

Anthropic inverse kinematics of robot manipulators in handwriting tasks

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Abstract. This paper deals with the problem of realizing anthropic movements with a robot manipulator performing handwriting tasks. A redundant seven degrees-of-freedom manipulator, having a kinematic structure similar to that of the human arm, is considered. The inverse kinematics is computed using a closed-loop algorithm with redundancy resolution where physically motivated secondary tasks are imposed to the internal motions to achieve a human-like behaviour. This approach is validated by comparing the output of the algorithm to the positions of the joints of a human handwriter performing the same task, computed from the images caught by a camera.

Keywords: Anthropic robotics, inverse kinematics, handwriting, redundancy.

1. Introduction

A handwriting task involves force and position constraints for the human arm. Manipulability ellipsoids may be used to study the relations between dexterity and efforts during handwriting (Chiu, 1988). Notice that, for writing on a surface, only three degrees of freedom (DOF's) are required; hence, the human arm is redundant to perform such a task, even though, a simplified 7-DOF kinematic model (not considering the hand articulated structure) is adopted (Potkonjak et al., 2001).

When a 7-DOF anthropomorphic robot manipulator performs handwriting tasks, the 4 redundant degrees of freedom can be suitably used to perform secondary tasks (Chiaverini et al., 1991). A possible way of exploiting redundancy is that of mimicking the human arm movements (Potkonjak et al., 1998). This can be achieved, for example, by directly feeding the joint values computed from measurements on a human experimenter into an inverse kinematics algorithm (Ilg et al., 2003). An example of application is rehabilitation robotics, where an exoskeleton may drive the correct movements of the injured arm of a patient (Mussa-Ivaldi & Patton, 2000). Moreover, in fine painting tasks, an anthropic behaviour may produce a smoother end-effector trajectory resulting in higher quality lines.

In this paper, a closed-loop inverse kinematics (CLIK) algorithm (Sciavicco & Siciliano, 2000) is adopted to compute the joint motions of a 7-DOF anthropomorphic robot manipulator performing a handwriting task on a horizontal plane, like a human writing on a desk. Differently from previous works, redundancy of the system is solved by defining secondary tasks suggested by kinematic and dynamic considerations about the human arm behaviour. In detail, the mobility of the last three joints, corresponding to the robot wrist, is suitably reduced with respect to the mobility of the other joints; moreover, the elbow and wrist are forced to stay close to the writing plane, in order to minimize the gravity acting on the links.

The outputs of the proposed algorithm, i.e., the joint motions, are compared to the positions of the joints of a human performing the same task, which are computed from the images captured by a camera. The results confirm the effectiveness of the proposed approach.

2. Kinematics and redundancy resolution

The kinematic structure of the handwriting robot (see Fig. 1) can be described by considering a 7-DOF kinematic chain corresponding to the joints and links of a human arm. The lengths of the links have been set on the basis of anatomic evaluations: 0.3 m for the first link, 0.25 m for the forearm and 0.15 m for the hand-pencil link.

To solve the inverse kinematics problem, the (7×1) vector $\mathbf{q}$ of the joint variables must be computed starting from the (3×1) position vector $\mathbf{p} = [x \ y \ z]^T$ of a point on the writing plane. Notice that only the x and z components are variable, while the y component remains constant during the execution of the writing task. The simplest way to compute the inverse kinematics is that of using the differential

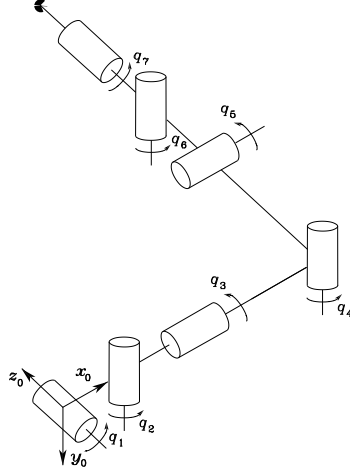


Fig. 1. Kinematic model of the handwriting robot

kinematics equation $\dot{\mathbf{p}} = \mathbf{J}(\mathbf{q})\dot{\mathbf{q}}$, mapping the joint space velocity $\dot{\mathbf{q}}$ into the task space velocity $\dot{\mathbf{p}}$, where $\mathbf{J}(\mathbf{q})$ is the (3×7) Jacobian matrix. This mapping may be inverted using the pseudo-inverse of the Jacobian matrix, i.e., $\dot{\mathbf{q}} = \mathbf{J}^\dagger(\mathbf{q})\dot{\mathbf{p}}$, where $\mathbf{J}^\dagger = \mathbf{J}^T(\mathbf{J}\mathbf{J}^T)^{-1}$ is a (7×3) matrix, which corresponds to the minimization of the joint velocities in a least-square sense (Sciavicco & Siciliano, 2000).

