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ANALYSING THE 2-7 DOF HUMANOID ROBOT ARM CONSTUCTIONS AND THE POSSIBILITIES OF CONTROLLING/LEARNING THEIR MOVEMENTS

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ABSTRACT: Previously the authors mainly dealt with the construction and modelling of 2 DOF (Degree of Freedom) and 2 links Humanoid robot arms which were operated in agonist-antagonist mode by 2 pairs of PAM (Pneumatic Artificial Muscle) elements to a target point in plane. The presented constructions were modelled and controlled by modifying the angles between shoulder-upper arm (α_{u0}) at the shoulder and between the upper arm -forearm (β_{f0}) at elbow artificial articulations. The kinematic systems fairly determine the trajectories of their structure joints, thus if the trajectory and derivatives are given - generally an inverse dynamic task has to be solved.
This lecture deals with the construction of 2-7 DOF and 3-4 links robot arms modelling and comparing to each other their advantages-disadvantages. The authors operate the links of the robot arm with the flexor—extensor agonistic-antagonistic pairs of PAM elements, also developed and analysed adaptive/learning algorithms for them. By developing the humanoid robot arm constructions — modelling and mimicking the very complex structured and controlled human arm one can be successful only by significantly simplifying the structures of the human muscles, tendons, articulations and bones. Similarly one can be successful in guiding and learning the limbs' movements if we make simplifications in modelling the functionalities of the human brain.

KEYWORDS: Humanoid robot arm, kinematic constructions, PAM, controlling movements, tripod

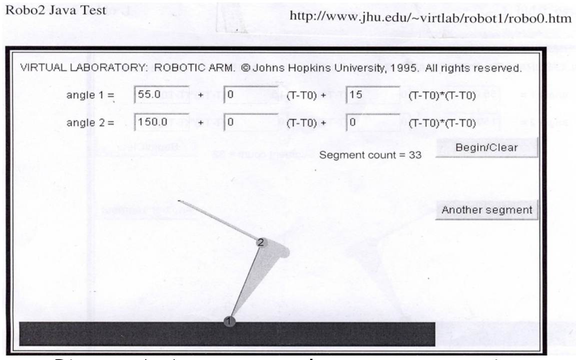
❖ INTRODUCTION

After some experiences having the manageable working points for any agonist-antagonistic pair of PAM (Pneumatic Artificial Muscle) elements, automatic/crude and adaptive/heuristic models have been made for driving the artificial wrist articulation of the robot arm through efficient series of points (line/arc segments) to the target point by harmonically controlling the flexor and extensor pneumatic muscles of the upper- and forearm [1.], [3.], [4.].

The punctiform considered elbow articulation can move on a circle with radius $R=l_{\text{upper arm}}$ and centre S_0 (shoulder) of a 2 DOF humanoid robot arm; while the wrist point is guiding from a starting point to the plane target point by modifying the angles between shoulder-upper arm (α_{u0}) at the shoulder and between the upper arm-forearm (β_{f0}) at elbow artificial articulations. The punctiform wrist can move on any given trajectory inside a semicircle with radius $R=l_{\text{upper arm}} + l_{\text{upper arm}}$ and S_0 centre by series of generated short lines/circle arcs up to the target point. Thus the wrist can go round arbitrary obstacles in plane.

Instead of the more expensive stepping-motor and servo-motor actuators the angle-measuring sensors, mass flow rate valve and on-off proportional pressure valves were used which were programmable by the height or number of electronic pulses. The electronic pulses-pressure steps controlling mode was chosen by agonist-antagonist operated PAM elements. Thus the human brain controlled flexor-extensor muscles were mimicked in the pulses-steps operating mode. A complex controlling equipment and its virtual models were developed with crude and adaptive/heuristic learning algorithms for controlling the movement trajectories of the wrist of the robot arm [3.].

There are many publications with agonist-antagonist pairs of PAM elements controlled by stepping-motors and servo-motor actuators e.g. at the Robot-laboratory of the Johns Hopkins University [5.], where they can also solve the guiding process from a starting wrist-point to the target-point in a plane, modifying the angle1 and angle2 by a, b and c parameters defining the position, velocity and acceleration by given functions. This example can also show the difficulties in controlling the punctiform wrist articulation via a given trajectory and its derivatives (Picture 1). This example gave a test and learning task possibilities following a given trajectory and its derivatives in the case of using stepping-motors. One can give 3 parametres for the position, velocity and acceleration -using the (T-T_0) time slice every time- to go to the target point by changing the angles at the “shoulder” and the “elbow”. The task is more difficult if one would like to follow a trajectory, etc.



