COORDINATION OF MUSCLES AND ARTICULATORS

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ABSTRACT

Internal models are important elements of the articulation control system. These models provide fullfilment of required targets both for the articulators position and speech signal parameters. Examples of the internal model action for the movement control of the jaw and lips are described.

Analysis of problems connected with the use of sensory information for control of human locomotion and articulation leads to necessity of an internal model existence in control systems. An internal model shapes control commands for a redundant mechanical system and provides adaptation to changing conditions - movements restrictions and various criteria of optimality.

Let us consider two tasks of movement control.

1. Movement of the finger tip from one point of space to another one along the given trajectory. Position of the finger tip during its movement is controlled by visual system and mechanoreceptors. Measured difference between visible position of the finger tip and the required trajectory must be transformed to muscle efforts of every link controlling the finger tip position in space. This is possible only in case the control system has an ability to predict the finger tip position for any set of muscle efforts even though approximately, i.e. there is an internal model of movements.

The situation is quite the same for the processing of feedback signals from mechanoreceptors. Every mechanoreceptor transmits an information on the muscle length or the joint angle only for one link of multylink system. To determine the finger tip position the information must be recalculated accordingly to kinematic connections, i.e. again there is a great need for an internal model.

2. Voice imitation of a melody not heard before. Here control of the length and tension of the larynx muscles that results in the required time change of the pitch of the vocal source. Difference between the given and the actual melodies is estimated in the perceptive analyser and can be transformed into muscle efforts only provided of an internal model existence which is "aware" of quantitative relationships between muscle efforts and voice pitch.

Therefore there is a necessity of an internal model for feedback closure in the control system. An internal model for the articulation control must have kinematics and dynamics equations for each level of the control system : motor units, muscles, articulators, vocal tract shapes, acoustical parameters of speech signal. An internal model also provides solutions for a set of important tasks as well as feedback closure. The main task of an internal model is the control shaping using mechanical system redundancy to satisfy imposed restrictions and optimality criteria.

Internal model notions have been under development for some time thus making contribution to the creation of the basis for a theory of purposeful movements [1,2, 5,6,8,9,10,12].

Let us consider an internal model functioning on an example of lips closure. Distance between lips h depends on the position of three articulators : the upper and lower lip and the jaw

$$h = y_3 - \Delta y_1 - \Delta y_2,$$

where Δy_1 is a vertical displacement of the jaw, Δy_2 is a vertical displacement of the lower lip, y_3 is a coordinate of the upper lip. As it is seen, this condition can be satisfied under different values of Δy_1, Δy_2 and y_3 but there is a set of restrictions both for articulator displacements and muscle efforts.

First of all let us consider joined movement of the jaw and the lower lip. Let h is the required height of the lower lip. Then equation of kinematics is

$$\Delta y_1 + \Delta y_2 = h$$

with restrictions

$$0 \leqslant \Delta y_1 \leqslant a_1 , \qquad 0 \leqslant \Delta y_2 \leqslant a_2$$

and initial conditions $\Delta y_1 = 0$, $\Delta y_2 = 0$

If the criterion of optimality is minimum of muscle efforts

$$\min \{ F_1 + F_2 \}$$

then, considering only elastic forces

$$F_1 = c_1 \Delta y_1$$

$$F_2 = c_2 \Delta y_2$$

have

$$\min \{ c_1 \Delta y_1 + c_2 \Delta y_2 \}$$

where c_1 , c_2 - coefficients of elastic resistance. From $\Delta y_2 = h - \Delta y_1$ obtaine criterion

$$\min \{ (c_1 - c_2) \Delta y_1 + c_2 h \} \qquad (1)$$

with new restrictions

$$\max (0,h-a_2) \leqslant \Delta y_1 \leqslant \min (a_1,h)$$

As it is seen, (1) is a straight line having the minimal value on one of the boundaries of the displacement range. In case of $c_1 > c_2$ the minimum is reached for $\Delta y_1 = 0$, $\Delta y_2 = h$, if $h \leqslant a_2$, and for $\Delta y_1 = h - a_2$, when $h > a_2$.

In case of $c_2 > c_1$ there is inverse relashionship - the minimum is achieved for $\Delta y_1 = a_1$, $\Delta y_2 = h - a_1$ if $h > a_1$ and for $\Delta y_1 = h$, $\Delta y_2 = 0$, if $h \leqslant a_1$.

Let us consider now contrary lips movements. The condition of the lips closure is $y_3 - y_2 = 0$, where y_2 is a vertical coordinate of the lower lip, y_3 is a coordinate of the upper lip. Restrictions for displacements are

$$a_2 \leqslant y_2 \leqslant b_2$$

$$a_3 \leqslant y_3 \leqslant b_3$$

with initial conditions $y_2 = a_2$, $y_3 = b_3$.

