INVERSE KINEMATICS AND CONTROL OF THE ASSISTIVE ROBOT FOR DISABLED

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Abstract: Paper presents an assistive robot for disabled people with specific genetic disorders or persons who suffer spinal cords injuries. Robot consists of the manipulator arm with 4 DOF mounted on the electrically powered wheelchair. Such robot provides the disabled person with the facility that augments both mobility and manipulation capabilities. Kinematic structure of this robotic system together with suitable control approach are introduced.

Keywords: rehabilitation robotics, mobile manipulator, kinematic redundancy

1. INTRODUCTION

Assistive Robot for DISabled (ARDIS), which is being build at DCMI, belongs to the rank of rehabilitation robots. Such robots are devices that may be operated by individuals with severe disabilities to carry out manipulation tasks that they would otherwise be unable to perform. A rehabilitation robot is similar in purpose to an upper limb prosthesis, but is not directly attached to the user's body. For this reason, it has less constraints on size, power requirements and application approach, and is therefore appropriate for use by individuals with a wide range of manipulation disabilities.

Rehabilitation robots may be classified into three groups, (Applied Resources Corp., 1998):
Task specific devices. Simple electromechanical devices used to perform simple tasks, e.g., powered feeders and pageturners. Some more sophisticated systems may be used to accomplish a great variety of tasks, depending on the extensions used, e.g., allowing to feed, cleanse, make up, clean teeth etc.
Workstation robots. Special sets of various assistive devices designed to meet the specific requirements arising from the given human activity, e.g., in work, study or ADL tasks (Activities of Daily Living).
Wheelchair robots. Consisting of the manipulator arm mounted on the electrically powered wheelchair, such robot provides the disabled person with the facility that augments both mobility and manipulation, allowing him/her to hold a cup and drink, eat a sandwich, turn off the lights, or open doors.

Introduction of advanced technical aids into the daily living of disabled has several positive aspects:
Economical. The working time of the personal assistant can be reduced which can lead to economical savings. Thus, resulting reduced reliance on an attendant would have paid for the workstation or assistive robotic aid in several years.
Social. The quality of life of such disabled people is directly improved.

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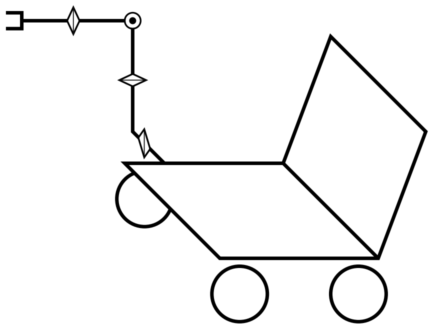

Fig. 1. Kinematic structure of the robotic arm

Psychological. Such systems can increase self-esteem, assertiveness, and motivation towards developing the manipulation skills further and working towards independence. Although the presence of personal assistants usually can not be completely eliminated, the necessary time when the assistant is serving the handicapped can be significantly reduced. This way the privacy of disabled is increased, and also some possible problems with interpersonal relations can be avoided.

ARDIS is a device from the class of wheelchair robots designed for people with specific genetic disorders or persons who suffered spinal cords injuries. Although there is no exact statistics available that would summarize the number of people with this handicap, it is known that only at accident hospitals around the Czech Republic there are 30 to 50 cases of cervical spine injury every year. The mission of ARDIS is to allow such people to interact independently with their environment.

2. KINEMATIC STRUCTURE

Kinematic structure of ARDIS is shown in Fig. 1. ARDIS offers 4 DOF: flexion/extension and rotation of the shoulder, flexion/extension of the elbow, and rotation of the wrist. Since the gripper itself cannot attain arbitrary position/orientation in the space, it is a compromise between the design complexity (i.e., price) and usability. Arm kinematics is designed so that it can reach objects on the floor, on a table, turn on switches or elevator buttons etc. Robotic arm is mounted on the wheelchair introducing three additional DOF. Resulting robotic system (mobile manipulator) possesses together 7 DOF. ARDIS is illustrated in Fig. 2.

