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Human-Robot Analogy − How Physiology Shapes Human and Robot Motion

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Abstract

The fast grow of expectations from robots and the technical obstacles the robot developers face when trying to meet the requests, force an orientation towards designing and controlling robots by following biological paragons. This tendency increases interest in human-robot analogy, and the present work is a part of this stream. The paper questions the voluntariness of human motion by relating it to physiological processes. We concentrate on the important question of redundancy. One notes that humans do not resolve the redundancy on the level of consciousness, except in some specific examples (like obstacle avoidance), but rather on a lower level of decision-making – the human reaction to the faced problem is somehow "automatic". We suggest that this automatism is closely related to physiological processes, particularly to the progress of fatigue. Then we try to mathematically model these processes and their influence to human motion. The mathematical model of fatigue progress is derived as well as an algorithm for human-like redundancy resolution. We finally consider the implications of the obtained results to anthropomimetic robotics. The concept is verified by simulating the system behavior and comparing it qualitatively with the behavior of a human control group.

Introduction

In the last decade we witness the fast growing interest in technical systems, in particular robots, mimicking living beings. A new class of robots have appeared – anthropomimetic robots – imitating humans regarding their mechanical structure, actuation, and intelligence (Holland & Knight, 2006; Diamond, et al., 2012; Potkonjak, et al., 2011; Wittmeier, et al. 2013; Mizuuchi, et al., 2007; Sodeyama, et al., 2008). Mimicking humans is an ultimate response to the increasing expectations and complexity of tasks imposed to robots, on one hand, and the technical and technological obstacles robot developers face when trying to meet the requirements, on the other.

With such approach the deep relations between motion/actuation, intelligence, and physiological processes have to be explored. For instance, motion used to be considered as a purely voluntary action resulting from consciousness and intelligent process. This was specially the case with robots where the voluntariness of motion was almost an axiom. However, the new concepts question this viewpoint. Regarding consciousness, it has been found that with humans a motor activity starts even before we are aware of the intention (Haggard & Libet, 2001). Researchers have also recognized the significance of morphology and motor activities in shaping human intelligence (Pfeifer & Bongard, 2007). The present work does not elaborate these interesting problems but questions the voluntariness of human motion from another standpoint being dependant on the physiological processes. We concentrate on the important question of redundancy. The kinematic redundancy is normally present in humans and accordingly in anthopomimetic robots as well, offering multiple choice when deciding about joint motions that will execute some given end-effector motion task (e.g., some manipulation in space). One notes that humans do not resolve the redundancy on the level of consciousness, except in some specific examples (like obstacle avoidance), but rather on a lower level of decision-making – the human reaction to the faced problem is somehow "automatic". We suggest that this automatism follows from physiological processes, particularly from the progress of fatigue. Then we try to mathematically model these processes and their influence to human motion, to finally see whether the obtained results have sense and implications in anthropomimetic robotics. Human-like reactions of robot to overloading and a kind of human-like communication have been achieved.

Background Research and the New Concept

Kinematic Redundancy

From a mechanical point of view, a human and a robot resembling a human are kinematically redundant, i.e., their mechanisms feature a higher degree of mobility than required for a given motion in operational space. Kinematic redundancy contributes to motion dexterity and facilitates coping with unpredictable changes within its environment. Some advantages resulting from redundancy are exploited on the level of consciousness and intelligence (e.g., avoiding obstacles in the workspace) while others are exploited automatically, on a lower level of decision-making (this being the case with avoiding singularities and avoiding mechanical limits in joints). However, very often redundancy is not an advantage but rather a problem that needs resolution. Its implications are particularly emphasized in the well-known inverse kinematics (IK) problem. This is a problem of searching for joint motions that provide a desired trajectory of the end-effector in operational space. The presence of kinematic redundancy means that the same end-effector's trajectory can be executed with different joint motions. Hence, the problem of the particular choice between available joint motions arises. If there are no specific constraints (like obstacles in workspace) that require the engagement of redundancy, then we have a "useless" surplus of joints and need to find the optimization criterion that will allow for the unique choice. The work done by Potkonjak et al. (2003) explored a typically human redundant task – handwriting, and showed little difference in results obtained by using engineering and biologically-inspired criteria for optimization.

Among optimization criteria which are mainly engineering, we mention the following. Joint movement time is an example of a kinematic cost function. Examples of dynamic cost functions are: quadratic norm of joint control torques (Hollerbach & Suh, 1987), kinetic energy (Khatib, 1983), jerks in joints (Hogan, 1984). Several neuro-physiological and psychophysical cost functions were also suggested (Sief-Naraghi & Winters, 1989): “input energy” was defined as a quadratic norm of input neural signals of motor units (muscles), while “input fatigue” denote the magnitude of such neural signals. The authors suggested some proper combination of these functions, rather than their separate application.

