Modeling Robot “Psycho-Physical” State and Reactions – A New Option in Human–Robot Communication
Part 2: MODELING AND SIMULATION

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(Received: 10 December 2001; in final form: 26 February 2002)

Abstract. This part of the paper examines numerically the possibility of modeling “robot fatigue” being representative of a human psychophysical state that can be applied to robots. Temperatures of driving motors are suggested as analogs to fatigue in muscles. Simulation of robot behavior is performed on a typical human task, namely handwriting. Three phases of task execution, characteristic for humans, are observed, i.e. regular motion, reconfiguration after symptoms of fatigue, and degeneration caused by the too long, hard work.

Key words: human–robot communication, humanoids, psychophysical state, gestural language, robot fatigue, redundancy.

1. Introduction

Part 1 of this paper elaborated the idea of modeling robot psychophysical state in order to allow a new way of human–robot communication. As a state suitable for the initial research in modeling, fatigue was adopted. Robot fatigue was modeled via motor temperatures considered as the analog of human fatigue. The principles of the concept were derived. To prove mathematically the approach presented in Part 1, we consider here a part of the robot body – its redundant anthropomorphic arm. As a task, a typical human motion is adopted, namely handwriting. Writing is performed in the sagittal plane. This task appeared to be appropriate

* Part of this work was carried out while Veljko Potkonjak was a research collaborator at the IRAL/NTUA.
for testing anthropomorphic configurations [4–9] but at the same time was shown to be a suitable example for testing any configuration given a kinematically and dynamically demanding task [1].

2. The System: Geometry and Dynamic Model

Let us discuss the number of degrees of freedom (DOF) needed to simulate the system. The task space is two-dimensional \((m = 2)\) and involves Cartesian coordinates \(x\) and \(y\). This means that the reference task trajectory is defined by means of the vector function:

\[
X^*(t) = \begin{bmatrix} x^*(t) \\ y^*(t) \end{bmatrix}^T.
\]  

(1)

Since \(X^*(t)\) is a reference task trajectory, it is prescribed, while \(X(t)\) denotes the realized (actual) motion. In order to avoid the unnecessary complexity and to preserve all the relevant effects, we define the arm as a planar mechanism consisting of: one-DOF shoulder, one-DOF elbow, and one-DOF wrist. These joints and the corresponding configuration coordinates are denoted by: \(q_1\), \(q_2\), and \(q_3\), and shown in Figure 1.

In handwriting, the fingers make a synergetic motion. All nineteen DOFs reduce to two translations as shown in Figure 2. So, the robot arm will be supplied with two linear DOFs emulating the role of fingers. These two linear joints and the corresponding coordinates are denoted as: \(q_4\) and \(q_5\), and shown in Figure 1.

In this way we arrive to the five-dimensional configuration space \((n = 5)\). The position vector is:

\[
q = [q_1 \quad q_2 \quad q_3 \quad q_4 \quad q_5]^T.
\]  

(2)

Here, \(q^*(t)\) denotes the reference configuration motion which is calculated from \(X^*(t)\) as explained in Section 4 of Part 1. The actual position is denoted by \(q\); it follows from the system dynamics and the applied control. Since \(n(= 5) > m(= 2)\), the system is kinematically redundant.

“fingers” (hand) 

\[\text{pencil} \]

wrist

elbow

shoulder

Figure 1. Anthropomorphic planar robot arm for handwriting.
The mechanism parameters are given in Table I. The arm is actuated by DC motors (the parameters are given in Table II).

The dynamics of the arm is described by means of five differential equations. If put together, they form the matrix model:

$$\tau = H(q)\ddot{q} + h(q, \dot{q}).$$  \hspace{1cm} (3)
where \( \mathbf{\tau} = [\tau_1, \ldots, \tau_5]^T \) is the vector of driving torques and forces in joints (torques for revolute joints \( j = 1, 2, 3 \), and forces for linear joints \( j = 4, 5 \)), \( \mathbf{H} \) is the \( 5 \times 5 \) inertial matrix, and \( \mathbf{h} \) is a \( 5 \times 1 \) vector involving gravitational and Coriolis’ effects.

