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# ALGORITHMIC CONTROL OF ASSISTIVE DEVICES FOR SEVERELY HANDICAPPED PERSONS

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*Summary*

In the paper is presented a new approach to the control of active anthropomorphic mechanisms, based on the two-level control concept: level of prescribed artificial synergy and level of adaptation to large deviations from nominal dynamic regimes. The presented concept is applied to control tasks of stable regular biped gait and posture, as well of upper extremities, with full number of degrees of freedom. Concrete examples are presented, demonstrating application of the described approach to the synthesis of artificial skeletal activity of the locomotion and manipulation type.

## *Introduction*

During the last years a new class of mechanisms, serving for the realization of various artificial motions of locomotion and manipulation type, profited of sensibly accelerated development. Such class of mechanisms could be conditionally termed: anthropomorphic active mechanisms. In the same time period great interest could be noted for studying the motion of living beings, notably the human skeletal activity, as well as the analysis of the control mechanisms in the scope of the activity mentioned. Such interest, apart from being motivated with basic research, evidently contains the practical reason, too, reflected in introducing of anthropomorphic mechanisms into rehabilitation and industrial practice, as well as other unusual or dangerous environments, unsufficiently explored outer space and underwater sites.

The problem of artificial motion control presents a control problem of multivariable mechanical systems, possessing redundant degrees of freedom. There exists an enormous number of publications and realizations in the field of control and application of anthropomorphic devices, notably concerning its rehabilitation version. By this occasion the particular approaches to motion control will not be reviewed. Only one common characteristic of the same can be underlined, consisting in simultaneously solving the synthesis and control problem of anthropomorphic mechanisms motion with the problem of redundancy. Such manner of solving the manipulation and locomotion tasks complicates very much the control algorithms, inducing greater complexity of the control system computer part, in other words its price, dimensions and efficiency in the case of on-line control of motion.

Taking into account the limits of the linear control theory, a new approach to the study of complex machanical systems dynamics was formed from the engineer's point of view, as well as to the synthesis of suboptimal control algorithms for the stabilization of various working regimes under conditions of small and large perturbations. The method was established keeping in maind the realistic needs of the control of legged systems motion, notably anthropomorphic ones.

In order to stress out greater possibilities of such a control concept, in the first section of this part are presented the general postulates of the nominal and perturbed regimes synthesis of mechanical systems, while in further presentation the details of the application of the mentioned procedure to the problem of the stable biped gait synthesis are given.

The control procedure proposed is based on the following levels:

- level of nominal dynamic regimes,
- level of adaptation.

*Synthesis of Nominal Regimes*

There exists a large scope of control problems, with which only some particular dynamic states are of interest. In such cases it is possible to introduce the notion of prescribed synergy, which is being imposed to one part of the system. In such way one arrives to a specific reduction of dimensionality, which by its nature has a new characteristic. Namely, in this case there does not exist some system simplification in the classical sence, because to some system parts particular dynamics is prescribed, while from the resting "open" dynamics it is demanded that it performs balancing of the whole system, at the basis of satysfying some specific conditions, nominated dynamic connections in the broader sence. The supplementary dynamics, calculated in that way, has been nominated the compensating synergy [1], [2], [3]. By prescribing various synergies, the corresponding set of compensating synergies is being calculated, by the means of which the large dynamic possibilities are substituded by such dynamic forms, which are interesting for the considered control task.

Let a class of dynamic systems be considered, the mathematical models in the state space of which can be presented in the following form:

$$\dot{\xi} = f(\xi,t) + B(\xi,t)\cdot u \tag{1}$$

where $\xi$ - state vector nx1
$f(\xi,t)$ - vector function nx1
$B(\xi,t)$ - matrix of order nxm
$u$ - input vector mx1

In this class of control tasks it is supposed that there exists linearity with respect to the control vector, as well that the output is presented by a complete state vector of the system.

Without considering the classical types of control tasks, when the synthesis of the nominal states is performed according to set inputs, or when the same are being calculated based on the given outputs, in this consideration let the generalized case be treated, in which the inputs (generalized formes) and the outputs (dynamics) are partially known.

Let the known part of the input vector and state vector be designated $u_o$ $(m_1 x1)$ and $\xi_o$ $(n_1 x1)$, and their unknown parts by $u_x(m_2 x1)$ and $\xi_x(n_2 x1)$ respectively, where $m_1 + m_2 = m$, and $n_1 + n_2 = n$.

In order to obtain the equations with respect to the unknown input vector ($u_x$) and state vector ($\xi_x$), the following transformation matrices P and R are introduced:

$$[P_o \mid P_x]\left\{\frac{u_o}{u_x}\right\} = \{u\} \qquad \text{and} \qquad \left[\frac{R_o}{R_x}\right]\{\xi\} = \left\{\frac{\xi_o}{\xi_x}\right\} \tag{2}$$

By multiplying the matrix $[B(\xi,t)]$ with $[P]$ and $[R]$ one gets:

$$\left[\frac{R_o}{R_x}\right][B(\xi,t)][P_o \mid P_x] = \left[\begin{array}{c|c} B_{oo} & B_{ox} \\ \hline B_{xo} & B_{xx} \end{array}\right] \tag{3}$$

where the submatrices have the dimensions

$B_{oo} - n_1 \times m_1$, $B_{ox} - n_1 \times m_2$, $B_{xo} - n_2 \times m_1$, $B_{xx} - n_2 \times m_2$ .

Now the system (1) can be divided into two subsystems:

$$\{\dot{\xi}_o\} = \{f_o(\xi,t)\} + [B_{oo}]\{u_o\} + [B_{ox}]\{u_x\} \tag{4}$$

$$\{\dot{\xi}_x\} = \{f_x(\xi,t)\} + [B_{xo}]\, u_o + [B_{xx}]\{u_x\} \tag{5}$$

where

$$\left[\frac{R_o}{R_x}\right] f(\xi,t) = \left\{\frac{f_o(\xi,t)}{f_x(\xi,t)}\right\} \tag{6}$$

$f_o(\xi,t)$ - vector function $n_1 x1$,
$f_x(\xi,t)$ - vector function $n_2 x1$.

