和 2 的传动比为 i_1 和 i_2 ; 飞轮 1 和 2 质量和转动惯量分别为 $m_{k_1}, m_{k_2}, J_{k_1}, J_{k_2}$ 。

设关节 K_1 和 K_2 处的广义坐标为 q_1 和 q_2 , 则系统动能为:

$$E = \frac{1}{2} (J_{11}\dot{q}_1^2 + J_{22}\dot{q}_2^2) + J_{12}\dot{q}_1\dot{q}_2 \quad (3)$$

式中: E ——系统动能;

J_{11} —— K_1 处等效转动惯量;

J_{22} ——关节 K_2 处等效转动惯量;

J_{12} ——关节 K_1 和 K_2 的耦合惯量。

设构件 i 的质心坐标为 (x_i, y_i) , 角位移为 φ_i , 即:

$$\begin{cases} x_i = x_i(q_1(t), q_2(t)) \\ y_i = y_i(q_1(t), q_2(t)) \\ \varphi_i = \varphi_i(q_1(t), q_2(t)) \end{cases} \quad (4)$$

则构件 i 的动能 E_i 的表达式为:

$$E_i = \frac{1}{2} m_i v_i^2 + \frac{1}{2} J_i \dot{\varphi}_i^2 = \begin{bmatrix} \frac{1}{2} m_i \left[\left(\frac{\partial x_i}{\partial q_1} \right)^2 + \left(\frac{\partial y_i}{\partial q_1} \right)^2 + \frac{J_i}{m_i} \left(\frac{\partial \varphi_i}{\partial q_1} \right)^2 \right] \\ m_i \left(\frac{\partial x_i}{\partial q_1} \frac{\partial x_i}{\partial q_2} + \frac{\partial y_i}{\partial q_1} \frac{\partial y_i}{\partial q_2} + \frac{J_i}{m_i} \frac{\partial \varphi_i}{\partial q_1} \frac{\partial \varphi_i}{\partial q_2} \right) \\ \frac{1}{2} m_i \left[\left(\frac{\partial x_i}{\partial q_2} \right)^2 + \left(\frac{\partial y_i}{\partial q_2} \right)^2 + \frac{J_i}{m_i} \left(\frac{\partial \varphi_i}{\partial q_2} \right)^2 \right] \end{bmatrix}^T \begin{bmatrix} \dot{q}_1^2 \\ \dot{q}_1 \dot{q}_2 \\ \dot{q}_2^2 \end{bmatrix} \quad (5)$$

式中: m_i, v_i, J_i ——构件 i 的质量、质心速度和转动惯量。

在差动轮系中,由轮系传动关系可得到式(5)中各齿轮角速度,齿轮 4 和齿轮 8 的角速度 ω_4 和 ω_8 分别为:

$$\begin{cases} \dot{\varphi}_{z_4} = \omega_4 = -\frac{(\omega_1 - \omega_H) z_1 z_2 z_3}{z_3 z_4 z_4} + \omega_H \\ \dot{\varphi}_{z_8} = \omega_8 = -\frac{(\omega_5 - \omega_H) z_5 z_6 z_7}{z_6 z_7 z_8} \end{cases} \quad (6)$$

由机构的运动传递关系得到角速度 $\omega_1, \omega_5, \omega_H$ 分别为:

$$\begin{cases} \omega_1 = 0 \\ \omega_5 = \dot{q}_1 + \dot{q}_2 \\ \omega_H = \dot{q}_1 \end{cases} \quad (7)$$

将式(7)代入式(6)得到:

$$\begin{bmatrix} \dot{\varphi}_{z_4} \\ \dot{\varphi}_{z_8} \end{bmatrix} = \begin{bmatrix} \omega_4 \\ \omega_8 \end{bmatrix} = \begin{bmatrix} 1 + \frac{z_1 z_2 z_3}{z_3 z_4} & 0 \\ 1 & \frac{z_5 z_6 z_7}{z_6 z_7 z_8} \end{bmatrix} \begin{bmatrix} \dot{q}_1^2 \\ \dot{q}_2^2 \end{bmatrix} \quad (8)$$

系统动能 E 与构件 i 动能 E_i 关系为:

$$E = \sum_{i=1}^N E_i = \frac{1}{2} \sum_{i=1}^N (m_i v_i^2 + J_i \dot{\varphi}_i^2) \quad (9)$$

式中: N ——系统构件数。

将式(5)、式(6)代入式(9),并与式(3)联立,得到 J_{11}, J_{12}, J_{22} 的表达式:

$$\begin{cases} J_{11} = \sum_{i=1}^N \left\{ m_i \left[\left(\frac{\partial x_i}{\partial q_1} \right)^2 + \left(\frac{\partial y_i}{\partial q_1} \right)^2 \right] + J_i \left(\frac{\partial \varphi_i}{\partial q_1} \right)^2 \right\} \\ J_{12} = \sum_{i=1}^N \left[m_i \left(\frac{\partial x_i}{\partial q_1} \frac{\partial x_i}{\partial q_2} + \frac{\partial y_i}{\partial q_1} \frac{\partial y_i}{\partial q_2} \right) + J_i \frac{\partial \varphi_i}{\partial q_1} \frac{\partial \varphi_i}{\partial q_2} \right] \\ J_{22} = \sum_{i=1}^N \left\{ m_i \left[\left(\frac{\partial x_i}{\partial q_2} \right)^2 + \left(\frac{\partial y_i}{\partial q_2} \right)^2 \right] + J_i \left(\frac{\partial \varphi_i}{\partial q_2} \right)^2 \right\} \end{cases} \quad (10)$$