The motor dynamics involves rotor rotation and current flow. For the motor of joint \( j \), it holds that:

\[
\begin{align*}
J_j \ddot{\theta}_j &= C_{M_j} i_j - M_j, \\
u_j &= R_j i_j + C_{E_j} \dot{\theta}_j,
\end{align*}
\]

(4)

where the following variables are involved: \( \theta_j \) – the motor shaft angle, \( i_j \) – armature current, \( u_j \) – input control voltage, \( M_j \) – motor output torque; and the following parameters: \( J_j \) – rotor moment of inertia, \( C_{M_j}, C_{E_j} \) – constants of torque and counter e.m.f., \( R_j \) – armature resistance. Friction and armature inductivity have been neglected.

The joint variables \((q_j, \tau_j)\) and motor variables \((\theta_j, M_j)\) are connected by the following linear relations:

\[
\begin{align*}
q_j &= \frac{\theta_j}{N_j}, \quad \tau_j = M_j N_j, \quad j = 1, 2, 3, \\
q_j &= \theta_j r_j, \quad \tau_j = \frac{M_j}{r_j}, \quad j = 4, 5,
\end{align*}
\]

(5)

where \( N_j \) is the gear-box ratio and \( r_j \) involves rotation-to-translation conversion. If we further neglect the rotor inertia in (4), and introduce relations (5), then (4) gives the expressions for the currents and the joint torques (or forces) as functions of the input controls \( u_j \) and the measured velocities \( \dot{q}_j \):

\[
\begin{align*}
i_j &= \begin{cases} 
\frac{1}{R_j} (u_j - C_{E_j} N_j \dot{\theta}_j), & j = 1, 2, 3, \\
\frac{1}{R_j} \left( u_j - \frac{C_{E_j} \dot{\theta}_j}{r_j} \right), & j = 4, 5,
\end{cases}
\\
\tau_j &= \begin{cases} 
C_{M_j} N_j i_j, & j = 1, 2, 3, \\
\frac{C_{M_j}}{r_j} i_j, & j = 4, 5.
\end{cases}
\end{align*}
\]

(6)

If the current limiter is not active (\( D = 1 \)), these currents and drives really apply. When the limiter is activated, then the so-called required currents \((i_{\text{req}})_j\) are calculated by using (6), and the actual currents are obtained by multiplying by damping factors (according to Equation (9) from Part 1). Thus, the final expressions for the
currents and the joint drives are:

\[
i_j = \begin{cases} 
\frac{D(\Theta_j)}{R_j}(u_j - C_{Ej}N_j\dot{q}_j), & j = 1, 2, 3, \\
\frac{D(\Theta_j)}{R_j}(u_j - C_{Ej}\dot{q}_j/r_j), & j = 4, 5, 
\end{cases}
\]

\[
\tau_j = \begin{cases} 
C_{Mj}N_ji_j, & j = 1, 2, 3, \\
C_{Mj}i_j/r_j, & j = 4, 5.
\end{cases}
\]

3. Thermal Dynamics

The thermal behavior of robot motors was first studied in [2] as an effort towards computer-aided design (CAD) of robots. Our study is based on the models derived in [4, 8, 9]. 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. 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:

\[
\begin{align*}
T_{rj}\dot{\Theta}_{rj} &= Z_{rj}R_{ji}^2\dot{r}_j - (\Theta_{rj} - \Theta_{hj}), \\
T_{hj}\dot{\Theta}_{hj} &= Z_{hj}Z_{rj}(\Theta_{rj} - \Theta_{hj}) - (\Theta_{hj} - \Theta_{a}),
\end{align*}
\]

where \( \Theta_{rj} \) and \( \Theta_{hj} \) 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 rotor-to-housing and housing-to-ambient, \( \Theta_{a} \) is the ambient temperature, and \( R_{ji}^2 \) represents the Joule power loss. The time constants influence the slope of the temperature progress while the resistances define the steady state levels. The dynamic model can be reduced to a first-order if appropriate choice of parameters is made. All the relevant effects will be preserved [3]. The first-order model is:

\[
T_{j}\dot{\Theta}_j = Z_{f}R_{ji}^2\dot{j} - (\Theta_j - \Theta_{a}).
\]

4. The Complete Simulation Model

The system for the simulation of the proposed concept involves the following.

- Inverse kinematics for reference motion: This is expressed by Equation (4) of Part 1 along with Equations (7) and (8) that define the weighting matrix and the penalty functions, and the expression (5) which introduces the sec-
Figure 3. Task definition: Reference sequence of letters in task space \((x^*, y^*)\); inclination of letters 20°.

