Robotic Handwriting: Why and How?

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Abstract. Handwriting has always been considered an important human task, and accordingly it attracted attention of researchers working in biomechanics and other related fields. There exist a number of studies on this matter. This paper considers human-machine analogy and relates robots with handwriting. The work is two-fold: it improves the knowledge in biomechanics of handwriting, and introduces some new concepts in robot control. The idea is to find the biomechanical principles humans apply when resolving kinematic redundancy, express the principles by means of appropriate mathematical models, and then implement them in robots. This is a step forward in generation of human-like motion of robots. Two approaches are described: (i) “Distributed Positioning” (DP) which is based on a model appropriate to represent the arm motion in the absence of fatigue, and (ii) “Robot Fatigue” approach, where robot movements similar to the movements of a human arm under muscle fatigue are generated. The simulation study includes the issues of legibility and inclination of handwriting. The results demonstrate the suitability and effectiveness of both approaches.

1. Introduction

It was recently when humanoid robots were finally recognized as the main direction in the entire work on robotics (Fukuda & al., 2001). The mathematical models and walking machines developed in sixties and seventies (Vukobratovic & al., 1969; 1974) represented the true start of robotic science. Industrial potentials of robots turned the focus of research to practical problems of automation. It took researchers and manufacturers a long time to solve so many different problems in industry. The accumulated knowledge and experience, the technology growth, and the saturation in industrial robotics, allowed the robotic community to recognize the service and especially humanoid robots as a new and profitable direction of work. Recent results show that this was a prospective idea.

Since humanoid robots are expected in activities that understand close cooperation with humans, it was necessary to supply them with the ability to move in a human-like fashion, to communicate in a human-like manner, and to feature human-like intelligence (Fukuda & al., 2001). The first ability, being the topic of this article, required an extensive study of biomechanics and human-robot analogy. This is how we came to handwriting - a task that seamed to be appropriate only for humans. So, we now pose a crucial question: ***what robot has to do with handwriting***? There are few answers. Some of them concerns just robotics, and we start from them. Handwriting, being a typical human motion, is a highly demanding task regarding kinematics and dynamics. It involves a redundant number of joints (degrees of freedom - DOF). So, handwriting is seen as a "perfect test" for humanoids and even industrial robots. There is also a possibility to improve robot control by learning from humans. Human handwriting engages different levels of motion control: learned patterns (with all associated problems), on-line tracking, etc. By studying biomechanics of handwriting, one can learn about the control concepts, skill acquiring, redundancy resolution, etc. So, perhaps robots will never have to write by hand, but the study of this possibility is still very useful. However, the statement "*never*" should be used conditionally – if humanoids continue to improve their human-likeness, the true robot handwriting might become reality.

The other answer to the dilemma about robots and handwriting concerns biomechanics of human handwriting. The mathematical approaches derived to describe robot kinematics and dynamics could be used to improve models of human handwriting, thus leading to new results. In addition, robotic devices could be developed for diagnostics and rehabilitation of malfunctions in finger-hand-arm coordination.

This article highlights some problems in ***robotic handwriting***, trying to keep a ballance between pure robotics and biomechanics.

2. Handwriting: From Human to Robot

Handwriting was considered an important human task, and accordingly it attracted attention of researchers working in biomechanics and other related fields. There exist a number of studies on this matter. Since the majority of them are not of direct interest to our work in robotics, we simply refer to web site *http://www.psychomot.ups-tlse.fr/Ecriture.rtf*, where an extensive listing of such studies may be found, and to paper (Potkonjak & al., 1998) where relevant biomechanics results have been explained. The work of Potkonjak and his associates (Potkonjak & al., 1992; 1998) was the first to relate robot with handwriting. The work was two-fold: it improved the knowledge in biomechanics of handwriting, and introduced some new concepts in robot control. The idea was to find the biomechanical principles humans apply when resolving redundancy, and to implement these principles in robots. Robotic background for this work was found in the concept of micro-macro manipulation (Salisbury, Abramowitz, 1985).

In (Potkonjak & al., 1990; 1992; 1996), the concept of distributed positioning (DP) was proposed to resolve redundancy and improve robot kinematic and dynamic performances. It suggested separation of required motion into a smooth global and fast local motion. These components should be distributed to a redundant number of joints in accordance with their inertial properties: high-inertia joints should take care of smooth global motion while low-inertia redundancy is engaged to solve highly accelerated local motion. The idea was to enable massive industrial robots to perform fast and precise manipulation. Paper (Potkonjak, Krstulovic, 1992) introduced handwriting as a test-motion for checking the efficiency of the DP concept. Study (Potkonjak & al., 1998) was more close to biomechanics. It considered an anthropomorphic arm engaged in handwriting. Due to higher degree of redundancy, DP concept could not resolve it completely. The pseudoinverse (optimization) was needed to solve the wrist motion. The obtained results related some important characteristics of handwriting: legibility, inclination of letters, and engagement of fingers (fingers were critical due to relatively quick fatiguing). It was shown that for a given level of legibility, there existed an optimal inclination that minimized the engagement of fingers.

