SIGNIFICANCE OF THE FORCE-FEEDBACK IN REALIZING ARTIFICIAL MOVEMENTS OF EXTREMITIES

M. Vukobratović and D. Stokić

Summary

This paper presents the principles of utilizing the force feedback in synthesizing artificial movements. The basic characteristic of this principle lies in applying the useful information on the forces in external environment - extremity contact points when forming simple control algorithms. Algorithms based on this principle are illustrated by the example of artificial gait synthesis and some manipulation tasks.

Introduction

The notion of force feedback is mainly associated to the control of technical systems or, to be more precise, to the synthesis of the accompanying servosystems. Since this is a purely technical problem, such an aspect of control systems synthesis will not be discussed here. The force feedback, as considered in this paper, has a completely different meaning.

Namely, what is in question here is an idea, concerning the delicate problems of synthesizing and controlling artificial motion, on how to simplify sufficiently the control system itself so as to render it purposeful, which means applicable to rehabilitation devices for severely handicapped persons. Accordingly, measuring the forces and utilizing the permanent information on intensity and position of the resultant force, form part of the control algorithm. In what way are the forces used in a general control algorithm? Explanation of such a concept is based on the idea of a two-level concept according to which motion synthesis and control is accomplished by forming nominal regimes and maintaining them under perturbed conditions /1,2,3/. In both synthesis and control of basic regimes, the dynamic force and simple operations with it may substitute the compensating movements which ought to have been realized otherwise by separate actuators and corresponding accompanying servosystems. In order to profit of the advantage of such a procedure it is certainly necessary to have force transducers at disposal. Three cases, being of interest for the practical application of motion synthesis and control, will be considered in this paper. These are the problems of gait, posture and manipulation. What they all have in common is the problem of maintaining the necessary orientation in space. So, for instance, in the case of gait it is necessary to determine the compensating body movements for the given /desired/ motion of lower extremities. The case of posture maintenance is just a special regime of the preceding problem. If manipulation is in question then, e.g., the transfer of a glass with liquid, the so-called "drink test" also reduces to the problem of maintaining the particular object orientation in the working space in which the manipulation task is performed. Let us now consider each of the three mentioned practical rehabilitation tasks separately.

Models and Control of Active Rehabilitation Mechanisms

Biped systems, as well as rehabilitation manipulators, belong to the class of anthropomorphic active mechanisms composed of members connected mainly by revolute joints /4,5/. Taking into account the fact that environment acts on such mechanisms via forces in extremity - environment contact points, the mathematical model of mechanism dynamics may be written in the general form:

$$\mathcal{M} = H(\emptyset)\ddot{\emptyset} + h(\emptyset,\dot{\emptyset}) + \sum_{\ell=1}^{L} \delta_\ell g_\ell(\emptyset)F_\ell \qquad (1)$$

where: $\mathcal{M} \in R^n$ - the vector of driving torques in mechanism joints, $\emptyset \in R^n$ - the vector of internal angles of the mechanism /angles between adjacent chain members/, $H(\emptyset) : R^n \rightarrow R^{nxn}$, $h(\emptyset,\dot{\emptyset}) : R^n x R^n \rightarrow R^n$,

$$\delta_\ell = \begin{cases} 1 & \text{if contact exists in point } \ell \text{ of the mechanisms and the environment} \\ 0 & \text{otherwise} \end{cases}$$

$g_\ell(\emptyset) : R^n \rightarrow R^{nx3}$, $F_\ell \in R^3$ -the vector of the force acting on the mechanism in the l-th mechanism - environment contact point, L- - the number of contact points /if $L \rightarrow \infty$, the sum in equation (1) is substituted by the resultant external force/, **n** - the number of mechanism degrees of freedom. If, for example, a rehabilitation device for producing artificial gait /exoskeletons for paraplegics/ or a rehabilitation manipulator are in question, then, out of **n** degrees of freedom of the mechanism, $m(\angle n)$ degrees are powered by the corresponding actuators. The general form of actuators models is given as

$$\dot{x}^i = A^i(x^i) + b^i u^i + f^i \mathcal{M}_i \,, \qquad i = 1,2,\ldots,m \qquad (2)$$

where: $x^i \in R^{n_i}$- the vector of the i-th actuator state coordinates, $A^i(x^i) : R^{n_i} \rightarrow R^{n_i}$, $b^i \in R^{n_i}$, $f^i \in R^{n_i}$, u^i- the scalar input for the i-th actuator, n_i - the model order for the i-th actuator.