From subsystem (4) the unknown input vector $u_x$ should be determined.

Here the case is being considered, which is adequate to the class of tasks, being the subject of this paper, complementarity existing between the unknown dynamics and the unknown inputs, which means that $m_2 = n_1/2$. Then from system (4) one gets:

$$\{u_x\} = ([B_{ox}]^T[B_{ox}])^{-1}[B_{ox}]^T(\{\dot{\xi}_o\} - \{f_o(\xi,t)\} - [B_{oo}]\{u_o\}) \tag{7}$$

together with the condition that the matrix $[B_{ox}]^T\ [B_{ox}]$ is nonsingular.

Substituting $\{u_x\}$ into (5) a subsystem with respect to the unknown state vector is obtainted, which is independent from the input vector $\{u_x\}$:

$$\{\dot{\xi}_x\} = \{f_x(\xi,t)\} + [B_{xo}]\{u_o\} + [B_{xx}]([B_{ox}]^T\ [B_{ox}])^{-1}[B_{ox}]^T(\{\dot{\xi}_o\} - - \{f_o(\xi,t)\} - [B_{oo}]\{u_o\}) \tag{8}$$

From the subsystem (8) first the unknown state vector $\xi_x$ is obtainted, then from the algebraic subsystem (7) the unknown control $\dot{u}_x$ is determined. Accordingly, subsystems (7) and (8) represent the mathematical formulation of the synthesis of the nominal dynamics of the system.

*Synthesis of the Level of Adaptation*

This level can be explained by the control scheme given in Fig.1. According to that scheme, the system can be controlled in perturbed working regimes in two ways. The corrections are carried out by means of servosystems along some contour, based upon the chosen criterion and the measured deviations of the real from the ideal (nominal) synergy. In the case of greater deviations it is possible to choose along a different contour some from the disponsable synergies, calculated in advance and memorized in the control system. In these cases the dynamic process can be continued along the new synergy, or gradually returned to the starting working (nominal) regime.

The essential suitability of this control concept lies in the possibility to control complex dynamic systems in real time. Namely, some dynamic processes cannot be controlled in real time at the basis of calculating new dynamic states and generating the corresponding control signals, even at the most modern level of computer technology and languages. The advantage of such control manner consists in the fact, that calculation of the system dynamics in real time is avoided and the control task itself reduces to the choice of some new synergy, mostly adapted to the real working conditions. In other words, the processor for calculation of the system dynamic states reduces to a programmer of memorized synergies, calculated in advance. In that way a certain prediction of working conditions, in which the system may find itself in the course of work, has been carried out.

Independently from way of perturbed regimes compensation, there stays the question of the deviation criterion of the real state from the nominal synergy.

The classical control theory yields the possibility of perturbed regimes stabilization for the case of small deviations from the nominal (programmed) trajectories. More interesting here is to consider the case of large deviations from the programmed trajectories, wich in fact is the basis of the proposed control concept.

Let $\Xi^{o}$ be some ideal synergy in the absence of perturbations. For the sake of stability maintaining in the case of large deviations let us temporarily choose another nominal synergy, which we will denote with $\Xi^{*}$.

Let us suppose the existence of a family of external synergies $\Xi^{*}$ depending on the parameter vector p: $\Xi^{*}(p)$

$$p = (p_1, p_2, \ldots, p_m)^T \tag{9}$$

where m is the number of system parameters.

The values of $\Xi^{*}$ should be chosen in such a way, that in the first place it is nearest to the real synergy $\beta$, and then to ensure a gradual approach to the original ideal synergy $\beta^{o}$. First, from the family (9), we find the synergy which is nearest to the real synergy $\Xi$. Let us denote this synergy with $\Xi^{A}$ and write a criterion of the form:

$$J_i = \frac{1}{2}\left[C_{oi}(\xi_i - \xi_i^A)^2 + C_{1i}(\dot{\xi}_i - \dot{\xi}_i^A)^2\right] \tag{10}$$

$$(i = 1, \ldots, n)$$

Now let us find the minimum of the expressions (10):

$$\frac{\partial J_\Sigma}{\partial p_j} = 0, \qquad (j = 1, 2, \ldots, m) \text{ where, } J_\Sigma = \sum_{i=1}^{n} J_i ,$$

which gives possibility to find $p_A$.

In the described method, the most difficult task is to define point $p^A$. As the vector $\Xi$ has many components and is function of several parameters and of time, it is impossible to store all possible combinations in the control computer memory. So for the sake of a practical realization of the method described, it is necessary to find an analytical representation of the ideal synergies as function of parameters and time.

*Synthesis of Biped Gait*

At the basis of such approach the synthesis of anthropomorphic gait has been carried through. The problem of artificial gait synthesis belongs, by its nature, to the combined type of control task. However, the problem of the biped gait synthesis, in the scope of the task, formulated in that manner, has some specificities, which deserve to be explained.

Firstly, in spite of the synergy, prescibed to one part on the anthropomorphic mechanism (prescribed trajectories of the leg joints), their driving torques are unknown (Fig. 2). This is evident if the fact is recalled, that the dynamic reactions during the gait are functions both of the prescribed and supplementary (compensating) synergy and are acting in the form of external forces on the mechanism. Due to that it is impossible to calculate the driving torques even in the joints with prescribed trajectories. In order to resolve this dynamic indefinitness, there were prescribed the points, in which the resultant forces of the reactions between the feet and ground were acting (Fig. 2). These points were denominated Zero-Moment Points and for a coordinate system, connected to the instantaneous positions of these point, specific equations of dynamic equilibrium were formed. In that way, for prescribed motion of the legs and the chosen trajectories of the zero-moment points (ZMP), the moments, with respect to them and the joints of passive members (arms) are equal zero (Fig. 2). In this case the driving torques $M_o$ are equal zero and the system of differential equations, solved for the unknown part of the synergy becomes (8):

$$\{\dot{\xi}_x\} = \{f_x(\xi,t)\}+[B_{xx}]([B_{ox}]^T[B_{ox}])^{-1}[B_{ox}]^T(\{\dot{\xi}_o\} - \{f_o(\xi,t)\} \qquad (11)$$