In this study, special attention is paid to functions of joint “discomfort”, which were experimentally derived to identify arm postures of maximum comfort (Cruse, et al., 1990). They were determined upon analysis of recorded electromiographic (EMG) signals taken from subjects engaged in experiments, as well as by using their subjective psychophysical evaluations of maximum comfort postures. The fact that a variety of cost functions has already been used to explain principles of human arm motor control indicates that the CNS does not obey any one particular cost function, but also does not violate general physical and technical principles of optimality, from which particular cost functions come about (Latash, 1993). Hence, additional efforts in searching for new appropriate and effective cost functions are justified. They contribute to a better understanding of biological principles of motor control.

When we speak about *comfort* and *discomfort* we certainly have in mind states closely related to some physiological processes, in particular to *fatigue*, but we are still missing the way to mathematically describe these relations.

Comfort and Fatigue

The underlying idea of the paper has both theoretical and experimental foundations. Practical experience shows that the human arm commonly takes those postures and executes those movements that are the most comfortable. The term “comfortable” relates to joint positions and engagement of motor units and may also be described by the term “pleasant” (a more precise definition will be given later). On the other hand, endurance contractions of motor units cause muscle fatigue, thus introducing an unpleasant feeling, that is, a sense of discomfort. In everyday life it is easy to observe that after a sensation of discomfort caused by muscle fatigue, the human arm normally reduces engagement of the fatigued motor units, by taking postures that require lower participation of these units. This means that while performing repetitive movements requiring continual repetition of motions in operational space (like in screw-driving tasks), the human arm occasionally reconfigures itself by taking a more comfortable posture, rather than proceeding with some particular pose. The ability to rearrange its motion is enabled by the presence of both actuator and kinematic redundancy in the human arm (Fuentes & Nelson, 1994). Actuator redundancy comes from the possibility to use several motor units for the same motion of any arm joint. Kinematic redundancy results from the existence of seven degrees of freedom (DOFs) in the arm (from shoulder to wrist), which is more than six independent movements required for an arbitrary positioning and orientation of an object in operational space (Potkonjak, et al., 1998; Sciavicco & Siciliano, 1996). Actuator redundancy and its implementation in robotics are challenging problems that deserve attention. However, they are not considered in this paper, although their role in performing movements in biological mechanisms must be pointed out. Instead, this paper focuses on kinematic redundancy and investigates possibilities to distribute the engagement of robot joints in a human-like fashion, imitating the arm’s inherent property to execute comfortable motions. The main objective is to achieve a human-like motion. This can be done if an adequate mechanism is established that simulates biological processes of comfort and discomfort in the arm. It would be useful to rely on relevant findings from already published results of theoretical and experimental investigations. A result which is strongly correlated with our work deals with psychophysical cost functions of joint comfort/discomfort and was presented by Cruse et al. (1990). Their validity was practically justified for arm reach posture prediction by Jung et al. (1994). A psychophysical cost function describes an immediate deviation of joint position from the location of maximum comfort. According to experimental findings given by Cruse et al. (1990), the CNS controls arm motion by minimizing the efforts (from a psychophysical point of view) invested during the movements. Physiological and psychophysical investigations indicated that, in the absence of muscle fatigue, a more comfortable joint pose is closer to the middle of the physiological motion range in that joint. Locally minimizing the function describing a deviation from the position of maximum joint comfort, it is possible to determine comfortable motions of a kinematically redundant mechanism.

Mathematical functions representing current distances from middle positions of joints were used in robotics for joint limits avoidance (Liégeois, 1977; Chan & Dubey, 1995). The applied IK method took care of these distances and forced joint motions to the direction opposite to mechanical boundaries. In this paper, such functions are chosen as starting points in the formulation of an analytic procedure for generating joint movements that are equivalent to the movements of a human arm after appearance of discomfort due to muscle fatigue.

Fatigue in humans is a rather complex issue. On one hand, it is a physiological process related to accumulation of metabolic products. This is the aspect that could be, more or less accurately, modeled. On the other hand, fatigue has a psychological aspect – e.g. a fatigued human feels much better if he simply changes the work he is doing – this aspect cannot be modeled and will not be considered in this paper. Physiological sources of fatigue, although extensively studied, are still not thoroughly known. Basically, fatigue appears after long-standing and powerful contractions of muscle motor units. Increase of lactic acid concentration accompanies the progress of fatigue sensation (pH value decrease in muscle tissue). Simultaneously, the oxygen distribution is reduced, while concentration of some substances particularly influencing the mechanism of muscle contractions and dilatations decreases, e.g., Adenosine Triphosphate (ATP). As a result, muscular activity declines. The progress in a human's feeling of discomfort due to fatigue grows simultaneously with the progress of fatigue itself. The beginning manifestation is like a slight sense of discomfort in a certain part of the arm, then the discomfort transforms into an unpleasant squib which, finally, results in obtuse pain (Öberg, 1994). Additional engagement of other motor units is then required to sustain the necessary arm actuation.