Ordinary criterion – comfort (all equation numbers refer to Part 1). Note that the solution of the reference kinematics depends on the actual values of the temperatures.

- **Arm dynamics**: This is described by the model (3) of Part 2.
- **Motors** (together with transmissions): These are modeled by Equation (7) of Part 2 along with the expression (10) of Part 1, which defines the current-damping factor.
- **Control**: This is realized applying PD feedback defined by expression (6) of Part 1.
- **Thermal dynamics**: This is described by the first-order model (9) of Part 2.

The above set of equations constitutes the complete mathematical model which is used to simulate the system behavior.

5. The Task

As mentioned, a typical human motion is chosen as a test task. This is the handwriting performed in the sagittal plane. The robot arm has to write the sequence of letters shown in Figure 3. After finishing the sequence in forward direction, the arm will follow the same pattern but in reverse direction. This will be repeated as many times as necessary, thus simulating a long-term writing.

The sequence of letters has to be written in 9 seconds. Figure 4 shows the reference task-space motion, i.e. the time histories of Cartesian coordinates \(x^*(t)\) and \(y^*(t)\), which produce the required sequence. The robot starts from a resting position with configuration coordinates:

\[
q(0) = [\pi/4 \quad \pi/2 \quad 0 \quad 0 \quad 0]^T.
\]
6. Results and Discussion

Simulation in this work was performed to prove the feasibility. Thus, the parameters need not be realistic but rather chosen so as to stress the relevant effects. In addition, a too long simulation should be avoided. Having this in mind the following parameter values have been adopted. The coefficient used for utilization of the secondary objective in the IK solution (Equation (4) in Part 1): $k_\alpha = 900$. The elements $w_j, k_{\phi,j}, j = 1, \ldots, 5$, defining the penalty functions (8), and thus the weighting matrix (7) (equation numbers refer to Part 1), are given in Table III. The feedback control gains $(K_{Pj}, K_{Vj})$, used in expression (6) of Part 1, are given in the same table. The table finally shows the limits of the robot fatigue (temperatures $\Theta_{j,cr}, \Theta_{j,max}$), as well as the parameters of the thermal model (9) (i.e. $T_j, Z_j$).

To show the most interesting simulation results 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. Figure 5(a) presents the progress of motor temperature (joint fatigue $\Theta_4$). Figure 5(b) presents the variation of joint involvement. As a measure showing how much a particular joint (e.g., the $j$th
Table III. Simulation parameters

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<td>100</td>
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</tr>
</tbody>
</table>

![Figure 5](image)

Figure 5. Behavior of joint No. 4: (a) joint fatigue $\Theta_4(t)$, (b) joint involvement $KI_4(t)$, (c) reference motion $q_4^*(t)$, and (d) realized motion $q_4(t)$.

One joint 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: $KI_j = \int_{T=9s} |\dot{q}_j| \, dt$, where $T = 9$ s is the time needed to accomplish one sequence. Figure 5(c) shows the reference motion of the joint, $q_4^*(t)$, and Figure 5(d) shows its real motion ($q_4(t)$). Figure 6 presents the behavior of the joint No. 5.
Figure 6. Behavior of joint No. 5: (a) joint fatigue $\Theta_5(t)$, (b) joint involvement $K_{I5}(t)$, (c) reference motion $q^*_5(t)$, and (d) realized motion $q_5(t)$.

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.

Phase 1 (regular motion), starts immediately and lasts until the fatigue in some joint (motor temperature $\Theta_j$) exceeds the assigned critical level $\Theta_{j,cr}$ (it happens at about $t_1 = 80$ s). In this phase the continuous progress of fatigue in both joints is monitored (diagrams 5(a) and 6(a)). The joint involvements are at a constant level (Figures 5(b) and 6(b)) meaning a steady situation in the distribution of the task to robot joints. This steady distribution is supported by the diagrams 5(c), (d) and 6(c), (d), where the oscillations with constant magnitudes can be observed. In this phase, the error of writing (DEV in Figure 7) is rather small.