Lately, the human-robot analogy led to the study of the behavior of a "fatigued robot". The reason for this was the fact that humans use their redundancy to avoid, or at least delay, the fatigue problems. When feeling fatigue in some joint, a human reconfigures itself: by engaging other joints more, the exhausted joint is given a chance to rest. This reconfiguration does not compromise the task execution. The idea was to apply the same principle to robots when overloaded. The next benefit from research in fatigue problems is the possibility to achieve some of human-like communication. The mentioned reconfiguration, which takes place with fatigued human, can be observed and than it represents a message sent to the surrounding. We wish the robot to behave in the same manner so that we could recognize when it is overloaded. These problems have been elaborated in (Potkonjak & al., 2001; 2002; 2002; 2003). The appropriate mathematical models were derived. The biological background – description of fatigued muscle behavior – was found in (Vodovnik, Rebersek, 1975; Giat, 1996).

3. Robot Arm Kinematics and Dynamics

A robot arm with n DOF is described by means of n joint coordinates (internal or configuration coordinates) forming the configuration vector $\mathbf{q} = [q_1 \ldots q_n]^T$. From the task point of view, one is concerned with the m-dimensional operational space $\mathbf{x}$, being the a subset of external positions: $\mathbf{x} \subset [x\, y\, z\, \theta\, \varphi\, \psi]^T$, where x, y, and z are Cartesian coordinates, and θ, φ, and ψ are orientation angles (yaw, pitch and roll). It holds that $m \leq 6$.

Kinematic model understands relation between configuration and operational space. In its first-order and second-order forms, the model is

$$\dot{\mathbf{x}} = \mathbf{J(q)}\dot{\mathbf{q}}\ ;\ \ddot{\mathbf{x}} = \mathbf{J(q)}\ddot{\mathbf{q}} + \mathbf{K(q, \dot{q})}, \qquad (1)$$

where $\mathbf{J} = \partial\mathbf{x}/\partial\mathbf{q}$ is the Jacobian matrix of dimension $m \times n$ and $\mathbf{K} = \partial^2\mathbf{x}/\partial\mathbf{q}^2\ \dot{\mathbf{q}}^2$ is the $m \times 1$ adjoint vector. Redundancy resolution understands so-called inverse kinematics, i.e., calculation of $\mathbf{q}$ for given $\mathbf{x}$. If $m = n$, the system is nonredundant and the unique solution is possible. If $m < n$, the system is redundant and there exists an infinite number of solutions of the inverse kinematics, meaning that different configuration motions can produce the same operational motion. If one solution is to be selected, then additional requirements, which will "employ" the redundancy, has to be imposed.

A redundant arm usually has a heavy part consisting of m joints, which is called the "nonredundant basic configuration". The rest of the arm (n-m joints) constitutes the redundancy.

Dynamics of the arm – the mechanical part plus second-order actuators – is described by the well-known model

$$\widehat{\mathbf{H}}\mathbf{(q)}\ddot{\mathbf{q}} + \widehat{\mathbf{h}}\mathbf{(q,\dot{q})} = \mathbf{u} \qquad (2)$$

where $\mathbf{u}$ is the vector of the control inputs, $\widehat{\mathbf{H}}$ is the inertial matrix, and $\widehat{\mathbf{h}}$ takes care of gravity and velocity-dependent effects. Dynamic model is used to simulate the system behavior.

4. Modeling Handwriting Sinergy – DP Concept

4.1. *Principles and mathematics*

DP is formulated in analogy with human behavior and is intended to model a robot arm involved in fast manipulation. The required robot task, end-effector operational motion $\mathbf{x}(t)$ of dimension m, is assumed to have m_a highly accelerated elements. These elements form the subvector $\mathbf{x}_1(t)$. The other elements are smooth (subvector $\mathbf{x}_2(t)$). Now, $\mathbf{x} = [\mathbf{x}_1, \mathbf{x}_2]^T$. We suppose a situation where the massive basic nonredundant configuration (vector $\mathbf{q}_b$ of dimension *m*) cannot solve the task due to the presence of accelerations. DP concept resolves this problem.

Basic nonredundant configuration (*m*-dimensional $\mathbf{q}_b$) is supplemented by a low-inertia redundancy ($\mathbf{q}_r$ of dimension n_r). The entire configuration is now $\mathbf{q} = [\mathbf{q}_b, \mathbf{q}_r]^T$, and has dimension of $n = m + n_r$.

Accelerated motion $\mathbf{x}_1(t)$ is separated in two components: a smooth component $\overline{\mathbf{x}}_1(t)$ and a highly accelerated component $\widetilde{\mathbf{x}}_1(t)$; thus $\mathbf{x}_1 = \overline{\mathbf{x}}_1 + \widetilde{\mathbf{x}}_1$. Some suitable smoothing method is to be applied (a low-pass filter could be used to make this separation). The "basic operational motion" is now defined to be the motion that contains the smoothed component $\overline{\mathbf{x}}_1(t)$ and the subvector $\mathbf{x}_2$ (being already smooth): $\mathbf{x}_b = [\overline{\mathbf{x}}_1, \mathbf{x}_2]^T$. The basic nonredundant configuration $\mathbf{q}_b$ is capable of solving the motion $\mathbf{x}_b$. Mathematically, the solution for $\mathbf{q}_b(t)$ involves the inverse of a nonredundant quadratic ($m \times m$) Jacobian. This represents the *first step* in DP concept.