The corresponding driving torques* $\{M\}$ can be calculated using equation (7). The unknown synergy part $\{\xi_x\}$ describes in this case the motion of the compensating members, necessary for attaining equilibrium, or serves for establishing step repeatability, as well as free motion of the passive members (upper extermities). When cosidering stationary motion, the needed state vector values at the beginning and end of the step are unknown. The state vector values can be determined from the repeatability conditions, which can be defined in the following way: all angles $\{\xi\}$and their derivatives $\{\dot{\xi}\}$ at the end of the step period should equal those at the beginning of the same, i.e.:

$$\{\xi\}_T = \{\xi\}_o \quad \text{and} \quad \{\dot{\xi}\}_T = \{\dot{\xi}\}_o \qquad (12)$$

where T - full step period.

At the basis of the elaborated algorithms for finding solutions of (11), together with the repeatability conditions (12), there were obtained various compensating synergies of the system. In Fig. 3, for example, are demonstrated results of the digital simulation of level gait, i.e. compensating synergies for various combinations of the characteristic parameters S and T, where S presents the step scaling factor.

*In this concrete case, control vector is replaced by driving torques $M$.

According to the presented hierarchical structure of anthropomorphic system control, the problem of dynamic gait stabilization is being solved by means of the adaptation level synthesis, i.e. synthesis of the system for returning the biped to one of the nominal synergies in case of perturbations.

In the case of small perturbations (small deviations from the prescribed ideal synergy), classical methods for the system stabilization, based on the linearization of the dynamic equations round the ideal synergies, can be profited of, as well as approximative procedures for stabilization, understanding small deviations of the synergy from the ideal one. Here will be not treated the case of small deviations from the nominal gait regimes. That case was treated earlier [4], [5], [6]. In this section will be treated the problem of gait stabilization in the presence of large deviations from the nominal working regimes. In the case of large deviations it is profitable not to insist in compensating them by changing the internal synergy, aimed at returing to the starting nominal synergy $\xi_o$, but pass to some new internal synergy. Let $\xi_o$ be the ideal synergy of the anthropomorphic mechanism. In order to maintain stability in the conditions of large perturbations, let some new nominal synergy $\xi^*$ be chosen. During stabilization $\xi^*$ should be chosen in such maner, that it be nearest to the real synergy $\xi$ and that it enables a gradual return to the initial synergy, if this be necessary. Let this synergy be denoted $\xi^A$, in which case expession (10) can be used. As already mentioned, in one of the previous sections, in the process of recognizing the synergy, which is the nearest to the momentaneous state vector of the system, the most difficult task is obtaining point $p^A$, i.e. the parameter vector, corresponding to the chosen synergy. To achieve practical realization of the stabilizing procedure, it is useful to represent the nominal synergies analytically, as functions of some parameters. Analyzing various gait types, some characteristics of their synergies were observed. So it was demonstrated, that the synergies of regular gait can be represented with sufulcient accuracy by means of two-parameter curves. These parameters are: S - step scaling factor (relative step length) and T - full step period. At the basis of these parameters, sufficiently simple approximation of a set of synergies can be obtained.

Let $\xi^o$ be some synergy (gait) chosen as the basic synergy. Now we can represent the mentioned family of synergies in the following form (let us denote the lower part of the locomotion system by the index d):

$$\xi_d(t) = S\xi_d\left(\frac{t}{d}\right) \tag{13}$$

By varying the values of S and T we can acquire a series of curves which illustrate the upper locomotion system synergy change as a function of these parameters. The analysis of these curves shows that for the system upper part the dependence between $\xi_{up}$ and p can be approximately written as the linear form of S and T:

$$\xi = \xi^o + B_S(S - S^o) + B_T(T - T^o) \tag{14}$$

where $B_S$ and $B_T$ are the coefficients achieved by using criterion of square error minimum. Introducing this expression into (10) instead of $\xi^A$ and setting the condition of minimum:

$$\frac{\partial J_\Sigma}{\partial p_j} = 0 \;, \qquad (j = 1,2,\dots,m) \tag{15}$$

we get:

$$a_{11}S + a_{12}T = b_1 \; ; \; a_{21}S + a_{22}T = b_2 \qquad (16)$$

where $a_{11}$, $a_{12}$, $a_{21}$, $a_{22}$ - functions of coefficients $B_S$, $B_T$, $\dot{B}_S$, $\dot{B}_T$, $b_1$, $b_2$ - functions of state coordinates.

The system of eqs. (16) makes it possible to acquire values of S and T minimizing (10), i.e. to obtain point "A" in the working region, nearest to the instantaneous system state.

In order to investigate the applicability of the described procedure for the choice of nominal synergies in the presence of certain perturbations, an example is presented, processed by means of digital simulation. For a set of particular prescribed leg synergies, from the conditions of dynamic stability of the complete anthropomorphic mechanism, corresponding synergies of the upper system part (compensating motions) were calculated.

Let it be supposed, that the biped was moving along synergy No 1. In the relative time t/T = 0,7 acted some perturbing impuls on the system, so all the state coordinates were also perturbed. This perturbed state vector can be evidenced (measured) by means of gyroscopes. Introducing the measured values into expressions (16), together with the memorized values of coefficients and the state coordinates $\xi_o$ and $\dot{\xi}_o$ of the basic synergy (for the same time instant), the computer easily calculates new values of the parameters S and T. The parameters, determined in that manner define the synergy, which the nearest to the perturbed position of the system phase point. In the example illustrated by Fig. 4, the computer obtains new parameter values S = 0,4 and T = 0,5, thus recognizing that the phase point is nearest to the synergy No 4. Transfer from one to another synergy in the presence of perturbations is illustrated in the drawing by means of bold lines. In this example the hypothetical case of perturbations has been considered, changing the phase coordinates in such manner, that they are very close to some of the prepared synergies. In real-life situations, the perturbation could bring the phase point in such position, which is not close to anyone of the available synergies. Consequently, it is evident, that as a result of local feedback loops in the servosystems of joints, round each nominal synergy there must exist a certain, non-negligible zone, in which each deviation from the nominal synergy will be automatically compensated. In that way, when the phase point does not find itself on anyone of the nominal synergies, but in the mentioned "ε-zone", the servosystems will ensure positive transferring onto the given synergy. This process demands a transient time, depending on the system performance.