The control for realizing the functional movements of anthropomorphic mechanisms is taken in the form /1,2,6/:

$$u^i = u^i_{nom}(t) + u^i_{loc} + u^i_{G\,1} + u^i_{G\,2} \,, \quad i = 1,2,\ldots,m \qquad (3)$$

where: $u^i_{nom}(t)$ - the nominal programmed input realizing the functional movement under ideal conditions without perturbations and errors in initial conditions.

u^i_{loc} - the local control introducing the feedback with respect to only model state coordinates of the i-th degree of freedom: $u^i_{loc} = u^i_{loc}(x^i)$;

$u^i_{G\,1} = u^i_{G1}(\mathcal{M}_i)$ - the global control which is to diminish the influence of coupling /loading/ $\mathcal{M}_i$ on the i-th actuator subsystem and thus provide for tracking of the nominal trajectory with the i-th actuator;

$u^i_{G\,2} = u^i_{G\,2}(F_\ell)$ – the global feedback with respect to forces in mechanism – environment contact points which is to provide the global dynamic system stability.

As may be seen, the force feedback may be applied to diminishing the influence of coupling among mechanism degrees of freedom which provides for the local stability of subsystems – degrees of freedom. On the other hand, the feedback with respect to environmental forces acting on the mechanism enables the realization of the desired mechanism orientation with respect to the environment.

As has already been pointed out in the Introduction, this paper deals with a different aspect of the force feedback. Obviously, the feedback with respect to the loading in mechanism joints makes it possible to diminish the influence of coupling and, thus, simplify the control /renders possible the decoupled control/, while the global force feedback provides for the global functional system task to be realized, i.e., the global dynamic system stability in the absolute system.

The Task of Anthropomorphic Gait Control

In the case of a biped anthropomorphic system of exoskeleton type /Fig. 1./, the contact with environment is realized via forces acting on the feet /7/. The condition imposed in this case is that, for the desired motion of lower extremities, the mechanism satisfies its orientation with respect to the absolute system, which means, to prevent the mechanism with a patient from falling down. Since the mechanism – environment contact is realized via forces which are, by their nature, dynamic ones, this condition of maintaining the orientation in space may be transformed into the dynamic condition of maintaining the resultant force, acting on the foot in contact point with the support, in the desired position, namely on the desired path on the foot. The point in which the support resultant force is acting is called the zero moment point /ZMP/, since the total moment of all gravitational and inertial forces must equal zero for that point /1,5/. From this dynamic condition requiring the ZMP during gait to be on the prescribed trajectory on the foot, we may calculate the compensating movements of the trunck which provide the dynamic system equilibrium for the prescribed leg trajectories. This renders possible the determination of programmed inputs

The local control u^i_{loc} and global control u^i_{Gl} provide for tracking of prescribed /calculated/ trajectories under perturbed conditions as well, for the degrees of freedom powered by the corresponding actuators. However, the degrees of freedom between the support and feet in real biped systems have no actuators /directly uncontrollable/, so maintenance of the mechanism orientation with respect to the absolute system is not provided under perturbed conditions. It is, therefore, necessary to introduce the feedback with respect to forces in foot – support contacts which is to provide for maintaining the ZMP in the desired momentary position, namely it is necessary to introduce the global control $u^{F}_{G\,2}(F_\ell)$. For this purpose, force transducers are introduced in mechanism feet /1,8/. Minimum three force transducers have to be introduced in the foot, as shown in Fig. 2. It is possible, by measuring the forces, to calculate the ZMP deviation from the desired momentary position, namely, to introduce the correcting control with respect to external forces moments with regard to the desired ZMP position:

$$u^{\psi}_{G\,2} = K^{\psi} \Delta M_y = K^{\psi}\left[s_3F_3 - s_2(F_1 + F_2)\right]$$

$$u^{\theta}_{G\,2} = k^{\theta} \Delta M_x = K^{\theta} s_1(F_1 - F_2) \qquad (4)$$

$$s_j = s_j(t)\ , \quad j = 1,\ 2,\ 3$$

where: u^{ψ}_{G2}, u^{θ}_{G2} – global control for the trunck degrees of freedom. The angles ψ, θ are as shown in Fig. 1. What is achieved by introducing (4) is that the trunck performs compensating movements for the purpose of maintaining the ZMP in the desired position in case of perturbations. So, by introducing the global force feedback $u_{G2}(F_\ell)$ it is possible to realize the tracking of prescribed nominal trajectories and provide for the global, dynamic system equilibrium.