将各参数代入式(10)得到不同工况下各等效转动惯量表达式:

$$J_{11} = \frac{m_{11} L_{11}^2}{4} + J_{L_{11}} + m_{12} \left(L_{11}^2 + \frac{L_{12}^2}{4} + L_{11} L_{12} \cos q_2 \right) + J_{L_{12}} + J_M + M \left(L_{11}^2 + L_{2M}^2 + 2L_{11} L_{2M} \cos q_2 \right) + J_{L_{22}} + m_{22} \left[L_{11}^2 + \frac{L_{12}^2}{4} + L_{11} L_{12} \cos q_2 \right] + \frac{J_{z_2} + J_{z_6}}{i_2^2} + \frac{J_{z_3} + J_{z_7}}{i_1^4} + \frac{J_{z_4} + J_{m_{11}}}{i_1^6} + J_{z_5} + J_{z_8} + J_{z_9} + J_{z_{10}} + J_{z_{11}} + J_{z_{12}} + J_{z_{13}} + J_{z_{14}} + J_{z_{15}} + J_{z_{16}} + J_{z_{17}} + J_{z_{18}} + J_{z_{19}} + J_{z_{20}} + J_{z_{21}} + J_{z_{22}} + J_{z_{23}} + J_{z_{24}} + J_{z_{25}} + J_{z_{26}} + J_{z_{27}} + J_{z_{28}} + J_{z_{29}} + J_{z_{30}} + J_{z_{31}} + J_{z_{32}} + J_{z_{33}} + J_{z_{34}} + J_{z_{35}} + J_{z_{36}} + J_{z_{37}} + J_{z_{38}} + J_{z_{39}} + J_{z_{40}} + J_{z_{41}} + J_{z_{42}} + J_{z_{43}} + J_{z_{44}} + J_{z_{45}} + J_{z_{46}} + J_{z_{47}} + J_{z_{48}} + J_{z_{49}} + J_{z_{50}} + J_{z_{51}} + J_{z_{52}} + J_{z_{53}} + J_{z_{54}} + J_{z_{55}} + J_{z_{56}} + J_{z_{57}} + J_{z_{58}} + J_{z_{59}} + J_{z_{60}} + J_{z_{61}} + J_{z_{62}} + J_{z_{63}} + J_{z_{64}} + J_{z_{65}} + J_{z_{66}} + J_{z_{67}} + J_{z_{68}} + J_{z_{69}} + J_{z_{70}} + J_{z_{71}} + J_{z_{72}} + J_{z_{73}} + J_{z_{74}} + J_{z_{75}} + J_{z_{76}} + J_{z_{77}} + J_{z_{78}} + J_{z_{79}} + J_{z_{80}} + J_{z_{81}} + J_{z_{82}} + J_{z_{83}} + J_{z_{84}} + J_{z_{85}} + J_{z_{86}} + J_{z_{87}} + J_{z_{88}} + J_{z_{89}} + J_{z_{90}} + J_{z_{91}} + J_{z_{92}} + J_{z_{93}} + J_{z_{94}} + J_{z_{95}} + J_{z_{96}} + J_{z_{97}} + J_{z_{98}} + J_{z_{99}} + J_{z_{100}} + J_{z_{101}} + J_{z_{102}} + J_{z_{103}} + J_{z_{104}} + J_{z_{105}} + J_{z_{106}} + J_{z_{107}} + J_{z_{108}} + J_{z_{109}} + J_{z_{110}} + J_{z_{111}} + J_{z_{112}} + J_{z_{113}} + J_{z_{114}} + J_{z_{115}} + J_{z_{116}} + J_{z_{117}} + J_{z_{118}} + J_{z_{119}} + J_{z_{120}} + J_{z_{121}} + J_{z_{122}} + J_{z_{123}} + J_{z_{124}} + J_{z_{125}} + J_{z_{126}} + J_{z_{127}} + J_{z_{128}} + J_{z_{129}} + J_{z_{130}} + J_{z_{131}} + J_{z_{132}} + J_{z_{133}} + J_{z_{134}} + J_{z_{135}} + J_{z_{136}} + J_{z_{137}} + J_{z_{138}} + J_{z_{139}} + J_{z_{140}} + J_{z_{141}} + J_{z_{142}} + J_{z_{143}} + J_{z_{144}} + J_{z_{145}} + J_{z_{146}} + J_{z_{147}} + J_{z_{148}} + J_{z_{149}} + J_{z_{150}} + J_{z_{151}} + J_{z_{152}} + J_{z_{153}} + J_{z_{154}} + J_{z_{155}} + J_{z_{156}} + J_{z_{157}} + J_{z_{158}} + J_{z_{159}} + J_{z_{160}} + J_{z_{161}} + J_{z_{162}} + J_{z_{163}} + J_{z_{164}} + J_{z_{165}} + J_{z_{166}} + J_{z_{167}} + J_{z_{168}} + J_{z_{169}} + J_{z_{170}} + J_{z_{171}} + J_{z_{172}} + J_{z_{173}} + J_{z_{174}} + J_{z_{175}} + J_{z_{176}} + J_{z_{177}} + J_{z_{178}} + J_{z_{179}} + J_{z_{180}} + J_{z_{181}} + J_{z_{182}} + J_{z_{183}} + J_{z_{184}} + J_{z_{185}} + J_{z_{186}} + J_{z_{187}} + J_{z_{188}} + J_{z_{189}} + J_{z_{190}} + J_{z_{191}} + J_