Muscle fatigue can be quantified by means of objective and subjective methods. Objective methods include mechanical, electromagnetic (EMG), metabolic and physiological measurements (Mizrahi, 1997). Another group of methods is based on the subjective evaluation of the sensed fatigue level, given by the subjects participating in experiments (Öberg, 1994). Because there is a variety of factors indicating the current level of fatigue, it is not possible to distinguish an ultimate method for fatigue quantification. The same statement holds for the models of fatigue, available in literature (see, for example, the work by Kiryu (1998)). However, no matter which method is applied for fatigue quantification, it seems reasonable to consider fatigue as an increasing function. That function is often assumed to be exponential (Peckham, 1972; Vodovnik & Rebersek, 1975; Giat, et al., 1996). The slope of the function depends on the actual engagement of motor units and the current level of fatigue. After some time, saturation appears, as a result of reduced activity of exhausted motor units. An example of a diagram with such characteristics is available in (Jenkins & Quigley, 1992) and corresponds to the increase of lactic acid concentration in a muscle engaged in demanding movements.

Keeping in mind the described principal characteristic of the fatigue function, we will suggest for a mathematical non-dimensional variable to be a measure of fatigue in humans. Later, we will explore eventual meaning, sense, and applicability of such variable in robots, introducing "robot fatigue". The temporal characteristic of robot fatigue must be equivalent to the functional characteristic of biological fatigue, thus opening the possibility of generating human-like motions of the robot joints. The aim is to force a redundant anthropomorphic robot arm to track a given end-effector operational space trajectory, along with producing the most comfortable configurations in the sense of the above mentioned psychophysical cost function. Functionally, robot fatigue will have a response equivalent to the biological muscle fatigue, that is, similar dynamic behavior. Results presented in the rest of the paper will justify this approach. An anthropomorphic seven-DOF human/robot arm performing the screw-driving task will be simulated. It will be shown that the robot arm attains postures and executes motions similarly to that of the human arm performing the same task.

Mathematical Formulation

Solution of IK Problem

The arm kinematics will be defined in terms of velocities (Nakamura, 1991; Sciavicco & Siciliano, 1996). The relation between vectors of configuration (joint) velocities $\dot{\mathbf{q}}$ and operational (end-effector) velocities $\dot{\mathbf{x}}$, is given by the Jacobian form

$$\dot{\mathbf{x}} = \mathbf{J}(\mathbf{q})\dot{\mathbf{q}} \,. \tag{1}$$

We assume that redundancy exists, i.e., the number of operational velocities, denoted by m, is strictly less than the number of configuration velocities, denoted by n. Normally, it is $m = 6$ (three translations plus three rotations). For a human arm it holds that $n = 7$ (3 degrees of freedom (DOF) in shoulder, 2 in elbow, and 2 in wrist). Dimension of the non-square Jacobian matrix $\mathbf{J}(\mathbf{q})$ is then $m \times n$. The redundancy implies a non-unique IK solution, since a given task, defined in terms of operational velocities, can be accomplished with an infinite number of combinations of configuration velocities. We are interested in those joint velocities that would be executed by a human arm in a given task. Adequate velocities can be found by local minimization of the cost function, formed by two quadratic terms (Sciavicco & Siciliano, 1996):

$$\mathbf{\Omega}(\dot{\mathbf{q}}) = 0.5\, \dot{\mathbf{q}}^{\mathbf{T}}\mathbf{W}'\dot{\mathbf{q}} + 0.5\, (\dot{\mathbf{q}} - \dot{\mathbf{q}}_{\alpha})^{\mathbf{T}}\mathbf{W}''(\dot{\mathbf{q}} - \dot{\mathbf{q}}_{\alpha}) \,. \tag{2}$$

$\mathbf{W}'$ and $\mathbf{W}''$ denote $n \times n$ positive definite symmetric weighting matrices, while $\dot{\mathbf{q}}_{\alpha}$ represents an n-component column vector. The first term in eq. (2) enables us to penalize motion of some joints relative to others. In this paper it should provide a distribution of operational motion to the redundant number of arm joints in accordance with the biologically-inspired concept of distributed positioning (DP) (Potkonjak, 1990; Potkonjak & Krstulovic, 1992[a, b]; Potkonjak, et al., 1998), which means stimulating motions of the joints with low inertia and penalizing motions of the joints with high inertia. It should also enable a proper reconfiguration of the arm, in accordance with the progress of fatigue. The second term in eq. (2) aims at the utilization of kinematic redundancy in the sense of a secondary criterion. Minimization of objective (2) subject to constraint (1) is performed by using the method of Lagrange multipliers (Gottfried & Weisman, 1973). Optimal joint velocities are obtained:

$$\dot{\mathbf{q}} = \mathbf{J}_{\mathbf{W}}^{\#}\,\dot{\mathbf{x}} + (\mathbf{I} - \mathbf{J}_{\mathbf{W}}^{\#}\,\mathbf{J})\mathbf{W}^{-1}\mathbf{W}''\dot{\mathbf{q}}_{\alpha} \,, \tag{3}$$

where $\mathbf{W}=\mathbf{W}'+\mathbf{W}''$ and $\mathbf{J}_{\mathbf{W}}^{\#}$ denotes the weighted pseudo-inverse of the Jacobian:

$$\mathbf{J}_{\mathbf{W}}^{\#} = \mathbf{W}^{-1}\mathbf{J}^{\mathrm{T}}\,(\mathbf{J}\mathbf{W}^{-1}\mathbf{J}^{\mathrm{T}})^{-1} \tag{4}$$