The redundancy is now forced to solve the high accelerations $\widetilde{\mathbf{x}}_1(t)$. The necessary condition (regarding dimensions) is $n_r \geq m_a$. In the original concept, equality held ($n_r = m_a$) and the unique solution for $\mathbf{q}_r(t)$ was obtained (Potkonjak & al., 1990; 1992; 1996). This constituted the *second step* in resolving the inverse kinematics. Thus, the entire configuration motion $\mathbf{q}(t)$ was found. Besides the industrial tasks the concepts was checked on the handwriting example (Potkonjak, Krstulovic, 1992). The idea for a handwriting test-task follows the fact that letters require high accelerations and a human solves them by distributing the pencil motion between the massive arm and the low-inertia fingers.

When the focus was moved from industrial robots to humans and humanoids, it was recognized that the wrist joint played an essential role in handwriting. Wrist allows long-term fast writing by reducing the involvement of fingers that are precise but quick fatiguing. The wrist is responsible for inclination of letters, often present with humans. Introduction of the wrist increases the entire degree of redundancy, causing $n_r > m_a$. The *second step* now cannot be performed as described above. The *first step* reduces the redundancy degree from n_r to $n_r - m_a$ but does not eliminate it completely. So, the *second step* needs an additional condition and it is always some optimality criterion. Among different options, we select minimization of finger involvement. This comes out from the fact that fingers can move very precisely but cannot stand long-term fast movement. To measure the finger involvement, an integral criterion was suggested (Potkonjak & al., 1998): *IKI* – integral kinematic involvement, being the sum of amplitudes of fingers motions. Some other reasonable criteria (reducing energy or motors temperatures) produced results rather comparable with *IKI* ones (Potkonjak & al., 2003).

4.2. *Example*

In a simplified (but still representative) example we consider a planar arm consisting of the shoulder q_1, the elbow q_2, and the wrist q_3 (Fig. 1). In writing, the fingers work together to produce two translations as shown in Fig. 2. Hence, with the robot arm, true fingers are substituted by two linear joints (q_4 and q_5 in Fig.1). The motion ranges for such "sliding fingers" are $\Delta_4 = q_{4\max} - q_{4\min} = 0.05m$ and $\Delta_5 = q_{5\max} - q_{5\min} = 0.05m$. The complete set of numerical parameters used in the example is not seen important to understand the method and the key results.

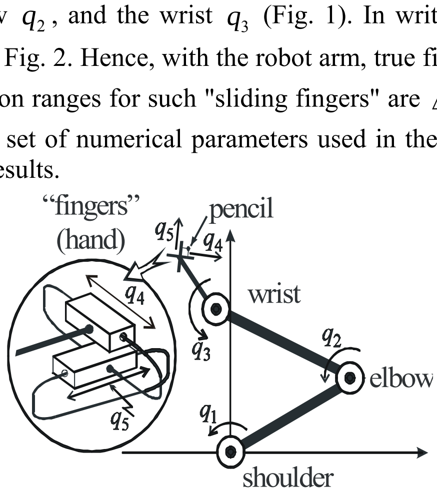

Figure 1. Mechanism configuration with five DOF

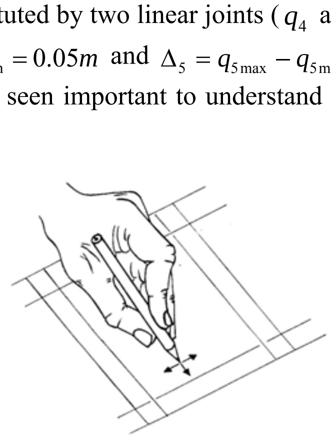

Figure 2. Coordinated motion of fingers produces two translations

The task consists in writing a prescribed sequence of letters shown by solid lines in Fig. 3. Under (a), an *x-y* representation is presented (*x* and *y* being operational coordinates), while (b) and (c) show the time histories $x(t)$ and $y(t)$. This reference sequence is set so as to be close to real letters and, at the same time, to be easy to describe mathematically (cycloids, circles, and straight lines have been used).

For this example, it holds that $\mathbf{x} = \mathbf{x}_1 = [x,\, y]^T$, $m = m_a = 2$, and $\mathbf{x}_2$ does not exist. Smoothing understands separation: $x = \bar{x} + \tilde{x}$, $y = \bar{y} + \tilde{y}$. The results, smooth components $\bar{x}(t)$ and $\bar{y}(t)$, are shown in Fig. 3 by dashed lines. The basic operational motion contains these smooth components: $\mathbf{x}_b = \bar{\mathbf{x}}_1 = [\bar{x},\, \bar{y}]^T$.

