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CONTROL OF ASSISTIVE SYSTEMS BY EXTERNAL REFLEX ARCS

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ABSTRACT - A non-numerical method for the control of externally powered assistive systems is presented. The approach is based on bionic principles. Basic control element is the artificial reflex arc which acts upon four state joint actuators when appropriate external proprioceptive and exteroceptive sensory patterns are recognized. The knowledge base, consisting of collection of reflex arcs, is transferred from the man to the computer by analyzing functional motions in vivo. Method to identify formally the necessary reflex arcs controling specific functional motions is described. Applications pertinent to rehabilitation engineering are given.

1. INTRODUCTION

Externally powered assistive systems have been given much consideration in rehabilitation engineering. A wide spectrum of solutions, ranging from simple servomechanisms to computer controlled multivariable systems, have been proposed as active prosthetic and orthotic devices for upper and lower extremities. Taking into account all the advances in control engineering and computer technology in last decades, it is surprising to discover that only a rather narrow range of active prosthetic and orthotic devices have found their way to field applications.

Evidently, the inefficient transfer of advanced technology into the rehabilitation field cannot be explained by the lack of efforts. The reasons for such a state of affairs are much deeper. In this paper, we shall deal only with fundamental issues related to the control of externally powered assistive systems. Even this specific aspect appears to be too general since control of human extremities is a highly complex phenomenon. The control of functional motions can be divided into following levels:

- scene analysis,
- motion planning,
- motion execution.

In rehabilitation engineering, as different from general robot design, the direct involvement of the handicapped in the control of the assistive system takes care of the voluntary and the vision level. Even so, externally powered assistive systems represent a unique challenge to the control tehory. Namely, externally controlled machine must be integrated into a multi-level, biologically controlled, system.

So far, a general, rigorous, principle, serving to derive optimal multi-level control structure for assistive systems is lacking. The best what can be done is to transfer to the assistive machine some general rules which govern the biological motor control rather than to impose upon the handicapped the principles of machine control. Following this line of reasoning, two basic ideas have served as guidelines in the quest for new types of assistive systems, and robots, in general:

- Non-numerical nature of certain motor activities in the buological world[1,2].
- Principle of Maximum Autonomy[3].

Since the whole paper discusses non-numerical control methods for assistive systems, no further comments on this issue need to be made now. The Principle of Maximum Autonomy, on the other side, simply states that the multilevel structure controling functional motions operates in such a way as to minimize the interventions from upper levels. In other words, the execution level should perform functional activities with minimum amount of information exchange with upper levels. It turns out that the non-numerical control of man-machine assistive systems, especially in the form of artificial reflex arcs, provides maximum autonomy in the execution of motions.

2. NON-NUMERICAL CONTROL

Advantages of external reflex arcs in the control of multivariable grasping devices have been presented in several papers[1,4]. However, a general theoretical background for the design of such control systems was not given at that time. The approach applied in above cases relied essentially on intuition and heuristics.

The fact that natural joints display a reduced number of distinct operational modes has led to the conjecture that repetitive functional activities of the animal, especially locomotion, can be artificially reproduced using control models in the form of algorithms performed by asynchronous finite state machines[2]. As known, following four states occur in biological joints: flexion, extension, locked, loose. In this way, the invariant aspects of locomotion cycles come into foreground while the form of transition trajectories between terminal positions of respective artificial joints depends on local control (on-off, linear, non--linear, etc.).

Although the finite state approach to the design of assistive devices offers interesting advantages over conventional solutions, it could not be considered as the final step in the development of non-numerical, biologically oriented, control methods. In order to come closer to this goal, computer methods based explicitely on bionic sensors (proprioceptive, exteroceptive, visual, etc.), non-numerical pattern recognition and pattern matching are needed. The method of artificial reflex arcs to control active assistive systems represents a further move in the desired direction.

3. ARTIFICIAL REFLEX ARCS

The term "reflex arc" as used in this context has no ambition to be the equivalent of its counterpart in neural networks. Nonetheless, it reflects some rudimentary features of reflex loop reactions in the living matter.

The term reflex arc is used here in the following way:

a) Externally powered and controlled joint is activated by artificial proprioceptive and exteroceptive sensors (touch, pressure, angle, etc.).

b) Sensory input to the joint controller is used for recognition of bionic patterns: heel strike, foot contact, terminal flexion, terminal extension, emergency, etc. As seen later, the patterns in question can be recognized by non-numerical, logical expressions.

c) Recognized sensory patterns are directly matched to one of the four joint actuator states: flexion, extension, locked, loose. The mapping rules are derived by analyzing the available data on neuromuscular control of functional motions in the man or in the animal. As explained later, the pattern matching rules stored in the computer of the assistive system reflect actually certain aspects of the accummulated knowledge in the man which he uses to control functional activities.

Above definition of the artificial reflex arc points out clearly to its constraints when comapred with corresponding events in neuromuscular control. In the first place, the definition does not speak of conditioned reflex arcs, adaptive loops, modifications and interactions of the execution level with higher order control. This remains to be studied in the course of the evolution of the expert system in question.

4. RULE BASED CONTROL

Machine control of any dynamic object can function only if a formal model of the plant is available. Evidently, the inherent power of a specific control system to handle complex multivariable dynamic plants depends on general principles used to derive the machine control. As known, the synthesis of numerical control systems relies on principles of physics and mechanics. Control based on artificial reflex arcs cannot be derived in the above way. The methodology by which non-numerical control based on reflex arcs is designed implies the transfer of functional sequences of reflex reactions from the man to the computer. Consequently, the basic issue in this type of control is how to represent the relevant aspects of motor control in the machine.