*Control of Anthropomorphic Manipulators*

In the case of the anthropomorphic manipulator the prescribed synergy of motion solves the problem of attaining the goal unifoldly, while the compensating synergy movements of the terminal device solves some specific manipulation task. In that way the problem of anthropomorphic manipulation is being solved applying two groups of degrees of freedom. The first group brings the terminal device, i.e. its "wrist" jont into the region of the working point in space, while the second group finishes the manipulation task by means of its compensating movements.

In this way the problem has been solved, using the full number of degrees of freedom of the manipulator and applying coordination of the movements (prescribed synergy), which eliminates the redundant degrees of freedom.

In accordance with this concept, control of the anthropomorphic manipulator can be divided into two levels:

- level of prescribed synergy (programmed kinematics),
- level of compensating synergy (dynamic compensation).

The mechanical configuration, consisting of three members, can be divided into the minimal configuration of two members, realizing the prescribed kinematics, and the compensating member, which, by its compensating movements, supplements the unsufficient number of the minimal configuration degrees of freedom depending on the type of the set manipulation task (Fig.5).

*Synthesis of the Programme Dynamics via Prescribed Kinematics*

It is started from the trivial fact, that it is possible to attain some arbitrary point of the working space, respecting the kinematic constraints of the manipulator, by using only three degrees of freedom. In that case there exists an unifold connectinon between the mentioned three angles and the corresponding point C, defined for instance by Cartesian coordinates x, y, z. It follows that by using only the so-called basic manipulator configuration, consisting of two members, possibility is acquired to move its tip along some prescribed trajectory from one point to another in unifold manner. The chosen manipulator tip trajectory can have an arbitrary form and the synthesis itself of the prescribed kinematics is in principle invariant with respect to its form. Hence in the general case the connection between the working point C(x,y,z) and the angular coordinates of the manipulator can be represented as

$$x = f_1(\Phi_1,\Phi_2,\Phi_3) \;;\quad y = f_2(\Phi_1,\Phi_2,\Phi_3) \;;\quad z = f_3(\Phi_1,\Phi_2,\Phi_3) \tag{17}$$

Under the supposition of sufficiently small increments of the manipulator tip motion between two points, the following relations can be written, connecting the increments of the Cartesian and angular coordinates [7], [8], [9].

$$\left(\frac{\partial f_i}{\partial \Phi_1}\right)_{\Phi=\Phi_o}\Delta\Phi_1 + \left(\frac{\partial f_i}{\partial \Phi_2}\right)_{\Phi=\Phi_o}\Delta\Phi_2 + \left(\frac{\partial f_i}{\partial \Phi_3}\right)_{\Phi=\Phi_o}\Delta\Phi_3 = \Delta q, \qquad \Delta q = (\Delta x,\ \Delta y,\ \Delta z)^T \tag{18}$$

whence it follows:

$$[A]\begin{Bmatrix}\Delta\Phi_1\\ \Delta\Phi_2\\ \Delta\Phi_3\end{Bmatrix} = \begin{Bmatrix}\Delta x\\ \Delta y\\ \Delta z\end{Bmatrix} \tag{19}$$

where the general element of matrix A has the form

$$a_{ij} = \frac{\partial f_i}{\partial \Phi_j}\ , \qquad i,j = 1,2,3$$

In the scope of the manipulator basic configuration kinematic trajectories, constructed in such manner, various typical manipulation tasks can be formulated.

One of such tasks is the so-called "drink-test", originally created in the period of realizations of the rehabilitation manipulators.

At the basis of algorithm (19) the corresponding trajectories of the basic adopted configuration of the manipulator have been constructed.

Based on the prescribed kinematics, the nominal driving torques of the minimal configuration can be calculated [8]. These driving torques realize the nominal trajectories ensuring desired movements of manipulator.

The incapability to solve the complete manipulation task by means of the minimal manipulator configuration is remplenished by the third member (terminal device), which performs the compensating movements. The complete manipulation task concerns in the general case transfer of particular objects and operations on (or with) the same. Thus some particular manipulation task is defined via certain dynamic conditions, to be satisfied during its motion or operation. In other words, conditions are set on the inertial force of the object $\vec{F}_o$ and the moment due to inertial forces $\vec{M}_o$:

$$f(\vec{F}_o, \vec{M}_o) = 0 \tag{20}$$

Evidently that these dynamic conditions can be reduced to purely kinematic conditions (constraints). Under the supposition that slippage does not exist between the object and the terminal device the inertial force and the moment of inertial forces are determined by means of the complete manipulator dynamics and the external forces (reactions), acting on the object:

$$\begin{aligned} \vec{F}_o &= \Phi_1(\tilde{\phi},\dot{\tilde{\phi}},\ddot{\tilde{\phi}},\phi^*,\dot{\phi}^*,\ddot{\phi}^*,\vec{R}^E) \\ \vec{M}_o &= \Phi_2(\tilde{\phi},\dot{\tilde{\phi}},\ddot{\tilde{\phi}},\phi^*,\dot{\phi}^*,\ddot{\phi}^*,\vec{M}^{R}E) \end{aligned} \tag{21}$$

where $\tilde{\phi}$ - are generalized coordinates of the minimal configuration (programmed kinematics), $\phi^*$ - generalized coordinates of the mechanism compensating part (terminal device), $\vec{R}^E, \vec{M}^{R}E$ - resultant of the external forces (reactions) and the resultant moment due to them.