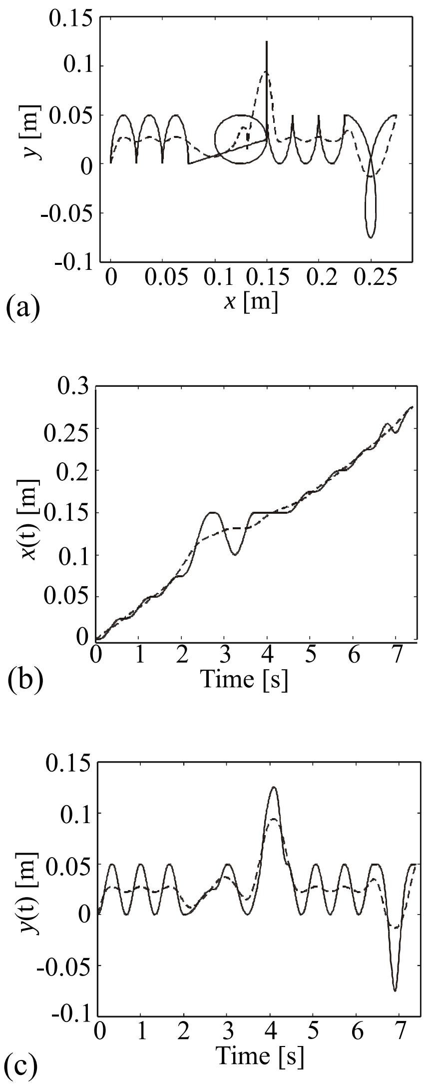

Figure 3. Definition of the task: (a) sequence of letters; (b), (c) time histories of operational coordinates. The solid lines show the prescribed motion, and the dashed lines show the smooth components

Mechanism configuration is separated in two functional parts. Shoulder and elbow constitute the nonredundant basic configuration: $\mathbf{q}_b = [q_1, q_2]^T$, $m = 2$. The wrist and the two linear "fingers" represent the redundancy: $\mathbf{q}_r = [q_3, q_4, q_5]^T$, $n_r = 3$.

The basic configuration $\mathbf{q}_b$ cannot handle the original task $\mathbf{x}(t) = [x(t),\, y(t)]^T$ due to the presence of high accelerations. The *first step* of DP concept is to force the basic configuration to solve the smooth motion $\mathbf{x}_b = [\bar{x},\, \bar{y}]^T$. In order to get the maximum from the configuration, minimum smoothing (by using the "sliding window" method) is performed, i.e., just to the level that configuration can handle.

Once the motion $\mathbf{q}_b(t)$ is found, we start the *second step* in order to solve for the redundancy $\mathbf{q}_r$. Since $n_r = 3 > m_a = 2$, *step two* still faces the problem of redundant DOF: two operational motions, $\tilde{\mathbf{x}}_1 = [\tilde{x},\, \tilde{y}]^T$, are to be solved by using three configuration coordinates, $\mathbf{q}_r = [q_3, q_4, q_5]^T$. In order to get a unique solution of the inverse kinematics, we introduce an optimality criterion by trying to minimize the involvement of fingers. The criterion *IKI* is applied. Such calculation was made and showed that motions of fingers (q_4 and q_5) violated the ranges Δ_4 and Δ_5 (during writing letters d and j), meaning that the found solution was not possible to realize. This was the consequence of the fact that wrist was not of great help in the case of strictly vertical letters, and accordingly, too much was required from the fingers (they were not long enough). In order to allow the wrist to help more efficiently, we modified the task (i.e., the reference) by inclining the letters. Example of inclined writing (for the angle $\alpha = 20^0$) is shown in Fig. 8a. With the inclination, the engagement of the wrist (q_3) increased and the engagement of the fingers (q_4 and q_5) reduced. After an inclination of 24^0, translation q_4 reduced to fit the allowable region Δ_4, while, after 34^0, the other translation q_5 reduced to Δ_5. This means that any sequence, inclined for 34^0 or more, could be written "ideally".

After introducing inclination, we make a step forward and note a general fact that humans often do not insist on ideal execution of a given task. In the topical example, handwriting, this means that some deformed shape of letters is acceptable until legible. This relaxed condition opens the possibility for some additional optimization. Here, we prescribe some level of legibility and try to further reduce the involvement of fingers (*IKI* criterion). Legibility of a sequence of letters is defined on the basis of the mean square deviation from the ideal sequence. If e is the mean square error, then legibility is its normalized value, $L_e = (e_{\max} - e)/(e_{\max} - e_{\min})$, being in the interval $L_e \in [0, 1]$. Let us note that (Potkonjak & al., 1998) used a modified definition based on a function that introduced subjective feeling of legibility.

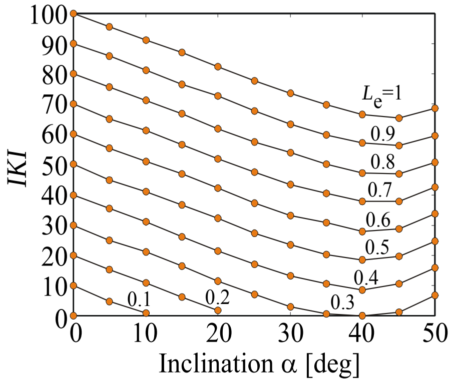

Figure 4. Relation of finger involvement (IKI), inclination of writing (α), and legibility (L_e).

Fig. 4 presents the results; it relates involvement of fingers (*IKI*), inclination (α), and legibility (L_e). Each curve corresponds to some level of legibility L_e and shows how *IKI* depends on inclination angle α. Each curve features a clear minimum. Observing the diagram, one can conclude that, for any selected level of legibility, there exists an optimal inclination that minimizes the involvement (*IKI*) of fingers. For other criteria (*IKI* replaced by energy consumption or by motor heating) the diagrams feature similar behavior (Potkonjak & al., 2003).