Vector $\dot{\mathbf{q}}_{\alpha}$ enables the local optimization of some secondary objective function $G(\mathbf{q})$, used for the proper utilization of kinematic redundancy. Following (Liégeois, 1977), $\dot{\mathbf{q}}_{\alpha}$ is defined as the gradient of $G(\mathbf{q})$:

$$\dot{\mathbf{q}}_{\alpha} = -\mathbf{k}_{\mathbf{a}}\left(\frac{\partial \mathrm{G}(\mathbf{q})}{\partial \mathbf{q}}\right)^{\mathbf{T}} \tag{5}$$

where k_a is a scalar coefficient. The final form of the IK solution is obtained by substituting (5) into (3):

$$\dot{\mathbf{q}} = \mathbf{J}_{\mathbf{W}}^{\#}\,\dot{\mathbf{x}} - \mathbf{k}_{\mathbf{a}}(\mathbf{I} - \mathbf{J}_{\mathbf{W}}^{\#}\,\mathbf{J})\mathbf{W}^{-1}\mathbf{W}''\left(\frac{\partial \mathrm{G}(\mathbf{q})}{\partial \mathbf{q}}\right)^{\mathbf{T}} \tag{6}$$

Choise of the Secondary Objective Function

Definition of the secondary objective function $G(\mathbf{q})$ providing comfortable motion is discussed in this subsection. The distances of current joint positions q_i , i=1,...,n, from the mechanical joint limits $q_{i,\min}$ and $q_{i,\max}$ will be the basis for definition of the secondary objective function. In the previous section it was already pointed out that the middle values of human arm joint ranges coincide with positions of the maximum comfort. This fact justifies the choice of $G(\mathbf{q})$ as a function penalizing deviation from the middle values (Liégeois, 1977; Chan & Dubey, 1995):

$$G(\mathbf{q}) = \frac{1}{2n}\sum_{i=1}^{n}\left(\frac{q_i-\bar{q}_i}{q_{i,max}-q_{i,min}}\right)^2, \; \bar{q}_i = \frac{q_{i,max}+q_{i,min}}{2} \tag{7}$$

or

$$G(\mathbf{q}) = \sum_{i=1}^{n}\frac{1}{4}\frac{(q_{i,max}-q_{i,min})^2}{(q_{i,max}-q_i)(q_i-q_{i,min})} \tag{8}$$

Model of Arm Dynamics

The dynamics of the arm plays an important role in establishing a procedure that provides human-like motions of joints. We adopt the standard representation of arm dynamics:

$$\mathbf{H}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{h}(\mathbf{q},\dot{\mathbf{q}}) = \boldsymbol{\tau} + \mathbf{J}^{\mathrm{T}}\mathbf{F} \tag{9}$$

where $\mathbf{q}$, $\dot{\mathbf{q}}$, and $\ddot{\mathbf{q}}$ denote $n \times 1$ vectors of joint positions, velocities, and accelerations; $\mathbf{H}$ is an $n \times n$ inertia matrix; $\mathbf{h}$ is an $n \times 1$ vector of centripetal, Coriolis', friction and gravitational torques; $\boldsymbol{\tau}$ denotes the $n \times 1$ vector of driving torques in the joints; $\mathbf{J}$ is the Jacobian, and $\mathbf{F}$ is the m-component external force/torque. Driving torques are produced by actuators – muscles in humans and motors in robots.

Model of Fatigue Process

This subsection suggests a method that should be used to simulate the effects of physiological fatigue in human muscles.

The key features of the fatigue function were revealed in subsection "*Comfort and Fatigue"*. We now look for a proper mathematical model to express these features. We first introduce a non-dimensional variable being the measure of fatigue. It will be called simply *fatigue*. Let z_i be the fatigue in joint i (i=1,...,n). We assume that the level of fatigue directly depends on the accumulation of metabolic products – concentration of lactic acid. So, the concentration could be considered as fatigue, after normalizing it to become a non-dimensional variable.

We consider fatigue as an accumulation process. Like in modeling any accumulation process, we will consider the gradient of the state coordinate as balancing input and output. A good paragon is the process of heating a body, being the accumulation of thermal energy: temperature θ is the state variable, Ri^2 is the input from electric heater, $k(\theta - \theta_0)$ is the output (energy transition body-to-ambient), and the model is finally $C\dot{\theta} = Ri^2 - k(\theta - \theta_0)$, where C is the specific thermal capacity. With the fatigue process, z_i is the state variable. Let us discuss the input and the output.

- One notes that there exists an input, a source of lactic acid – these are metabolic processes which intensify with the stronger muscle activity i.e. with the higher joint torque τ_i. There are no reliable results reveling how the production of acid depends on the torque τ_i. In order to develop the methodology, we follow the paragon and adopt a quadratic function. So, the input rate can be expressed as $A_i\tau_i^2$, where A_i is the coefficient that should be determined experimentally.
- Next, one notes that there is also an output – blood takes the acid out of the muscle. The output rate can be considered proportional to the difference in concentration between the muscle (z_i) and the blood ($z_{i,0}$), and so it is: $K_i(z_i - z_{i,0})$, where K_i is the conductance (transition coefficient).