{z_{192}} + J_{z_{193}} + J_{z_{194}} + J_{z_{195}} + J_{z_{196}} + J_{z_{197}} + J_{z_{198}} + J_{z_{199}} + J_{z_{200}} + J_{z_{201}} + J_{z_{202}} + J_{z_{203}} + J_{z_{204}} + J_{z_{205}} + J_{z_{206}} + J_{z_{207}} + J_{z_{208}} + J_{z_{209}} + J_{z_{210}} + J_{z_{211}} + J_{z_{212}} + J_{z_{213}} + J_{z_{214}} + J_{z_{215}} + J_{z_{216}} + J_{z_{217}} + J_{z_{218}} + J_{z_{219}} + J_{z_{220}} + J_{z_{221}} + J_{z_{222}} + J_{z_{223}} + J_{z_{224}} + J_{z_{225}} + J_{z_{226}} + J_{z_{227}} + J_{z_{228}} + J_{z_{229}} + J_{z_{230}} + J_{z_{231}} + J_{z_{232}} + J_{z_{233}} + J_{z_{234}} + J_{z_{235}} + J_{z_{236}} + J_{z_{237}} + J_{z_{238}} + J_{z_{239}} + J_{z_{240}} + J_{z_{241}} + J_{z_{242}} + J_{z_{243}} + J_{z_{244}} + J_{z_{245}} + J_{z_{246}} + J_{z_{247}} + J_{z_{248}} + J_{z_{249}} + J_{z_{250}} + J_{z_{251}} + J_{z_{252}} + J_{z_{253}} + J_{z_{254}} + J_{z_{255}} + J_{z_{256}} + J_{z_{257}} + J_{z_{258}} + J_{z_{259}} + J_{z_{260}} + J_{z_{261}} + J_{z_{262}} + J_{z_{263}} + J_{z_{264}} + J_{z_{265}} + J_{z_{266}} + J_{z_{267}} + J_{z_{268}} + J_{z_{269}} + J_{z_{270}} + J_{z_{271}} + J_{z_{272}} + J_{z_{273}} + J_{z_{274}} + J_{z_{275}} + J_{z_{276}} + J_{z_{277}} + J_{z_{278}} + J_{z_{279}} + J_{z_{280}} + J_{z_{281}} + J_{z_{282}} + J_{z_{283}} + J_{z_{284}} + J_{z_{285}} + J_{z_{286}} + J_{z_{287}} + J_{z_{288}} + J_{z_{289}} + J_{z_{290}} + J_{z_{291}} + J_{z_{292}} + J_{z_{293}} + J_{z_{294}} + J_{z_{295}} + J_{z_{296}} + J_{z_{297}} + J_{z_{298}} + J_{z_{299}} + J_{z_{300}} + J_{z_{301}} + J_{z_{302}} + J_{z_{303}} + J_{z_{304}} + J_{z_{305}} + J_{z_{306}} + J_{z_{307}} + J_{z_{308}} + J_{z_{309}} + J_{z_{310}} + J_{z_{311}} + J_{z_{312}} + J_{z_{313}} + J_{z_{314}} + J_{z_{315}} + J_{z_{316}} + J_{z_{317}} + J_{z_{318}} + J_{z_{319}} + J_{z_{320}} + J_{z_{321}} + J_{z_{322}} + J_{z_{323}} + J_{z_{324}} + J_{z_{325}} + J_{z_{326}} + J_{z_{327}} + J_{z_{328}} + J_{z_{329}} + J_{z_{330}} + J_{z_{331}} + J_{z_{332}} + J_{z_{333}} + J_{z_{334}} + J_{z_{335}} + J_{z_{336}} + J_{z_{337}} + J_{z_{338}} + J_{z_{339}} + J_{z_{340}} + J_{z_{341}} + J_{z_{342}} + J_{z_{343}} + J_{z_{344}} + J_{z_{345}} + J_{z_{346}} + J_{z_{347}} + J_{z_{348}} + J_{z_{349}} + J_{z_{350}} + J_{z_{351}} + J_{z_{352}} + J_{z_{353}} + J_{z_{354}} + J_{z_{355}} + J_{z_{356}} + J_{z_{357}} + J_{z_{358}} + J_{z_{359}} + J_{z_{360}} + J_{z_{361}} + J_{z_{362}} + J_{z_{363}} + J_{z_{364}} + J_{z_{365}} + J_{z_{366}} + J_{z_{367}} + J_{z_{368}} + J_{z_{369}} + J_{z_{370}} + J_{z_{371}} + J_{z_{372}} + J_{z_{373}} + J_{z_{374}} + J_{z_{375}} + J_{z_{376}} + J_{z_{377}} + J_{z_{378}} + J_{z_{379}} + J_{z_{380}} + J_{z_{381}} + J_{z_{382}} + J_{z_{383}} + J_{z_{384}} + J_{z_{385}} + J_{z_{386}} + J_{z_{387}} + J_{z_{388}} + J_{z_{389}} + J_{z_{390}} + J_{z_{391}} + J_{z_{392}} + J_{z_{393}} + J_{z_{394}} + J_{z_{395}} + J_{z_{396}} + J_{z_{397}} + J_{z_{398}} + J_{z_{399}} + J_{z_{400}} + J_{z_