Under the supposition that $\vec{R}^E$ and $\vec{M}^{R}E$ are determined by measurement, by simultaneously solving expressions (20) and (21) one gets the conditions to be satisfied by the compensating dynamics. Based on these dynamic conditions the synthesis of the adaptive level is carried out; the fulfilling of these conditions in the control sence can be realized in several ways [7],[10].

Here is proposed a procedure for the synthesis of the adaptive control level, based on force feedback. As already stated, the conditions of the manipulation tasks mostly concern the object dynamics, i.e. the inertial force $\vec{F}_o$ and the moment $\vec{M}_o$, so it follows that significant simplifications in the control synthesis can be obtained if the mentioned dynamic parameters are directly measured and controlled. With this goal, force transducers are introduced in the points of contact between the gripper and object, so that the forces acting between the object and the terminal device are measured.

If we denote by $\vec{R}_\ell$ the force of the $\ell$-th transducer at the gripper and by $\vec{r}_{o\ell}$ the vector from the object center of gravity to the $\ell$-th transducer, then from the conditions of kinetostatic equilibrium of forces and moments, acting on the object, one gets the following expressions:

$$\begin{aligned} &\vec{F}_o + \vec{G}_o + \sum_\ell (-\vec{R}_\ell) + \sum_k \vec{R}^E_k = 0 \\ &\vec{M}_o + \sum_\ell \vec{r}_{o\ell} \times (-\vec{R}_\ell) + \vec{M}^{R}E = 0 \end{aligned} \tag{22}$$

where $\vec{G}_o$ is the force of the object gravitation, and the summation with respect to $\ell$ comprises all transducers on the gripper. By measuring $\vec{R}_\ell$ can be, as follows, obtained $\vec{F}_o$ and $\vec{M}_o$, under the condition that the external forces and the moment due to them are known.

Let the values of $\vec{M}^*_o$ and $\vec{F}^*_o$ be known, satisfying the dynamic conditions (20) of the considered manipulation task. By measuring $\vec{R}_\ell$ the deviations $\Delta\vec{F}_o$ and $\Delta\vec{M}_o$ from the ideal values can be determined. The compensation of these deviations can be realized directly via feedback from the transducers to the driving torques of the joints.

Here the problem of classical "drink-test" will be examined in brief. The precalculated "drink-test" synergy of the two-member part of the manipulator is presented in Fig. 6. Desired transfer of the glass from one point to another has to be performed in such a way to keep the longitudinal axes of the glass parallel with Z-axes. In this case, the moment of inertial forces $\vec{M}_o$ of the object should be equal zero. It is recommandable to impose some limitations to the values of inertial forces of the glass in order to prevent liquid spilling from the glass. Thus, in this particular case dynamic condition (20) of the particular task can be written in the following concrete from $\vec{M} = 0$, $|\vec{F}_o| < |F|$, where $|F|$ is norm of restricted inertial force. In this way we are able to determine compensating driving torques in unifold manner. The second condition can be achieved by moderately slow motion of the first two members. The remaining part of the dynamic task reduces to the condition that the total angular velocity and acceleration of the third member be made equal zero. The condition to be satisfied by the reaction forces is:

$$\sum_{(\ell)} \vec{r}_{o\ell} \times (-\vec{R}^*_\ell) = 0 \tag{23}$$

where $\vec{R}^*_\ell$ - ideal value of reaction force, which has to be reached in order to obtain appropriate transfer of the glass. Now by measuring the reaction forces it can be verified whether in the particular moment, during the transfer of the glass, the conditions (23) were fulfilled. If this is not the case, it means that some rotations of the glass and some additional accelerations appear and thus, correcting driving torques have to be introduced [8],[9].

*Example*

Simulation of the 6 degrees of freedom manipulator dynamics (Fig.5) has been performed. The synthesis of the manipulator minimal configuration dynamics, based on prescribed kinematics (Fig. 6), has been described in earlier text of the paper.

The synthesis of the programmed dynamics was realized via force feedback. The results of the compensating movements of the third member are given in Fig. 6.

However, one can conclude, that the performance of maintaining the object axis vertically is not fully satisfied in the intervals of accelerating and deccelerating of the manipulator, which evidently originates from two reasons. The first one lies in the fact, that the dynamics of the basic configuration is developing fast (whole movement in 1,5 sec.), while the second one should be sought in the too strict request of maintaining the object axis vertically during the manipulation task. By the way, the mentioned condition is not purposeful in certain cases of liquid transfer, because it demands limitations in the motion velocity of the minimal configuration, due to the advent of great inertial forces, liable to cause spilling of the liquid. In further development of these algorithms, this fact will be taken care of.

*Realization of Artificial Anthropomorphic Gait*

With the goal of verifying the presented theoretical approach, during the last few years have been designed and constructed several versions of the biped walking machine in the form of active anthropomorphic exoskeletons. Power was supplied by compressed air of 6-10 bars pressure, and the actuators were double-acting pneumatic cylinders of classical design, but special technology had to be applied in order to enable execution of the whole cylinders from duralumin tubes and stock, with the exception of the rods, made of stainless polished steel. Fig. 7. shows the latest version of the active exoskeleton with pneumatic drives.

During 1974 was constructed the prototype of the active exoskeleton with electric drives (Fig. 8). With this version the electronic control system was mounted on the chest part of the main corselet and electric D. C. servomotors of high specific power were used as primary actuators, with adjoint mechanical reducers of special design. The motors, driving the hip joints, actuated kinematically two more degrees of freedom: round the vertical axis, producing artificial "pelvic twist", and round the longitudinal axis, producing artificial "pelvic tilt", thus realizing all three degrees of freedom in the hip joint. The motors at the knee joints actuated in the swing phase the knee joint, the foot being fixed, while in the stance phase the same motor actuated the ankle joint, the knee joint being fixed in the position of full extension. The weight of the prototype was excessive, round 19 kp, but in the future models, profiting of the experience, new materials (titanium) and technology, it is expected to reduce this figure to 12-13 kp. This model awaits full evaluation with several patients. It is also expected to mount special type batteries onto the corselet in the nearest future, creating a fully autonomous walking system.

