

A biomimetic approach to mobility distribution for a human-like redundant arm

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Abstract—In this paper the problem of planning trajectories using human-like vision information, and of solving inverse kinematics of robots by weighting joint involvement in a biomimetic fashion is considered. Movements of a redundant seven degree-of-freedom (DOF) robot manipulator, having a kinematic structure similar to that of the human arm, have been simulated. The design of the trajectory is based on theory about attentive vision in humans, and biomimetic considerations are used to infer laws to obtain human-like movements in inverse kinematics. The inverse kinematics is computed using a closed-loop algorithm with redundancy resolution where physically motivated secondary tasks are imposed to the internal motions, with the “Virtual End-Effectors” approach. Outputs of the IK algorithm related to drawing trajectories in the task space are compared with the positions of the joints of a human performing the same drawing task, computed from the images caught by a three-camera system.

Index Terms—Biomimetics, human-like trajectory, inverse kinematics, redundancy resolution.

Topic: Bio-inspired control models

I. INTRODUCTION

Many anthropic tasks involve force and position constraints for the human arm. The inverse kinematics the trajectory planning for human arm positioning may depend on these constraints. Manipulability ellipsoids may be used to study the relations between dexterity and efforts during handwriting [1], painting and other tasks where the human arm has to perform a precise motion while balancing forces acting on it. Notice that for many tasks such as writing on a surface, only three degrees of freedom (DOF's) are required. In some cases, also orientation is important; however, the human arm is redundant to perform such tasks, even though a simplified 7-DOF kinematic model (not considering the hand articulated structure) is adopted. The solution to the inverse kinematics for a human-like arm during drawing tasks can be evaluated and compared with arm movements of human experimenters. Biologically motivated computer vision techniques are to be considered for trajectory planning in robotic systems whose aim is to execute draws in human-like fashion, also to infer mobility distribution in the human arm among available joints. The direction of gazes when a picture to be reproduced is observed is crucial for trajectory planning, and the postures assumed while executing an assigned task are strictly related to optimizations performed by the human

evolution. Therefore, it is interesting to investigate human and animals' behaviours to infer laws for biomimetic trajectory planning and inverse kinematics. When a 7-DOF anthropomorphic robot manipulator performs a drawing task or a handwriting task, the 4 redundant DOF's can be suitably used to perform secondary tasks [2]. A possible way of exploiting redundancy is that of mimicking the human arm movements [3]. This can be achieved, for example, by directly feeding the joint values computed from measurements on a human experimenter into an inverse kinematics algorithm [4]. An example of application is rehabilitation robotics, where an exoskeleton may drive the correct movements of the injured arm of a patient [5]. Moreover, in fine painting tasks, an anthropic behaviour implemented in the control law may produce a smoother end-effector trajectory resulting in higher quality lines. In this paper, a closed-loop inverse kinematics (CLIK) algorithm [6] is adopted to compute the joint motions of a 7-DOF anthropomorphic robot manipulator performing a task on a plane; as an example, we consider a drawing task, i.e., humans writing on a desk. Differently from previous works, redundancy of the system is solved by defining secondary tasks inspired by kinematic and dynamic considerations about the human arm behaviour. 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, if the task is at desk, the elbow and wrist are forced to stay close to the writing plane, in order to minimize the gravity acting on the structure. The trajectories for wrist and elbow, considered as “virtual end-effectors” [7], are planned in the task space. Simulation results are provided: the outputs of the proposed algorithm, i.e., the task-space and joint-space motions of a 7-DOF robot, in drawing tasks, are compared to human movements while performing the same tasks. Experiments have been performed with three humans in different drawing tasks at different speeds. Preliminary results confirm the effectiveness of the proposed approach.