Picture 1. A test example: one can practice and learn how he can follow a given trajectory with its derivatives by giving 3 parametres and using the (T-T_0) time slice every time

The humanoid robot arm generally has shoulder, elbow, wrist artificial articulations and -at the other end of the hand- a holder modellizing the human articulations and fingers/thumb.

It is well-known that the humanoid robot can possess more than 1 DOF at any articulation by the artificial bones and muscles of its kinematic systems. Any way at the industrial robot generally every link/tag has only 1 DOF.

Thus *at the shoulder* -as at an origo- one can realise *1, 2 or 3 flexing DOF the upper arm around x,y and z axes*, besides sometimes it has a *1 twisting DOF* around the axe of the upper arm;

- ❖ at other end of the upper arm -*at the elbow* origo articulation- one can realise *1 flexing DOF for the forearm* around the perpendicular axe to the upper arm, besides it can have *1 twisting DOF around the axe of the forearm* (around the radius);
- ❖ at wrist 1 flexing DOF for the hand around the perpendicular axe to the forearm;
- ❖ finally at the other end of the hand there is a holder by the thumb and the fingers, but this later one can be operated by other typed tools, not by PAM elements.

These twisting DOFs can be operated and analysed separately from the other flexing DOFs at the shoulder, elbow and wrist. In the case of 3 DOF flexing around parallel axes it can lose the unambiguous trajectory moving of the hand’s holder point from starting to target point.

This lecture mainly deals with constructing 3 or more DOF kinematic systems, humanoid robot arms, their virtual models and their guiding/learning movements. Our basic motivation was that we should define several kinds of kinematic (mechanical) constructions without building up them but their virtual model could be operated for the given tasks and could be tested ([3.]; see also: Balara, M. et al., (2004), [6.]; Fagg, A. H.,et al., 1999, [7.]).

Having designed these robot arm constructions (and all of their parts) kinematically we gave the adequate constraints in every artificial articulation in order to be able to assemble the whole robot arm afterwards. *Thus every motion type, controlling and/or learning their typical movements should be studied/analysed without building up all of our constructions* to spare a lot of time, money and material.

❖ ROBOT ARM CONSTRUCTIONS

The artificial shoulder articulation can be modellized by a ball-and-socket joint (spherical joint) or 3 cylindrical flexing joints and 1 twisting joint around the upper arm-axe.

The elbow can be modellized by 1 cylindrical flexing joint.

Finally the artificial wrist can be realised virtually by 1 cylindrical flexing joint and 1 other twisting joint around the forearm-axe which operates the forearm and hand equally. Keeping the notations for the artificial articulations’ angles at shoulder (α) and at elbow (β), we can choose (γ) at wrist for the angle between the axes of the hand and forearm. Thus, at the beginning of the movements to guard the unambiguous solution, one can transform the arm’s holder point by ($\Delta\gamma = 0$), that is the forearm and the hand will move together. One can move the Inventor-made virtual robot arm models directly and also by *VBA Macro program*. So, this lecture deals with guiding and controlling movement-strategies in the following cases:

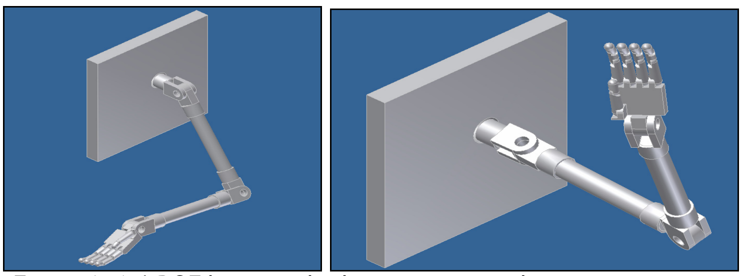


Figure 1. A 6 DOF humanoid robot arm in two characteristic states

- ❖ guiding the wrist or holder point of the robot arm from a starting to the target point,
- ❖ guiding the wrist/holder point movements via given trajectory and its derivatives.

There are some moving/controlling strategies but all of them can be characterised by a kind of inverse dynamic controlling process. The Figure 1 shows a 6 DOF robot arm which was analysed by object oriented VBA Macro programs, too. We tested its movements step by step at some given trajectories. In this robot arm we wanted to modellize 1-1 flexing DOF by cylindrical joints at the shoulder, elbow and wrist artificial articulations.