Experiments with several paraplegic patients were carried through, using the pneumatic version of the active exoskeleton. Best results so far were achieved with the latest model (Fig. 9), the patient carrying with himself a light duralumin four-legged support. After approximatelly two hours' practice, the partient was able to perform very stable walk, make shallow turns to either side and pass through relatively narrows doors [11], [12].

It is expected to achieve self mounting of the modified apparatus by the patient himself, and autonomous use of the same in closed environments in the near future.

*Conclusion*

This paper was intended to present a new method for the synthesis and control of anthropomorphic motion, e.g. artificial gait and manipulation movements. Beside the synthesis of the nominal dynamic states, the algorithm for the system stabilization under the action of large perturbations has been elaborated. By solving the problem of the synthesis and control of artificial anthropomorphic motion the real possibility has been acquired to solve the problems of great diomensionality in an efficient way also with some other, quite different classes of systems. The presented method has the advantage of enabling the calculation of various nominal states of the system at the basis of partially given solutions, which are interesting for its working region. By means of memorizing the mentioned solutions one arrives to the real possibility to control such systems in real time, without calculating the system dynamics in real time. It should be underlined here that recognizing the set of trajectories, which correspond the best to the momentary perturbation of the system and the execution of the control signals, can be performed in a time interval, by two orders of magnitudes shorter from that one, needed for on-line calculations of the new dynamic states in changed working conditions of the system. In that way the problem of the control in real time has been solved in the case of systems, which are very critical concerning the need for fast stabilization of their perturbed states. The problems of stabilizing the biped gait or manipulation movements present cases of dynamic processes, where the decisions should be taken during a time interval of 1-2 secs. which is a normal time interval of an usual step or manipulation movement.

The displayed theoretical results have found its application and full justification in the realization of orthotic and prothetic devices, notably their control parts. They have enabled high dynamic performance of active exoskeletons and rehabilitation manipulators without the use of expencive and bulky control equipment, containing some sort of electronic processor.

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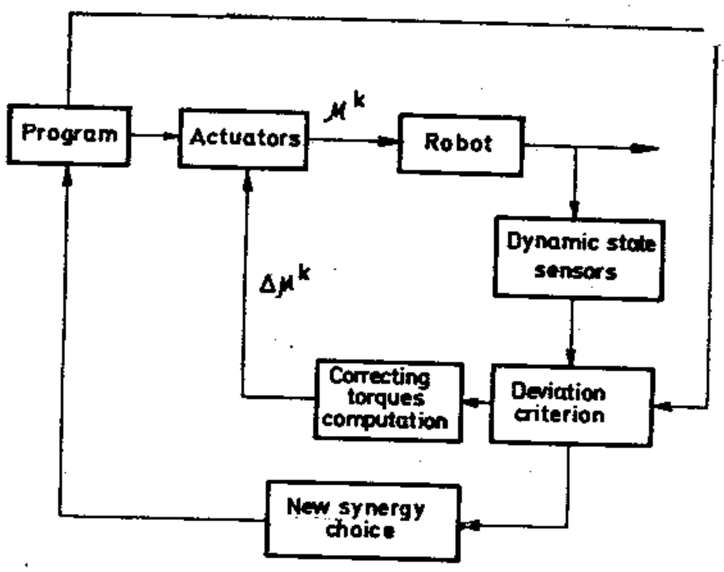