Now the balance is:

$$M_i\dot{z}_i = A_i\tau_i^2 - K_i(z_i - z_{i,0}) \tag{10}$$

where M_i is the specific accumulation capacity. The model can be rewritten to the form

$$T_i\dot{z}_i = \frac{A_i}{K_i}\tau_i^2 - (z_i - z_{i,0}) \tag{11}$$

revealing the time constant T_i.

Model (11) considers $z_{i,0}$ as being constant. This means that we neglect the accumulation process in the blood. If one wishes to expend the fatigue dynamics to include bloodstream system, he should note that the acid taken from the muscle should be treated as input to the blood. The output should be defined as the place where the "cargo" is unloaded (liver). The concentration $z_{i,0}$ now becomes a new state variable and the fatigue process becomes of the second order.

The Full Model

The full model means the set of equations that can be numerically integrated to calculate the system behavior in all its aspects. So, we talk about simulation and it goes in few steps:

- We start from the fact that a given task means a prescribed motion in operational space, $\mathbf{x}(t)$.
- IK is resolved by applying expression (6) along with (8). This way, the joint-space motion $\mathbf{q}(t)$ is obtained which satisfies the request for comfort.
- With known joint motions, the joint torques $\boldsymbol{\tau}(t)$ are found from the dynamic model (9).
- Finally, the progress of fatigue $\mathbf{z}(t)$ is calculated by integrating the model (11).

What still remains an open question is: does and how fatigue influences the above formulated simulation procedure.

How Fatigue Influences the Arm Motion

Here, we suggest the proper means for establishing the functional dependence between fatigue time history $z_i(t), i = 1,\ldots,n$, and robot arm motions. For this purpose, we should reinstate the expected effects of fatigue progress. During manipulation, a human arm performs movements adequate to the desired manipulation task, permanently accommodating its configurations to the actual level of muscle fatigue. Present kinematic and actuator redundancy allows execution of the manipulation task in a comfortable way, by appropriate distribution of joint motions and participation of different motor units. In such ways exhausted muscles may recover and other muscles increase their activity. A similar strategy could be applied to a robotic arm. Note that capabilities of the kinematic redundancy will be utilized only – actuator redundancy is out of scope of this paper.

Reconfiguration

For each arm joint it is necessary to specify an appropriate critical level of the fatigue: $z_{i,\mathrm{cr}}$. It is the level when a human starts to feel unpleasant sensations in the considered joint. Thus, $z_{i,\mathrm{cr}}$ should not be seen as a definite limit but rather a bound of a desired region of working mode. If the fatigue z_i is less then $z_{i,\mathrm{cr}}$, a human feels fine and will continue working in the same way. If z_i exceeds the critical value, the human can still work in the same way but he will not feel comfortable. To prevent the discomfort, a proper depression of motion in the critical join is needed. It is necessary to reconfigure the arm by taking a posture that will engage other joints more thus giving the exhausted joint a chance to rest. Note that reconfiguration is done in the joint space and does not affect the operational motion $\mathbf{x}(t)$ and the execution of a given task. Reconfiguration of joint motions can be achieved on the IK level, by means of the proper weighting matrices. We remind that there are two matrices making a sum **W**= **W**'+**W**''. Matrix **W**' should provide human-like distribution of joints motions (DP concept) and an adequate reconfiguration of the arm with respect to actual levels of joint fatigue. By means of **W**'' one can specify higher engagement of some joints in realization of the secondary objective. In this paper, it is assumed that all joints have equal priority in realization of the secondary objective. In such a way, the role of **W**' determines a particular choice of **W**. To ensure the proper reconfiguration, penalty functions are introduced into the weighing matrix:

$$\mathbf{W} = \mathrm{diag}[\varphi_1(z_1), \dots, \varphi_n(z_n)] \tag{12}$$

Penalty functions $\varphi_i(z_i)$ should penalize the exhausted joints and stimulates those that are still "fresh". Mathematically speaking, $\varphi_i(z_i)$ should be constant untill z_i reaches $z_{i,\mathrm{cr}}$ and monotonically increasing above $z_{i,\mathrm{cr}}$. In this way, the penalty functions will contribute to reduced movement of each joint in which the actual value of fatigue exceeds an assigned critical level. The choice of a particular penalty function is task dependent. For the simulation study of this article we adopt a quadratic function:

$$\varphi_i(z_i) = \begin{cases} w_i\,, \; z_i < z_{i,\mathrm{cr}} \\ w_i + k_i(z_i - z_{i,\mathrm{cr}})^2, \; z_i \geq z_{i,\mathrm{cr}} \end{cases}, \tag{13}$$

where the initial weighing factor w_i is a scalar constant and the coefficient $k_i > 0$ determines the desired slope of the penalty function.