{401}} + J_{z_{402}} + J_{z_{403}} + J_{z_{404}} + J_{z_{405}} + J_{z_{406}} + J_{z_{407}} + J_{z_{408}} + J_{z_{409}} + J_{z_{410}} + J_{z_{411}} + J_{z_{412}} + J_{z_{413}} + J_{z_{414}} + J_{z_{415}} + J_{z_{416}} + J_{z_{417}} + J_{z_{418}} + J_{z_{419}} + J_{z_{420}} + J_{z_{421}} + J_{z_{422}} + J_{z_{423}} + J_{z_{424}} + J_{z_{425}} + J_{z_{426}} + J_{z_{427}} + J_{z_{428}} + J_{z_{429}} + J_{z_{430}} + J_{z_{431}} + J_{z_{432}} + J_{z_{433}} + J_{z_{434}} + J_{z_{435}} + J_{z_{436}} + J_{z_{437}} + J_{z_{438}} + J_{z_{439}} + J_{z_{440}} + J_{z_{441}} + J_{z_{442}} + J_{z_{443}} + J_{z_{444}} + J_{z_{445}} + J_{z_{446}} + J_{z_{447}} + J_{z_{448}} + J_{z_{449}} + J_{z_{450}} + J_{z_{451}} + J_{z_{452}} + J_{z_{453}} + J_{z_{454}} + J_{z_{455}} + J_{z_{456}} + J_{z_{457}} + J_{z_{458}} + J_{z_{459}} + J_{z_{460}} + J_{z_{461}} + J_{z_{462}} + J_{z_{463}} + J_{z_{464}} + J_{z_{465}} + J_{z_{466}} + J_{z_{467}} + J_{z_{468}} + J_{z_{469}} + J_{z_{470}} + J_{z_{471}} + J_{z_{472}} + J_{z_{473}} + J_{z_{474}} + J_{z_{475}} + J_{z_{476}} + J_{z_{477}} + J_{z_{478}} + J_{z_{479}} + J_{z_{480}} + J_{z_{481}} + J_{z_{482}} + J_{z_{483}} + J_{z_{484}} + J_{z_{485}} + J_{z_{486}} + J_{z_{487}} + J_{z_{488}} + J_{z_{489}} + J_{z_{490}} + J_{z_{491}} + J_{z_{492}} + J_{z_{493}} + J_{z_{494}} + J_{z_{495}} + J_{z_{496}} + J_{z_{497}} + J_{z_{498}} + J_{z_{499}} + J_{z_{500}} + J_{z_{501}} + J_{z_{502}} + J_{z_{503}} + J_{z_{504}} + J_{z_{505}} + J_{z_{506}} + J_{z_{507}} + J_{z_{508}} + J_{z_{509}} + J_{z_{510}} + J_{z_{511}} + J_{z_{512}} + J_{z_{513}} + J_{z_{514}} + J_{z_{515}} + J_{z_{516}} + J_{z_{517}} + J_{z_{518}} + J_{z_{519}} + J_{z_{520}} + J_{z_{521}} + J_{z_{522}} + J_{z_{523}} + J_{z_{524}} + J_{z_{525}} + J_{z_{526}} + J_{z_{527}} + J_{z_{528}} + J_{z_{529}} + J_{z_{530}} + J_{z_{531}} + J_{z_{532}} + J_{z_{533}} + J_{z_{534}} + J_{z_{535}} + J_{z_{536}} + J_{z_{537}} + J_{z_{538}} + J_{z_{539}} + J_{z_{540}} + J_{z_{541}} + J_{z_{542}} + J_{z_{543}} + J_{z_{544}} + J_{z_{545}} + J_{z_{546}} + J_{z_{547}} + J_{z_{548}} + J_{z_{549}} + J_{z_{550}} + J_{z_{551}} + J_{z_{552}} + J_{z_{553}} + J_{z_{554}} + J_{z_{555}} + J_{z_{556}} + J_{z_{557}} + J_{z_{558}} + J_{z_{559}} + J_{z_{560}} + J_{z_{561}} + J_{z_{562}} + J_{z_{563}} + J_{z_{564}} + J_{z_{565}} + J_{z_{566}} + J_{z_{567}} + J_{z_{568}} + J_{z_{569}} + J_{z_{570}} + J_{z_{571}} + J_{z_{572}} + J_{z_{573}} + J_{z_{574}} + J_{z_{575}} + J_{z_{576}} + J_{z_{577}} + J_{z_{578}} + J_{z_{579}} + J_{z_{580}} + J_{z_{581}} + J_{z_{582}} + J_{z_{583}} + J_{z_{584}} + J_{z_{585}} + J_{z_{586}} + J_{z_{587}} + J_{z_{588}} + J_{z_{589}} + J_{z_{590}} + J_{z_{591}} + J_{z_{592}} + J_{z_{593}} + J_{z_{594}} + J_{z_{595}} + J_{z_{596}} + J_{z_{597}} + J_{z_{598}} + J_{z_{599}} + J_{z_{600}} + J_{z_{601}} + J_{z_{602}} + J_{z_{603}} + J_{z_{604}} + J_{z_{605}} + J_{z_{606}} + J_{z_{607}} + J_{z_{608}} + J_{z_{609}} + J_{z_{610