With certain approximations /comparatively slow gait/, the control scheme can be considerably simplified. Namely, we may take that $u^{\psi,\theta}_{nom} = 0$, $\psi_{nom}=0$, $\theta_{nom}=0$, and prescribe only the lower extremities trajectories realized by the corresponding systems in leg joints via local u^i_{oc} and global control u^i_{Gl}. In this case, nominal trajectories for the trunck are not calculated from the dynamic equilibrium condition; the dynamic equilibrium condition is completely provided by the global control of form (4), by ensuring the desired ZMP motion through (4). Such control is extremely simple, which results from the fact that the feedback with respect to forces in mechanism – environment contact provides direct information on the system state with respect to environment, its orientation with respect to the absolute space, namely on the dynamic system equilibrium for which these forces are directly "responsible". In this case, we may easily calculate the on-line control (4) which, by prescribing $s_j(t)$, $j= 1,2,3$ provides the desired ZMP motion, through (4) which determines the compensating motion of the trunck. Stabilization of uncontrollable degrees of freedom is practically realized with this feedback. Force feedback renders possible the global feedback which stabilizes these degrees of freedom and, thus, provides the mechanism orientation with respect to the absolute system.

The Task of Biped Posture Maintenance

Posture maintenance of a biped anthropomorphic system may be reduced to the previous case of anthropomorphic gait under the assumption that the positions of legs' angles in the desired posture are prescribed instead of nominal trajectories of the legs. The task reduces to maintaining these positions of degrees of freedom under perturbed conditions. What should be provided in this case is that the **point of attack** of the resultant of external forces /static/ acting on the foot due to the support takes the position corresponding to the desired system posture. This task may be solved with the global force feedback in the form (4), /9,10/, with $s_j(t) = s_j$=const, j=1,2,3 in this case. The servosystems in leg joints are to provide, via u^i_{loc} and u^i_{G2}, the maintenance of the desired angles of leg degrees of freedom, while the global feedback (4) is to realize the trunck motion, so that the resultant static* force due to the support assumes the corresponding position.

It should be mentioned here that in both cases /posture and gait/ the force feedback is effective only in a finite zone of initial conditions, determined both by constraints with respect to control and physical characteristics of the system /loss of the foot - support contact due to larger deviations in angle/. In case of larger perturbations, a higher control level should be applied, the so-called stabilization of large perturbations /1,2,8,9,10/.

Early results achieved in practical realization of the force feedback for the case of posture of the exoskeleton with a patient are quite satisfactory.

The Task of Rehabilitative Manipulation

In the case of an anthropomorphic manipulator, the task most often imposed consists in transferring a working object maintaining at the same time its particular orientation in space. A typical task in rehabilitative manipulation is the drink-test. The procedure of solving this task is the same as in the case of biped gait. Nominal trajectories are prescribed to manipulator minimal configuration /the first three degrees of freedom in Fig. 3./ so as to provide for the motion of the terminal device, namely working object along a desired trajectory in space. In the drink-test, the condition imposed is that the dynamic moment acting on the vessel with liquid round the center of gravity be equal zero /or, of minimum value/ during the transfer, which may be reduced to the kinematic condition of the vessel orientation with respect to the absolute vertical. The nominal compensating movements of the terminal device are calculated from this condition, namely   for all manipulator degrees of freedom is calculated /11, 12/.

The realization of nominal trajectories under perturbed conditions may be performed via u^i_{loc} and global control with respect to joints moments u^i_{G1}.

