Robotic Handwriting: Why and How?

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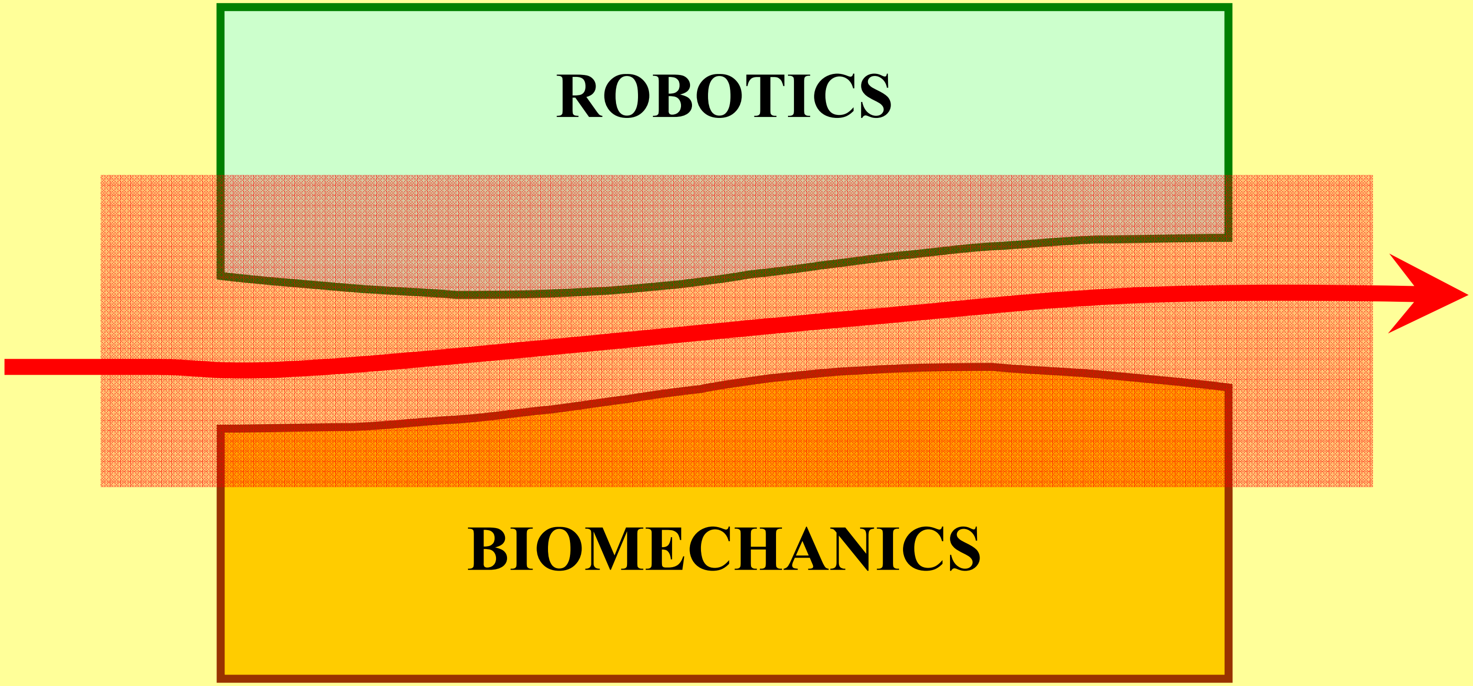
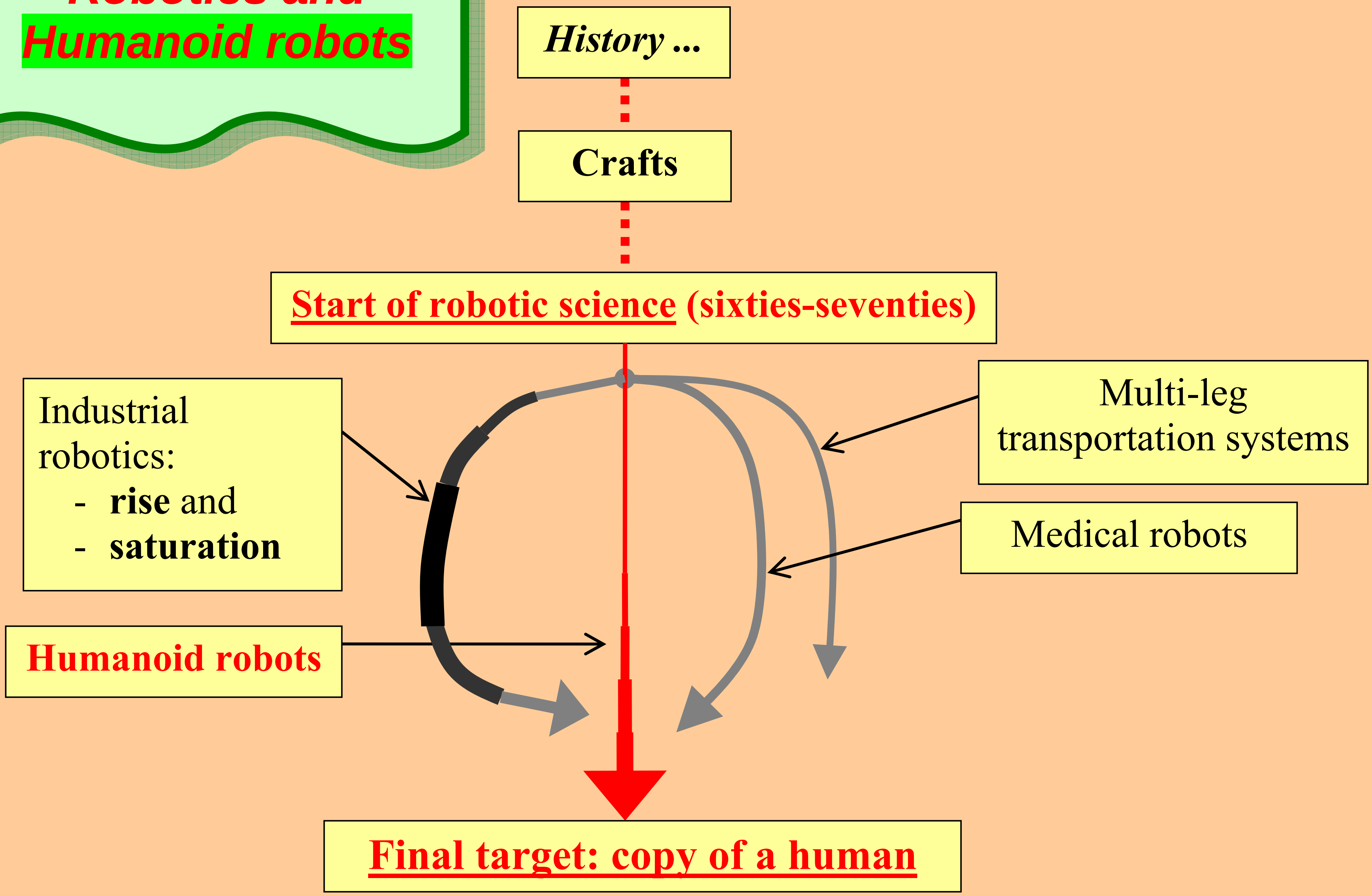
Instead of Abstract.

A **two-fold** research



Robotics and Humanoid robots



Humanoid robots 2

<u>Humanoid robots (personal robots)</u>
work in a human-oriented environment,
closely cooperating with humans

They feature:

- ♦ **<u>human-like motion</u>**,
- ♦ human-like intelligence, and
- ♦ human-like communication.

our primary interest

Interest for biomechanics of human motion

Humanoid robots and biomechanics

What can Humanoid robotics take from Biomechanics ?

Roboticians can learn about the ***principles humans apply when controlling their motion***, like in : waking, running and jumping, manipulation, etc.

It this way, the robot control might be improved.

What can Biomechanics take from Humanoid Robotics

Mathematical models derived to describe kinematics and dynamics of robots might be used in biomechanics and applied to human motion.

This improves the possibilities to use computers in biomechanics.

So, **the present work in Robotic handwriting is two-fold as well !!**

- **Contributes to robotics.**
- **Contributes to biomechanics .**

Well, finally, *why robotic handwriting ?*

There are few answers.

► ***Some of them concern 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**. 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.

► ***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 balance between pure robotics and biomechanics.

Robotic handwriting – history

Handwriting was considered an important human task, and accordingly it attracted attention of researchers working in biomechanics, physiology, and related fields. There exist a number of studies on this matter.

The work of Potkonjak and his associates was the first to relate robot with handwriting.