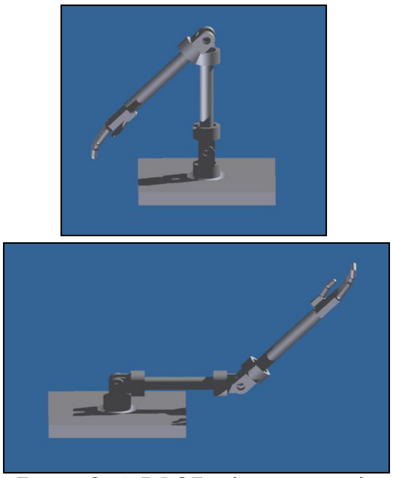


Figure 2. A 5 DOF robot arm with Angle1 and Angle2 parametres at the shoulder and elbow articulations were identified for the control VBA Macro program

Figure 2 shows a 5 DOF humanoid robot arm (which had not flexing DOF at the wrist, that is Δγ = 0) in two characteristic states: at the starting state of its wrist and at end state with its wrist at the target point of a plane.

The controlling Macro program is the following:

```
Sub Move()
Dim AssemblyDocument As AssemblyDocument
Dim Angle1Param, Angle2Param As Parameter
Dim AssCompDef As AssemblyComponentDefinition
Dim CY1 As Integer
Set AssemblyDocument = ThisApplication.ActiveDocument
Set AssCompDef = AssemblyDocument.ComponentDefinition
Set Angle1Param = AssCompDef.Parameters.Item("Angle1")
Set Angle2Param = AssCompDef.Parameters.Item("Angle2")
For CY1 = 1 To 45
Angle1Param.Value = 90 / 180 * 3.14 – 2* CY1 / 180 * 3.14
AssemblyDocument.Update
Angle2Param.Value = 45 / 180 * 3.14 + 2 * CY1 / 180 * 3.14
AssemblyDocument.Update
Next        End Sub
```

Figure 2 shows how these Inventor made kinematic models could be controlled by identifying the I.1. (constraint) = Angle1 and the II.1. (constraint) = Angle2 parameters of this 5 DOF robot arm after modificated them by the above VBA macro program. We can see the results only for the Angle1 and Angle2 parameters. We also mention that only 2 flexing DOF must be used out of the 3 flexing DOF around the same (parallel) direction axes to preserve the unambiguous solution. In the 6 DOF case the 3rd one at the wrist, e. g. the III.1. (flexing constraint) has to be fixed at the first motion step. At the shoulder and wrist articulations 1-1 twisting DOF (I.2. and II.2. constraints) can be realised around the axes of the links (actual pieces of the arm), the twisting angles are addable sum. At the shoulder we can use 1 other flexing DOF by a cylindrical joint (I.3. constraint) to realise the 3rd DOF at the shoulder. But it is more useful if one has a 7 DOF robot arm with 3 flexing DOF around the x,y and z axes besides the 1 twisted DOF around the axe of the upper arm at the shoulder.

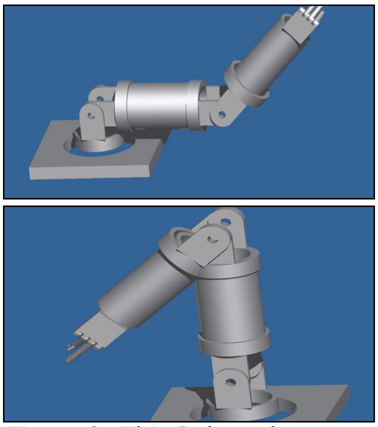


Figure 3. This Reha-robot arm also can be controlled by the same VBA Macro program

There are some other applications of the robot arms: e.g. Figure 3 shows a virtual kinematic model (5 DOF Reha-robot arm) for rehabilitating movements for somebody who has arm, muscles, tendons, articulations, but after a stroke or spinal/cerebral injury needs motion-rehabilitation by a kind of robot control. This model was also tested with some VBA macro programs by circular moving steps for any planar target points.

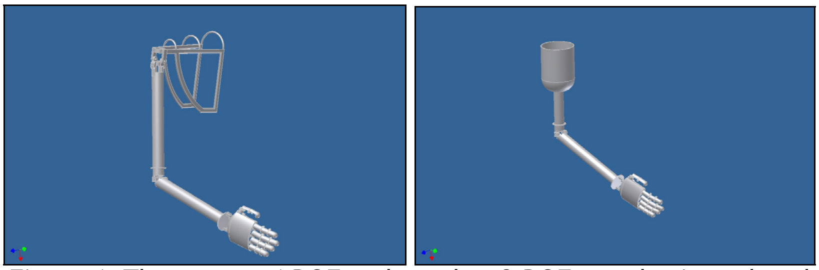
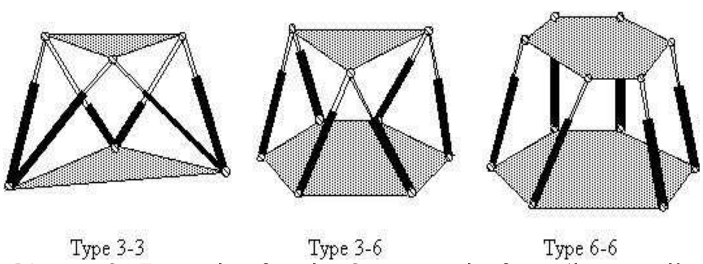


Figure 4. There are a 4 DOF and another 3 DOF prosthesis analysed

Figure 4 shows two experimental arm-prosthesis constructions: 4 DOF prosthesis for replacing the upper and forearm and the other one with 3 DOF for a person who partially lost this upper arm, too.