It is expected that reduced engagement of the 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 reach the critical levels. If the imposed task is not too tough, the arm will finally finds a steady state in which it can operate for a longer time. We remind that reconfigurations do not affect the execution of the task since it does not reflect in the operational space **x**.

Degeneration

If the task is too demanding, it may happen that, in spite of reconfiguration, the fatigue functions $z_i(t)$ continue to rise. This means that reconfiguration delays the fatigue problem but does not eliminate it. To handle this situation, some upper limits of fatigue are adopted: $z_{i,\max}, i = 1, \dots, n$. The limit in the *i*-th joint, $z_{i,\max}$, determines the level when discomfort in the joint turns into pain that cannot ne endured. In this situation, a further rise of fatigue must be prevented regardless of the consequences, even if the execution of the task is compromised. Hence, we call this phase degeneration. The over-exhausted joint must rest and we emulate this process by using a "torque limiter". The limiter will allow the torque that is smaller than the required value by the factor *D*, and thus for the joint *i* it will be:

$$\tau_i = D_i(z_i)\tau_i^{\mathrm{req}} \tag{14}$$

where τ_i is the actual torque and τ_i^{req} is the value required by the dynamics of the given task. The damping factor $D_i(z_i)$ depends on the actual level of fatigue. In order to efficiently relax the over-exhausted joint, an exponentially decreasing function is adopted:

$$D_i(z_i) = \begin{cases} 1\,, \; z_i \leq z_{i,\max} \\ e^{-(z_i - z_{i,\max})}\,, \; z_i > z_{i,\max} \end{cases} \tag{15}$$

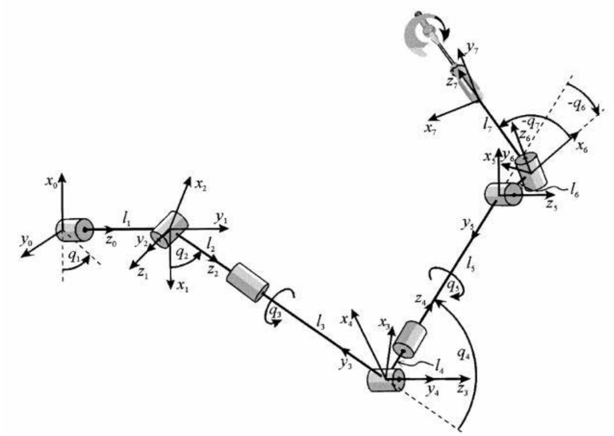
Damping the torque will result in insufficient joint drive and accordingly in the degeneration of motion trajectories, in both joint (**q**) and operational (**x**) space. Thus, the task is no more executed properly.

Implications to a Robotic Arm

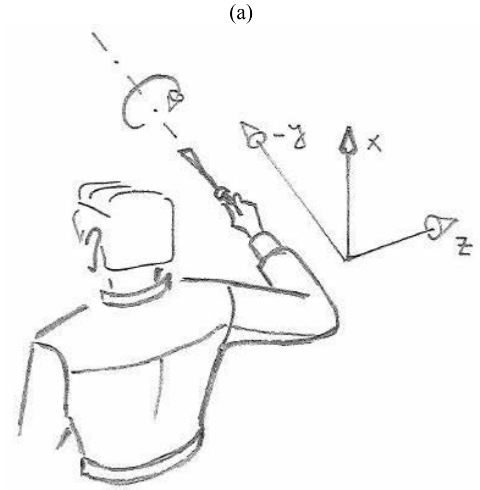
The above discussion was mainly focused on human arm but with the idea in the background to find a proper interpretation and implication in robots. The answer is generally in the possibility to achieve a human-like behavior of robot. Potkonjak et al. (2002[a, b], 2005) suggested approaching this problem from the aspect of human-robot communication, and contributing to gestural communication. The research paid particular attention to generation of a nonverbal message about overloading. The thermal dynamics, that is, robot motors heating, was considered and the rise of temperatures was used as the measure of "robot fatigue". Redistribution of joint engagements was suggested as the solution which would relax the overheated motors. This reconfiguration would be observable to people being around and thus would be a nonverbal message about fatigue and exhaustion. The authors mainly concentrated on robots engaged in fine-motor-control tasks and particularly handwriting. The present research shares some basic ideas but it generalizes the problem by putting it in a wider context of mathematical modeling of physiological processes and human-robot analogy.

Example − Screw-Driving Task

Effects of the suggested method are analyzed for a task very demanding regarding applied force and torque – the screw-driving task. A human and/or an athropomorphic robot arm has to screw the bolt into the hole on the vertical work surface (wall). Although this operation often involves a specific motorized tool, an electric screw-driver, we here consider screw-driving as a purely manual operation. This means that, apart from enabling the proper position of the “old-fashion” screwdriver in the space, the arm should also provide angular screw-driving movements about the longitudinal screwdriver’s axis (Fig. 1).



(a)



(b)

Fig. 1. Redundant arm in screw-driving task: (a) configuration, (b) initial position

The considered arm configuration is shown in Fig. 1a. It has seven DOFs, meaning that it is redundant for the given task that requires six. Initial position is shown in Fig. 1b.