Distributed positioning (DP)

The concept was **proposed** to resolve redundancy and improve robot kinematic and dynamic performances:

- V. Potkonjak, "Distributed Positioning for Redundant Robotic Systems", *Robotica*, Vol.8, No.1, pp.61-67, (1990).
- V. Potkonjak, A. Krstulovic, "Contribution to the Kinematics and Dynamics of Redundant Robots Via Distributed Positioning", *Journal of Intelligent and Robotic Systems* (Kluwer Academic Publishers) 5, pp. 229-239, 1992.

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 a massive industrial robots to perform fast and precise manipulation**.

Some robotic background was found in micro-macro manipulation:

- J.K. Salisbury, J.D. Abramowitz, "Design and Control of a Redundant Mechanism for Small Motion", *Proc. IEEE Intl. Conf. Robotics and Automation*, pp. 323-328, 1985.

DP and Handwriting

Handwriting was ***first introduced*** as a test-motion for checking the efficiency of the DP concept:

- V. Potkonjak, A. Krstulovic, "Mathematical Modeling of a Redundant Anthropomorphic Arm", *Robotics and Autonomous Systems* (Elsevier) 9, pp. 165-170, 1992.
- V. Potkonjak, A. Krstulovic, A., "Simulation of a Redundant Anthropomorphic Arm", *Robotics and Autonomous Systems* (Elsevier) 9, pp. 171-179, 1992.

Next study was ***more close to biomechanics***:

- ► V. Potkonjak, M. Popovic, M. Lazarevic, J. Sinanovic, "Redundancy Problem in Writing: From Human to Anthropomorphic Robot Arm", *IEEE Transactions on SMC*, Part B: Cybernetics, Vol. 28, No. 6, pp. 790-805, Dec. 1998.
  - It considered an anthropomorphic arm engaged in handwriting. The wrist was given the adequete attention.
  - The work related some important characteristics of handwriting: legibility, inclination of letters, and engagement of fingers (fingers were seen critical due to relatively quick fatiguing).

Robot Fatigue

Lately, the human-robot analogy led to the study of the behavior of a "fatigued robot":

- V. Potkonjak, & al., “Human-Like Behavior of Robot Arms: General Considerations and the Handwriting Task”, Part I: “Mathematical Description of Human-Like Motion: Distributed Positioning and Virtual Fatigue”, Part II: “The Robot Arm in Handwriting”, *Robotics and CIM* (Elsevier) 17, pp. 305-327, 2001.
- V. Potkonjak, D. Kostic, M. Rasic, G. Djordjevic, “Motion in Human and Machine: A Virtual Fatigue Approach”, *IEEE Trans. SMC* Part A: Systems and Humans , Vol. 32, No. 5, pp. 582-595, 2002.
- V. Potkonjak, S. Tzafestas, J. Radojicic, D. Kostic, “Modeling Robot “Psycho-Physical” State and Reactions – A New Option in Human-Robot Communication”, Part 1 and Part 2, *Journal of Intelligent and Robotic Systems*, Vol. 35, No. 4, pp. 339-364, Oct. 2002.
- V. Potkonjak, S. Tzafestas, D. Kostic, G. Djordjevic, M. Rasic, "Illustrating man-machine motion analogy in robotics - The handwriting problem", *IEEE Robotics & Automation Magazine*, Vol. 10, No. 1, pp. 35-46, March 2003.

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***.

Robot Fatigue (cont.)

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.

The concept of robot fatigue was tested on the example of handwriting

Robot / Human Kinematics and Dynamics

Kinematics

- Number of joints (DOF): n
- **Joint coordinates** (internal or **configuration** coord.): $\mathbf{q} = [q_1 \dots q_n]^T$.
- End-effector motion – external coord.: $\mathbf{X} = [x\, y\, z\, \theta\, \varphi\, \psi]^T$
- **The task – operational coord**. : a subset $\mathbf{x} \subset [x\, y\, z\, \theta\, \varphi\, \psi]^T$, $\dim = m \leq 6$.
- **Kinematic model relates joints space q and task space x** :

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

where $\mathbf{J} = \partial\mathbf{x}/\partial\mathbf{q}$ is the **Jacobean** 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.

Kinematics (contin.)

Inverse kinematics, i.e., calculation of $\mathbf{q}$ for given $\mathbf{x}$:

$$\boxed{\mathbf{x}} \rightarrow \boxed{\textbf{kinem. model}} \rightarrow \boxed{\mathbf{q}}$$

- If $m = n$, the system is **nonredundant** and the **unique solution** is possible.

- If $m < n$, the system is **redundant** (**surplus of joints**) 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, have to be imposed.

♠ A redundant arm usually has:

► a heavy part consisting of m joints, which is called the "***nonredundant basic configuration***", coordinates $\mathbf{q}_b$, while

► the rest of the arm (n-m joints) constitutes the ***redundancy*** $\mathbf{q}_r$.

Dynamics

- Dynamics **relates control inputs and system motion** (output).

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

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

  where

  $\mathbf{u}$ is the n–vector of the control inputs;

  $\widehat{\mathbf{H}}(\mathbf{q})$, $\dim = n \times n$, is inertial matrix; and

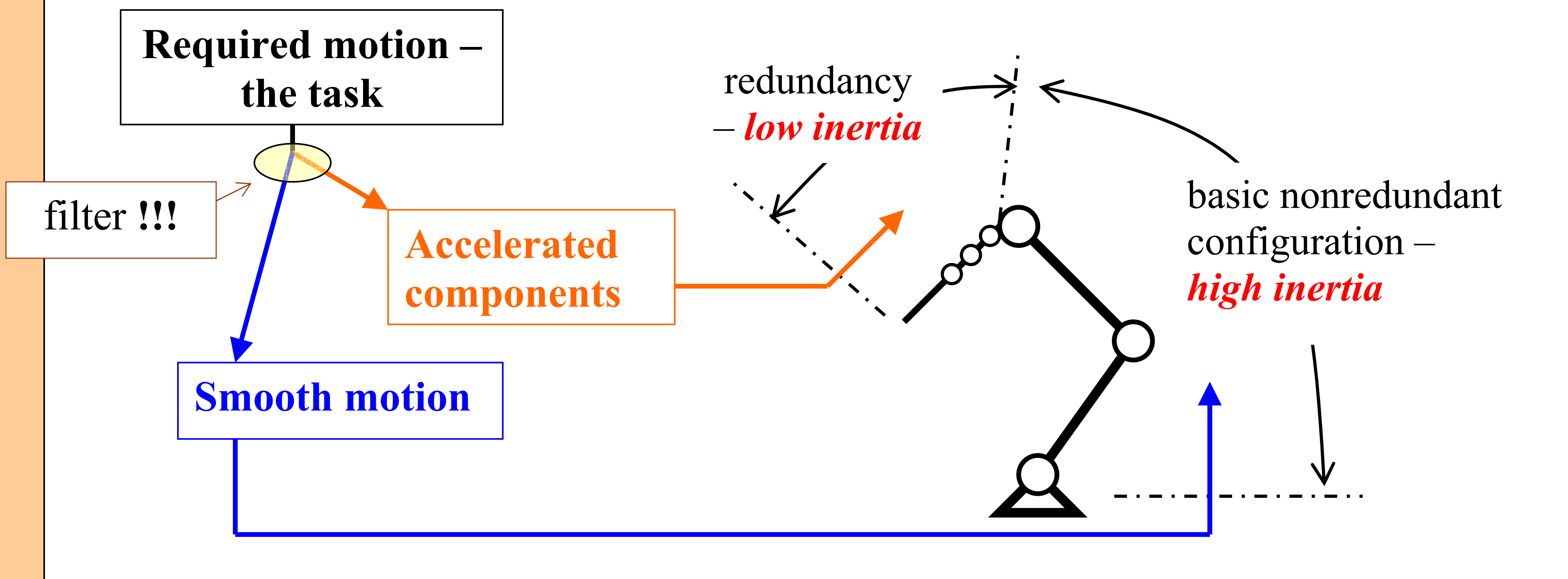
  $\widehat{\mathbf{h}}(\mathbf{q}, \dot{\mathbf{q}})$, $\dim = n \times 1$, takes care of gravity and velocity-dependent effects.

- Computer-aided formulation of dynamic model is available, working for any robot configuration.

- Dynamic model is used to :
  - ► calculate the **feedforward control** term, and
  - ► **simulate** the system behavior.

DP Concept
Principles and Mathematics

Principles



Original idea was to make heavy industrial robots capable of performing small and fast motions.

The concept follows biological principles !!

Mathematics (simplified !): Two steps of DP concept

Step 1:

$\mathbf{x}(t)$ → **Filter** → $\bar{\mathbf{x}}(t)$ smooth / $\tilde{\mathbf{x}}(t)$ fast (acc.)

$\bar{\mathbf{x}}(t)$ → **basic kinem. model** → $\mathbf{q}_b$

unique solution !!

Step 2:

$\tilde{\mathbf{x}}(t)$ → **redund. kinem. model** → $\mathbf{q}_r$

unique solution
or
infinite number of solutions
!!

