

Biomimetic elbow positioning of a redundant robot arm

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Abstract— This paper deals with the problem of positioning the elbow of a redundant robot arm realizing biomimetic movements while performing typical anthropic tasks. A redundant 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 secondary tasks, inspired by kinematics and dynamics, are imposed to the internal motion to achieve a human-like behaviour. To minimize the forces acting on the joints, the arm searches a plane on which to lie its elbow; otherwise, it attains a position which minimizes the gravity torques. This approach is validated by comparing the output of the algorithm to the positions of the joints of a human experimenter performing two handwriting tasks, computed from the images caught by a camera.

I. INTRODUCTION

A simplified kinematic model of the human arm considers it as a manipulator with seven degrees of freedom (DOF's), without including in the model the hand articulated structure. However, for the description of many tasks such as writing on a surface, only three DOF's are required; hence, the human arm is kinematically redundant even though a simplified 7-DOF kinematic model is adopted [1].

In those cases, the 4 redundant DOF's can be suitably used to perform secondary tasks [2]. A possible way of solving redundancy is that of mimicking the human arm movements, by directly feeding, e.g., the joint values computed from measurements on a human experimenter. An example of application is rehabilitation robotics, where an exoskeleton may drive the correct movements of the injured arm of a patient [3].

In this paper, a closed-loop inverse kinematics (CLIK) algorithm [4] is adopted to compute the joint motions of a 7-DOF anthropomorphic robot manipulator performing a handwriting task on a horizontal and a vertical plane. In detail, following a biomimetic approach, 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 task of minimizing the gravity torques on the joints is transformed to a proper positioning task for elbow and wrist in the task space, by using nested inverse kinematics schemes. If the writing task is at desk, the elbow and the wrist are forced to stay close to the writing plane; on the other hand, when the task is performed on a vertical plane, the positioning task will be simply formulated directly in the joint space.

Two simulations are provided: the outputs of the proposed algorithm, i.e., the joint motions, in two handwriting

tasks, are compared to the positions of the joints of a human performing the same tasks, which are computed from the images captured by a camera. The results confirm the effectiveness of the proposed approach.

II. INVERSE KINEMATICS FOR A REDUNDANT HUMAN-LIKE ROBOT ARM

The kinematic structure of the handwriting robot (see Fig. 1) can be described by considering a 7-DOF arm 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.

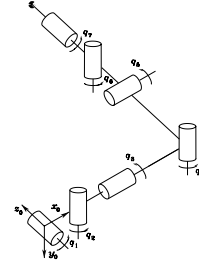


Fig. 1. Kinematic model of the handwriting robot

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.

An effective way to compute the inverse kinematics is that of resorting to the differential 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 minimizes the joint velocities in a least-squares sense [4].

Because of the different characteristics of the available DOF's, it could be required to modify the velocity distribution with respect to the least-square minimal solution. This can 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 weighting 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 [5] 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 $G(\mathbf{q})$, i.e.,

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

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

To avoid numerical drift due to discrete-time integration, a closed-loop inverse kinematics (CLIK) algorithm can be adopted [4], 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.

III. BIOMIMETIC ELBOW POSITIONING

In order to confer a biomimetic behaviour to the arm during the execution of a 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 task execution using, e.g., soft computing techniques [6].

Moreover, during the action 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 arm by assigning to the elbow and the wrist a position close to the writing plane without modifying the trajectory of the pencil. This can be achieved by considering the three-layer priority algorithm [7] described in the following, which exploits null-space motions to nest the different positioning tasks for pencil, wrist and elbow.

At the low layer, the differential mapping corresponding to the velocity of the elbow along the y axis is considered, i.e.,

$$\dot{y}_e = \mathbf{j}_e(\mathbf{q}_e)\dot{\mathbf{q}}_e \quad (5)$$

where $\mathbf{q}_e = [q_1 \ q_2 \ q_3]^T$ 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:

$$\dot{\mathbf{q}}_e = \mathbf{J}_{We}^\dagger(\mathbf{q}_e)v_e, \quad (6)$$

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 in (6) is

$$\mathbf{J}_{We}^\dagger = \mathbf{W}_e^{-1}\mathbf{J}_e^T(\mathbf{J}_e\mathbf{W}_e^{-1}\mathbf{J}_e^T)^{-1} \quad (7)$$

with $\mathbf{W}_e^{-1} = \text{diag}\{\beta_1, \beta_2, \beta_3\}$.

At the middle layer, the differential mapping corresponding to the velocity of the wrist along the y axis is considered, i.e.,

$$\dot{y}_w = \mathbf{J}_{Ww}(\mathbf{q}_w)\dot{\mathbf{q}}_w \quad (8)$$

where $\mathbf{q}_w = [q_1 \ q_2 \ q_3 \ q_4]^T$ and $\mathbf{J}_{Ww}(\mathbf{q}_w)$ is a (1×3) row vector. Again, a CLIK algorithm with weighted pseudo-inverse and secondary task is adopted to compute the inverse kinematics:

$$\dot{\mathbf{q}}_w = \mathbf{J}_{Ww}^\dagger(\mathbf{q}_w)v_w + \left(\mathbf{I}_4 - \mathbf{J}_{Ww}^\dagger(\mathbf{q}_w)\mathbf{J}_w(\mathbf{q}_w)\right)\dot{\mathbf{q}}_{aw}, \quad (9)$$

The pseudo-inverse matrix in (9) is

$$\mathbf{J}_{Ww}^\dagger = \mathbf{W}_w^{-1}\mathbf{J}_w^T(\mathbf{J}_w\mathbf{W}_w^{-1}\mathbf{J}_w^T)^{-1} \quad (10)$$

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 $G = -\frac{1}{6} \sum_{i=1}^3 \frac{q_i - q_{ei}}{q_{iM} - q_{im}}$, 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, at the high layer, 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 $G = -\frac{1}{8} \sum_{i=1}^4 \frac{q_i - q_{wi}}{q_{iM} - q_{im}}$, 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.