Because of the different characteristics of the available degrees of mobility, it could be required to modify the velocity distribution with respect to the least-square minimal solution. This might be achieved by adopting a weighted pseudo-inverse matrix $\mathbf{J}_W^\dagger$

$$\mathbf{J}_W^\dagger = \mathbf{W}^{-1} \mathbf{J}^T (\mathbf{J} \mathbf{W}^{-1} \mathbf{J}^T)^{-1} \quad (1)$$

with $\mathbf{W}^{-1} = \text{diag}\{\beta_1, \dots, \beta_7\}$, where β_i is a weight factor belonging to the interval $[0, 1]$ such that $\beta_i = 1$ corresponds to full motion for the i -th degree of mobility and $\beta_i = 0$ corresponds to freeze the corresponding joint. The redundancy of the system can be further exploited by using a task priority strategy corresponding to a solution of the form

$$\dot{\mathbf{q}} = \mathbf{J}_W^\dagger(\mathbf{q})\dot{\mathbf{p}} + \left(\mathbf{I}_7 - \mathbf{J}_W^\dagger(\mathbf{q})\mathbf{J}(\mathbf{q}) \right) \dot{\mathbf{q}}_a \quad (2)$$

where $\mathbf{I}_7$ is the (7×7) identity matrix, $\dot{\mathbf{q}}_a$ is an arbitrary joint velocity vector and the operator $\left(\mathbf{I}_7 - \mathbf{J}_W^\dagger \mathbf{J} \right)$ projects the joint velocity vector in the null space of the Jacobian matrix. This solution generates an internal motion of the robotic system (secondary task) which does not affect the motion of the writing point $\mathbf{p}$ (primary task). The joint velocity vector $\dot{\mathbf{q}}_a$ can be chosen to be aligned with the gradient of a scalar objective function $W(\mathbf{q})$, i.e.:

$$\dot{\mathbf{q}}_a = -k_s \frac{\partial W(\mathbf{q})}{\partial \mathbf{q}} \quad (3)$$

with $k_s > 0$, in order to achieve a local minimum for $W(\mathbf{q})$ (Liégeois, 1977).

To avoid numerical drift due to discrete-time integration, a closed-loop inverse kinematics (CLIK) algorithm can be adopted (Sciavicco & Siciliano, 2000), which computes $\mathbf{q}$ by integrating the vector:

$$\dot{\mathbf{q}} = \mathbf{J}_W^\dagger(\mathbf{q})\mathbf{v} + \left(\mathbf{I}_7 - \mathbf{J}_W^\dagger(\mathbf{q})\mathbf{J}(\mathbf{q}) \right) \dot{\mathbf{q}}_a \quad (4)$$

with $\mathbf{v} = \dot{\mathbf{p}}_d + \mathbf{K}(\mathbf{p}_d - \mathbf{p})$, where $\mathbf{K}$ is a (3×3) positive definite matrix gain to be chosen so as to ensure convergence to zero of the error $\mathbf{p}_d - \mathbf{p}$. Notice that in (4) the subscript d denotes the components of the position and velocity vectors that are input to the CLIK algorithm; the position components without subscript d are those computed from the joint position vector $\mathbf{q}$ (the output of the algorithm) via the direct kinematics equation.

To confer an anthropic behaviour to the manipulator during the execution of the writing task, the weights β_i in (1) and the vector $\dot{\mathbf{q}}_a$ in (4) must be suitably chosen.

Observing a human writer, it can be recognized that the joints of the shoulder and of the elbow shall have higher mobility with respect to the joints of the wrist. This can be easily obtained by choosing the weights β_i close to 1, for $i = 1, 2, 3, 4$ and close to 0 for $i = 5, 6, 7$. These values could be modified during the task execution using, e.g., soft computing techniques (De Santis et al., 2005).

Moreover, during the acting of writing at a desk, the elbow and the wrist are usually taken close to the desk, in order to minimize the effects of the gravity on the arm. This behaviour can be enforced to the manipulator by assigning to the elbow and to the wrist a position close to the writing plane without modifying the trajectory of the pencil. This can be achieved by considering the three-step algorithm described in the following.

In the first step, the differential mapping corresponding to the velocity of the elbow along the y axis is considered, i.e. $\dot{y}_e = \mathbf{J}_e(\mathbf{q}_e)\dot{\mathbf{q}}_e$ where $\dot{\mathbf{q}}_e = [q_1 \ q_2 \ q_3]^T$ and $\mathbf{J}_e(\mathbf{q}_e)$ is a (1×3) row vector. Hence, a CLIK algorithm with weighted pseudo-inverse is adopted to compute the inverse kinematics:

$$\dot{\mathbf{q}}_e = \mathbf{J}_{We}^\dagger(\mathbf{q}_e)v_e, \quad (5)$$

with $v_e = \dot{y}_{de} + k_e(y_{de} - y_e)$, being y_{de} the desired elbow position and $k_e > 0$. The pseudo-inverse matrix is $\mathbf{J}_{We}^\dagger = \mathbf{W}_e^{-1}\mathbf{J}_e^T(\mathbf{J}_e\mathbf{W}_e^{-1}\mathbf{J}_e^T)^{-1}$, with $\mathbf{W}_e^{-1} = \text{diag}\{\beta_1, \beta_2, \beta_3\}$.