☼ For **industrial systems** Step 2 has a unique solution.

☼ For **human/humanoid** Step 2 has an infinite number of solutions

Besides other examples, the concepts was **checked on handwriting** as well. 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 focus was moved from industrial robots to humans and humanoids → it was recognized that the **wrist joint** played an essential role in handwriting.

Explain:

- **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.

Infinite number of solutions in Step 2 means that some additional condition is needed **:**

→ **Optimization criterion**

Optimization criterion ??

different options

- Minimization of energy consumption (eng. approach) 2
- Minimization of fatigue / motor temperatures 3
- ***Minimization of finger involvement*** first choice – **1**

Why ?? Fingers can move very precisely but cannot stand long-term fast movement.

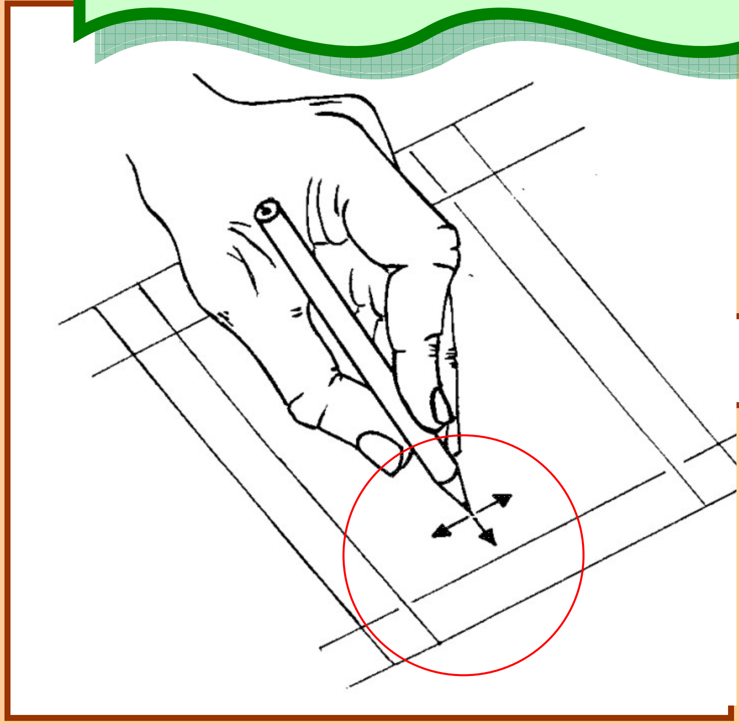
How to define the criterion ?? To measure the finger involvement, an integral criterion was suggested:

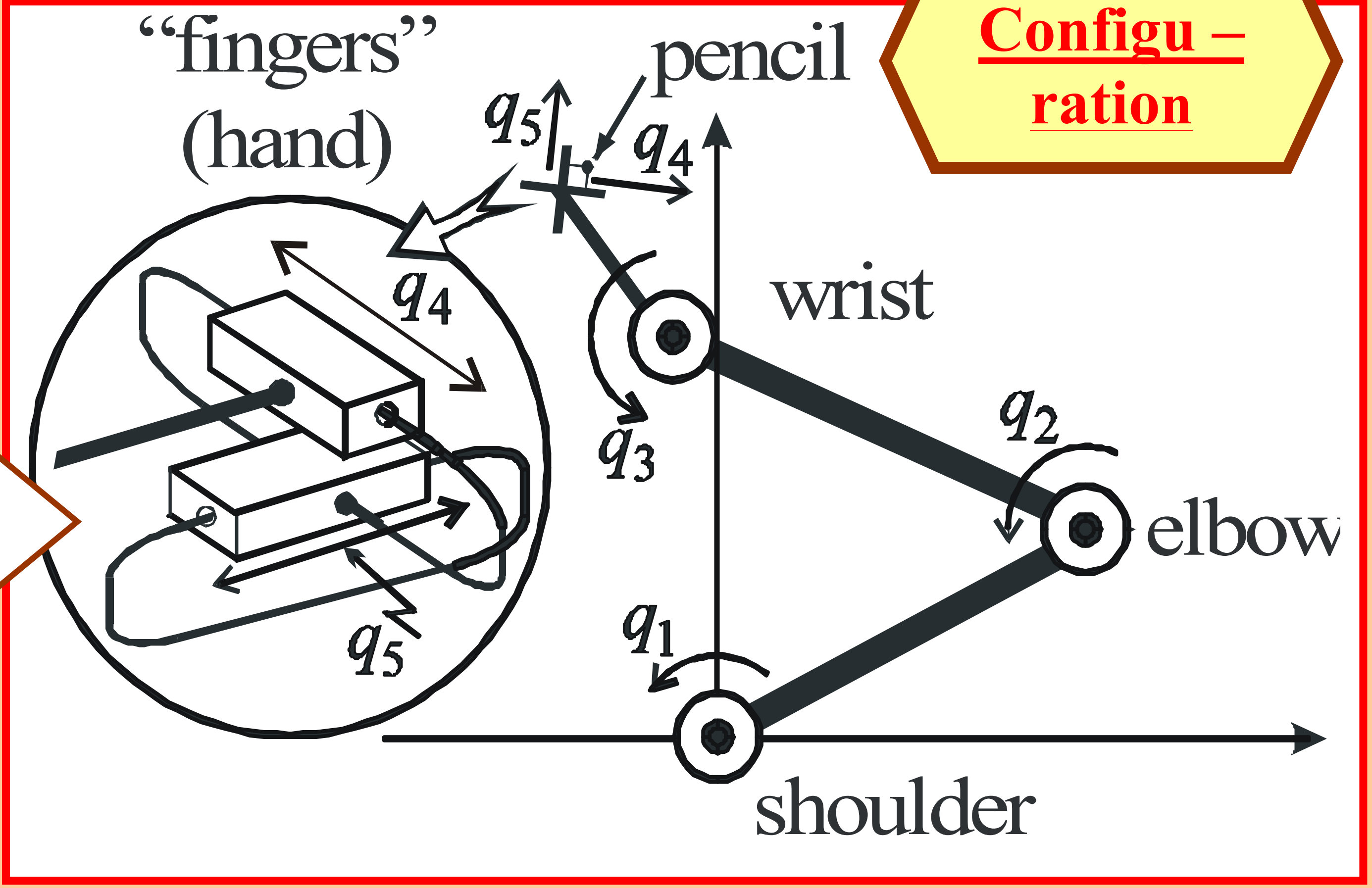
► *IKI* – integral kinematic involvement is the sum of amplitudes of fingers motions.

♣ We have checked other reasonable criteria, i.e. 2 and 3, as well !!

DP Concept – Example

Configu – ration





- It holds that $\boldsymbol{n} = \mathbf{5}$ (five joints)
  - Shoulder and elbow constitute the nonredundant basic configuration: $\mathbf{q}_b = [q_1, q_2]^T$.
  - The wrist and the two linear "fingers" represent the redundancy: $\mathbf{q}_r = [q_3, q_4, q_5]^T$.
- The "linear fingers" have limited range of motion:

$$\Delta_4 = q_{4\max} - q_{4\min} = 0.05m, \quad \Delta_5 = q_{5\max} - q_{5\min} = 0.05m.$$

- It holds that $\mathbf{x} = (x, y)$, $m = 2$.
- Smoothing (**filtering**) understands separation : $x = \bar{x} + \tilde{x},\ y = \bar{y} + \tilde{y}$.
- Now, $\mathbf{q}_b = (q_1, q_2)$ should solve smooth component $(\bar{x}, \bar{y})$

  $\mathbf{q}_r = (q_3, q_4, q_5)$ solves accelerated component $(\tilde{x}, \tilde{y})$