Initial position of the robot arm is defined by: $q(t = 0) = (0, 45^o, 0, 90^o, -45^o, 0, 0)$. Accordingly, the initial arm posture has a stretched wrist and the forearm and the screwdriver are aligned perpendicularly to the wall.

A screw-driving task requires rotational motion of a screw about its longitudinal axes, along with keeping its perpendicularity to the wall. It is assumed that screwing consists of a series of single revolute movements (forward and backward), each of π/2 [rad]. A forward rotation (screwing in) is indicated in Fig. 1. Backward rotation does not drive the screw, but only prepares the screwdriver for the next turn. Each movement takes T=0.5s. Different studies investigating motor control of human movements have shown that human arm performs smooth voluntary movements with bell-shaped velocity profiles (for illustration, see (Hogan, 1984)). In our simulations the bell-shaped velocity profile was approximated with a cosine velocity profile (Vukobratovic & Kircanski, 1986) and applied to rotational motions of the screwdriver. This way we complete the definition of the end-effector motion task. The full task, however, includes the force and the torque which the screwdriver applies to the screw – the arm motor units have to provide longitudinal force F=50N, and the torque M=6Nm about the longitudinal axis. The force and the torque are applied only while turning the screwdriver forward – the backward rotation is relaxed.

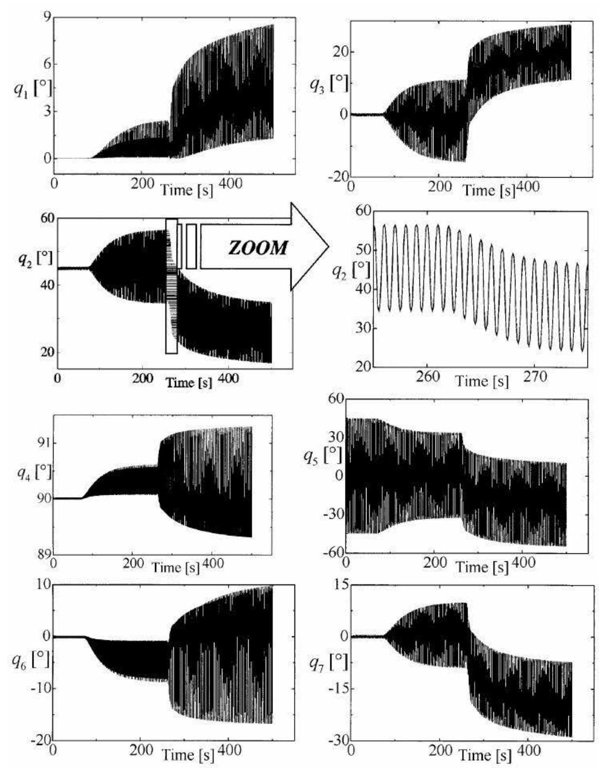


Fig. 2. Joint motions: $q_i(t), t = 1, \ldots, 7$. Zoomed view of q_2 shows the motion drift in shoulder: upper arm starts to move down toward the trunk.

We now apply the derived models of fatigue progress and the suggested method for IK resolution, with the aim to simulate the arm behavior in the imposed task. The calculated behavior will then be compared with the behavior observed with a control group of 5 human study subjects. Note that the model parameters used in simulation were tuned (using simulation experiments) so as to stimulate the system to feature relevant effects earlier, thus eliminating the need for too long simulation. Hence, the parameters used in simulation differ from those of study subjects. Monitoring of the control group was not based on some measurement but rather on the visual observation and the verbal descriptions given by the study subjects. Therefore, the simulation results and the experiment can be compared on the qualitative level only.

The joint motions, $q_i(t), t = 1, \ldots, 7$, obtained by simulation are shown in Fig. 2 (note that the applied order 1, 3, 2, … instead of regular 1, 2, 3, … uses the space in the figure more economically). Note that the total time of monitoring the event was 500 s. Since a cycle of screwing-in (forward-plus-backward rotation) lasts 1 s, it is not possible to observe a particular oscillation in joint motions. One can only see the envelope, but it is sufficient for understanding the results. The only exception is the zoomed diagram for joint 2, where oscillations are visible. Bearing in mind the arm starting position, it is clear why the screw driving is initially performed by joint 5 alone. It is the only joint able to provide the rotational motions about the longitudinal axis of the screwdriver.

The simulated progress of fatigue, $z_i(t), i = 1, \ldots, 7$, is presented in Fig. 3.