In the second step, the differential mapping corresponding to the velocity of the wrist along the y axis is considered, i.e., $\dot{y}_w = \mathbf{J}_{Ww}(\mathbf{q}_w)\dot{\mathbf{q}}_w$, where $\dot{\mathbf{q}}_w = [q_1 \ q_2 \ q_3 \ q_4]^T$ and $\mathbf{J}_{Ww}(\mathbf{q}_w)$ is a (1×4) row vector. Again, a CLIK algorithm with weighted pseudo-inverse and secondary task is adopted to compute the inverse kinematics:

$$\dot{\mathbf{q}}_w = \mathbf{J}_{Ww}^\dagger(\mathbf{q}_w)v_w + \left(\mathbf{I}_4 - \mathbf{J}_{Ww}^\dagger(\mathbf{q}_w)\mathbf{J}_{Ww}(\mathbf{q}_w)\right)\dot{\mathbf{q}}_{aw}, \quad (6)$$

The pseudo-inverse matrix is $\mathbf{J}_{Ww}^\dagger = \mathbf{W}_w^{-1}\mathbf{J}_w^T(\mathbf{J}_w\mathbf{W}_w^{-1}\mathbf{J}_w^T)^{-1}$, with $\mathbf{W}_w^{-1} = \text{diag}\{\beta_1, \beta_2, \beta_3, \beta_4\}$ and $v_w = \dot{y}_{dw} + k_w(y_{dw} - y_w)$, being y_{dw} the desired wrist position, $k_w > 0$; $\dot{\mathbf{q}}_{aw}$ is the gradient of the objective function:

$$G(\mathbf{q}_w) = -\frac{1}{6} \sum_{i=1}^3 \frac{q_i - q_{ei}}{q_{iM} - q_{im}}$$

where q_{iM} (q_{im}) is the maximum (minimum) value of the joint variable q_i . The above choice corresponds to achieve a joint motion, for the first 3 joint variables, close to that computed in the first step. This is imposed as a secondary task, hence it is fulfilled only if it does not interfere with the primary task.

Finally, in the third step, the complete manipulation structure with the CLIK algorithm in (4) is considered, where $\dot{\mathbf{q}}_a$ is chosen as the gradient of the objective function:

$$G(\mathbf{q}) = -\frac{1}{8} \sum_{i=1}^4 \frac{q_i - q_{wi}}{q_{iM} - q_{im}},$$

corresponding to a motion for the first 4 joints close to that computed in the second step.

Notice that the weights β_i of the matrix $\mathbf{W}$, and thus of $\mathbf{W}_e$, $\mathbf{W}_w$, are chosen according to the criterion described above, i.e., the mobility of each joint is different.

In order to better define the desired positions of elbow and wrist, which determine the internal motions, information on the force acting on the pencil should be provided.

3. Case study

In order to evaluate the performance of the proposed algorithm for a robot writer in comparison to a human writer, the same handwriting trajectory has been assigned to a human experimenter and to the robot manipulator. The handwriting task executed by a person was acquired using a camera from two different points of view. In Fig. 2 the top view and the side view are reported, where markers are to be noticed. Exploiting the grids on the writing plane and on the vertical plane, the positions of the joints of the human arm can be computed. Then, the joint angular positions can be evaluated via simple trigonometric calculations. For example, the angle between arm and forearm can be evaluated from Carnot's cosine theorem knowing the positions of the arm and forearm and the distance between the wrist and the shoulder (see Fig. 2). Notice that, in order to neglect the lens distortion effects, the center of the scene was used to extract the measurements, with the lens plane parallel to the grid plane. The time history of the acquired measurements is reported in Fig. 3(a).



Fig. 2. Handwriting task executed by a person

The acquired trajectory of the pencil is used as input to the inverse kinematics scheme (the trace of the pencil is reported in Fig. 4(a)), with $\mathbf{K} = 300\mathbf{I}_3$, $k_e = k_w = 200$. The output of a MATLAB-Simulink® simulation is reported in Fig. 3(b). It can be recognized that the time histories of the joint variables during the execution of the task are close to those recorded on the human writer: only the elbow angle is a bit different since the robot elbow is not always exactly laid on the desk.