***Step* 1**

$(\bar{x}, \bar{y})$ **calculate** $\mathbf{q}_b = (q_1, q_2)$

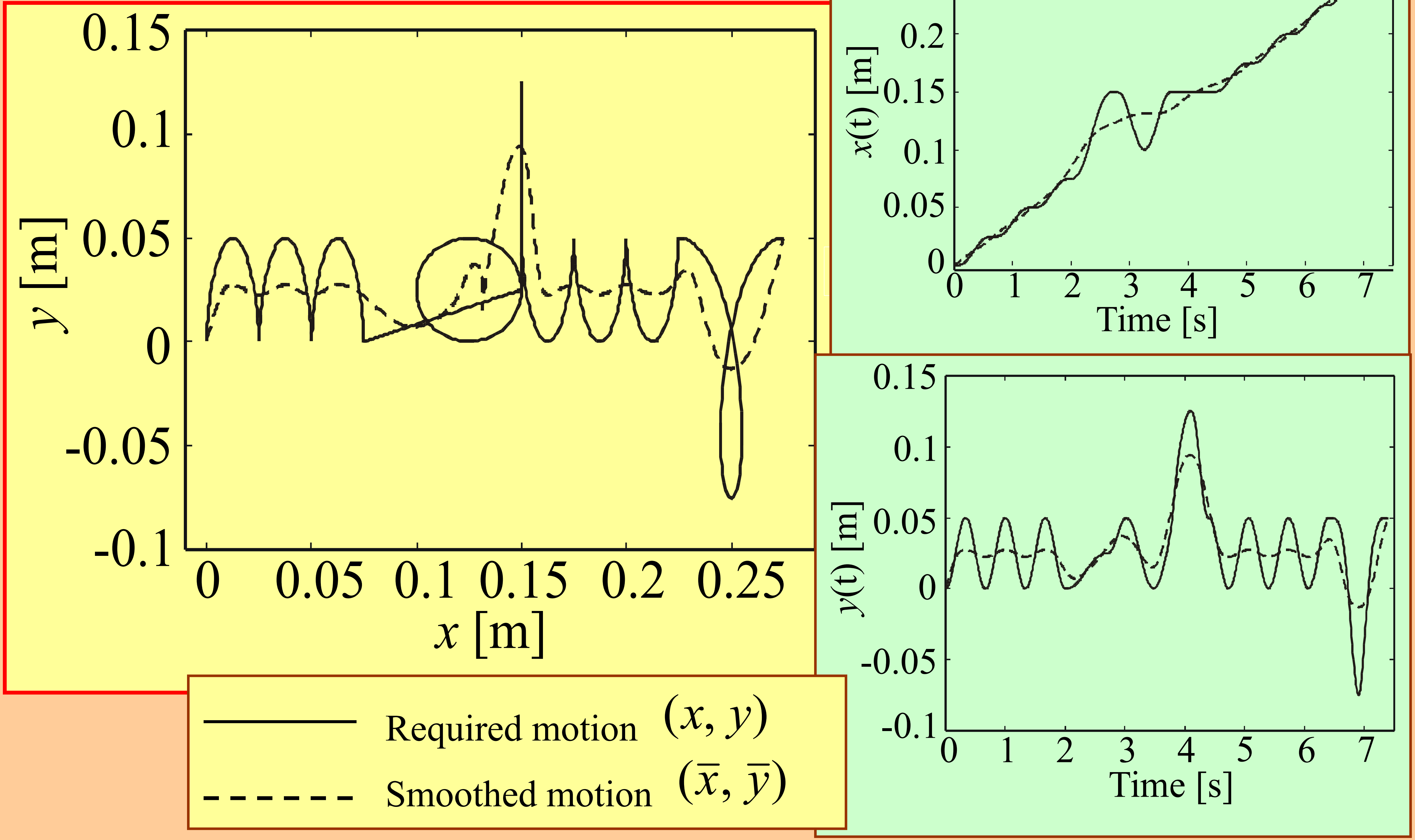
unique solution !!