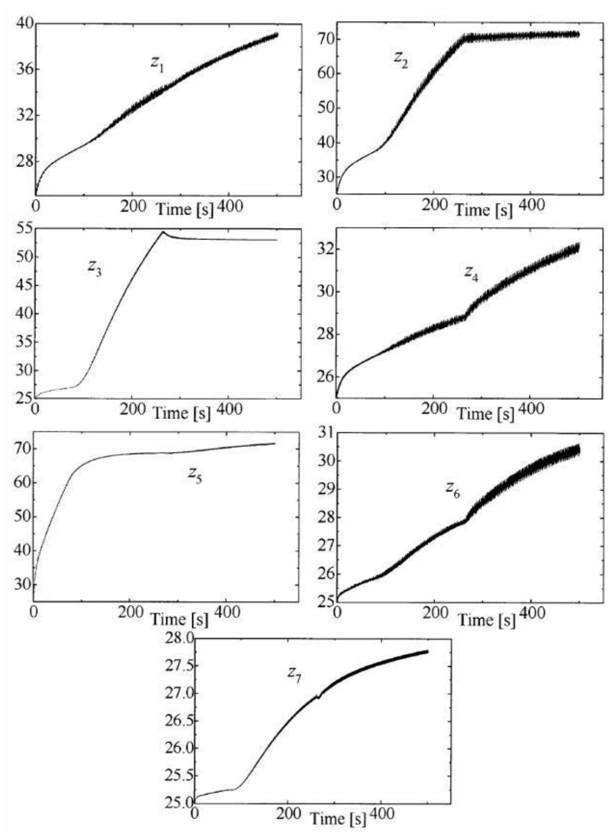


Fig. 3. Progress of fatigue, $z_i(t), t = 1, \ldots, 7$.

Relations between time histories of $q_i(t)$ and $z_i(t)$ should be considered next. This will be done by comparing diagrams from Figs. 2 and 3. Let us start from joint 5. Diagram q_5 in Fig. 2 shows large turns which generate the screwing torque. Hence, fatigue z_5 (Fig. 3) progresses fast. When $z_5(t)$ reaches the assigned critical level $z_{5,\text{cr}} = 60$, penalty function $\varphi_5(z_5)$ starts to work, causing reduced engagement reflecting in decreased amplitude of motion in diagram $q_5(t)$ (Fig. 2). z_5 features a reduction of slope. The change in slope is not sharp, but comes some time after reaching $z_{5,\text{cr}}$, resembling human reaction. So, with appearance of fatigue symptoms in the joint 5, its engagement decreases. This is enabled by proper participation of other joints, which starts exactly at the moment when joint 5 reaches its critical value. This effect is apparent from all diagrams $q_i(t)$.

Diagrams of motions in joints 2, 3, and 7 deserve special attention, because of their prevalent participation in compensating the reduced involvement of joint 5. This is also similar to the natural behavior of human arm, which after sensing the discomfort (fatigue) in the forearm, engages exactly the same joints to relax exhausted muscles. Increased engagement of these joints results in increase of their fatigue. Two of the three most actively participating joints (2 and 3) are in the shoulder. These joints, besides other roles, compensate the gravity load of the complete arm. The third active rotation (joint 7) is in the wrist and it coincides with that rotation of a human wrist which is able to participate in endurance movements. Joint 7 can stand significant dynamical demands and slowly fatigues. Its engagement in providing speeded-up motions in the writing task has been investigated in (Potkonjak, et.al, 1998). These facts imply that fatigue effects should appear in the shoulder first, rather than in the wrist. This is equivalent to the natural behavior of a human arm. As a consequence, fatigue z_2 is the next (after z_5) to reach its adopted threshold $z_{2,\text{cr}} = 70$. After reaching the threshold, the penalty function will keep the fatigue in the vicinity of that level. The motion in joint 2 (shoulder) drifts toward lower values of q_2. This is shown in Fig. 2 and zoomed for better observation. The suggested method for redundancy resolution based on actual fatigue provides reconfiguration of the arm mechanism in a way identical to a human arm after appearance of biological fatigue. The arm puts its elbow closer to the trunk, after subject to fatigue caused by endurance movements during screw driving. This new posture of a human arm is more comfortable to work. It is important to note that the arm proceeds its normal operation (in the sense of task execution), just taking the new posture. Redistribution of motion, depression of some joint motions and stronger engagement of others, does not compromise the end-effector motion. The complete redistribution is shown in diagrams $q_i(t), t = 1, \ldots, 7$ (Fig. 2).

In the above discussion, the statements that some behavior calculated by simulation resembled the human behavior, ware based on the qualitative comparison between the simulation results and the observation from the human control group. The most visible reaction of human study subjects was turning the elbow down to the trunk This is also visible in the simulation diagram of q_2 in Fig.2.

Conclusion

The objective of the paper was to explore how physiological processes, in particular fatigue, influence human motion, with the idea of formulating mathematical models describing this relation. Resolution of the inverse kinematics of redundant arm was discussed fist, proposing a biologically inspired method that took care of the comfort of motion and utilized the actual level of fatigue in arm motor units. The method allowed the reconfiguration of the arm that gave the fatigued joints a chance to rest by engaging more the joints which were "fresher". In order to simulate the progress if fatigue, mathematical model of fatigue was derived based on a general model of accumulation processes. The developed methods ware tested by simulation and qualitative comparison with the observed behavior of the human control group. Results obtained by simulation featured a human-like behavior that qualitatively agreed with the observation from study subjects. Implications of the results to anthropomimetic robots were indicated.

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