❖ APPLICATION STEWART-PLATFORM STRUCTURE DEVELOPING A 3 DOF ROBOT ARM ARTICULATION

The *Stewart-platform* (known as 'hexapod' too) has 6 DOF, and it has high payload-to-weight ratio (alike PAMs) since the payload is carried by several links in parallel (Ronen Ben-Horin, 1996, [14.]). Generally it is used as a base of the motion in the flight or automobile simulators, too (Picture 2).



Picture 2. Examples for the Stewart-platform 'hexapod'

We can similarly use a 3 DOF tripod PAM controlled structure as a more simple variation of Stewart-platform. This compact kinematic structure is analogue the 3 DOF spherical joint at the artificial shoulder articulation of the 6 or 7 DOF controlled by PAMs humanoid robot arms analysed above. It can replace the 2 or 3 flexing/twisting DOF articulations with 2 or 3 cylindrical joints or 1 spherical joint.

Picture 3 shows the developed tripod-platform virtual model flexing/twisting around x, y and z axes in CCW (+) and CW (-) directions, which shows also its efficiency.

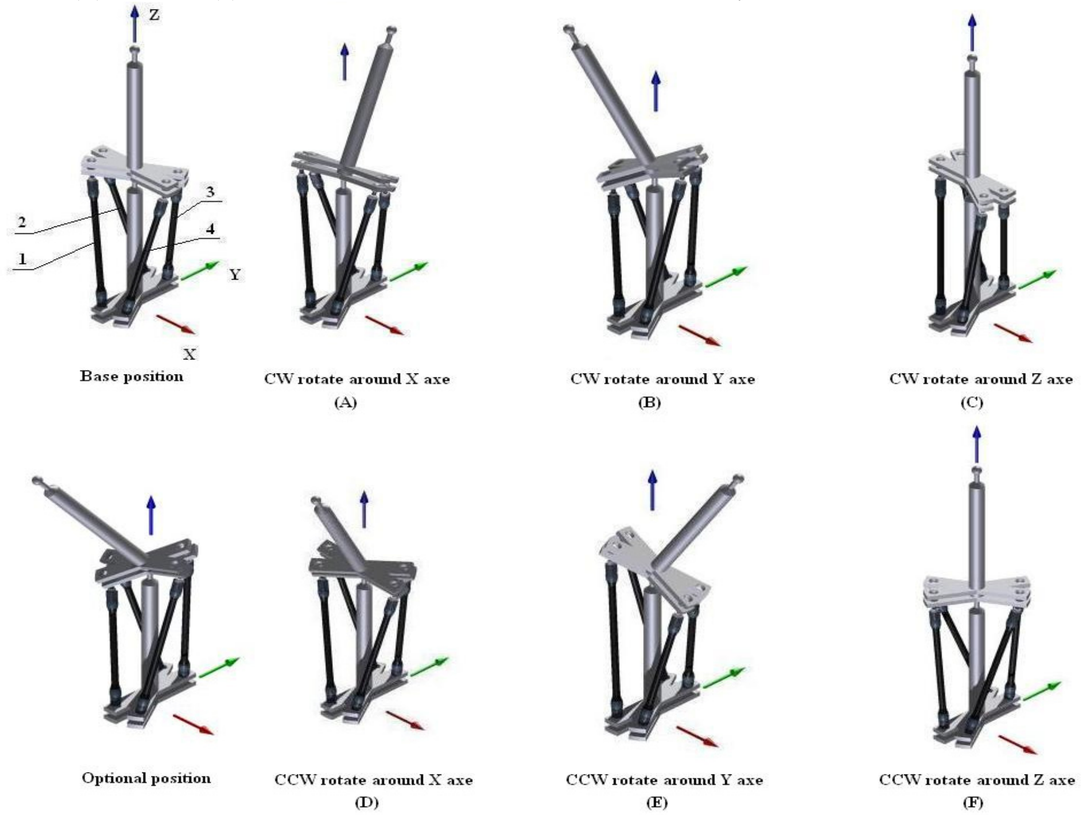


Figure 5. The basic solution of the developed Stewart tripod-platform by PAM actuators