4.3. *Discussion on application*

DP concept shows to be a good model to describe human motion in handwriting. Humans really distribute the prescribed motion to a redundant number of joints in accordance with their inertial characteristics and the muscles potentials. On the other hand, the method is very suitable to be implemented in robots. An interesting issue, left for discussion, is the way of smoothing the accelerated motion (here, a kind of low-pass filter was used).

5. Robot Fatigue – A New Option in Human-Robot Communication

5.1. *Principles*

If human arm is given a long-term or heavy work, fatigue will appear. Until the symptoms of fatigue appear, we talk about the REGULAR MOTION. When fatigue in some muscles of human arm exceeds the threshold level, the arm tends to reconfigure itself and thus disturbs the steady state imposed by the DP concept. RECONFIGURATION means depressed involvement of the exhausted joint and higher engagement of the others. In this way, the exhausted joint (or joints) is given a chance to rest. This reconfiguration is an "inner" process, meaning that it does not effect the correct execution of the task. Mathematically speaking, a redundant system has an infinite number of configuration motions $\mathbf{q}(t)$ for one operational motion $\mathbf{x}(t)$, and reconfiguration means the selection of a new configuration from this set.

When a fatigued human changes the posture, this can be observed, and thus, reconfiguration represents a message about his state. People in surrounding may react to the message although the task execution is not compromised.

If the heavy-duty task lasts too long, then arm joints, one by one, will become fatigued. After few reconfigurations, there will be no joint able to help. From this moment, the task execution will not be correct any more. Deviations will appear and we talk about DEGENERATION phase. This could be considered as a new message to the surrounding.

We try to find models of the described behavior and apply it to both human and robot arms. The biological background – description of fatigued muscle behavior – was found in (Vodovnik, Rebersek, 1975; Giat, 1996). Measure of robot joint fatigue is the motor temperature. The threshold is the temperature that exceeds the allowable level, meaning that the arm is overloaded.

5.2. *Mathematics*

REGULAR MOTION. Redundancy resolution is based upon the DP concept, along with the request for the maximal comfort. The later follows from the observed behavior of humans (Cruse & al., 1990). Instead of a low-pass filter used for DP in Section 4, here we directly apply the method of pseudoinverse. To achieve this, the appropriate criterion is introduced:

$$\Omega(\dot{\mathbf{q}}) = 0.5 \cdot \dot{\mathbf{q}}^T \mathbf{W}' \dot{\mathbf{q}} + 0.5 \cdot (\dot{\mathbf{q}} - \dot{\mathbf{q}}_\alpha)^T \mathbf{W}'' (\dot{\mathbf{q}} - \dot{\mathbf{q}}_\alpha) \qquad (3)$$

where $\mathbf{W}'$ and $\mathbf{W}''$ are $n \times n$ positive-definite symmetric weighing matrices. The first term enables penalization of the motion of some joints relative to others and is used to distribute the joint motions in accordance to DP concept (i.e., to stimulate the motion of low-inertia joints and penalize the motion of high-inertia joints). The second term is used to maximize the “comfort” (Liégeois, 1977; Cruse & al., 1990; Chan, Dubey, 1995). Comfortable motion of a joint is seen as the motion being near the middle position of the joint range.

The minimization of the criterion (3) is performed via the method of Lagrange multipliers. The Lagrangean corresponds to the functional (3) and the kinematic constraint (1). The calculation of the configuration velocities $\dot{\mathbf{q}}$ involves the weighed pseudoinverse of the Jacobian matrix (according to (Whitney, 1972)). This calculation finally produces the reference motion $\mathbf{q}^*(t)$.

Regarding the control, a PD regulator could be adopted: $u_j = K_{Pj}(q_j^* - q_j) + K_{Vj}(\dot{q}_j^* - \dot{q}_j)$, $j = 1,...,n$, where q_j^* and q_j are the reference and the actual position, and K_{Pj} and K_{Vj} are feedback gains. Applying this control law, the motion $q_j(t), j = 1,...,n$ will result, which is expected to track closely the reference $q_j^*(t)$.

RECONFIGURATION. We now look for a mathematical method to force the reconfiguration in accordance with the actual progress of fatigue. With robots, motor temperature Θ_j is the measure of fatigue in joint j. The critical value $\Theta_{j,cr}$ is defined for each motor, limiting the desired motor working mode. It is not a final limit but rather a bound of a desirable region. Above the critical value, the robot joint "feels fatigue". Some appropriate algorithm should force redistribution of engagement in order to relax the exhausted joint. The algorithm introduces the penalty functions into the weighing matrix: $\mathbf{W} = \mathbf{W}' + \mathbf{W}'' = \text{diag}[\varphi_1(\Theta_1), \ldots, \varphi_n(\Theta_n)]$. "Penalty functions" $\varphi_j(\Theta_j)$ should penalize the exhausted joints and stimulate those that are still "fresh". Mathematically speaking, $\varphi_j(\Theta_j)$ should be constant until Θ_j reaches $\Theta_{j,cr}$, and monotonically increasing above $\Theta_{j,cr}$. In this way, the penalty functions $\varphi_j(\Theta_j)$ will contribute to reduced movement of each joint in which the actual value of fatigue exceeds an assigned critical limit. The choice of a particular penalty function is task dependent.