A handwriting task assigned on a wall parallel to the writer's body can also be considered. In this case, there is no surface where the writer could lie down his/her elbow. It is desired to keep the position of the elbow as close as possible to the body and thus minimize gravity. This leads to keep the elbow angle at $\frac{\pi}{2}$ degrees. Hence, the secondary task can be formulated directly in the joint space, i.e., $G = -\frac{1}{2} \left(\frac{q_1 - \frac{\pi}{2}}{q_{1M} - q_{1m}} \right)$.

IV. CASE STUDIES

In order to evaluate the performance of the proposed algorithm for a robot writer in comparison to a right-handed human writer, the same handwriting trajectory has been assigned to a human experimenter and to the robot arm in two different cases: a trajectory on a desk (horizontal plane) and a trajectory on a wall (vertical plane). The handwriting

task executed by a person was acquired using a camera from two different points of view [8]. In Fig. 2 the top view and the side view are reported for the first task, where markers have been evidenced. Exploiting the grids on the writing plane and on the vertical plane, the positions of the joints of the human arm can be evaluated via simple trigonometric calculations.

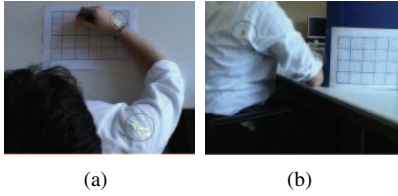


Fig. 2. Handwriting task executed by a person at a desk

For the handwriting task on a desk, the time history of the acquired measurements is reported in Fig. 3(a). 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 $\mathbf{K} = 30\mathbf{I}_3$, $k_e = k_w = 200$. The output of a MATLAB-Simulink[®] simulation is reported in Fig. 3(b). The elbow angle q_4 is a bit different since the robot elbow is not always exactly laid on the desk.

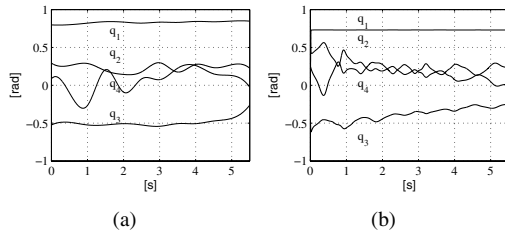


Fig. 3. Time history of joint variables during a handwriting task at a desk: (a) human and (b) robot

From Fig. 4(b), reporting the 3D trace of the elbow, wrist and pencil, it can be observed that both the wrist and the elbow remain close to the desk.

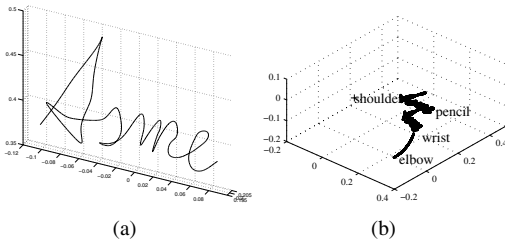


Fig. 4. 3-D trace of the pencil for the handwriting task at a desk (a) and of elbow and wrist of the arm with respect to the pencil (b)

For the task on a wall, the CLIK scheme with secondary tasks in joint space is considered with $\mathbf{K} = 30\mathbf{I}_3$. The time history of the acquired measurements of the movements of a human writer for the same task is reported in Fig. 5(a),

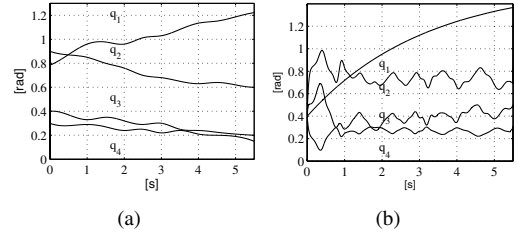


Fig. 5. Time history of joint variables during a handwriting task at a wall: (a) human and (b) robot

while Fig. 5(b) shows the outputs of the proposed algorithm implemented on the redundant robot.

The effects of human arm dynamics and control result in a sort of low-pass filtering of the relative tracked trajectories (see Figs. 3 and 5). Notice that cognitive issues in handwriting are to be investigated: studying people drawing figures or writing ideograms of an unknown language could help modelling of kinematic and dynamic strategies without cognitive conditioning. Ultimately, a statistical study shall be advocated to improve the model, by considering average human behaviours in performing such tasks.

V. CONCLUSION

In this paper an inverse kinematics algorithm for a 7-DOF anthropomorphic arm has been proposed and tested for two handwriting tasks, which are representative of a set of tasks involving precise positioning of an end-effector by a human arm. Redundancy of the system is exploited on the basis of biomimetic considerations, with the positioning of different parts of the articulated structure. The algorithm will be improved considering the dynamic model of the arm. Future work will be devoted also to include vision-based path planning and force sensing capabilities for the detection of the writing surface.

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