II. MODELLING AND CONTROL

A. Active vision-based trajectory planning

The aim of the work is to find an integrated system for trajectory planning and inverse kinematics for a robot capable of reproducing human draws with similar movements. This will lead to a better understanding of the optimization

performed by the human brain for the positioning of the arm. The design of the trajectory has been considered first. Starting from a picture with a draw, the human experimenters and the robot are asked to reproduce it. Our capacity of perceiving information from an image involves a process of selection of the regions of interest in it. For an attentive visual inspection we move eyes (saccadic movements) in the world, three/four times per second. After that, we integrate the information across subsequent fixations (foveation points) to extract the features “perceiving” the image. Biomimetics suggests finding a computational model that extracts the low-level features. Such a model was proposed in [8]; in the case of a gray map, the features are extracted from the intensity (I) and the orientation (O) pyramid, where center-surround differences, between a center fine scale and a surround coarser scale, yield the feature maps. The sequence of region of interest gives the sequence of fixation region (focuses of attention, FOAs). The proposed task for a 7-DOF robot is to replicate a picture using human-like trajectory planning and inverse kinematics. First of all, the search of salient points in the picture to be drawn (Fig. 1) guides the trajectory planning. If a picture is shown for less than 2 seconds, only 5-6 saccadic movements (FOAs) are possible for the human eye to perceive the most important features needed to reconstruct main information (shape, texture, colour) about the picture. Considering the coding of the most important point to reproduce the shape, it could be observed that saccades are posed only on the points where tangential speed of drawn curves is rapidly variant, or where crossing of lines is observable. For the draws proposed to humans and robots (Fig. 1), the fixed points found by a system implementing the algorithm proposed in [8], are reported in Fig. 2). These attention points are the same used during reading: humans filter only the information where the discontinuity is more relevant [9]. After the selection of the FOAs, a simplified approach has been used, in order to generate the trajectory for the pencil, based only on codified information (orientation and intensity). Gabor filtering is a well-known technique for shape characterization, edge detection and other useful image processing. Two-dimensional Gabor functions were proposed by Daugman [10] to model the spatial summation properties in the visual cortex. They are widely used in image processing, computer vision, neuroscience and psychophysics. It is possible, by such a filtering in 8 directions (with angular values $\{0, 22.5, 45, 67.5, 90, 112.5, 135, 157.5\}$), to give an estimation of the curvature of drawn lines in each region. Finally, it is possible to plan a trajectory for the pencil, based on manual selection of sequence of the FOAs, which can be different by the natural succession, due to the reorganization, (i.e. top-down evaluations or quicker solutions). The goal-directed attention is important in gaze shifts for planning. These shifts can depend also on cognitive evaluations about the shown picture: this is the reason why handwriting is a very interesting task for automatic systems that can be implemented also for orthosis-assisted

movements. It should be interesting also to compare goal-directed planning for movements of fingers (e.g., handwriting) and feet (locomotion).

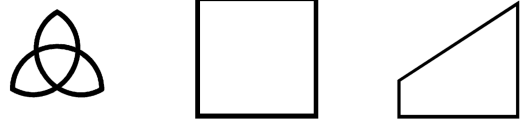


Fig. 1. Draws proposed for observation and reproduction

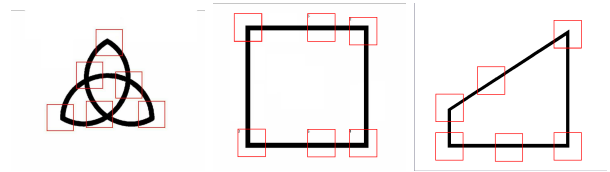


Fig. 2. Observed objects with evaluated focuses of attention

B. Inverse kinematics for a redundant human-like robot arm

Closed-loop control systems were emphasized since the Cybernetics of Wiener as a functional analogy between men and machines. The closed-loop inverse kinematics schemes [6] lead to obtaining joint variables of a robot manipulator starting from a differential mapping between task-space and joint-space values. Biomimetic inferences may be considered to evaluate how humans and animals distribute the motion required by a trajectory planned in the task space among the available degrees of freedom offered by the joints, especially when redundancy is present, i.e., when there are more DOF's than those required for the description of a task in the task space. As explained in the introduction, we focus on drawing tasks: the kinematic structure of the handwriting robot (see Fig. 3) 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.

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

$$\dot{\mathbf{p}} = \mathbf{J}(\mathbf{q})\dot{\mathbf{q}} \quad (1)$$

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.

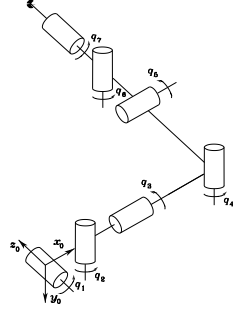


Fig. 3. Human-like 7-DOF's robot arm

This mapping may be inverted using the pseudo-inverse of the Jacobian matrix, i.e.,

$$\dot{\mathbf{q}} = \mathbf{J}^\dagger(\mathbf{q})\dot{\mathbf{p}} \quad (2)$$

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-squares sense [6].