In this case, as well, it is possible to introduce the feedback with respect to environmental forces acting on the mechanism. For this purpose, force transducers are introduced in contacts between the terminal device and working object, by means of which the environmental influence on the mechanism is directly measured. It is possible, by measuring these forces,

---

*) In principle, the global feedback need not necessarily be established on the trunck degrees of freedom. This feedback may be introduced via some degrees of freedom of legs /e.g. ankle joint/

to determine the moment round the c.o.g. of the working object if deviation from the nominal occurs. Introduction of the global feedback in form:

$$u^{i}_{G\,2} = -K^{i}\Delta M = -K^{i}\sum_{\ell=1}^{L} r_{o\ell} \times F_{\ell} \qquad , \quad i = 1,2,\dots,6 \qquad (5)$$

where: $\Delta M \in R^3$ - the moment vector round the object c.o.g., $r_{o\ell} \in R^3$ - the positional vector from the object c.o.g. to the 1-th transducer, can provide for tracking the nominal and maintaining the prescribed object orientation in the perturbed regime. The control (5) ensures the moments round the vessel c.o.g. to equal zero. However, the control may be significantly simplified in this case as well. Assuming the motion of minimal configuration to be relatively slow, we may take that $u^{i}_{nom} = 0$ for actuators of the terminal device; without explicitly calculating the trajectories of the terminal device, maintenance of the desired orientation in space is provided by the global control of form (5) only. Namely, it is sufficient to realize, by measuring the forces in terminal device - object contacts and calculating the moment acting on the object round the c.o.g., the compensating motion and the object will maintain the desired orientation in space /namely, the moment round the c.o.g. is maintained at zero, as in the case of gait, namely, maintaining the ZMP position/. Such control scheme is extremely simple, since forces measurement gives direct information on the object /terminal device/ orientation in space. Fig. 4. presents the result of digital simulation of the drink test; the minimal configuration realizes the motion of the terminal device and object along the desired trajectory in space on the basis of control in form (3), while the compensating motion of the terminal device is realized via global control in form (5).

It should be mentioned that such global control is insensitive to variations in parameters /weight, inertial moments, and the like/, which is of significance for rehabilitation applications. In addition, the force feedback renders possible simple control in tasks in which manipulator - working environment contact occurs /the example of inserting the object into the hole/. Environmental effects on manipulator functioning may be practically eliminated by such control.

Conclusion

This paper was aimed at emphasizing the extremely important role of the force feedback, which may and ought to find practical application in rehabilitative devices of both locomotion and manipulation type. When synthesizing the control system for these devices, it is of particular importance to simplify sufficiently the control concept to make it satisfy the specific application requirements for rehabilitation purposes. Experience gained up to now in the realization of similar systems, with the force feedback introduced into their control mechanisms, has proved them to be significantly advantageous over classical systems in which this information is not used. In the realization of various orthotic and prosthetic devices in both manipulation and locomotion, such a control concept applying the force feedback may be of extreme significance for wider application of these devices to the rehabilitation of handicapped persons. Such a statement implicitly assumes some other prerequisites to be satisfied, especially if real application of active exoskeletons is in question. However, the discussion on the purposefulness of exoskeleton application under present conditions as well as perspectives for their future application exceeds the thematic domain of this paper. A detailed review and insight into the state-of-the-art and prospectives of such devices may be found in References /13,14/.

References

/1/ Vukobratović, M., Stepanenko, Yu., "On the Stability of Anthropomorphic Systems", Mathematical Biosciences, Vol. 15, 1972.

/2/ Vukobratović, M., "How to Control the Artificial Anthropomorphic Systems", Trans. on Systems, Man and Cybernetics, Sept. Issue 1973.

/3/ Vukobratović, M, Stokić, D., "Dynamic Control of Unstable Locomotion Robots" /in Russian/, Technicheskaya Kibernetika, No. 5, 1875.

/4/ Vukobratović, M, Stepanenko, Yu., "Mathematical Models of General Anthropomorphic Systems", Mathematical Biosciences, Vol. 17, 1973.

/5/ Vukobratović, M., Legged Locomotion Robots and Anthropomorphic Mechanisms, Monograph, Institute "M. Pupin", POB 906, Beograd, Yugoslavia.

/6/ Vukobratović, M. et al., "One Method of Control for Large-Scale Humanoid Systems", Mathematical Biosciences, Vol. 36, No. 3-4, 1977.

/7/ Vukobratović, M., Hristić, D., Stojiljković, Z., "Development of Active Exoskeletons", Medical and Biological Engineering, January 1974.