Fig. 1 General Stabilization Block Scheme

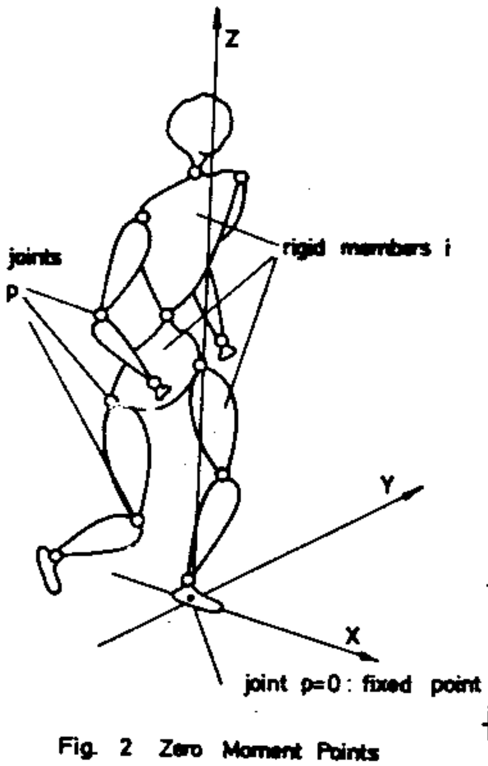



Fig. 2 Zero Moment Points of Anthropomorphic System

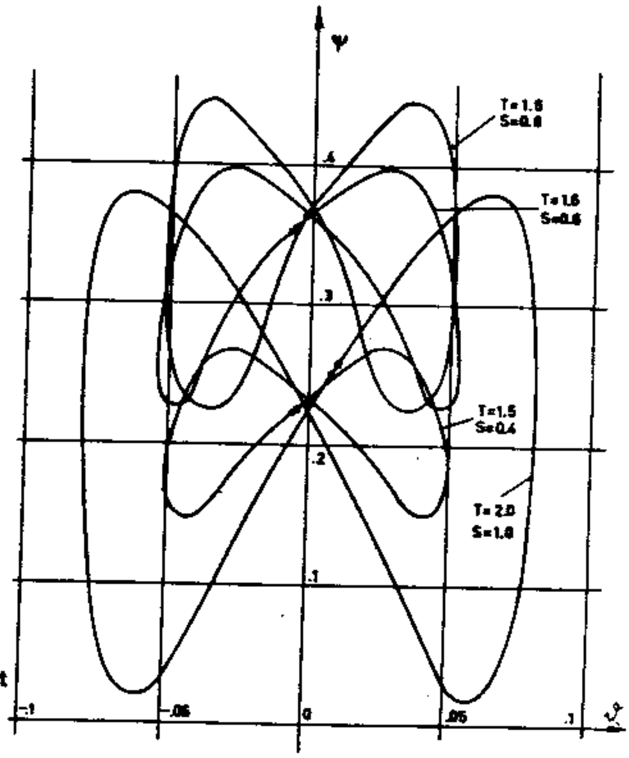
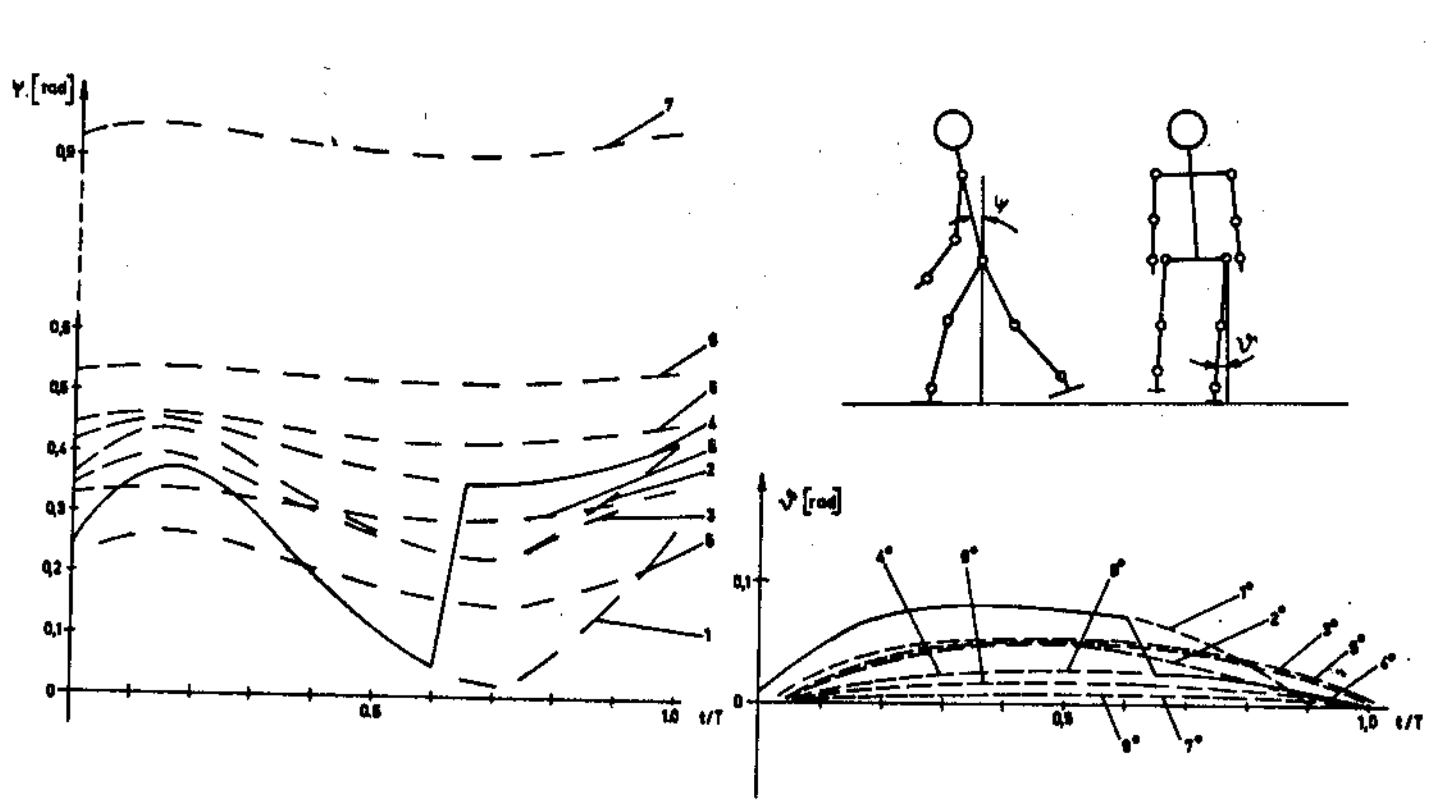



Fig. 3 Compensating Motion for Level Walk




a) angle of upper body in sagittal plane

b) angle of upper body in frontal plane

Fig. 4 Set of ideal synergies for upper part of biped system (Dotted lines)

Transition to new synergy in case of perturbations (Solid line)