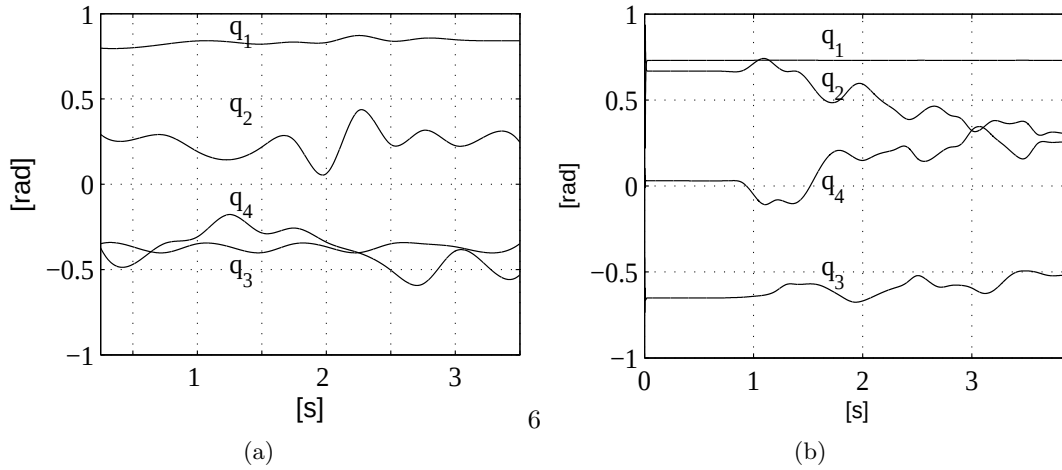


Fig. 3. Time history of joint variables: (a) human and (b) robot

In Fig. 4(b) the 3-D traces of the elbow, wrist and pencil, recorded during the execution of the handwriting task, are reported. It is possible to see how the primary task is fulfilled while position constraints for the elbow and the wrist are implemented as secondary tasks in the three-step algorithm discussed above. In fact, it can be observed that both the wrist and the elbow remain close to the desk as much as possible. To improve the performance of the algorithm, exact measurements of the mechanical limits of the human joints should be provided too.

4. Conclusion

In this paper an inverse kinematic algorithm for an 7-DOF anthropomorphic arm for the execution of handwriting tasks has been proposed. Redundancy of the system is exploited to achieve a human-like behaviour. Noticeably, this is obtained by setting few parameters of a CLIK algorithm with task priority, without imposing specific joint space trajectories. Simulation results show a good approximation to the recorded motion of a human arm, considering also wrist and elbow postures. Notice that handwriting tasks are representative of a set of tasks involving precise positioning of an end-effector by a human arm. Moreover, the three-step CLIK algorithm presented above may be used to plan a precise movement of an end-effector while keeping suitable positions of the whole kinematic structure of the robot. Future work

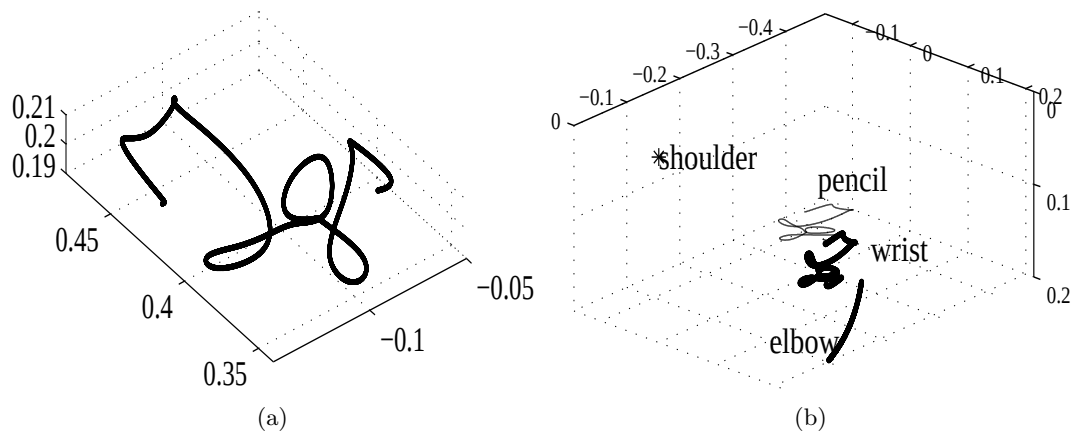


Fig. 4. 3-D trace of the pencil (a) and of elbow and wrist of the manipulator with respect to the pencil (b)

will be devoted to add force sensing capability for the detection of the writing surface (not necessarily planar) as well as visual sensing capability for obstacles avoidance. Notice that data about mechanical limits and actuators, with cognitively motivated considerations about the positioning of the arm depending on different tasks, should lead to obtaining an even more effective model.

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