The main difference of ARDIS compared to other wheelchair robots is that it is being developed in conjunction with omnidirectional wheelchair, which offers absolute freedom of motion in the plane. Such mobile wheelchair can freely translate and rotate in an arbitrary direction. This is accomplished by the so-called mecanum wheels.

Fig. 2. ARDIS consists of the 4 DOF robotic arm mounted on the 3 DOF omnidirectional wheelchair

Chassis of this wheelchair, utilizing four such wheels, is shown in Fig. 3.

3. CONTROL

There are two aspects of the rehabilitation robot control that affect its functionality: the interface between the user and the robot, and the interface between the robot and the objects it is manipulating.

Rehabilitation robots are controlled by the user through typical adaptive interfaces – joystick, keypad, or sip-and-puff device. There are limitations on the sophistication of the robot's operation that are due simply to the fact that the user is limited in the control he is able to exert. Nonetheless, advanced technologies like voice control or gesture recognition may increase the quality of the user interface significantly.

The interface between the robot and the objects being manipulated is usually a simple pincer-like gripper. Thus, the types of manipulations that can be performed are quite limited. However, a large portion of activities we perform in school, work, and daily living involve pick-and-place tasks which may be carried out even with this simple end-effector.

The control of wheelchair robots is usually split into two parts, both realized by separate input devices – control of the wheelchair itself, and the control of the robotic arm. Hence, when the user is trying to grasp an object which is outside the reach of the arm, he has to manipulate alternately with two input devices which makes the use of the system harder. Thus, the control of the ARDIS is designed so that the control of the whole system – a wheelchair and the arm – may be executed in

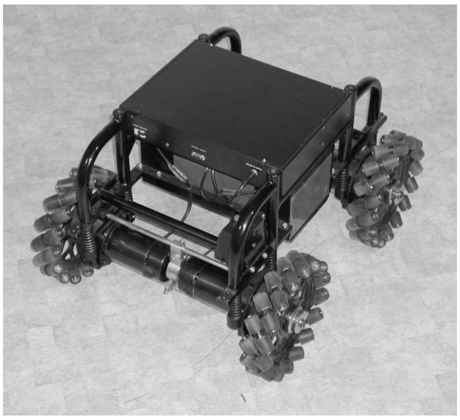

Fig. 3. Omnidirectional platform with mecanum wheels

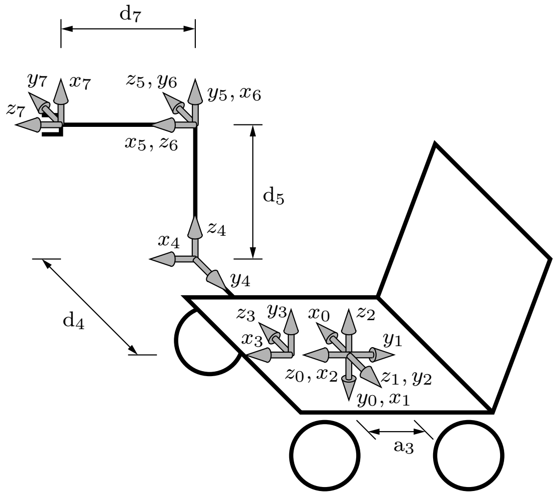

Fig. 4. ARDIS link frames

an unified framework. This way, when the user is trying to reach an object at the workspace boundary of the arm, the wheelchair is moving accordingly in the direction towards this object. In other words, the user is controlling the motion of the end-effector only with one input device, while the motion of the wheelchair is performed automatically. When using the system in environment with obstacles, system of sensors will guarantee the safety of the wheelchair movement.