Elastic forces are

$$F_2 = c_2(y_2 - a_2)$$

$$F_3 = c_3(b_3 - y_3)$$

and the criterion of the force minimum is

$$\min \{ (c_2 - c_3) y_2 + c_3 b_3 - c_2 a_2 \} \qquad (2)$$

with new restrictions

$$\max (a_2,a_3) \leqslant y_2 \leqslant \min (b_2,b_3).$$

Again (2) is a linear function. For vertical displacements of the upper lip it is required more efforts then for displacements of the lower lip since the upper lip is lowered only due to orbicularis oris contraction. Thus $c_3 > c_2$ and the minimum of efforts is reached for

$$y_2 = \min (b_2,b_3)$$

i.e. for $y_2 = b_2$, since $b_3 > b_2$, $y_3 = 0$.

Therefore, if the criterion of optimality is a minimum of efforts then both during joined movements of the jaw and the lower lip and contrary movements of the lips the most displacement has the articulator with the least elastic resistance.

If not effort but work $A = F \Delta y$ is minimized then displacement for each articulator depends also on the amount ofthe required displacement. For joined movement of the jaw and the lower lip the criterion of optimality is

$$\min \{ (c_1 + c_2) \Delta y_1^2 - 2c_2 h \Delta y_1 + c_2 h^2 \}$$

If

$$(c_1 + c_2) \Delta y_1^2 + c_2 h^2 > 2c_2 h \Delta y_1$$

then minimum is achieved for $\Delta y_2 = a_2$, $\Delta y_1 = 0$. If

$$(c_1 + c_2) \Delta y_1^2 + c_2 h^2 < 2c_2 h \Delta y_1$$

then minimum is achieved for

$$\Delta y_1 = c_2 h / (c_1 + c_2)$$

if $h \leqslant a_1$ and for $\Delta y_1 = \max(0,h - a_2)$ in opposite case.

For contrary movements of lips the criterion of optimality is

$$\min \{ (c_2 - c_3) y_2^2 + (c_3 b_3 - c_2 a_2) y_2 \}$$

which is reached in the point $y_2 = b_2$ if $y^* - a_3 < y^* - b_2$, and in the point $y_2 = a_2$, if $y^* - a_3 > y^* - b_2$, where

$$y^* = (c_2 a_2 - c_3 b_3) / 2(c_2 - c_3).$$

It is seen from the condition of lips closure, that if for some reason the change of any coordinate y_i is impossible or the range of displacement has reduced, then for the given criteria of optimality the control system will immediately recalculates the required efforts F as soon as it gets an information on new conditions. This event is virtually observed for various paralysis of facial muscles and in experiments with jaw movements restriction by means of bite-block or electromechanical device [3,7]. As it is known, in these cases lips closure is achieved by means of the change of another articulators movement, if such a change is physically possible.

An internal model governs joined movements of articulators in space as well as in time in such a way that a certain configuration of the vocal tract for the given time interval could be shaped. Prediction-type coarticulation is possible only if an internal model "knows" not only kinematics but dynamics of articulators as well. For instance, using dynamics equation

$$my'' + by' + cy = F(t) \qquad (3)$$

an internal model can determine an articulator position in any moment of time for the given target position $y = y_0$ and restrictions on velocity y' and acceleration y''.

The faster movement is required according to coarticulation conditions, the greater muscle effort is spent. The economy criterion of efforts or fulfilled work appears in continious speech in such a way that even for the same target positions of articulators development of muscle efforts for initial sounds is twice or thrice as slow as for sounds inside words [11]. The muscle is nonlinear system in regard to the contraction velocity, thus a simple change of rate of articulation leads to considerable reorganization of control - other motor units and muscles are activated. For example, masseter is activized only for fast articulation of meaningful utterances ; slow articulation of / t / is provided by both the tongue and the jaw movements, but fast articulation - mainly by the jaw movements [12].

It is known, that for the certain area of the vocal tract turbulent noises appear and determine phonetical quality of sounds. However, the control system must avoid turbulent noises during articulation of close vowels like / i / and a closure during fricatives articulation. This requirement imposes restriction on the constriction velocity in the vocal tract. Indeed, measurements show that for the jaw velocity of movement up is slower then velocity of movement down [4,12].

In comparison with other modes of control an internal model has the advantage of guaranteed achievement of any physically realized target without test movements if it has complete information on kinematics, dynamics and current conditions of the control system. For example, required force F(t) in (3) can be calculated straight from the given displacement, velocity and acceleration.

An internal model in the speech production control system is aware not only of the connection between physical levels but of the code structure of speech flow as well. That code structure allows to correct errors of articulation and speech signal distortions. Thus each speaker can speak different style depending on circumstances, i.e. can use different control commands to achieve the requiered intelligibility under the given conditions.

Important function of an internal model consists in the estimation intraspeaker speech using both mechanoreceptors signals and results of the perceptive process. Then it is quate natural to suppose that the function is used for other peoples speech recognition. Accepting this hypotesis we maintane the physiological basis for regeneration the perception motor theory on a new level.

The idea concernig an internal model permits to skip endless process of experimental investigations of every separate level of the articulation control system and come to an analysis of the whole system of speech production.

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