When feeling fatigue in some joints, the robot will reconfigure itself in the above way. This is done while keeping the required operational trajectory (thus, reconfiguration does not effect the execution of the task). It is expected that the reduced engagement of exhausted joints will give them a chance to rest and go out of the critical working mode. Several reconfigurations may happen, one after the other, as different joints are reaching the critical levels. If the task is not too tough, the robot will finally find a steady state in which it can operate for a longer time (some results that support this expectation are reported in (Potkonjak & al., 2001; 2002). To control the robot we still use the PD regulator.

DEGENERATION. If the task imposed to the robot is too demanding, it may happen that, in spite of reconfiguration, the motor temperatures continue to rise. This means that the reconfiguration will delay the fatigue problem but will not eliminate it. To handle this situation, some upper limits for the temperatures (fatigue) are adopted, i.e. $\Theta_{j,\max}$, $j = 1,...n$. These limits indicate the point of entering a dangerous motor working mode. In this situation, further rise of temperature must be prevented regardless of the quality of the output work. This is done by activating a "current limiter". Limiting motor current being the source of heating, should stop the rise of temperature. The limiter will allow the current that is smaller than the required value by the factor *D*, and thus, for joint *j* it will be:

$$i_j = D_j(\Theta_j) i_j^{req}, \quad (7)$$

where i_j is the actual current and i_j^{req} is the value required by the dynamics of the given task. $D_j(\Theta_j)$ is called the "current-damping factor". It depends on the actual level of temperature (fatigue). In order to efficiently relax the joint in accordance with its fatigue, a decreasing function should be adopted.

Damping the current will result in insufficient joint torques and accordingly in the degeneration of the actual trajectory. The reference configuration motion $\mathbf{q}^*(t)$ will still come out from the imposed (reference) task trajectory $\mathbf{x}^*(t)$, but the limited joint torques will result in actual motion $\mathbf{q}(t)$ that might be far away from the reference. As a result, the actual task trajectory $\mathbf{x}(t)$ will be considerably degenerated.

Thus, in the third phase, the robot will still "try to do the job", but since "it is tired", the results will be unsatisfactory.

For simulation purposes we need a mathematical model that relates the source of thermal energy (i.e. rotor winding current) and the temperatures of the rotor and the housing (Potkonjak & al., 2001). The thermal dynamics model involves the thermal capacities of the rotor and the housing and the transfer of energy, rotor-to-housing and housing-to-ambient. The second-order model (for the j^{th} joint motor) is:

$$T_{rj}\dot{\Theta}_{rj} = Z_{rj} \cdot R_j i_j^2 - (\Theta_{rj} - \Theta_{hj}), \quad T_{hj}\dot{\Theta}_{hj} = \frac{Z_{hj}}{Z_{rj}}(\Theta_{rj} - \Theta_{hj}) - (\Theta_{hj} - \Theta_a), \quad (9)$$

where Θ_{rj} and Θ_{hj} are the rotor and housing temperatures, T_{rj} and T_{hj} are the thermal time constants, Z_{rj} and Z_{hj} are the energy-transfer resistances, Θ_a is the ambient temperature, and $R_j i_j^2$ represents the Joule power loss. The thermal model, along with the dynamic model of the arm (eq. (2)), enables simulation.

5.3. *Example*

We consider the robotic arm shown in Fig. 1 in Sec. 4. The task (i.e., the reference) in that example was defined flexible, allowing different inclination of letters. For the present analysis, we set inclination to $\alpha = 20^0$ (as it will be seen in Fig. 8(a)).

Simulation in this work is performed to prove the feasibility of the concept. Thus, the system parameters need not be realistic but rather chosen so as to stress the relevant effects. In addition, a too long simulation should be avoided. Starting from this, we adopted the appropriate values for system parameters.

To show the most interesting simulation effects, we will explore the behavior of joints 4 and 5 ("fingers"), and the overall execution of the task.

Figure 5 shows the behavior of the joint No. 4. Fig. 5(a) presents the progress of motor temperature (joint fatigue Θ_4). Fig. 5(b) presents the variation of joint involvement. As a measure showing how much a particular joint (e.g. the *j*th one) is involved in the task execution, a variable called "kinematic involvement" – KI_j is introduced. It is calculated for each repetition of the sequence of letters: $KI_j = \int |\dot{q}_j| dt$, integration interval $T = 9s$ being the time needed to accomplish one sequence. Figure 6 presents the behavior of the joint No. 5.

Figure 7 shows the error in the task execution. This is the deviation (*DEV*) from the ideal sequence of letters, i.e. from the reference trajectory (x^*, y^*). The error is calculated for each repetition of the sequence and represents the normalized mean square error over the sequence.

Let us discuss the simulation results.