To make the design of the unified control approach possible, it is necessary to describe the kinematic parameters of the mechanical system as a whole. As mentioned above, manipulator arm possesses 4 DOF. Wheelchair offers additional 3 DOF and may be considered as another serial-link arm with two prismatic (position) and one revolute (orientation) joints. Thus, resulting robotic system may be represented by the virtual 7 DOF serial link manipulator with Denavit-Hartenberg parameters specified in Table 1. Particular link coordinate frames are shown in Fig. 4.

The end-effector control is realized using differential kinematics at the velocity level, and may be

Table 1. ARDIS link parameters

Joint i	θ_i (rad)	α_i (rad)	a_i (m)	d_i (m)	Joint type
1	$\frac{\pi}{2}$	$\frac{-\pi}{2}$	0	0	prismatic
2	$\frac{-\pi}{2}$	$\frac{\pi}{2}$	0	0	prismatic
3	0	$\frac{\pi}{2}$	a_3	0	revolute
4	0	$\frac{-\pi}{2}$	0	d_4	revolute
5	0	$\frac{\pi}{2}$	0	d_5	revolute
6	$\frac{\pi}{2}$	$\frac{\pi}{2}$	0	0	revolute
7	0	0	0	d_7	revolute

described by the following equation:

$$\dot{\boldsymbol{q}} = \boldsymbol{J}^+_{\boldsymbol{W}}\dot{\boldsymbol{r}} + (\boldsymbol{E} - \boldsymbol{J}^+_{\boldsymbol{W}}\boldsymbol{J})(-\nabla c)\, v(\dot{\boldsymbol{r}}) \,, \qquad (1)$$

where $\dot{\boldsymbol{q}}$ is the vector of joint velocities, $\boldsymbol{J}$ is the manipulator Jacobian matrix, $\boldsymbol{J}^+_{\boldsymbol{W}}$ is the Jacobian pseudoinverse weighted by the matrix $\boldsymbol{W}$, $\boldsymbol{r}$ is the vector of end-effector velocities, $\boldsymbol{E}$ is the identity matrix, and c is the scalar function penalizing the distance to the arm singular configurations and joint limits. This approach is often used for control of kinematically redundant serial-link manipulators, (Nenchev, 1989). The first term on the right hand side of (1) is the particular solution, which is used to perform the desired end-effector velocity $\dot{\boldsymbol{r}}$. The matrix $(\boldsymbol{E} - \boldsymbol{J}^+_{\boldsymbol{W}}\boldsymbol{J})$ from (1) is the Jacobian null space projectional operator. The homogeneous solution (second term on the right hand side of (1)) contributes to a motion in joint space only, the so-called self-motion of the mechanical system.

As the weighting matrix $\boldsymbol{W}$ manipulator inertia matrix may be used. In such case would the first term on the right hand side correspond to the local minimization of the kinetic energy. The physical interpretation of this control scheme is that as little mass as possible is moving at any given moment. This strategy leads to energy savings and also improves the manipulation precision, because the arm positioning is more accurate than the wheelchair movements.

Term $v(\dot{\boldsymbol{r}})$ in (1) is a scalar function of joint velocities, such as quadratic norm $\|\dot{\boldsymbol{r}}\|$ or a function of this norm, and is used for suppressing of self-motions. This way zero joint velocities corresponding to zero end-effector velocities are guaranteed. The reason for using differential kinematics and Jacobian pseudoinverse for solving the inverse kinematics is the fact that the arm together with the wheelchair form kinematically redundant system with 7 DOF (four for the arm and three for the wheelchair). Closed form solution of the inverse kinematics of kinematically redundant robots is hard to find or even does not exist at all.