Table 1 shows the logical conditions with **C**=contraction and L=lengthening the named PAM elements for operating the rotation of the platform around the x,y and z axes. The main information which comes from this table, is that the structure does not need 4 PAM elements for moving the platform in 3 different ways -for having 3 different flexing/twisting DOF. If any one of this table-rows will be cleared, all the columns will be different. This means that three PAM could give constraints for the 3 flexing/twisting DOF structure. The reason why it is better using 4 muscles here is that during the motions all the agonistic-antagonistic PAM elements have a twin/pairing element which gives more stability and balance for this developed tripod Stewart-type platform. The even-number of muscles give the easier way to solve the inverse kinematic task, too. Thus all the muscles need to be supported by another one operating in flexor or extensor mode. Many researches progressed this agonistic-antagonostic habit and finally used positioning by muscle pairs. The precise positioning is possible by using the sliding mode with the chosen PAM elements (Chin-I Huang et al., 1998, [11.]; and [3.]; [4.]; [2.]; [15.]).

Table 1. The state-table of the basic motions of this Stewart tripod-platform

	Motion					
PAM	A	B	C	D	E	F
1	L	C	L	C	L	C
2	C	C	C	L	L	L
3	C	L	L	L	C	C
4	L	L	C	C	C	L

❖ MOVING-STRATEGIES FOR 2-7 DOF ROBOT ARM

The authors would like to expound some fundamental robot arm moving-strategies which can solve inverse dynamic controlling programming task but we analysed only the unambiguous flexing DOF cases:

- ❖ <u>1st possibility</u>: One can determine the inverse transformation (more generally inverse Jakobi) $T_{j\,i} = T_{ij}^{-1}$ matrix which is simple enough to apply, but only in the 2 DOF cases and besides when only the starting and the target point are given for the robot arm holding point. If the trajectory is also given, we must apply the inverse transformation matrix for $P_i(x_i, y_i, z_i)$ points backward from the target point up to the starting point- densely enough (n-times) along the trajectory. But first we can choose the 2 DOFs (articulations/links) which are most important in the task to solve. In this method we can get a lot of difficulties even in the 2 DOF cases also if we have to solve the task with given 1st and 2nd derivatives of the trajectories and/or the robot arm possesses not only (parallel) flexing DOFs. To solve this task, e. g. the object oriented Inventor VBA Macro programming system is suitable for this aim: writing the controlling program.

- 2nd possibility: We can use the *Inventor CAD system* itself to produce the inverse dynamic programs to control movement-steps: by defining the “trajectory-rail/track” (for the robot arm holder point) as a continuous polyline which consists of any number of lines/arcs, segments with equal tangents between them constraint; otherwise we can use the so-called transitional constraint between the cylindrical/spherical holder (virtually) and a series of surface-pairs producing the composed trajectory. One can store data in a table at n pieces of the trajectory before the robot arm has to go along these $P_i(x_i, y_i, z_i)$ connecting points, the angles (α_i, β_i) of the shoulder and the elbow articulations for these places. That is the angles (α_i, β_i) will be needed in the expected applications to control the robot arm along the given trajectory from the starting to the target point.
- 3rd possibility: We can design/make also adaptive/heuristic control programs *considering the given trajectory and the position-errors in every i-th steps* between the starting and the target point Endrődy T. et al., 2009, [1.];. These adaptive control algorithms could be added with a kind of heuristic learning and/or remembering possibilities and if the adaptive/ heuristic learning control algorithms do not work (e.g. stopped further of the target point, one must use a kind of direct/crude algorithm to finish the process going to the target point. There are some direct and heuristic/adaptive moving algorithms on the Figure 6 and Figure 7.

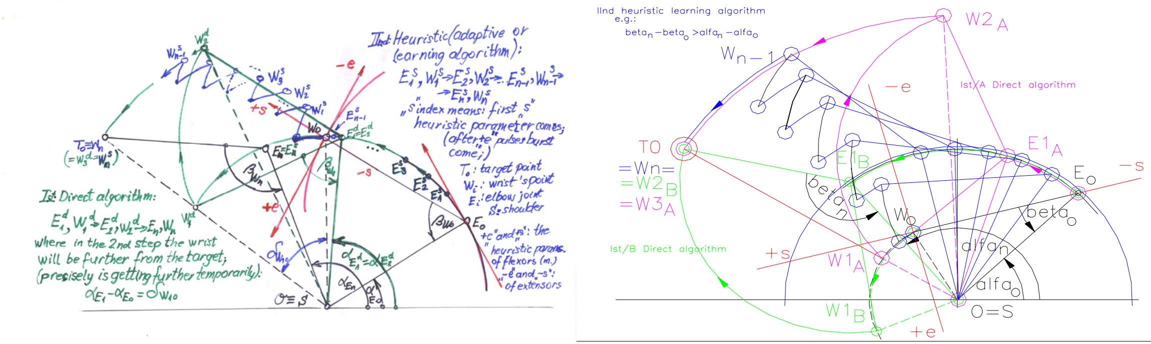


Figure 6 Direct and heuristic algorithms for controlling PAM elements of the upper- and forearm by electronic pulses controlled pneumatic valves

