Implementation and Kinematic Control of a Hyper-redundant Mobile Manipulator System

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Abstract: Redundant or hyper-redundant mobile manipulator can give lots of assistance to astronauts in space station. The design and implementation of a hyper-redundant mobile manipulator system are described, which is composed of an 8 DOF module robot and a 1 DOF motorized rail. Inverse kinematic resolution of the system is discussed and one simplified control method based on joint limit avoidance and configuration optimization is proposed. Simulation and experimental results are presented.

Key words: mobile manipulator; hyper-redundant manipulator; inverse kinematics

一个超冗余度移动操作臂机器人系统的实现与运动控制. 贾庆轩, 战 强, 孙汉旭, 洪 磊. 中国航空学报(英文版), 2006, 19(1): 83-88.

摘 要: 冗余度或超冗余度移动操作臂机器人可在空间站上为宇航员提供很大的帮助。对一个超冗余度移动操作臂机器人系统的设计和实现作了介绍, 这个系统由一个 8 自由度的模块机器人和一个 1 自由度的电机驱动的导轨组成; 对该系统的逆运动学解法进行了讨论, 提出了一种基于避关节极限与位形优化的简化逆运动学控制方法; 并提供了仿真和实验结果。

关键词: 移动操作臂; 超冗余度机器人; 逆运动学
文章编号: 1000-9361(2006)01-0083-06 中图分类号: V260.6; TP242 文献标识码: A

Nowadays human beings on earth have paid much more attention to space than ever before and launched many space systems, such as satellites, shuttles and airships, to carry out different outer space exploring tasks. Although the harsh space environment is not suitable for astronauts to stay there for a long time, it does almost no harm to space robots and space robots can manipulate much heavier load in space than on earth. Mobile manipulator composed of a mobile base and a manipulator will be used increasingly in space applications, for example, NASA has used a tracked CANADA ARM on the International Space Station[1, 2], and a wheel-driven microrover Sojourner on Mars. The mobile base of a mobile manipulator can greatly increase its workspace and make it execute tasks efficiently. In recent years, there has been a growing interest in mobile manipulators. Seraji discussed the on-line motion control of mobile redundant manipulators and proposed a unified approach to deal with the modeling and control[3]. Miskch and Schroeder discussed the performance optimization of a mobile manipulator[4]. Jindong Tan and Ning Xi developed a unified dynamic model to integrate mobile platform and on-board manipulator of a mobile manipulator and proposed an on-line kinematic redundancy resolution scheme[5]. Zhan Qiang, Zhang Qixian, *etc*. built a dual mobile redundant manipulator platform and did some research on motion planning of it[6]. With the development of the space exploring technology of our country, our own space station will be launched and mobile manipulator inner the space station can be used as assistants to astronauts to take care of experiments or repair-

Received date: 2005-05-18; Revision received date: 2005-07-21
Foundation item: "863" project of China(2002AA742030)

ing tasks. In order to do research relevant to the application of mobile manipulators in our own space station, a hyper-redundant mobile manipulator system was designed and implemented. The paper introduces the system and discusses the inverse kinematic control of it.

1 Implementation of the Hardware System

Because the mobile manipulator system is designed for the research of its application in the space station, and at present our country has no space station, referring to NASA's IVA Servicers the dimensions of the space station are supposed to be 3 m(Length) × 2 m(Height) × 2 m(Width). Because the system is an experimental platform on earth and gravity of the system is still there, the implemented one can only simulate its task in space rather than all true conditions, especially the low-gravity.

The setup of the hyper-redundant mobile manipulator system is shown in Fig. 1. It is mainly composed of an 8-DOF modular robot with a 1-DOF gripper (at the end) both from Amtec corporation of Germany, and a 1-DOF motorized rail from PARKER corporation of Germany. The rail is driven by a 450 W AC servo motor from Yaskawa of Japan and the motor is controlled by a PMAC card from Delta Tau of USA. A main controller is used to control the modular robot and the rail simultaneously by programming with Visual C++ in the Windows NT operating system. The total system has 10 DOF, in other words the robot system has three redundant DOF except 1 DOF for the control of the gripper. A CCD camera system is used to provide the position and pose of the object to be operated by the manipulator and the information is sent to the manipulator's controller by Internet. The hardware structure of the system is shown in Fig. 2.