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 $\mathbf{J}_W^\dagger$

$$\mathbf{J}_W^\dagger = \mathbf{W}^{-1}\mathbf{J}^T(\mathbf{J}\mathbf{W}^{-1}\mathbf{J}^T)^{-1} \quad (3)$$

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 [11] corresponding to a solution of the form

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

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.:

$$\dot{\mathbf{q}}_a = -k_s \frac{\partial G(\mathbf{q})}{\partial \mathbf{q}} \quad (5)$$

with $k_s > 0$, in order to achieve a local minimum for $G(\mathbf{q})$ [13].

To avoid numerical drift due to discrete-time integration, a closed-loop inverse kinematics (CLIK) algorithm can be adopted [6], which computes $\mathbf{q}$ by integrating the vector:

$$\dot{\mathbf{q}} = \mathbf{J}_W^\dagger(\mathbf{q})\mathbf{v} + \left(\mathbf{I}_7 - \mathbf{J}_W^\dagger(\mathbf{q})\mathbf{J}(\mathbf{q})\right)\dot{\mathbf{q}}_a \quad (6)$$

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 (6) 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.

In order to confer a biomimetic behaviour to the arm during the execution of a writing task, the weights β_i in (3) and the vector $\dot{\mathbf{q}}_a$ in (6) 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 [15].

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: these positions are planned in the task space, based on dynamics considerations. The desired behaviour can be achieved by considering the three-layer priority algorithm [14], [7], described in the following.

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

$$\dot{y}_e = \mathbf{j}_e(\mathbf{q}_e)\dot{\mathbf{q}}_e \quad (7)$$

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:

$$\dot{\mathbf{q}}_e = \mathbf{J}_{We}^\dagger(\mathbf{q}_e)\mathbf{v}_e, \quad (8)$$

with $\mathbf{v}_e = \dot{y}_{de} + k_e(y_{de} - y_e)$, being y_{de} the desired elbow position and $k_e > 0$. The pseudo-inverse matrix in (8) is

$$\mathbf{J}_{We}^\dagger = \mathbf{W}_e^{-1}\mathbf{j}_e^T(\mathbf{j}_e\mathbf{W}_e^{-1}\mathbf{j}_e^T)^{-1} \quad (9)$$

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.,

$$\dot{y}_w = \mathbf{j}_{Ww}(\mathbf{q}_w)\dot{\mathbf{q}}_w \quad (10)$$

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:

$$\dot{\mathbf{q}}_w = \mathbf{J}_{Ww}^\dagger(\mathbf{q}_w)\mathbf{v}_w + \left(\mathbf{I}_4 - \mathbf{J}_{Ww}^\dagger(\mathbf{q}_w)\mathbf{j}_{Ww}(\mathbf{q}_w)\right)\dot{\mathbf{q}}_{aw}, \quad (11)$$

The pseudo-inverse matrix in (11) is

$$\mathbf{J}_{Ww}^\dagger = \mathbf{W}_w^{-1}\mathbf{j}_{Ww}^T(\mathbf{j}_{Ww}\mathbf{W}_w^{-1}\mathbf{j}_{Ww}^T)^{-1} \quad (12)$$

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 (6) 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.

When the task is performed on a vertical plane, the secondary task of minimizing the gravity torques on the joints are to be transformed to the joint space, where reference values for the joint positions are provided to fulfill this requirement. Usually this constraint leads the arm to keep a posture attached to the body. Notice that, in order to seek for suitable kinematics postures to optimize the movements, information on the force acting on the end effector should be provided; as an example, the manual use of a camcorder is a typical task where positioning on a plane might be helpful; in such a task, in order to minimize the torques on the human arm, usually the forearm is kept close to the arm.

The proposed approach to the definition of secondary tasks related to the positioning of intermediate parts of the same kinematic structure, including proper trajectory planning, was presented in a more systematic fashion in ([7]).