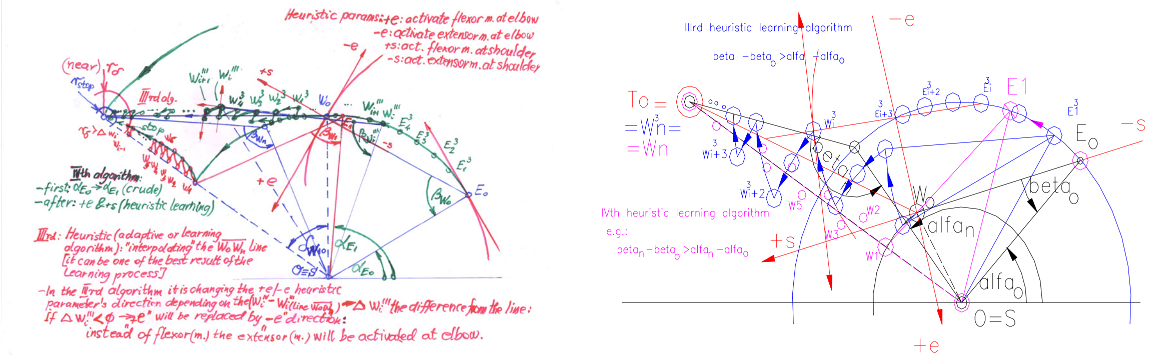


Figure 7. Two further more effective heuristic/learning controlling algorithms

In every controlled step the errors between the expected and the actual arrived i-th point of the trajectory can be corrected for the following experiences. For this aim the actual difference can be analysed between the wanted and the actual wrist/holder point supplementing the predicted deviation of the holder position of the robot arm to produce better and better controlling program (Fagg,. A. H., 1997, [9.]).

- 4th possibility: One can use Stewart typed tripod platform or other planarly actuated parallel robot construction for replacing e.g. a 3 DOF spherical joint at the shoulder artificial articulation (see Figure 5). At this type solution one can enjoy the kinematic and dynamic advantages of the parallel robot constructions, which are the following:
  - higher payload-to weight ratio (alike PAM elements) in the consequence of the payload is carried here by several link in parallel,
  - higher accurancy without cumulative joint error,
  - simpler solution of the inverse dynamic equations, etc. (Ronem Ben-Horin, et al., 1996, [14.]).
- 5th and the best possibility (but can be entirely realised only in the future):

The best controlling system for humanoid robot arm (upper arm-forearm-hand) could mime the human brain neuronal networks’ controlling process for the muscles, tendons and bones of the human limbs by a neural network e.g. the MLPNN structure with an inverse dynamic model and artificial muscle PAM elements (see: Ahn, K.A. and Anh, H. P. H. (2009), [**8.**]).

According to our present knowledge the required limbs' conscious movements are controlled first of all by motor cortex' nuclei given commands via the spinal cords' efferent neuronal networks. The eyes and visual cortex' neuronal networks watch the movements of the arm's articulations along the wanted trajectory. The visual system generates error-series along the trajectory between the actual and required positions, velocity, accelerate (Figure 8). This schema came from Smagt, van der P. (1998, [12.]) and it was added by the authors. Besides from the periphery, the neuronal network of Cerebellaris folium/folia gets information by the afferent fibers about the state of the tones and positions of the muscles, tendons, articulations and bones. Thus the nervous system can predict the position, error of the positions, the tensile forces and moments/torques, too. The Cerebral Motor-cortex nuclei can give the main commands for the muscles in consequence of the actual learned knowledge made by the Cerebellar Foliums' networks. The learning process based the percept and predicted position, velocity and acceleration errors during all of the motions. This is a very complex process, thus only the main information paths could be emphasized here.