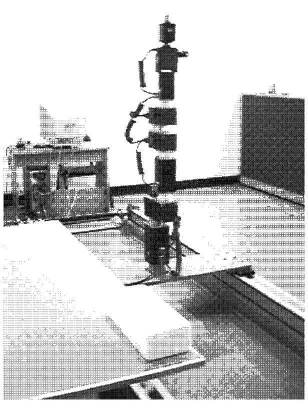


Fig. 1 The hyper-redundant mobile manipulator system

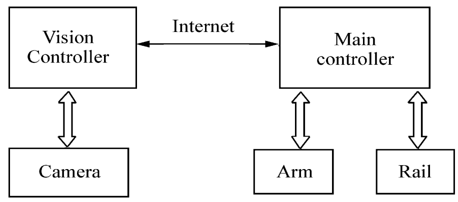


Fig. 2 The hardware structure of the system

2 Simplified Inverse Kinematic Resolution

It is well known that the inverse kinematic resolution of a redundant manipulator is usually infinite and hard to get an optimal one. Although the inverse kinematic resolution of 7-DOF redundant manipulator has been discussed extensively, there are few discussions on hyper-redundant manipulators, and less on hyper-redundant mobile manipulators. Many redundant DOF make the inverse kinematic resolution of a hyper-redundant manipulator compute costly, so a near real-time resolution is necessary in order to use hyper-redundant mobile manipulators in real applications.

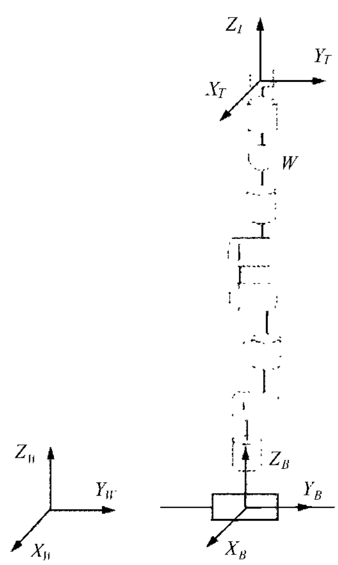


Fig. 3 The mobile manipulator

Although the hyper-redundant mobile manipulator system is composed of two different parts, it is easy to regard the sliding rail as 1-DOF of the manipulator and build the D-H coordinates of the whole system, then get the inverse kinematic resolution with its Jacobian matrix. However, because the dimensions of the Jacobian matrix are 6×9, it is very costly to get the inverse kinematic resolution and cannot make the system move in near real-time. Some simplified method must be developed in order to make the hyper-redundant mobile manipulator work naturally and smoothly.

The hyper-redundant mobile manipulator system is shown in Fig. 3. Three coordinates are defined, the first is the fixed world coordinates of reference $\{W\}$ in the robot workspace, the second is the moving rail coordinates $\{B\}$ and the last is the tool coordinates $\{T\}$ on the middle point of the tool of the mobile manipulator. Because the axis lines of the last three joints of the mobile manipulator intersect at one point, those three joints can be used to decide the pose of the end of the manipulator and the other 6 joints can be used to decide its position. In other words, the position of wrist point W (shown in Fig. 3) can only be decided by the first 6 joints of the manipulator and has nothing to do with the last 3 joints. With the method, the dimensions of the Jacobian matrix of the system to compute the position are only 3×6 and that to compute the pose are only 3×3, which undoubtedly can greatly decrease the computation complexness. To decide three dimensional positions of an object usually needs only 3 joints, here 6 joints are used to do it, so there are 3 redundant joints. The method to get one simple and optimum inverse position resolution of the hyper-redundant mobile manipulator will be discussed in the follows.

Suppose $\dot{\boldsymbol{p}} \in \mathbf{R}^3$ represents the velocity of point W of the mobile manipulator, $\dot{\boldsymbol{q}} \in \mathbf{R}^6$ represents the velocity of the mobile rail $\dot{\boldsymbol{q}}_{\mathrm{B}}$ and the first five revolute joints of the manipulator $\dot{\boldsymbol{q}}_{\mathrm{R}}$,

$$\dot{\boldsymbol{q}} = \begin{bmatrix} \dot{\boldsymbol{q}}_{\mathrm{R}} \\ \dot{\boldsymbol{q}}_{\mathrm{B}} \end{bmatrix}, \begin{cases} \dot{\boldsymbol{q}}_{\mathrm{R}} \in \mathbf{R}^5 \\ \dot{\boldsymbol{q}}_{\mathrm{B}} \in \mathbf{R}^1 \end{cases} \tag{1}$$