III. CASE STUDY

In order to evaluate the performance of the proposed algorithm for a robot writer in comparison to a right-handed human writer, the same pictures were proposed to a simulator for the robots and to humans for trajectory generation and inverse kinematics resolution during the drawing task. Simulation setup was provided at the Natural Computation Lab of the University of Salerno. The pencil trajectory of the human writer was acquired using files recorded on a tablet. A three-camera system was used to track markers placed on wrist and elbow of human experimenters, and for 3D reconstruction of tracked movements. MATLAB-Simulink[®] simulation were used for implementing the algorithm on a 7-DOF robot. An evaluation of the effectiveness of the trajectory planning scheme is presented in the

following. In the next figures, tracked movements of human experimenters in the task space are shown, which are very similar to those performed by the robot in simulations, following the described algorithm. Consider the draw of a trapezium by the robot: from Fig. 4, reporting the 3D trace of the elbow, wrist and pencil of the manipulator during the drawing of a trapezium, it can be observed that both the wrist and the elbow remain close to the desk (see, for a comparison of wrist movements with a human, Fig. 5). In this case study, there is no desk at the same level of the tablet, but people search to lay the elbow on the corner of the tablet, to find a support. This confirms the hypothesis of gravity force minimization during task execution.

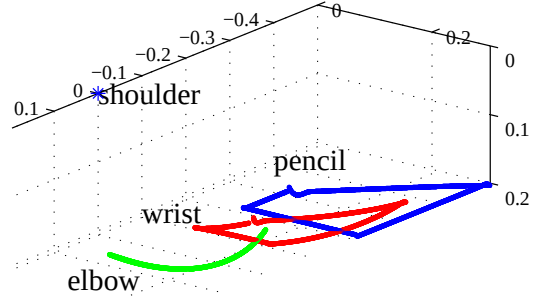


Fig. 4. Position of elbow, wrist and pencil for the robot during a drawing task at a desk



Fig. 5. Human drawer drawing a trapezium: tracked movements of the wrist

In order to better show the effectiveness of the CLIK scheme, also the joint angular positions can be evaluated via simple trigonometric calculations [12]. As an example, the angle between the 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 (Fig. 8). The automatic system, in order to reproduce the first picture in Fig. 1, inferred a trajectory, based on active vision, and results of simulations for the positioning of the robot in the task space are shown in Fig. 6.

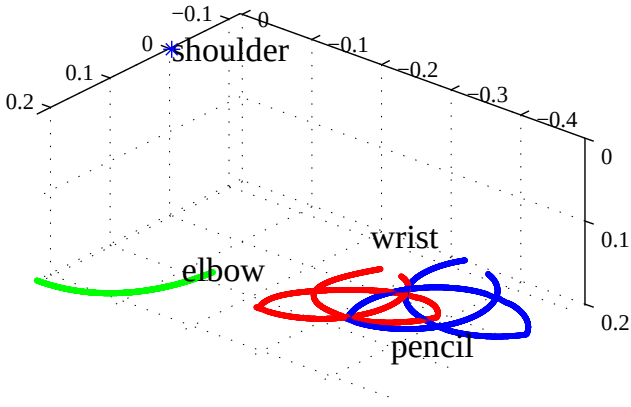


Fig. 6. 3D traces of elbow, wrist and pencil in simulation for the 7-DOF manipulator

A human experimenter, in the same task, is shown in figures 7 and 8.



Fig. 7. Human drawer in the same task of Fig. 6: tracked movements of the wrist

We are still organizing tracked data relative to the experiments shown, to provide deeper quantitative comparisons between human with human and human with robot: the comparison may be inaccurate depending on link dimensions for human and robot. Further work will be dedicated to provide a set of consistent comparisons. The acquired trajectory of the pencil is used as input to the CLIK scheme (the trace of the pencil is reported in Fig. 6), with $\mathbf{K} = 30\mathbf{I}_3$, $k_e = k_w = 200$. The output of the simulation, relative to the first four joint positions of the robot during task-space movements of Fig. 6, is reported in Fig. 10. For a comparison with joint involvement in human arm, in Fig. 9 it is possible to observe the time histories of the acquired joint movements of the human writer in the task of Figs. 7 and 8.