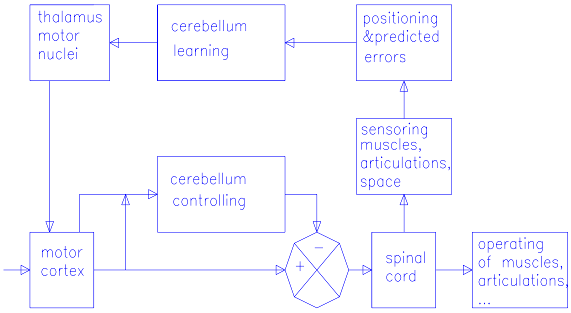


Figure 8. Controlling the human limbs' motion by the Motor cortex, Cerebellaris folium/folia and Spinal cord

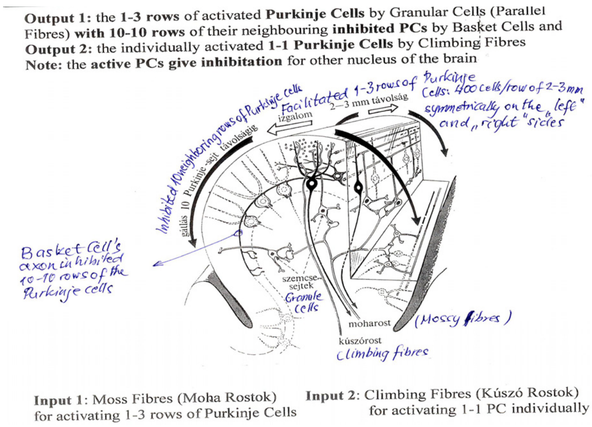


Figure 9. The main neuronal network of a typical Cerebellaris Folium by Pr. Szentágothai, J.

The cerebellum has homogenous folium-structures and deep nuclei for connecting other parts of the brain. The folium-networks have special "inverse neuronal structures", as Prof. J. Szentágothai said: it is similar to an organist who presses all the keys except the one which gives the sounds (Szentágothai, J., 1977, [13.]). Thus every folium can control by its inverse structure the agonistic-antagonistic and synergic mode operated muscles in an adequate way, because as well-known, the limbs and the articulations of the arm need inverse dynamic control. Besides the cerebellar folium-neuronal-structures can learn from the sensed and predicted positions, parameters of the limbs for the sophisticated movements. The "output" Purkinje neurons of folium bring inhibiting distributed commands via the cerebellar deep nuclei for spinal cord and via thalamus nuclei for cortex, so the folium-structures have very effective fluencies in controlling and learning the sophisticated movements of the arm. We developed a new controlling/learning neural system flowchart (Figure 10) which hopefully can use the advantages of the Folium's inverse structure to operate efficiently the needed inverse dynamic control process [16.]).

❖ CONTROLLING THE ROBOT ARM'S CIRCULAR STEPS BY PAM ELEMENTS

Till now we have not analysed how the robot arm-links can be moved along an arc separately/one-by-one and together along a kind of boved trajectory in the case of 2 flexing DOF arm by the PAM elements. These PAM elements can contract linearly in different extent. The PAMs operate only in one direction (pulling) so it must be used together with its agonist or antagonistic pair, similarly to the muscles in the human body. Last years we made a few test-bed constructions to analyse its highly nonlinear character (e. g. F [N], Δl [mm] and p [bar, Pa]), its other important parameters: its exact longitudinal (± 0.01mm) sliding control process and defined maximal contractions (e. g. ± 10 %). After fixing the angle domain (e. g. 0-90°) at every flexing articulation for moving a link of the robot arm, one can define (for the rotational torque) the measures of the actual force-arm [mm], the point of application of the force and the direction line of the force,

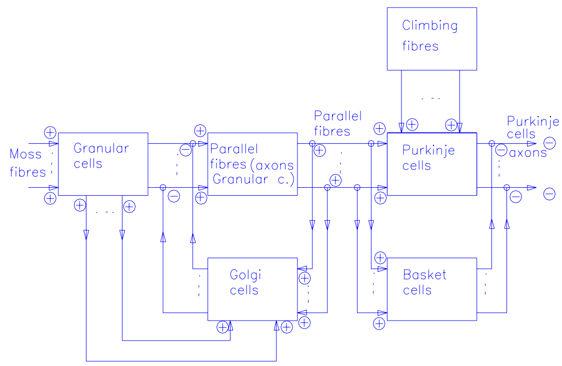


Figure 10. The neural model of the folium with feed-back and feed-forward control possibilities

that is the fixing places of the artificial muscle elements. One of the main problems at any 2 DOF robot arm-controlling process is how the given trajectory function of the holder point can be interpolated by little arcs from the starting point up to the target point (see: the Figure 6 and Figure 7, or more detailed: the publication [3.]). First we have to find better and better interpolating by arcs „in second order" for α_i and β_i at the elbow and the shoulder articulations. Then at any movement strategies controlling algorithms mentioned, it is simpler to map the α_i, β_i [°] angles to the controlled contractions of the agonistic-antagonistic pairs of PAM elements at the shoulder and elbow artificial articulations.