Phase 1 – REGULAR MOTION – lasts for $t \in [0\,, t_1 \approx 80s]$. Phase 1 starts immediately and lasts until the fatigue in some joint (motor temperature Θ_j) exceeds the assigned critical level $\Theta_{j,cr}$. In this phase the continuous progress of fatigue in both joints (4 and 5) is monitored (diagrams 5(a) and 6(a)). The joint involvements are at a constant level (Figs. 5(b) and 6(b)) meaning a steady situation in the distribution of the task to robot joints. In this phase, the error of writing (*DEV* in Fig. 7) is rather small. Phase 1 ends at about $t_1 = 80s$ when joint 5 feels fatigue, i.e. the motor temperature exceeds the critical level: $\Theta_5 \geq \Theta_{5,cr}$ (see Fig. 6(a)).

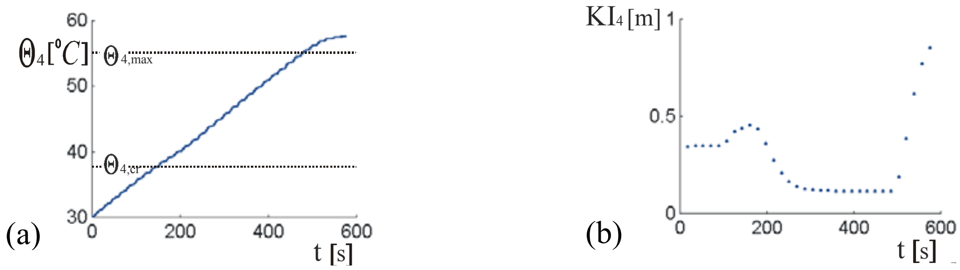

Figure 5. Behavior of joint No. 4: (a) joint fatigue $\Theta_4(t)$, (b) joint involvement $KI_4(t)$.

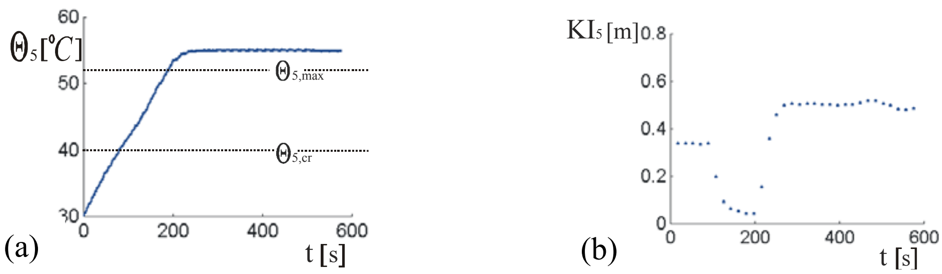

Figure 6. Behavior of joint No. 5: (a) joint fatigue $\Theta_5(t)$, (b) joint involvement $KI_5(t)$.

Phase 2 – RECONFIGURATION – lasts for $t \in [t_1 \approx 80s\,, t_2 \approx 190s]$. When joint 5 feels fatigue**,** phase 2 begins. Reconfiguration starts since the penalty function in joint 5 forces its reduced engagement. This reduction appears as a drop in the involvement KI_5 at $t_1 = 80s$ (Fig. 6(b)). Since the other joints have to help, one may observe the increased involvement KI_4 (Fig. 5(b)). The joint 4 is not the only one to help. So, if behavior of joint 3 was depicted, it would feature increased involvement as well.

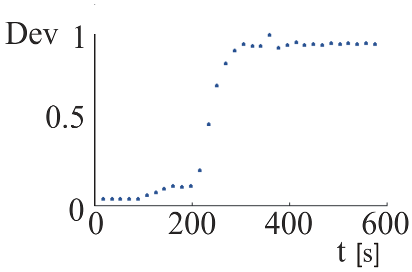

Figure 7. Error in task execution: deviation (*DEV*) of realized letters from the reference (ideal) sequence.

During the phase 2, at about $t' = 160s$, the temperature in joint 4 reaches the critical level: $\Theta_4 \geq \Theta_{4,cr}$ (see Fig. 5(a)). At that moment, the penalty function starts to depress the engagement of joint 4, thus causing the drop of involvement KI_4; see Fig. 5(b).

In spite of reconfiguration, the temperatures Θ_4 and Θ_5 continue to progress. This is due to a highly demanding task (relative to system parameters).

During the phase 2, the task error *DEV* is slightly increased (Fig. 7). The small rise od writing error means that the tracking of the reference sequence is still good.

Phase 2 ends at about $t_2 = 190\text{s}$, when the fatigue in joint 5 exceeds the next limit (upper level): $\Theta_5 \geq \Theta_{5,\max}$.

Phase 3 – DEGENERATION – lasts for $t > t_2 \approx 190s$**.** When joint 5 excedes $\Theta_{5,\max}$, phase 3 begins. The current limiter in the joint activates, reducing the joint drive. The reference joint motion still comes out from inverse-kinematics calculation (the robot still intends to follow reconfiguration procedure and write perfectly). However, the reduced (thus insufficient) joint drive makes the joint 5 less controllable, and hence, bad tracking results in large oscillations in actual motion. The kinematic involvement of joint 5 (KI_5 in Fig. 6(b)) rises rapidly. The fatigue Θ_5 stops rising and reaches the steady state (see Fig. 6(a)).