It can be recognized that time histories of the joint variables are qualitatively following those recorded on the human writer: the third angle q_3 is more difficult to evaluate from



Fig. 8. Human drawer in the same task of Fig. 6: tracked movements of the elbow

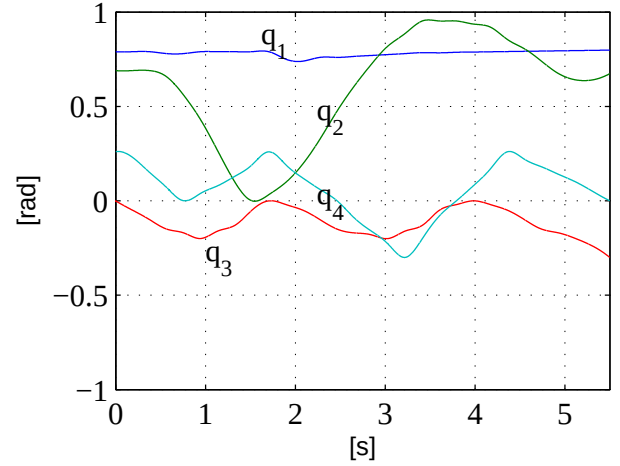


Fig. 9. Time histories of the first four joints of the human experimenter's arm in the task of Fig. 6

measurements, due to the volume of the arm, while robot links are considered without a volume; in some cases angle can be different, due to the position and orientation of the robot elbow, which is not exactly laid on the desk in every case, during the task. It is important to observe that joint movements depend on accurate dimensions of the robot with respect to compared human: differently from other simulations, a final link of 10 cm was considered for the robot mimicking the drawer of Fig. 8. Also the sequence of drawn parts of the pictures is relevant: in the presented example, if the robot starts drawing towards the lower extremity first, joint movements change, but the task-space strategy is preserved.

There is a stabilization of the human arm movements, which can be imputed to progressive learning in humans for minimum fatigue: in the time histories of joints (e.g., consider joint q_1) the effects of arm dynamics and control result in a sort of low-pass filtering of the trajectories tracked: dynamic modelling of the 7-DOF manipulator should be implemented for deeper comparisons, with mor-

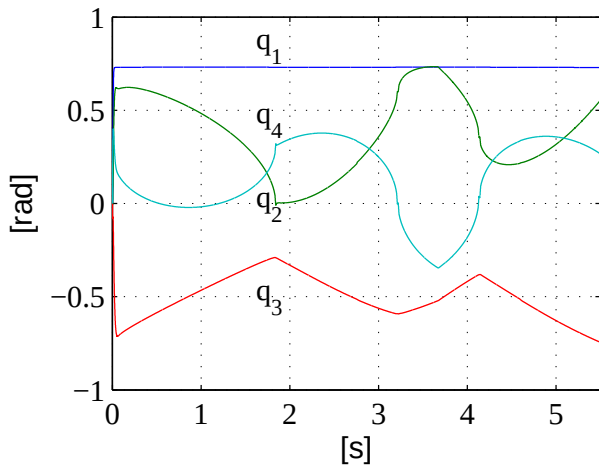


Fig. 10. Time histories of the first four joints of the robot relative to the drawing task reported in Fig. 6

phological and inertial properties of the robot arm close to the human ones in order to better validate the proposed approach. Notice that cognitive issues in handwriting are to be investigated: studying people drawing figures or writing ideograms of an unknown oriental 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. In the tasks with different drawers considered in our study, a qualitative homogeneity is observed: future work will be devoted to better organize measurements data for a deeper quantitative evaluation. In the future, a more comprehensive analysis of the entire set of acquired data will help to validate hypotheses about the biomimetic kinematic control scheme proposed.

IV. CONCLUSION

Biomimetic considerations have been exploited for trajectory planning and inverse kinematics of a robot performing a human-like task. An algorithm which includes attentive vision for task-space trajectories and proper inverse kinematics has been considered. Redundancy of the system is exploited to achieve a human-like behaviour and for qualitative and quantitative validation of hypothesis about redundancy resolution. The inverse kinematics weights in charge of the joint motion distribution are set on the basis of biomimetic evaluations too. Noticeably, this is obtained by setting few parameters of a CLIK algorithm with task priority, without imposing specific joint space trajectories. This should be useful in arm-hand systems, providing a simple kinematic control system for the arm and the forearm, while reserving additional computation for the grasping phase. Simulation results show a good approximation to the recorded motion of a human arm. Notice that data about actuators (muscles) and cognitively motivated considerations should lead to obtaining a more complete model. Future work will be devoted to add force

sensing capability, also for the detection of the writing surface (not necessarily planar), as well as improved visual sensing capability.

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