❖ CONCLUSIONS

The earlier cerebella models demonstrated the possibilities of the role of the folium in solving the inverse dynamic control tasks of the robot arm movements. The main possibility came by the Purkinje cells generated inhibitory output.

One must take into consideration that the new light mass-weight artificial muscles (PAMs) changed the traditional robot control methods. Recently large contradictions came between the earlier cerebellum models and understanding its role in the motor cortex-cerebellum-spinal cord neuronal networks for the controlling and learning processes of the human limbs' movements. It seems more important to define inverse and forward models, too. We ought to modellize not only the motor apparatus, sensory organs but also the external world from which the actual movement controlling tasks come. The mimesis of the cerebellum could get more attention in present-day research.

❖ REFERENCES

[1.] T. Endrődy, J. Gyeviki, J. Sárosi and Adrián Szőnyi, Constructions of humanoid robot arm, controlling and learning the movements of their joints, Synergy 2009 Conference, Gödöllő, Hungary, 30 August - 3 September, 2009, p 6

[2.] Sárosi, J., Gyeviki, J., Endrődy, T., Szabó, G. and Szendrő, P. (2009), Characteristics of the pneumatic artificial muscles, Synergy2009 Conference, Gödöllő, Hungary, 30 August - 3 September, 2009, p 6

[3.] Endrődy, T., Gyeviki, J., Sárosi, J., Véha, A., and Toman, P. (2008), Automatic and learning model of a planar humanoid robot arm controlled by 2 pairs of antagonistic PAMs moving to a target, ICoSTAF, Szeged, Hungary, 5-6 November, 2008, pp. 367-375

[4.] Toman, P., Gyeviki, J., Endrődy, T., Sárosi, J. and Véha, A. (2008), Design and fabrication of a test-bed aimed for experiment with pneumatic artificial muscle, International Conference on Science and Technique in the Agri-food Business, Szeged, Hungary, 5-6 November, 2008, pp. 361-366

[5.] http://www.jhu.edu/~virtlab/robot1/robo0.htm, Johns Hopkins University's Robot-laboratory, 1995

[6.] Balara, M. and Petík, A. (2004), The properties of the actuators with pneumatic artificial muscles, Journal of Cybernetics and Informatics, Volume 4, pp. 1-15.

[7.] Fagg, A. H., Barto, A.G., Zelevinsky, L. (Univ. of Massach., Dep. of Comp. Sci), Houk, J.C., Northwestern Univ., Dep. of Physio.: Using Crude Corrective Movements to Learn Accurate Motor Programs for Reaching,1999, pp.20-24

[8.] Ahn, K. A. and Anh, H. P. H. (2009), Design and implementation of an adaptive recurrent neural networks (ARNN) controller of the pneumatic artificial muscle (PAM) manipulator, pp.1-13.

[9.] Fagg, A. H., Zelevinsky, L., Barto, A. G. and Houk, J. C. (1997), Using Crude Corrective Movements to Learn Accurate Motor Programs for Reaching, Ch 6, NIPS*97 Workshop,1997, pp. 20-24.

[10.] M. Kawato Hikaridai, (1997), Multiple Internal Models in the Cerebellum, Ch5, NIPS*97 Workshop, 1997, pp. 17-19.

[11.] Chin-I Huang, Chih-Fu Chang, Ming-Yi Yu, Li-Chen Fu, Sliding-Mode Tracking Control of the Stewart Platform, 1998, p. 8

[12.] Smagt, van der P. (1998), Cerebellar control of robot arms, Inst. of Robotics and System Dynamics German Aerospace Center/DLR, Connection Science 10, pp.301-320.

[13.] Szentágothai, J. (1977), Funkcionális anatómia (Functional anatomy), Medicina publish., pp. 206-212., pp. 1426-1439., pp. 1484-1490.

[14.] Ronen Ben-Horin, Moshe Shoham and Shlomo Djerassi, Kinematics, Dynamics and construction of a planarly actuated parallel robot, Dep. of Mechanical Engineering Technion – Israel Institute of Technology, Haifa, 1996, p.2

[15.] P. Tomán, J. Gyeviki, T. Endrődy, J. Sárosi, A. Véha, Z. Szabó (2009),Sliding mode control of a robot arm driven by pneumatic muscle actuators, Journal of Engineering Annals of Faculty of Engineering Hunedoara, Tome VII (year 2009),Fascicule 4, (ISSN 1584-2665), pp.95-100

[16.] T. Endrődy: Developing product and prototype in integrated CAD/CAM system by application of complex modelling, effective communication, data- and knowledge base, PhD Dissertation, Eötvös Loránd University Budapest, Faculty of Informatics, Budapest, 2005, p. 174

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