}} + J_{z_{611}} + J_{z_{612}} + J_{z_{613}} + J_{z_{614}} + J_{z_{615}} + J_{z_{616}} + J_{z_{617}} + J_{z_{618}} + J_{z_{619}} + J_{z_{620}} + J_{z_{621}} + J_{z_{622}} + J_{z_{623}} + J_{z_{624}} + J_{z_{625}} + J_{z_{626}} + J_{z_{627}} + J_{z_{628}} + J_{z_{629}} + J_{z_{630}} + J_{z_{631}} + J_{z_{632}} + J_{z_{633}} + J_{z_{634}} + J_{z_{635}} + J_{z_{636}} + J_{z_{637}} + J_{z_{638}} + J_{z_{639}} + J_{z_{640}} + J_{z_{641}} + J_{z_{642}} + J_{z_{643}} + J_{z_{644}} + J_{z_{645}} + J_{z_{646}} + J_{z_{647}} + J_{z_{648}} + J_{z_{649}} + J_{z_{650}} + J_{z_{651}} + J_{z_{652}} + J_{z_{653}} + J_{z_{654}} + J_{z_{655}} + J_{z_{656}} + J_{z_{657}} + J_{z_{658}} + J_{z_{659}} + J_{z_{660}} + J_{z_{661}} + J_{z_{662}} + J_{z_{663}} + J_{z_{664}} + J_{z_{665}} + J_{z_{666}} + J_{z_{667}} + J_{z_{668}} + J_{z_{669}} + J_{z_{670}} + J_{z_{671}} + J_{z_{672}} + J_{z_{673}} + J_{z_{674}} + J_{z_{675}} + J_{z_{676}} + J_{z_{677}} + J_{z_{678}} + J_{z_{679}} + J_{z_{680}} + J_{z_{681}} + J_{z_{682}} + J_{z_{683}} + J_{z_{684}} + J_{z_{685}} + J_{z_{686}} + J_{z_{687}} + J_{z_{688}} + J_{z_{689}} + J_{z_{690}} + J_{z_{691}} + J_{z_{692}} + J_{z_{693}} + J_{z_{694}} + J_{z_{695}} + J_{z_{696}} + J_{z_{697}} + J_{z_{698}} + J_{z_{699}} + J_{z_{700}} + J_{z_{701}} + J_{z_{702}} + J_{z_{703}} + J_{z_{704}} + J_{z_{705}} + J_{z_{706}} + J_{z_{707}} + J_{z_{708}} + J_{z_{709}} + J_{z_{710}} + J_{z_{711}} + J_{z_{712}} + J_{z_{713}} + J_{z_{714}} + J_{z_{715}} + J_{z_{716}} + J_{z_{717}} + J_{z_{718}} + J_{z_{719}} + J_{z_{720}} + J_{z_{721}} + J_{z_{722}} + J_{z_{723}} + J_{z_{724}} + J_{z_{725}} + J_{z_{726}} + J_{z_{727}} + J_{z_{728}} + J_{z_{729}} + J_{z_{730}} + J_{z_{731}} + J_{z_{732}} + J_{z_{733}} + J_{z_{734}} + J_{z_{735}} + J_{z_{736}} + J_{z_{737}} + J_{z_{738}} + J_{z_{739}} + J_{z_{740}} + J_{z_{741}} + J_{z_{742}} + J_{z_{743}} + J_{z_{744}} + J_{z_{745}} + J_{z_{746}} + J_{z_{747}} + J_{z_{748}} + J_{z_{749}} + J_{z_{750}} + J_{z_{751}} + J_{z_{752}} + J_{z_{753}} + J_{z_{754}} + J_{z_{755}} + J_{z_{756}} + J_{z_{757}} + J_{z_{758}} + J_{z_{759}} + J_{z_{760}} + J_{z_{761}} + J_{z_{762}} + J_{z_{763}} + J_{z_{764}} + J_{z_{765}} + J_{z_{766}} + J_{z_{767}} + J_{z_{768}} + J_{z_{769}} + J_{z_{770}} + J_{z_{771}} + J_{z_{772}} + J_{z_{773}} + J_{z_{774}} + J_{z_{775}} + J_{z_{776}} + J_{z_{777}} + J_{z_{778}} + J_{z_{779}} + J_{z_{780}} + J_{z_{781}} + J_{z_{782}} + J_{z_{783}} + J_{z_{784}} + J_{z_{785}} + J_{z_{786}} + J_{z_{787}} + J_{z_{788}} + J_{z_{789}} + J_{z_{790}} + J_{z_{791}} + J_{z_{792}} + J_{z_{793}} + J_{z_{794}} + J_{z_{795}} + J_{z_{796}} + J_{z_{797}} + J_{z_{798}} + J_{z_{799}} + J_{z_{800}} + J_{z_{801}} + J_{z_{802}} + J_{z_{803}} + J_{z_{804}} + J_{z_{805}} + J_{z_{806}} + J_{z_{807}} + J_{z_{808}} + J_{z_{809}} + J_{z_{810}} + J_{z_{811}} + J_{z_{812}} + J_{z_{813}} + J_{z_{814}} + J_{z_{815}} + J_{z_{816}} + J_{z_{817}} + J_{z_{818}} + J_{z_{819}} + J_{z_{820}} + J_{z_{821}} + J_{z_{822}} + J_{z_{823}} + J_{z_{824}} + J_{z_{825}} + J_{z_{826}} + J_{z_{827}} + J_{z_{828}} + J_{z_{829}} + J_{z_{830}} + J_{z_{831}} + J_{z_{832}} + J_{z_{833}} + J_{z_{834}} + J_{z_{835}} + J_{z_{836}} + J_{z_{837}} + J_{z_{838}} + J_{z_{839}} + J_{z_{840}} + J_{z_{841}} + J_{z_{842}} + J_{z_{843}} + J_{z_{844}} + J_{z_{845}} + J_{z_{846}} + J_{z_{847}} + J_{z_{848}} + J_{z_{849}} + J_{z_{850}} + J_{z_{851}} + J_{z_{852}} + J_{z_{853}} + J_{z_{854}} + J_{z_{855}} + J_{z_{856}} + J_{z_{857}} + J_{z_{858}} + J_{z_{859}} + J_{z_{860}} + J_{z_{861}} + J_{z_{862}} + J_{z_{863}} + J_{z_{864}} + J_{z_{865}} + J_{z_{866}} + J_{z_{867}} + J_{z_{868}} + J_{z_{869}} + J_{z_{870}} + J_{z_{871}} + J_{z_{872}} + J_{z_{873}} + J_{z_{874}} + J_{z_{875}} + J_{z_{876}} + J_{z_{877}} + J_{z_{878}} + J_{z_{879}} + J_{z_{880}} + J_{z_{881}} + J_{z_{882}} + J_{z_{883}} + J_{z_{884}} + J_{z_{885}} + J_{z_{886}} + J_{z_{887}} + J_{z_{888}} + J_{z_{889}} + J_{z_{890}} + J_{z_{891}} + J_{z_{892}} + J_{z_{893}} + J_{z_{894}} + J_{z_{895}} + J_{z_{896}} + J_{z_{897}} + J_{z_{898}} + J_{z_{899}} + J_{z_{900}} + J_{z_{901}} + J_{z_{902}} + J_{z_{903}} + J_{z_{904}} + J_{z_{905}} + J_{z_{906}} + J_{z_{907}} + J_{z_{908}} + J_{z_{909}} + J_{z_{910}} + J_{z_{911}} + J_{z_{912}} + J_{z_{913}} + J_{z_{914}} + J_{z_{915}} + J_{z_{916}} + J_{z_{917}} + J_{z_{918}} + J_{z_{919}} + J_{z_{920}} + J_{z_{921}} + J_{z_{922}} + J_{z_{923}} + J_{z_{924}} + J_{z_{925}} + J_{z_{926}} + J_{z_{927}} + J_{z_{928}} + J_{z_{929}} + J_{z_{930}} + J_{z_{931}} + J_{z_{932}} + J_{z_{933}} + J_{z_{934}} + J_{z_{935}} + J_{z_{936}} + J_{z_{937}} + J_{z_{938}} + J_{z_{939}} + J_{z_{940}} + J_{z_{941}} + J_{z_{942}} + J_{z_{943}} + J_{z_{944}} + J_{z_{945}} + J_{z_{946}} + J_{z_{947}} + J_{z_{948}} + J_{z_{949}} + J_{z_{950}} + J_{z_{951}} + J_{z_{952}} + J_{z_{953}} + J_{z_{954}} + J_{z_{955}} + J_{z_{956}} + J_{z_{957}} + J_{z_{958}} + J_{z_{959}} + J_{z_{960}} + J_{z_{961}} + J_{z_{962}} + J_{z_{963}} + J_{z_{964}} + J_{z_{965}} + J_{z_{966}} + J_{z_{967}} + J_{z_{968}} + J_{z_{969}} + J_{z_{970}} + J_{z_{971}} + J_{z_{972}} + J_{z_{973}} + J_{z_{974}} + J_{z_{975}} + J_{z_{976}} + J_{z_{977}} + J_{z_{978}} + J_{z_{979}} + J_{z_{980}} + J_{z_{981}} + J_{z_{982}} + J_{z_{983}} + J_{z_{984}} + J_{z_{985}} + J_{z_{986}} + J_{z_{987}} + J_{z_{988}} + J_{z_{989}} + J_{z_{990}} + J_{z_{991}} + J_{z_{992}} + J_{z_{993}} + J_{z_{994}} + J_{z_{995}} + J_{z_{996}} + J_{z_{997}} + J_{z_{998}} + J_{z_{999}} + J_{z_{1000}} + J_{z_{1001}} + J_{z_{1002}} + J_{z_{1003}} + J_{z_{1004}} + J_{z_{1005}} + J_{z_{1006}} + J_{z_{1007}} + J_{z_{1008}} + J_{z_{1009}} + J_{z_{1010}} + J_{z_{1011}} + J_{z_{1012}} + J_{z_{1013}} + J_{z_{1014}} + J_{z_{1015}} + J_{z_{1016}} + J_{z_{1017}} + J_{z_{1018}} + J_{z_{1019}} + J_{z_{1020}} + J_{z_{1021}} + J_{z_{1022}} + J_{z_{1023}} + J_{z_{1024}} + J_{z_{1025}} + J_{z_{1026}} +$$