Phase 1 ends at about $t_1 = 80$ s when joint 5 feels fatigue, i.e. the motor temperature exceeds the critical level: $\Theta_5 \geq \Theta_{5,cr}$ (see Figure 6(a)). At that moment phase 2 begins (and will last up to $t_2 = 190$ s). Reconfiguration starts since the penalty function in joint 5 forces its reduced engagement. This reduction appears as a drop in the involvement $K_{I5}$ at $t_1 = 80$ s (Figure 6(b)). This is also obvious in the diagrams of Figure 6(c), (d) where the magnitudes of oscillations decrease. Since the other joints have to help, one may observe the increased involvement $K_{I4}$ (Figure 5(b)). This higher engagement of joint 4 can be recognized
in Figures 5(c), (d) as increased density of oscillation diagram. The joint 4 is not the only one to help. So, if behavior of joint 3 is depicted, it would feature increased involvement as well. During the phase 2, at about \( t' = 160 \text{ s} \), the temperature in joint 4 reaches the critical level: \( \Theta_4 \geq \Theta_{4,ct} \) (see Figure 5(a)). At that moment, the penalty function starts to depress the engagement of joint 4, thus causing the drop of involvement \( KI_4 \), as it is obvious from Figure 5(b). In spite of reconfiguration, the temperatures \( \Theta_4 \) and \( \Theta_5 \) 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 (Figure 7).

Phase 2 ends at about \( t_2 = 190 \text{ s} \), when the fatigue in joint 5 exceeds the next limit (upper level): \( \Theta_5 \geq \Theta_{5,max} \). At this moment, phase 3 (i.e. degeneration) begins. The current limiter activates, reducing the joint drive. The reference joint motion (shown in Figure 6(c)) still comes out from inverse-kinematics calculation. The slightly increased engagement, leading to increased magnitudes, expresses the attempt of joint 5 to help joint 4 a bit (according to the simultaneous action of the two penalty functions, 4 and 5). This means that the robot is still trying to do the job well, i.e. to write perfectly. However, the reduced joint drive will make the joint 5 less controllable, and hence, the magnitude of realized motion will rise considerably (as seen in Figure 6(d)). The kinematic involvement of joint 5 (\( KI_5 \) in Figure 6(b)) will rise rapidly. However, one should note that this rise is not forced by a strong drive, but contrary, caused by insufficient motor current and joint drive. So, the fatigue \( \Theta_5 \) will stop rising and will reach the steady state (see Figure 6(a)). The joint 4, still strongly driven, will continue to track the reference motion (obvious from the diagrams of Figure 5(c), (d)), and consequently, joint fatigue will continue to rise (Figure 5(a)). At about \( t'' = 480 \text{ s} \), joint fatigue exceeds the upper level: \( \Theta_4 \geq \Theta_{4,max} \). The current limiter activates and the drive reduction causes lower controllability. So, the joint will no more track the reference, and oscillations will rise (see diagrams of Figures 5(c), (d)). This increased kinematic involvement (obvious in Figure 5(b) as well), caused by insufficient drive, will not contribute to motor heating. The reduced current will allow the temperature \( \Theta_4 \) to reach the steady state (as shown in Figure 5(a)). During phase 3, the error in writing rapidly increases (see Figure 7), which means that the quality of task execution is becoming very low.
Figure 8. Gradual degeneration of writing; sequences are recorded for the following repetitions: (a) 12th forward sequence, time: $198 \leq t \leq 207$, (b) 14th forward sequence, time: $234 \leq t \leq 243$, (c) 22nd forward sequence, time: $378 \leq t \leq 387$.

The deviation of actual letters from the reference pattern deserves more attention. Figure 8 shows how the realized letters gradually degenerate from the reference sequence given in Figure 3. As mentioned above, during the phases 1 and 2, the writing error was rather small. However, in phase 3 the trajectory rapidly degenerates. Figure 8 presents several realized sequences, all belonging to phase 3.
Compared with the reference sequence shown in Figure 3, gradual degeneration is obvious. This is handwriting of a tired robot.

7. Conclusions

Part 1 of the paper investigated the concept and gave the theoretical background for modeling “robot psychophysical state”. As an example of human state that can be applied in robots, fatigue was chosen. The analogy between temperatures of robot motors and the fatigue in muscles was established.

Since human behavior is emulated, simulation in Part 2 was performed on a typical human task – handwriting. The three phases of task execution, 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,

were discussed.

The human-like reaction of a fatigued robot could be observed, giving a chance to prevent undesired consequences.

References