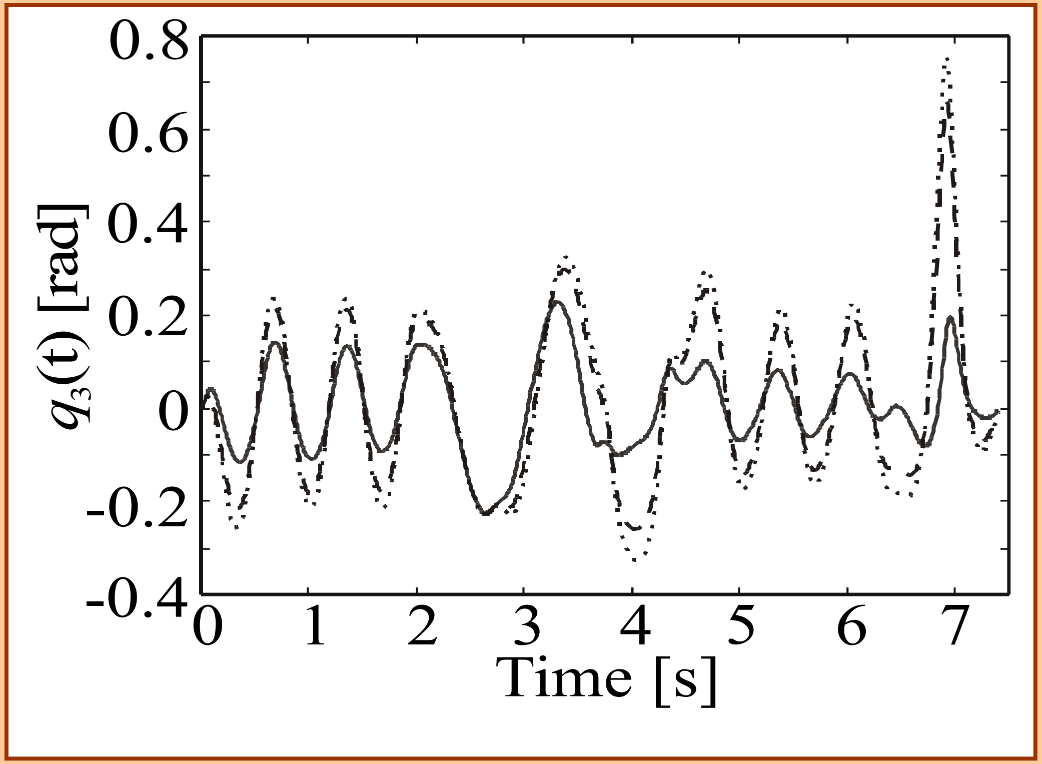
***Step* 2**

$(\tilde{x}, \tilde{y})$ **calculate** $\mathbf{q}_r = (q_3, q_4, q_5)$

infinite number of solutions → **apply optimization !!**

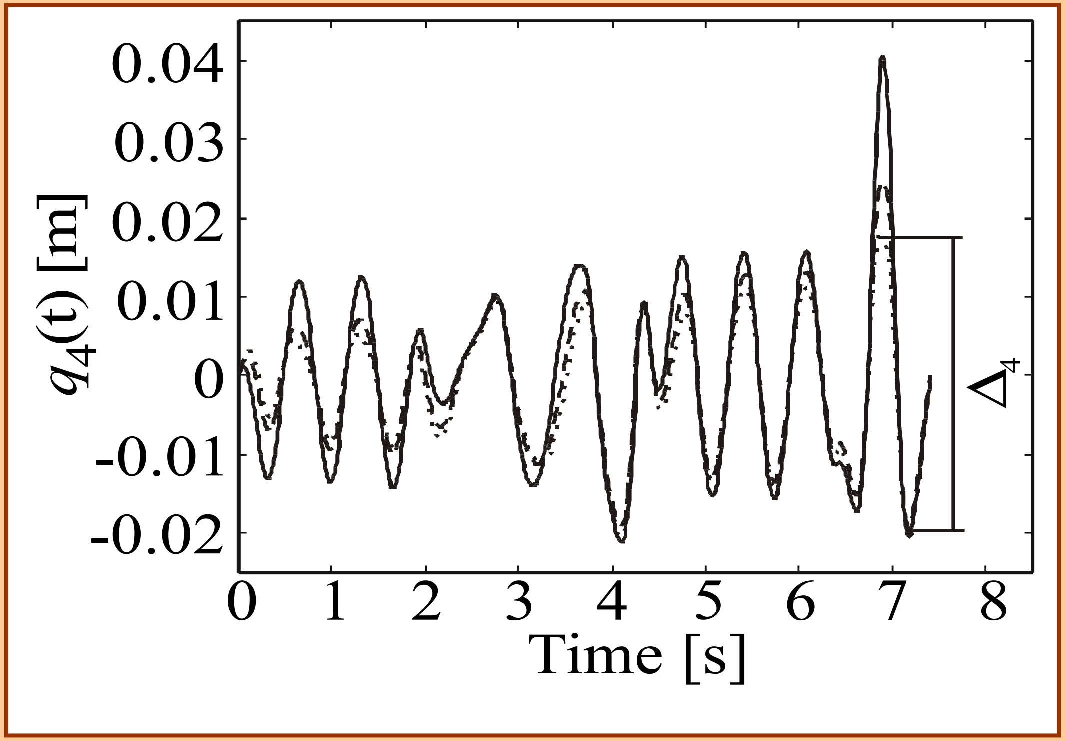
Task - handwriting

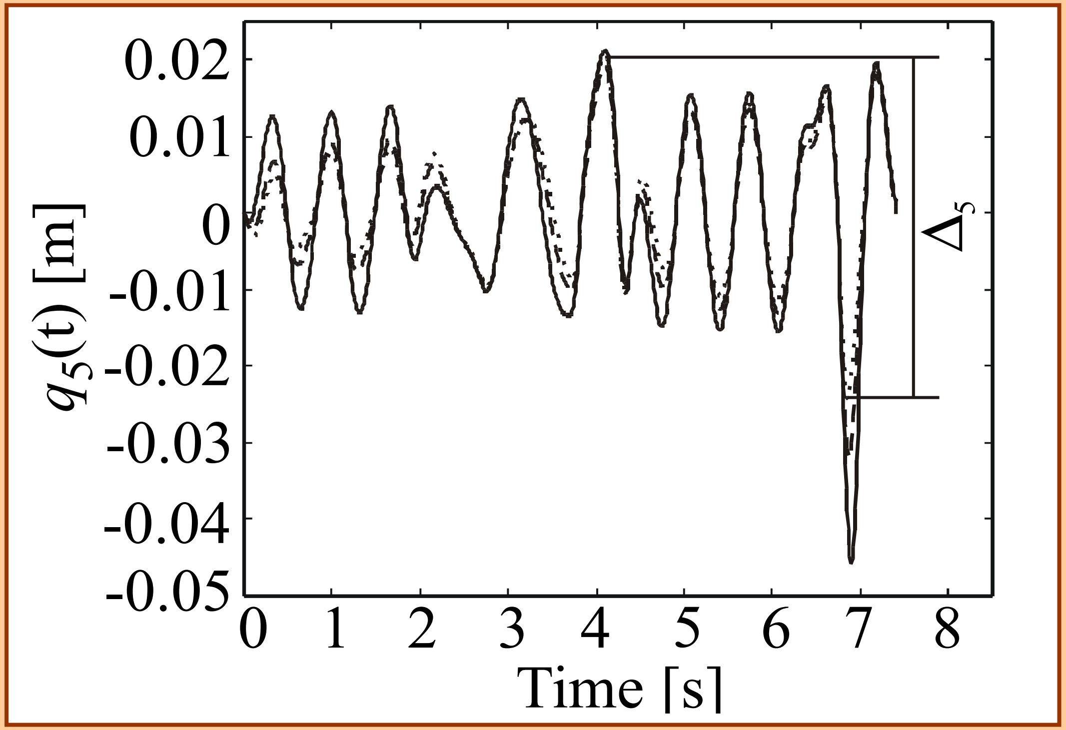




Simulation results for the wrist and fingers

- For the given motion, the linear fingers q_4 and q_5 cannot perform what is required, due to limited range (the range would be violated).
- This comes from the fact that for vertical letters the wrist cannot help efficiently.





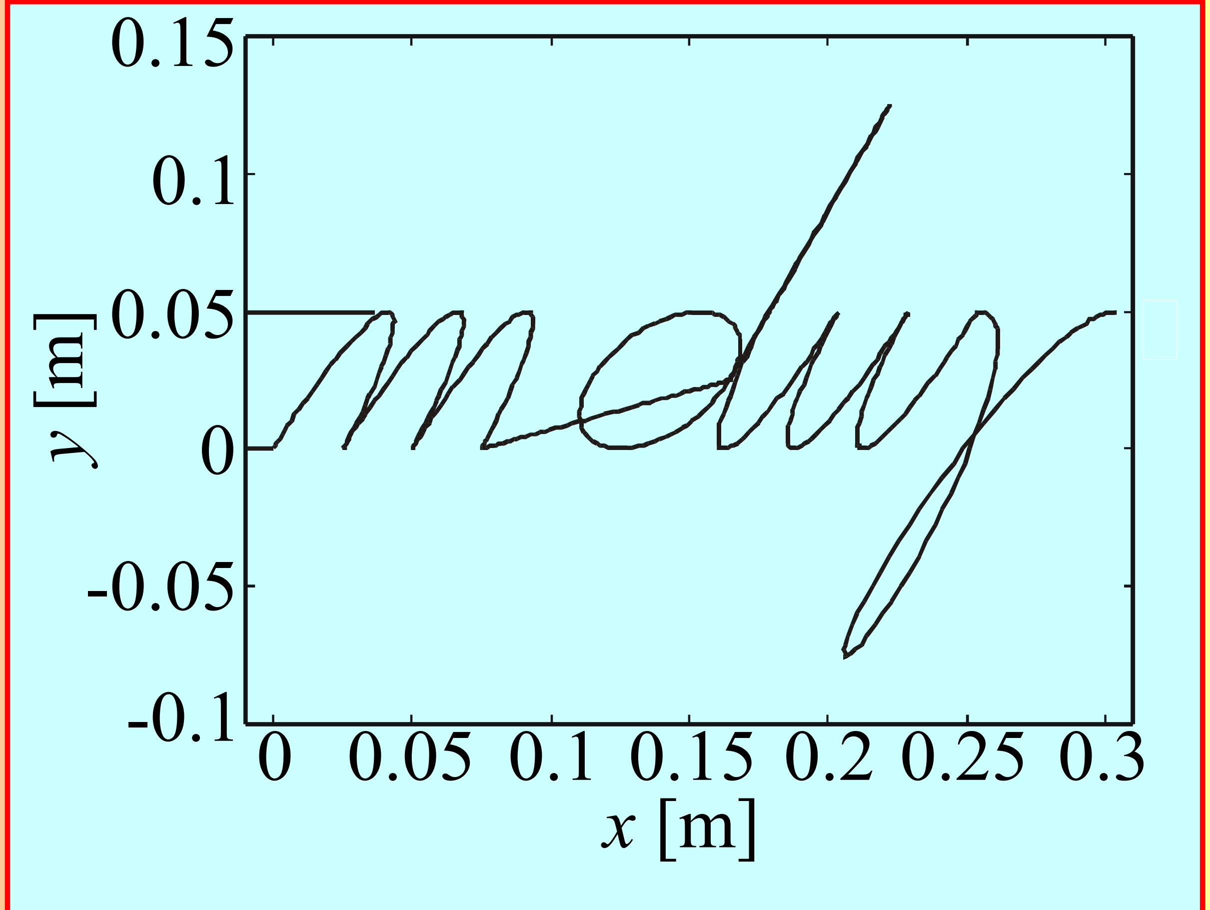
How to relax the fingers ??

How can the wrist help ??

Incline the letters **! ! !**

Example of **inclined writing**:

$\alpha = 30^0$.



Conclusion from simulation

With the inclination,

- the engagement of the wrist (q_3) increases and
- the engagement of the fingers (q_4 and q_5) reduces.

► After an inclination of 24^0, translation q_4 falls into the allowable range Δ_4, while,

► after 34^0, the other translation q_5 falls into Δ_5.

♠ This means that any sequence, inclined for 34^0 or more, can be written "ideally".

Discussion on Legibility

- 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 handwriting example, 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).

How to define Legibility ??

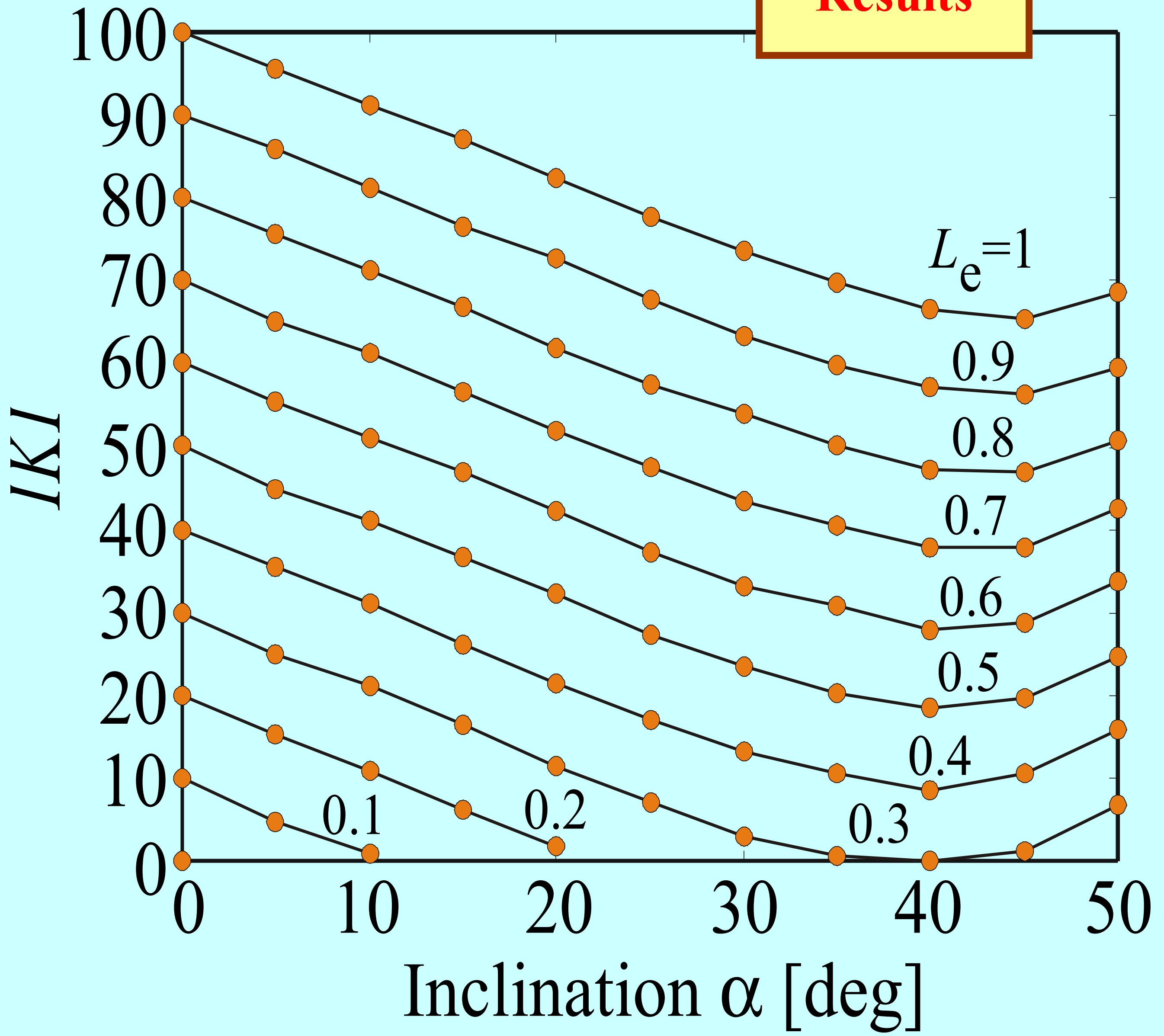
- Legibility of a sequence of letters is defined on the basis of the **mean square deviation** from the ideal sequence.
- If $\boldsymbol{e}$ is the mean square error, then legibility is its normalized value,
  $L_e = (e_{\max} - e)/(e_{\max} - e_{\min})$, being in the interval $L_e \in [0, 1]$.