Then the forward kinematics of the mobile manipulator is

$$\dot{\boldsymbol{p}} = \boldsymbol{J}\dot{\boldsymbol{q}} = [\boldsymbol{J}_R \ \vdots \ \boldsymbol{J}_{\mathrm{B}}] \begin{bmatrix} \dot{\boldsymbol{q}}_{\mathrm{R}} \\ \dot{\boldsymbol{q}}_{\mathrm{B}} \end{bmatrix} \tag{2}$$

Here, $\boldsymbol{J} \in \mathbf{R}^{3\times 6}$ is the Jacobian matrix of the first 6 joints of the mobile manipulator, $\boldsymbol{J}_{\mathrm{R}} = \dfrac{\partial \boldsymbol{f}}{\partial \boldsymbol{q}_{\mathrm{R}}} \in \mathbf{R}^{3\times 5}$ is the Jacobian matrix of the five joints of the manipulator and $\boldsymbol{J}_{\mathrm{B}} = \dfrac{\partial \boldsymbol{f}}{\partial \boldsymbol{q}_{\mathrm{B}}} \in \mathbf{R}^{3\times 1}$ is the Jacobian matrix of the moving rail. Eq. (2) treats the rail movement as one joint of the total system and deals with the two parts of the mobile manipulator in the same framework.

The composite system is kinematically redundant with degree of redundancy 3, and the redundancy can be used to control 3 user-defined kinematic functions $\boldsymbol{f}_{\mathrm{C}}(q)$. Then Eq. (2) can be rewritten as

$$\begin{bmatrix} \dot{\boldsymbol{p}} \\ \dot{\boldsymbol{f}}_{\mathrm{C}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{J}_{\mathrm{R}} & \vdots & \boldsymbol{J}_{\mathrm{B}} \\ & \boldsymbol{J}_{\mathrm{C}} & \end{bmatrix} \begin{bmatrix} \dot{\boldsymbol{q}}_{\mathrm{R}} \\ \dot{\boldsymbol{q}}_{\mathrm{B}} \end{bmatrix} = \boldsymbol{J}_{\mathrm{E}}\dot{\boldsymbol{q}} \tag{3}$$

Here, $\boldsymbol{J}_{\mathrm{C}} = \dfrac{\partial \dot{\boldsymbol{f}}_{\mathrm{C}}}{\partial \dot{\boldsymbol{q}}} \in \mathbf{R}^{3\times 6}$ is the constraint Jacobian matrix and $\boldsymbol{J}_{\mathrm{E}} \in \mathbf{R}^{6\times 6}$ is the augmented Jacobian matrix of the mobile manipulator.

Because the mobile manipulator has three redundant degrees of freedom, three constraint functions to optimize its motion are constructed. Here the shoulder angle α, elbow angle β and displacement of the first joint d are used to construct the constraint function $\boldsymbol{f}_{\mathrm{C}}(q)$.

$$\left.\begin{aligned} f_{1\mathrm{C}}(q) &= \alpha = q_3 \\ f_{2\mathrm{C}}(q) &= \beta = q_5 + q_6 \\ f_{3\mathrm{C}}(q) &= d = q_1 \end{aligned}\right\} \tag{4}$$

Because α and β determine the reach of the arm and d determines the motion range of the mobile rail, the constructed constraint function $\boldsymbol{f}_{\mathrm{C}}(q)$ can make the mobile manipulator stretch its arm and move the rail to the best when manipulating. Stretching arm to the best can make the manipulator avoid collisions of its own links and joints, and moving the rail to the best can make the manipulator reach the end position with the least joint motion (mainly using the first joint) so as to increase the motion response of the mobile manipulator.

With Eqs. (3) and (4) an inverse resolution of the mobile manipulator can be easily gotten, but each joint of the real manipulator has its own angle or motion range, so in order to promise that the resolution is suitable and practical the inverse resolution cannot go beyond the motion range of each joint. Weighted Least Norm method was first used to avoid joint limit by Chan[7], here it is used to construct the inverse kinematic resolution based on joint limit avoidance of the mobile manipulator as follows. When the order of $\boldsymbol{J}_E = 6$, the inverse kinematic resolution of the mobile manipulator is

$$\dot{\boldsymbol{q}} = \boldsymbol{W}^{-1}\boldsymbol{J}_E^T(\boldsymbol{J}_E\boldsymbol{W}^{-1}\boldsymbol{J}_E^T)^{-1}\dot{\boldsymbol{p}} \tag{5}$$