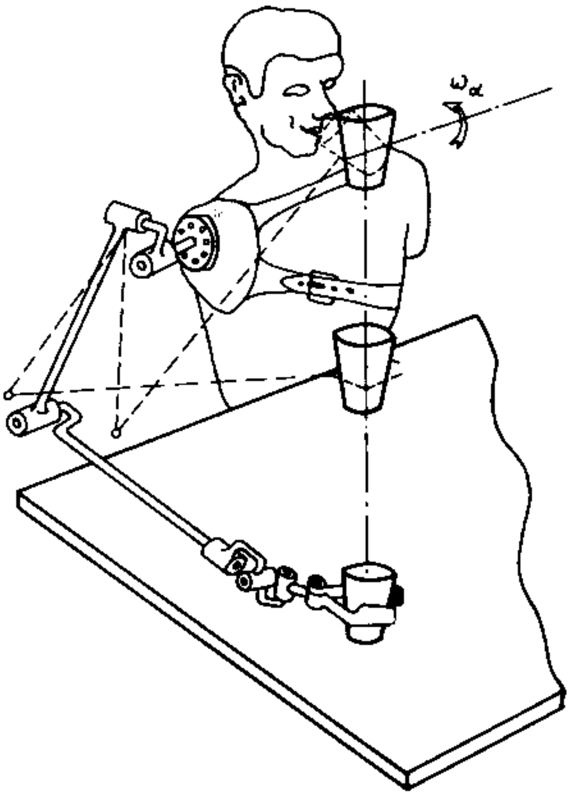



Fig. 5 "Drink — Test" Movement

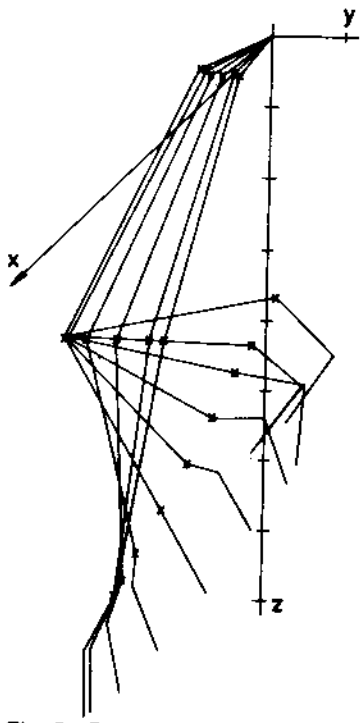



Fig. 6 Drink - Test Simulation with Compensating Movements

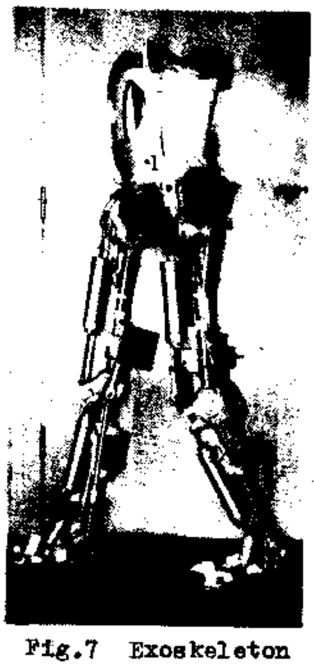


Fig.7 Exoskeleton

Fig.8 Exoskeleton

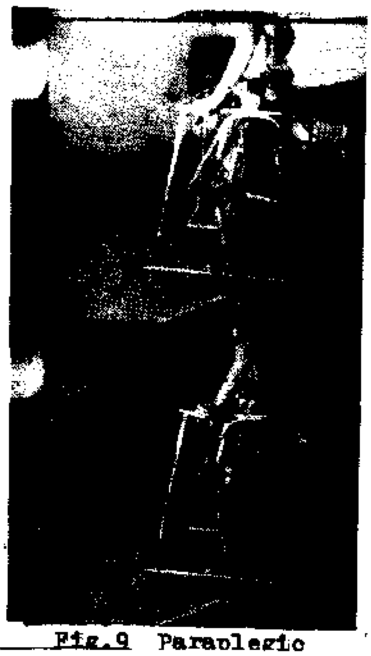


Fig.9 Paraplegic

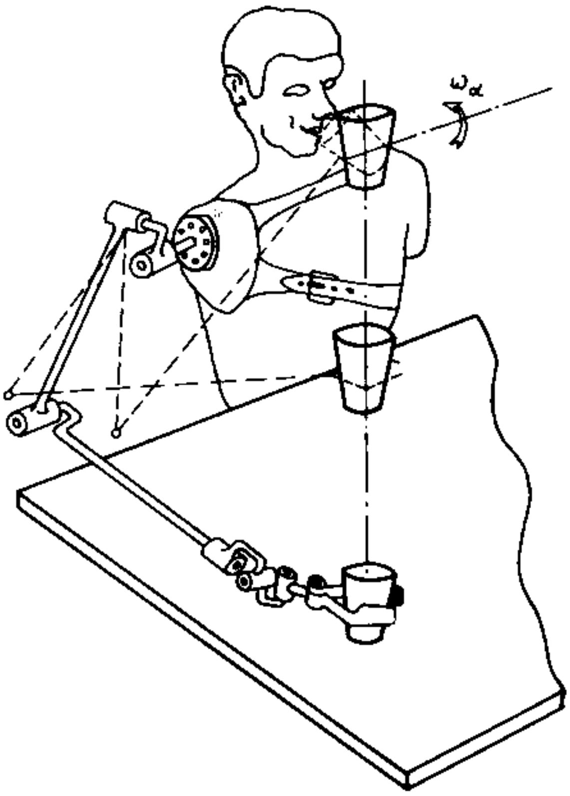



Fig. 5 "Drink — Test" Movement

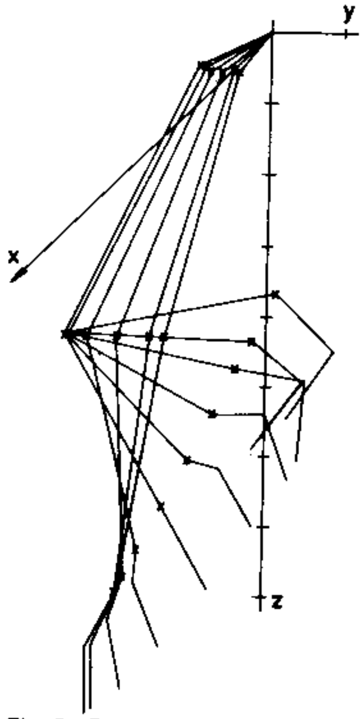



Fig. 6 Drink - Test Simulation with Compensating Movements

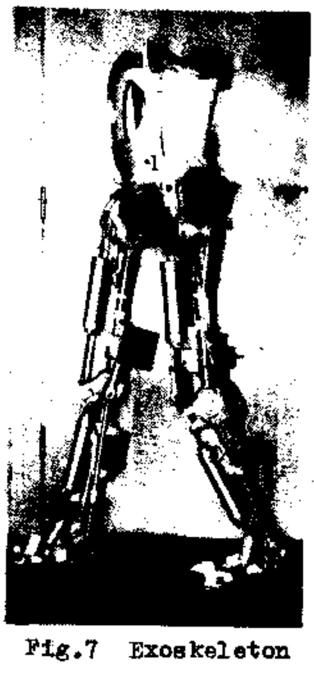


Fig.7 Exoskeleton

Fig.8 Exoskeleton

Fig.9 Paraplegic