- Let us note that the paper:

  V. Potkonjak, M. Popovic, M. Lazarevic, J. Sinanovic, "Redundancy Problem in Writing: From Human to Anthropomorphic Robot Arm", *IEEE Transactions on SMC*, Part B: Cybernetics, Vol. 28, No. 6, pp. 790-805, Dec. 1998.

used a **modified definition** based on a function that introduced **subjective feeling of legibility**.

Results



For instance, if legibility is set to 0.6, the optimal inclination is 40^0, and the corresponding *IKI* is about 28

Relation among:

- ♦ **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 !!!**

Robot Fatigue – 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.

☼ Message . . .

- 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 → **DEGENERATION** phase. ☼ New message . . .

♠ We try to find models of the described behavior and apply it to both human and robot arms.

♣ 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.

Robot Fatigue – Mathematics

REGULAR MOTION Phase

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. Instead of a low-pass filter used for DP in Section 4, here we 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 $\mathbf{W}''$, and $\mathbf{W} = \mathbf{W}' + \mathbf{W}''$ are $n \times n$ **weighing matrices**.

- The first term enables realizes DP concept (distributes the motion in acciordance with rthe inerrtial properties of joints).

- The second term is used to maximize the comfort. Comfortable motion of a joint is seen as the motion being near the middle position of the joint range.

- Regarding the control, a PD regulator could be adopted:

$$u_j = K_{Pj}(q_j^* - q_j) + K_{Vj}(\dot{q}_j^* - \dot{q}_j), \quad j = 1,\ldots,n, \quad \text{where } \ldots$$

RECONFIGURATION Phase

We now look for a mathematical algorithm to force the reconfiguration (redistribution of engagement) 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" ; it is "unpleasant" but still not dangerous .
- The algorithm introduces the **penalty functions** into the weighing matrix:

$$\mathbf{W} = \mathrm{diag}[\varphi_1(\Theta_1), \ldots, \varphi_n(\Theta_n)] \quad (5)$$

$$\varphi_j(\Theta_j) = \begin{cases} w_j\,, & \Theta_j < \Theta_{j,cr} \\ w_j + k_{\varphi,j}(\Theta_j - \Theta_{j,cr})^2, & \Theta_j \geq \Theta_{j,cr} \end{cases} \quad (6)$$

still about RECONFIG.

- "Penalty functions" $\varphi_j(\Theta_j)$ should penalize the exhausted joints (reduce their engagement) and stimulate those that are still "fresh".

- 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**.
- To control the robot we still use the PD regulator.

DEGENERATION Phase

- 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. $\Theta_{j,\max}$, $j = 1,\ldots n$. 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 :

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

$D_j(\Theta_j)$ is called the "current-damping factor". It is a decreasing function.

still about DEGENER.

Damping the current

Insufficient joint torques – **“tired robot”**

lower controllability of joints

$\mathbf{q}(t)$ differs considerably from reference $\mathbf{q}^*(t)$

Task execution $\mathbf{x}(t)$ differs considerably from reference $\mathbf{x}^*(t)$

DEGENERATION!

DEGENERATION means that the **shape of letters is deformed !!**

Robot Fatigue – *Simulation*

- 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 second-order model (for the j^{th} joint motor) is:

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

$$T_{hj}\dot{\Theta}_{hj} = \frac{Z_{hj}}{Z_{rj}}(\Theta_{rj} - \Theta_{hj}) - (\Theta_{hj} - \Theta_a) \qquad (9)$$

where . . . .

♦ The simplified first-order model is:

$$T_j \dot{\Theta}_j = Z_j R_j i_j^2 - (\Theta_j - \Theta_a) \qquad (9)$$

♠ The thermal model, along with the dynamic model of the arm (eq. (2)), enables simulation.

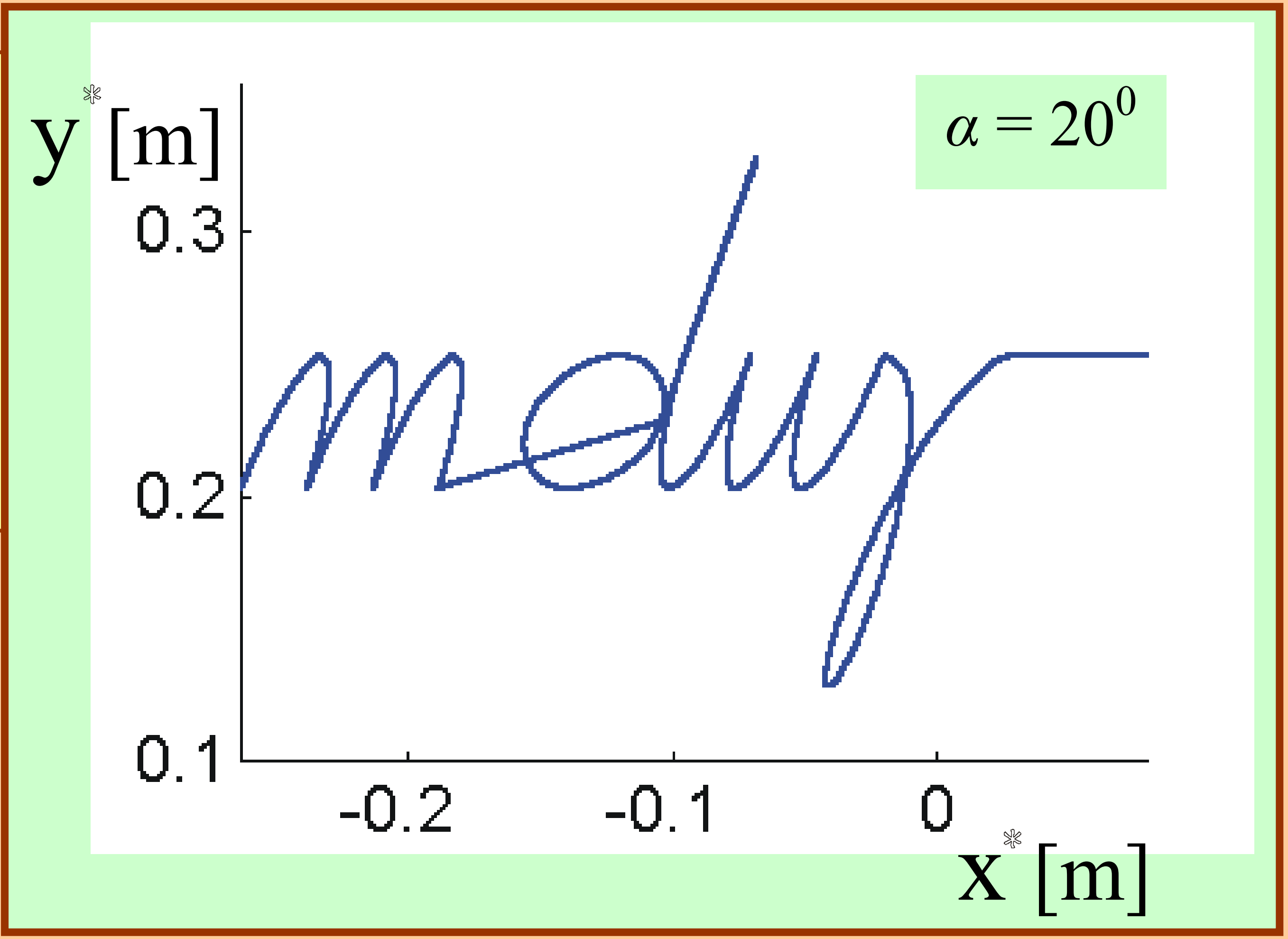
The model of **"robot fatigue"** in motors agrees with the measured progress of **biological fatigue in human muscles**.