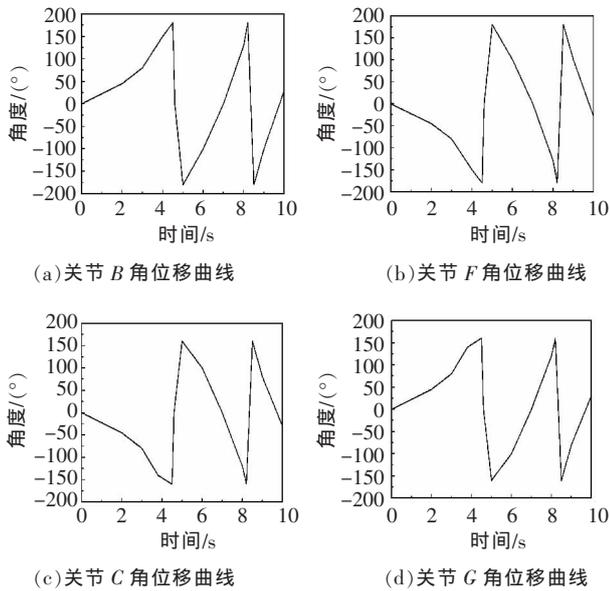


图 7 运动仿真曲线

4.2 基于 Adams 的动力学仿真

运动仿真的目的主要是研究机构模型的实际惯量是否满足腕关节、肩关节的转动惯量指标 $3.10 \times 10^6 \text{ kg} \cdot \text{m}^2$ 和 $2.90 \times 10^6 \text{ kg} \cdot \text{m}^2$, 以及转位机构是否能很好地实现实验舱的转位和制动。动力学仿真结果如图 8 所示。

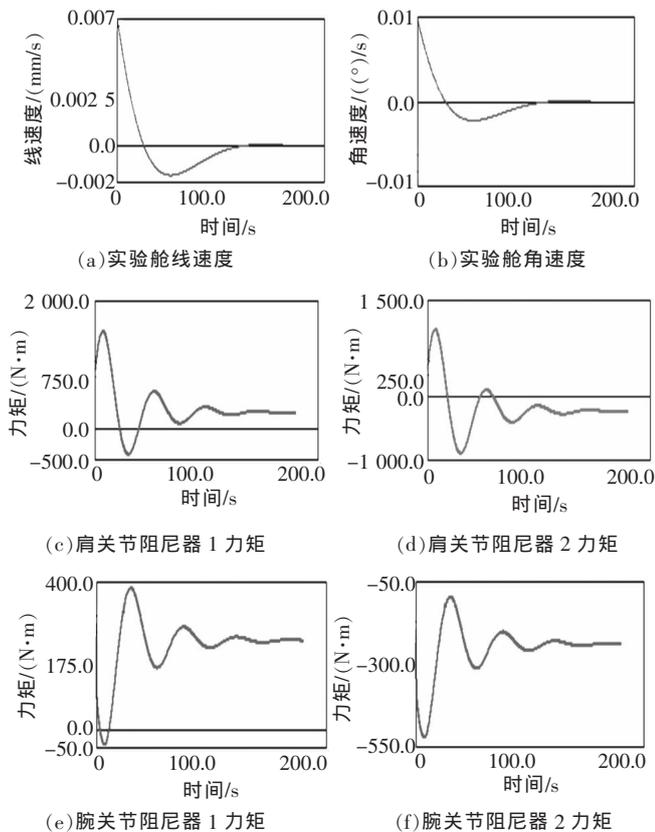


图 8 运动仿真结果

运动仿真中, 腕关节与肩关节的制动分别由各自的 2 个阻尼器来实现, 每个阻尼器都施加预载, 阻尼器

选用 Adams 中的卷簧来模拟。实验舱初始线速度为 $v=7 \text{ mm/s}$, 质量为 1700 kg , $J_M=1410 \text{ kg} \cdot \text{m}^2$, 腕关节初始角速度为 $0.5(^\circ)/\text{s}$, 肩关节的初始角速度为 $0.5(^\circ)/\text{s}$, 每组的 2 个阻尼器预载力矩大小为 $240 \text{ N} \cdot \text{m}$, 方向相反。

由仿真结果可知, 在建模完成后腕关节与肩关节的有效转动惯量 D_{11} 和 D_{22} 分别为 $3.1017 \times 10^6 \text{ kg} \cdot \text{m}^2$ 和 $2.8991 \times 10^6 \text{ kg} \cdot \text{m}^2$, 有效惯量与惯量指标误差在 $\pm 3\%$ 的范围内, 满足技术要求。从图 8a, b 可以看出, 实验舱线速度和角速度由初值 $0.007 \times 10^{-5} \text{ m/s}$ 和 $0.01(^\circ)/\text{s}$, 经过 116 s 后变为 0, 表明实验舱在阻尼器的作用下安全制动。由图 8c, d, e, f 可知, 肩关节阻尼器 1 和 2 最大制动力矩为 $1782.5 \text{ N} \cdot \text{m}$ 和 $1284.7 \text{ N} \cdot \text{m}$, 腕关节阻尼器 1 和 2 的最大制动力矩为 $391.7 \text{ N} \cdot \text{m}$ 和 $-525.1 \text{ N} \cdot \text{m}$, 力矩峰值出现在实验舱静止时刻附近, 之后阻尼器逐渐解除制动, 制动完成时力矩值稳定在预载值处, 表明转位装置运行良好。

5 结论

针对空间转位地面实验, 提出一种基于双轴惯量模拟理论的新型空间转位装置设计方法, 该方法通过增加惯量模拟增速机构解决了利用小结构尺寸装置模拟空间站的大惯量负载这一难题。采用 Lagrange 法建立空间转位系统的动力学方程, 通过系统惯量参数确定转位装置结构, 验证了装置中转位机构与增速机构组成的双臂模型运动轨迹的唯一性。动力学仿真结果表明转位装置的关节惯量负载能够满足技术指标并且在给定实验初始条件的情况下, 转位装置能够很好地完成实验舱的转位和制动, 说明该装置具有很好的创新性和应用性。