The joint 4, still strongly driven, continues to track the reference motion, and consequently, joint fatigue continues to rise (Fig. 5(a)). At about $t'' = 480s$, joint fatigue exceeds the upper level: $\Theta_4 \geq \Theta_{4,\max}$. The current limiter in the joint activates and the drive reduction causes lower controllability. So, the joint no more tracks the reference, and uncontrolled oscillations rise. This increases the kinematic involvement (obvious in Fig. 5(b)). The reduced current allow the temperature Θ_4 to reach the steady state (as shown in Fig. 5(a)).

During phase 3, the error in writing rapidly increases (see Fig. 7), which means that the quality of task execution is becoming very low (that is why we talk about degeneration). The deviation of actual letters from the reference pattern deserves more attention. Fig. 8 shows how the realized letters gradually degenerate from the reference sequence (mainly in phase 3). Figure 8(b)-(d) presents several realized sequences and gradual degeneration is obvious. This is handwriting of a tired robot.

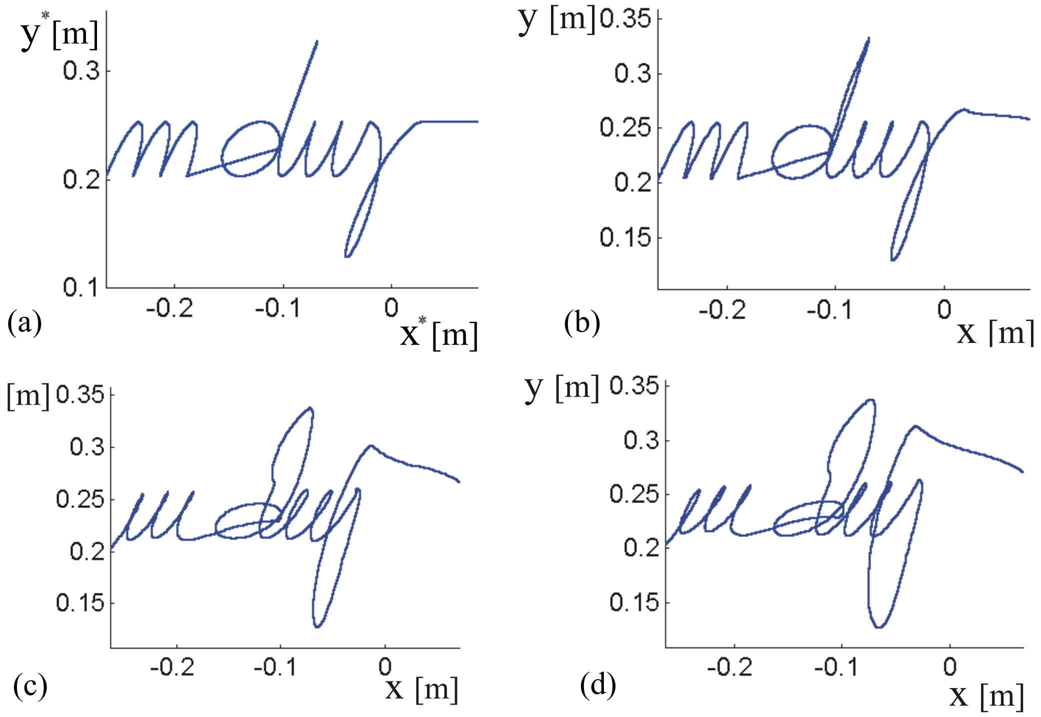

Figure 8. Gradual degeneration of writing. (a) Reference sequence.
(b)-(d) Degenerated sequences are recorded for the following repetitions: (b) 12th forward sequence, time: $198 \leq t \leq 207$, (c) 14th forward sequence, time: $234 \leq t \leq 243$, (d) 22nd forward sequence, time: $378 \leq t \leq 387$.

Conclusion

Robotic arm engaged in handwriting was considered. The work was two-fold: to improve the knowledge in biomechanics of handwriting, and to introduce some new concepts in robot control. Such control contributed to human-like motion of robots and opened the possibility to apply robots in diagnostics and rehabilitation of malfunctions in finger-hand-arm coordination.

Two approaches were proposed to model and control a human-like motion of robot arm in a writing task. The first approach, based on the concept of distributed positioning (DP), was suggested as a good model of arm motion in the phase where fatigue does not appear. The prescribed motion of the end-effector was distributed to a redundant number of arm joints in accordance to their acceleration capabilities. The justification of the usual inclination of letters was presented and the relation between the inclination, legibility, and fingers' involvement was discussed. It was found that for some prescribed level of legibility, the optimal inclination existed.

For the phase where fatigue appears, the concept of robot fatigue was proposed. It emulated the progress of biological fatigue. Penalty functions were utilized to ensure redistribution of the joint involvement when some of them "felt" fatigue. The arm automatically adapted to the situation, taking a new posture giving the exhausted joint the chance to rest while engaging more the other joints. The three phases of task execution were considered, namely: *regular motion*, before the symptoms of fatigue; *reconfiguration,* after some joints feel fatigue; and *degeneration,* caused by the too long, hard work that makes all joints tired. The human-like reaction of a fatigued robot could be observed (thus being a kind of a message), giving a chance to prevent undesired consequences.

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