So, the results obtained for the **"tired robot"** may be seen relevant for a **tired human** as well **!!!**

Robot Fatigue – Example

- Configuration of the arm is the one used in DP example.

- The task:
  - Write a sequence of inclined letters ($\alpha = 20^0$)
  - Do the sequence in 9 sec.
  - Repeat the sequence over and over



We are monitoring :

►► **joit fatigue** – the thermal behavior of motors – **temperatures** $\Theta_j(t)$

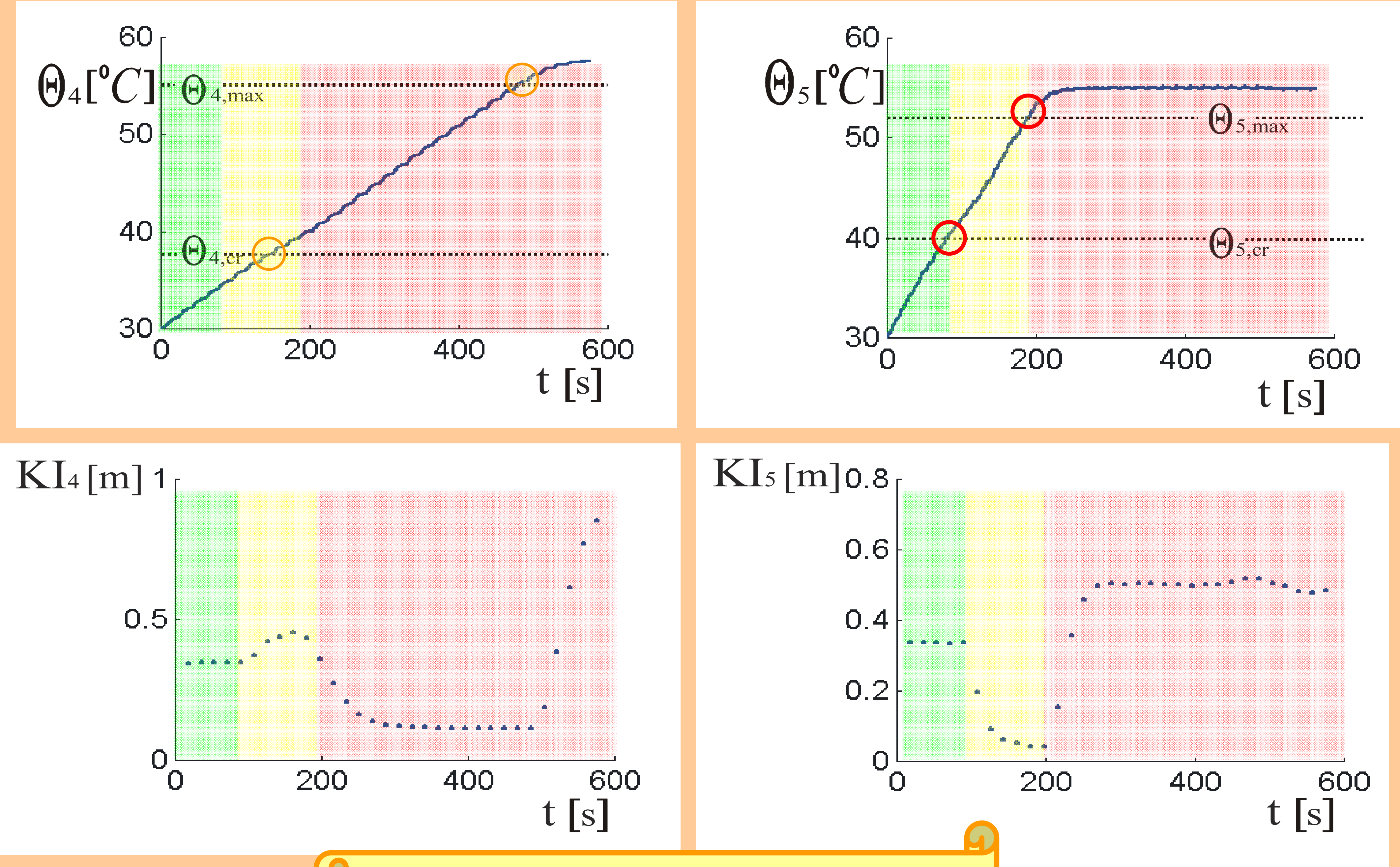
Temperature bounds are:

- desired region $\Theta_{j,\,cr}$
- allowable region $\Theta_{j,\,max}$ – final limit

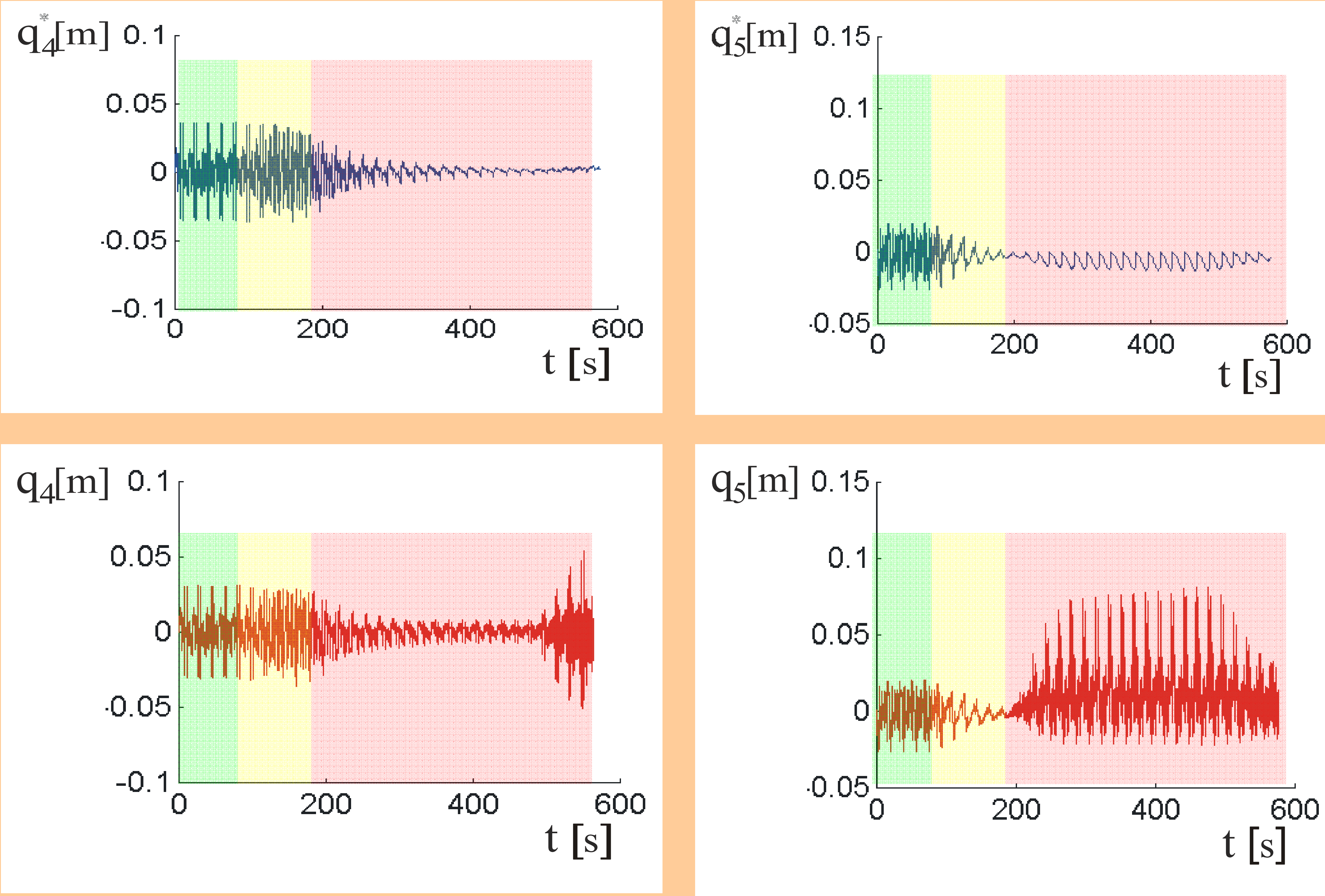
►► **engagement of joints** in each sequence – kinematic involvement $KI_j = \int_{T=9s} |\dot{q}_j| dt$, for each joint.