/8/ Vukobratović, M., Stokić, D., "Dynamic Stability of Anthropomorphic Active Mechanisms", Mathematical Biosciences, Vol. 26, 1975.

/9/ Vukobratović, M., Stokić, D., "Postural Stability of Anthropomorphic Active Mechanisms", Mathematical Biosciences, Vol. 26, 1975.

/10/ Stokić, D., Controbution to the Dynamic Stabilization of Unstable Locomotion Robots, /in Serbocroatian/, M.Sc. Thesis, Center for Multidisciplinary Studies, Beograd, 1976.

/11/ Vukobratović, M., Stokić, D., "Algorithmic Control of Anthropomorphic Manipulators" /in Russian/, Technicheskaya kibernetika, No. 3, 1976.

/12/ Vukobratović, M., et al., "Algorithmic Control of Assistive Devices for Severely Handicapped Persons", Proc. of V IFAC Symp. on External Control of Human Extremities, Dubrovnik, 1975.

/13/ Vukobratović, M., Hristić, D., "Synthesis and Control of Artificial Anthropomorphic Motion", Proc. IRIA [illegible], Basel, 1978., invited paper.

/14/ Hristić, D., Vukobratović, M., "Further Development of Lower Limbs Active Orthoses" /in German/, Journal of Orthopaedie Technik, No. 4, 1978.

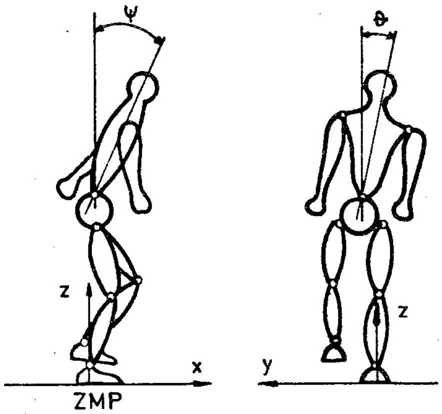

Fig. 1 Mechanical model of biped system

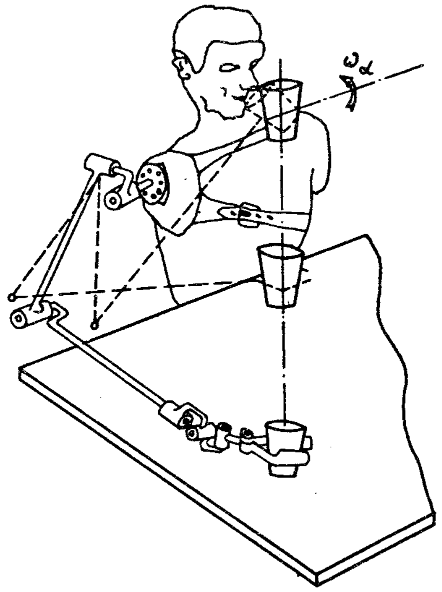

Fig. 3 6-Degrees of freedom manipulator

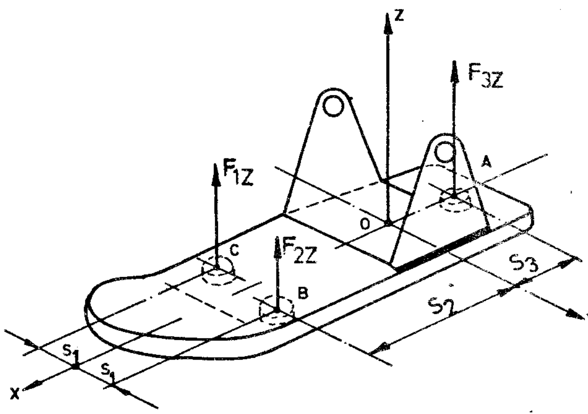

Fig. 2 Measurement of ground reaction forces

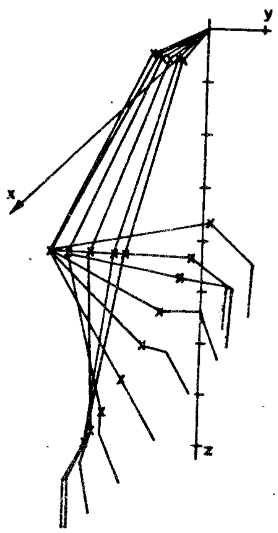

Fig. 4 "Drink-test"-simulation