Because the omnidirectional character of motion of the wheelchair is accomplished using the independently controlled mecanum wheels, these velocities have to be recomputed into the rotational velocities of particular wheels. The necessary relation is described by the next equation, (Hoelper, 1996):

$$\begin{bmatrix}\omega_1\\ \omega_2\\ \omega_3\\ \omega_4\end{bmatrix} = \frac{1}{R}\begin{bmatrix}-1 & 1 & (a+b)\\ 1 & 1 & -(a+b)\\ -1 & 1 & -(a+b)\\ 1 & 1 & (a+b)\end{bmatrix}\begin{bmatrix}v_x\\ v_y\\ \omega_z\end{bmatrix} , \quad (2)$$

where $\omega_1, \omega_2, \omega_3$, and ω_4 are particular wheel velocities, R is the mecanum wheels radius, a is the wheel gauge, b is the wheel base, v_x and v_y are translational and ω_z rotational velocities of the wheelchair. The first three elements of the vector $\dot{\boldsymbol{q}}$ in (1) correspond to translational and rotational velocities of the wheelchair in (2):

$$\begin{aligned} v_x &= \dot{q}_1 \\ v_y &= \dot{q}_2 \\ \omega_z &= \dot{q}_1 \end{aligned} \quad (3)$$

Although the inverse kinematics solution was presented on the system equipped with the omnidirectional wheels, it is also suitable for wheelchairs with the classical construction that cannot move sidewise. In this case some DOF of the robotic system are coupled, namely the joint variables $\dot{q}_1, \dot{q}_2$ and $\dot{q}_3$. These joint variables have to meet the non-holonomic condition caused by the rolling contact between the wheels and the floor, which is described by equation

$$\dot{q}_1 \sin q_3 - \dot{q}_2 \cos q_3 = 0 \; . \quad (4)$$

This equation may be considered as an additional task imposed on the robotic system and can be incorporated into the concept of differential kinematics. The augmented task has the following form:

$$\begin{bmatrix}\dot{\boldsymbol{r}}\\ 0\end{bmatrix} = \begin{bmatrix} & & \boldsymbol{J} & & \\ \sin q_3 & -\cos q_3 & 0 & \cdots & 0\end{bmatrix}\dot{\boldsymbol{q}} \; . \quad (5)$$

The augmented task defined by (5) is then solved in the same way as was shown in (1).

4. USER INTERFACE

Presented approach to the inverse kinematic solution based on the differential kinematics is in fully accordance with the desired ARDIS user interface. Since the arm end-effector should be controlled in real-time by the operator by a kind of joystick-like input device, velocity control is desirable. ARDIS Jacobian matrix $\boldsymbol{J} \in \mathbf{R}^{6\times 7}$ relates the 6-element vector of end-effector velocities to the 7-element vector of joint velocities. Use of this Jacobian matrix would require the definition of the full 6-element vector of end-effector velocities (3 for position and 3 for orientation), which would make the successful ARDIS control difficult. This is partially due to the necessity of use of 6 DOF input device, which could not be operated by the disabled operator, and partially by the limited ARDIS dexterity, caused by simple kinematic structure. Simulation experiments that have been performed show that good results can be achieved also with 2 DOF input device (joystick), which is used in switched mode for control of four task-space coordinates (this means that only two variable are controlled at a time): translational velocity of the end-effector controlled in the wheelchair coordinate frame (three coordinates x_0, y_0, z_0) and rotational velocity of the wrist controlled in the wrist coordinate (rotation about the axis z_7, see Fig. 4). Thus, only two rows of the ARDIS Jacobian matrix are needed for the inverse kinematics computation at a time.

5. CONCLUSION

The goal of rehabilitation robotics is to provide such assistive devices that would allow disabled people to perform useful tasks, i.e., tasks that truly result in independence of the user. That is the necessary condition, because only technical aids that are medically necessary or that directly reduce healthcare costs can lead to reimbursement.

ARDIS is an assistive robotic aid that is suitable especially for use in cluttered environment, where the advantages of the omnidirectional wheelchair come into play. An important feature of the presented system is also the unified framework used for the end-effector control, which may simplify many manipulation tasks.

Simplicity of ARDIS mechanical design results in reduced cost, which is an important factor, since such devices are usually financed by insurance companies or other reimbursement organizations with limited budget.

Another issue when constructing the wheelchair robot is the design of man-machine interface, which is usually strongly user-specific and is therefore not discussed here. This problem is subject to the future work.

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