Here, $\boldsymbol{W}$ is a diagonal weighting factor matrix, $\boldsymbol{W}=\mathrm{diag}\{W_i\}$.

$$W_i = \begin{cases} 1+\left|\dfrac{\partial H(q)}{\partial q_i}\right| & \text{if} \quad \Delta\left|\dfrac{\partial H(q)}{\partial q_i}\right| \geqslant 0 \\ 1 & \text{if} \quad \Delta\left|\dfrac{\partial H(q)}{\partial q_i}\right| < 0 \end{cases} \tag{6}$$

$$\frac{\partial H(Q)}{\partial q_i} = \frac{(q_{\max}[i]-q_{\min}[i])^2(2q[i]-q_{\max}[i]-q_{\min}[i])}{4(q_{\max}[i]-q[i])^2(q[i]-q_{\min}[i])^2} \tag{7}$$

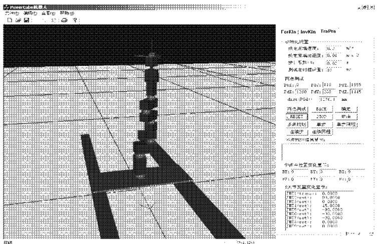
When one joint moves to the joint limit the value of $\Delta\left|\dfrac{\partial H(q)}{\partial q_i}\right|$ is positive and increases, when the joint moves off the joint limit the value of $\Delta\left|\dfrac{\partial H(q)}{\partial q_i}\right|$ is negative and when the joint stops $\Delta\left|\dfrac{\partial H(q)}{\partial q_i}\right|$ becomes zero. Although W_i is not a continuous function of joint angles, it has no effect on the continuousness of joint speed.

With Eq. (5), not only the inverse kinematic resolution of the mobile manipulator based on joint limit avoidance can be gotten, but also its motion and configuration can be optimized through those three factors: shoulder angle, elbow angle and displacement of the first joint. Here the inverse kinematic resolution when $\boldsymbol{J}_E < 6$ is not discussed. Seraji and Colbaugh[8] have pointed out that three conditions can lead to singularity of $\boldsymbol{J}_E$ in Eq. (5), the first is when $\boldsymbol{J}$ is singular, the second is when constraint Jacobian $\boldsymbol{J}_C$ is singular and the last is when any row of $\boldsymbol{J}_C$ is orthogonal to the null space of $\boldsymbol{J}$.

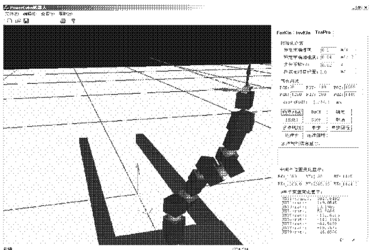
3 Simulations and Experiments

In order to test the near real-time inverse kinematic resolution proposed in Section 2, some simulations are done. The Vector Product method is used to get Jacobian matrix $\boldsymbol{J}_R$ of the manipulator, and direct differential method is used to get Jacobian matrix $\boldsymbol{J}_B$, constraint Jacobian matrix $\boldsymbol{J}_C$. Limited by the paper space, here the detailed expression of $\boldsymbol{J}_E$ is not given. The motion range of the first joint is (−1500~1500) mm and that of the rest five joints is (−160°~160°). Suppose the wrist point W of the mobile manipulator moves in straight line from initial position (0, 110, 1370) to final position (1060, 280, 1260) in 10 seconds in the reference coordinates {W} and in the process the pose of the manipulator is fixed. Note that if the manipulator has a fixed base, it will not reach the position, but with the moving base it can easily reach it. From this point it can be said that the mobile base can greatly increase the manipulator's work space and improve its operation ability. During the simulation, the initial and the final configuration of the mobile manipulator are shown in Fig. 4. The path of the 6 joints of the mobile manipulator is shown in Fig. 5. From the simulation results it can be found that the proposed method can easily get the inverse kinematic resolution of the mobile manipulator and no joint exceeds its joint limits.

The proposed method is also used to control the real hyper-redundant mobile manipulator to grasp an object from one end of a desk and transport it to another end. Pictures of the transporting experiment are shown in Fig. 6. The experiments show that the proposed method is near real-time and can make the mobile manipulator work smoothly.