参考文献

- [1] 秦文波, 陈萌, 张崇峰, 等. 空间站大型机构研究综述 [J]. 上海航天, 2010(4): 32-42.
- [2] 谭益松, 刘伊威, 刘宏, 等. 大型空间末端执行器在轨操作运输舱策略 [J]. 机械工程学报, 2011, 47(3): 109-115.
- [3] Jain A, Rodriguez G. Decoupled dynamics of space manipulators [J]. IEEE Int Conf Robotics & Automation Atlanta. 1993(3): 609-614.
- [4] Nakamura Y, Mukerjee R. Exploiting nonholonomic redundancy of free-flying space robots [J]. IEEE Tran Robotics & Automation, 1993, 9(4): 499-506.
- [5] Lee S H, Lee C W. Hybrid control scheme for robust tracking

球面并联式人形机器人髋关节机构运动学与仿生设计*

侯雨雷¹, 赵春秀², 范建凯¹, 胡鑫喆¹, 曾达幸¹, 周玉林¹

(1.燕山大学 机械工程学院, 河北 秦皇岛 066004; 2.河北工业职业技术学院 计算机技术系, 河北 石家庄 050000)

摘要:从结构和功能仿生角度出发,提出球面并联式人形机器人髋关节机构,并针对其开展运动学分析与仿生设计。根据人体髋关节结构和运动特性,选取3-SPS(S为球面副,P为移动副)球面并联机构作为髋关节仿生原始构型;依据螺旋理论对髋关节原型机构自由度数目、性质及位置反解进行分析;采用遗传算法,以姿态工作空间最大化为目标对并联髋关节机构进行优化;结合人体髋关节实际结构特点,提出偏置输出方式,从而使得机构实际输出空间的形状和位置更加符合人体髋关节运动轨迹需求。研究内容为人形机器人髋关节仿生的理论研究和进一步的样机研制奠定了基础。

关键词:髋关节;球面并联机构;关节仿生;偏置输出;工作空间

中图分类号:TH112;TP242 文献标识码:A 文章编号:1001-2354(2014)12-0025-06

仿生机器人是仿生学理念与机器人应用技术的很好结合,作为仿生机器人中的一类,人形机器人是机器人技术领域最活跃的分支之一,受到国内外学者的广泛关注^[1]。迄今为止,各国学者已经开发出大量的各种人形机器人^[2-3]。而作为机器人实现运动和承重的髋关节,在机器人的各类动作中发挥着不可替代的作用,是最重要的关节之一。

现有各类人形机器人关节多为串联构型,即2个

或3个单转动副串联、双球铰串联^[4]等串联构型机器人,各关节间无耦合,控制比较容易,但也存在一定的不足,诸如下级驱动器的质量成为上级驱动器的负载、尺寸大、刚度小、灵活性、准确性和稳定性差等。此外,人体关节的工作过程极其复杂,无论关节为单自由度还是多自由度,均为肌肉并联驱动,故以单转动副串联来作为关节原型机构,其本身与人类真实关节相比,在结构和功能上存在较大差别。

of two-Link flexible manipulator[J]. Journal of Intelligent and Robotic Systems, 2001, 2(4): 389-410.

- [6] 高征, 苏锐. 广义坐标的选择在 Lagrange 动力学分析中的作用[J]. 机械设计与制造, 2010(11): 54-56.
- [7] 康忠, 李振平, 凌云, 等. 基于拉格朗日方法的行星齿轮特性研究[J]. 机械设计, 2009, 26(7): 45-47.
- [8] Vo Gamarra-Rosado, Eao Yuhara. Dynamic modeling and simulation of a flexible robotic Manipulator[J]. Robotica, 1999, 17(5): 523-528.

Research on spatial indexing manipulator based on large inertia simulation

HA Le¹, FANG Li-jin¹, XU Zhi-gang²

(1.College of Mechanical Engineering and Automation, Northeastern University, Shenyang 110000, China; 2.Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang 110000, China)

Abstract:In the space docking experiment, a new spatial indexing manipulator was designed based on the theory of biaxial inertia simulation. A speed increasing mechanism was used to simulate the large inertia load in the station. The dynamical equations of the system were built by Lagrange method. The device structure was determined by the inertia coupling parameters of the rotational joints. The indexing and speed increasing mechanisms of the manipulator constitute an arm model which was proved to be unique in the trajectory. A kinematics simulation was made for the device by SimMechanics and ADAMS. The results show that using a small device can simulate a large inertia loads. Given the initial conditions, the translocation and brake in the device can be finished well. So, the spatial indexing manipulator is proved to be feasible and applicable.

Key words:spatial indexing; inertia simulation; Lagrange equation; dynamics simulation

Fig 8 Tab 0 Ref 8

"Jixie Sheji" 4229

* 收稿日期 2014-04-18, 修订日期 2014-10-13

基金项目:国家自然科学基金资助项目(51275443);河北省自然科学基金资助项目(E2012203034);教育部高等学校博士学科点专项科研基金资助课题(20111333120004);河北省高等学校科学技术研究优秀青年基金资助项目(Y2011114);教育部科学技术研究重点资助项目(212012)

作者简介:侯雨雷(1980—)男,河北定州人,副教授,博士,主要研究方向:并联机构学、多维力传感器技术、人形机器人仿生,发表论文50余篇。