►► **quality of task execution**, DEV – normalized mean square error over a sequence

Results are presented for the "fingers" – linear joints 4 and 5.



Discussion . . . phase by phase . . .



q*4[m]
0.1
0.05
0
-0.05
-0.1
0
200
400
600
t [s]
q*5[m]
0.15
0.1
0.05
0
-0.05
0
200
400
600
t [s]
q4[m]
0.1
0.05
0
-0.05
-0.1
0
200
400
600
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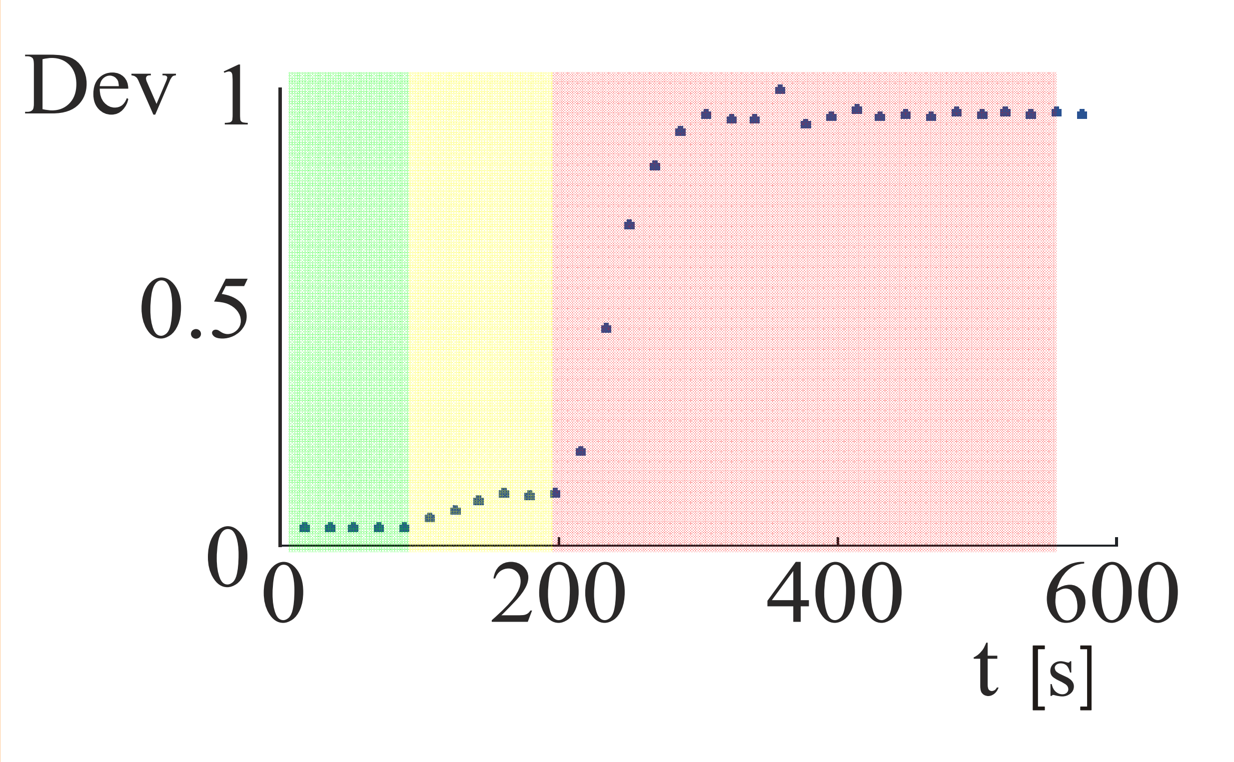
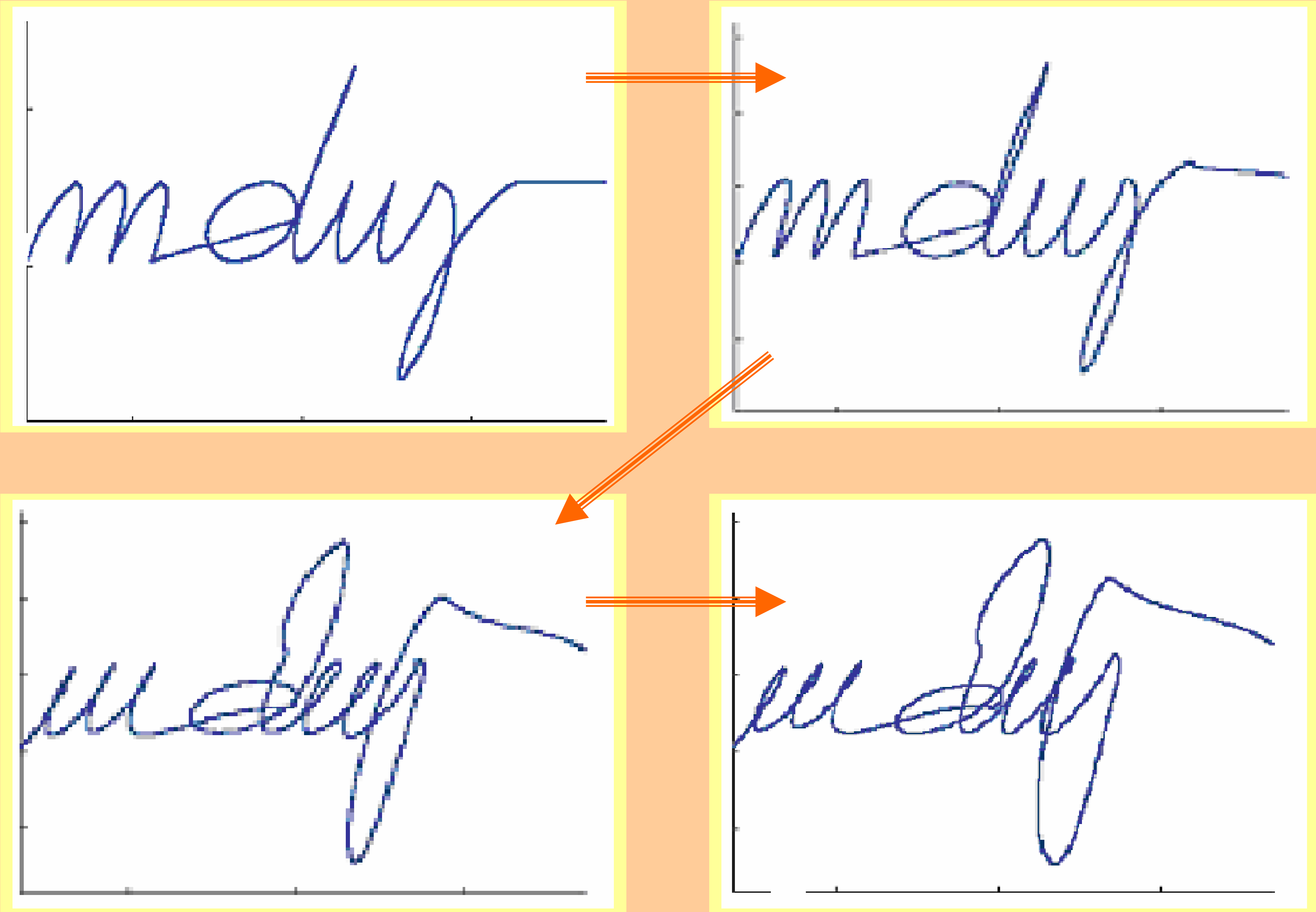


- This is the **measure of deviation** of the actual motion (sequence of letters) from the ideal (reference) sequence.
- It shows the **level of degeneration**.
- It is a normalized mean square error over a sequence.

<u>**Let us see the effects of degeneration**</u>

Ideal sequence and three sequences from degeneration phase are recorded and shown

Handwriting of a tired robot !!



Conclusion

The work was two-fold:

For roboticians.

Contributes to biologically inspired control of humanoid robots .

For biomechanics.

- The kinematic and dynamic models and procedures originaly developed for robotics might be applied to biomechanical systems.
- Robots might be used to check concepts and ideas in handwriting analysis – whenever it is necessary to repeat a motion perfectly (like in forensic appl.).
- Robotic systems could be used in diagnostics and rehabilitation of malfunctions in finger-hand-arm coordination.

later !

- 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 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, 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 !!.

What's next in the biomechanics branch of work ?

1

- The experimental results (from biology) in fatigue could be used to identify the dynamic model of fatigue progress.
- This model was combined with the kinematic and dynamic model of the arm.

→ **Handwriting of a fatigued human/robot.**

Perhaps this idea can be applied for stress, fear, etc.

2

A robotic system, an exoskeleton for the arm, is being designed.

It would be used in

- ***diagnostics*** and
- ***rehabilitation***

of malfunctions in finger-hand-arm coordination.