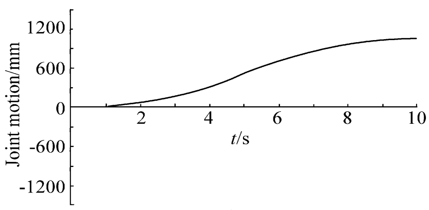


Initial configuration

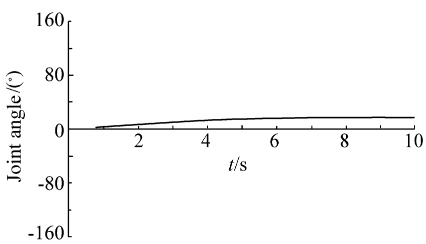


Final configuration

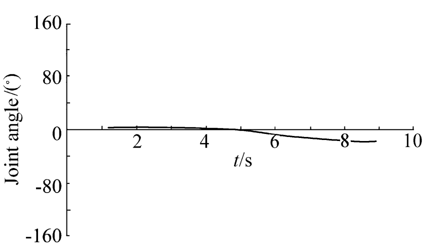
Fig. 4 Initial and final configurations during simulation



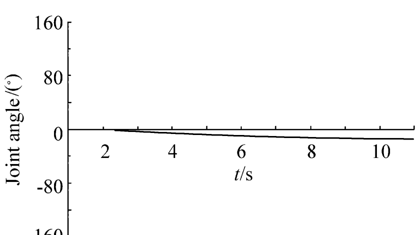
joint 1



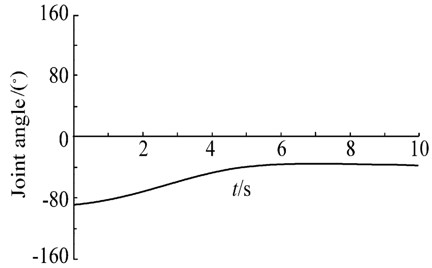
joint 2



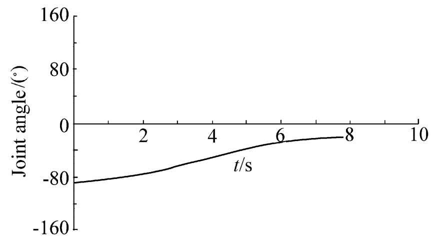
joint 3



joint 4

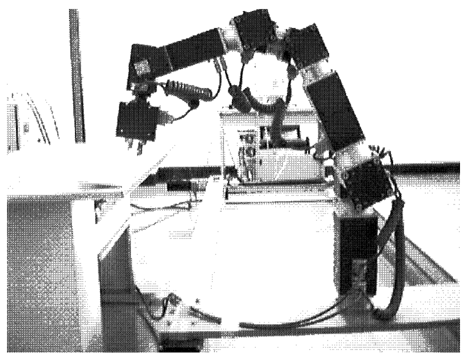


joint 5

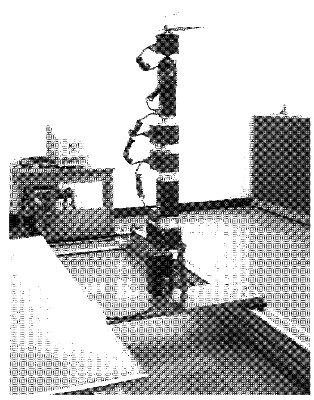


joint 6

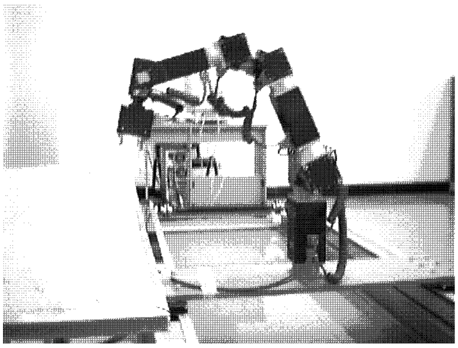
Fig. 5 Joint motions of simulation



(a) pick the object



(b) transport the object



(c) put the object

Fig. 6 Transporting object experiment

4 Conclusions

In the paper, a hyper-redundant mobile manipulator system implemented for the research of its application to inner space station is described and a simplified and near real-time inverse kinematic method based on joint limit avoidance and configuration optimization is proposed in order to control it smoothly in the same framework. The system can be used to test some typical tasks in space station, such as taking care of crystal growth experiments, pushing electric buttons and transporting objects, *etc*.

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