Taking into account the well known AI principles of knowledge representation, it is essential to select the convenient knowledge "chunks" as basic elements of the control data base. In our case, artificial reflex arcs, as defined above, are taken as knowledge "chunks". Implementation of this approach requires, then, a well defined procedure by which the desired reflex arcs can be identified on the man or on the animal. Since it is postulated that functional motions can be performed using four characteristic joint states, the sensory patterns and pattern matching rules are identified as singular events within the observed motor activity of the respective living creature. Speaking of singularities, we mean discontinuous changes of dynamic variables (speed, direction, acceleration), extremal values of state variables (terminal angles, maximum speed), etc. The assumption that reflex reactions are associated with singular events in sensory information flow and with terminal states of joint rotations is certainly plausible when analyzing neuromuscular control.

In order to illustrate the implementation of the proposed procedure, we shall apply it to the design of rule-based control for the artificial leg with active hip and active knee. The starting information for the synthesis of rule based control in this case is taken from the gait analysis records, Fig. 1.[5] In our terminology, the events in Fig. 1 represent singular points which can be uniquely identified by sensory patterns and joint states. The proposed procedure has been applied and results are presented in Fig. 2 and Fig. 3.

Interesting conclusions can be derived by analyzing the content of the table presented in Fig. 2. In the first place, the reduced amount of the bionic sensory feedback needed for pattern recognition (foot contacts, joint angles) is due to the fact that no dynamics has been involved as yet. It will be shown later how the dynamic situations can be handled by the same approach. A more fundamental conclusion suggested by the table in Fig. 2. is related to pattern recognition. It turns out that patterns associated with proprioceptive and exteroceptive sensory information can be identified by boolean expressions. When interpreted in the context of this application, boolean expressions imply following conclusions:

a) The simultaneous presence of singular sensory inputs is essential for pattern recognition. In other words, the pattern recognition mechanism remains always the same. Only the number of simultaneous inputs changes from case to case.

b) The pattern recognition mechanism being boolean, the time needed to fire a reflex response is independent of the complexity of the recognized pattern. Namely, the time needed to solve boolean equations depends on constant delays associated with the hardware technology rather than on nonlinear functions like in the case of numerical procedures.

c) The changes in joint states are associated with singular values of sensory inputs which provide information about body attitude and body-environment interaction.

The validity of above conclusions cannot be taken, evidently, as rigorously established since they were derived by induction. Only by extending the reflex arcs control to more complex cases, above general statements will gain more credibility.

The table in Fig. 2 represents the nucleus for the design of the desired control system. For that purpose, it is essential to feed the required bionic sensory information to computer input, to organize the access to production rules, define the search procedure and supply adequate control outputs to joint actuators. Details about joint actuators and control software, can be found in references[6,7]. Let it be mentioned that in repetitive functional activities the rule search is deterministic and cyclic, which makes the task quite easy.

5. APPLICATIONS

Due to the very nature of artificial reflex arcs control, it is rather difficult to predict exactly the system performances in real situations. Two important facts must be kept in mind when dealing with this type of control:

1) This approach generates open control systems. Namely, the performance of the control system depends on how much knowledge (reflex arcs) has been transferred to the computer. In addition, a number of parameter values associated with joint state transitions are left open (terminal angles, contact surfaces, etc.) so that they can be adjusted in order to suit the individual needs.

2) Reflex arcs control opens a highly interesting new avenue of research. As known, the spectrum of functional activities in the man is very wide in terms of complexity. It ranges from cyclic, stationary, locomotion activities to posture control, sports, dansing, etc. How far one can proceed along the path of complexity relying just on reflex arcs? At what stage, proportional and voluntary control must be introduced? How is the interaction between hierarchical levels of control organized? Above questions may seem to be irrelevant at the first glance. But, as one proceeds with artificial reflex arcs control up, from the bottom to the top, he will run unavoidably into above dilemmas. They can be solved only by experimenting with more complex machines, i.e., by enriching the knowledge base.

Consequently, two basic lines of experiments must be arranged in order to explore the potentials of reflex arcs machines:

1) Build machines with bionic sensors and reflex arcs which

reproduce more and more complex functional activities.

2) Test man-machine assistive systems under external and internal (biological) reflex arcs control.

We have followed both lines of research in the development of reflex arcs machines.

Active Knee Joint

The design of above knee prosthesis with reflex arcs control of the knee joint is a very convenient case to begin with. The assistive system thus obtained consists of one natural joint (hip), one externally controlled joint (knee) and one passive joint (ankle). With one-sided amputation, one can compare thus the performance of the sound leg and the assisted extremity. Rehabilitative features of such an assistive system are described elsewhere[7].

Adaptive Reflex Arcs

Previously described control rules were concerned with fixed speed, fixed step length locomotion. Terminal angles of the hip and the knee in Fig. 3 are treated as parameters which are preset or modified at the voluntary level. This is in contrast with the biological motor control where the step length, i.e. terminal angles of joints, are automatically adjusted to power and speed variations.

In order to extend the reflex arcs control to dynamic functional activities several basic questions must be answered. In the first place, the deterministic nature of the step length adaptation to speed variations implies an optimization criterion affecting the values of joint terminal angles. There is a general agreement that the evolution of functional motions has followed the path of minimum effort criterion. If so, it still remains to be guessed:

a) what kind of non-numerical procedure can be used to select optimal functional motions,

b) what kind of sensory inputs and patterns are associated with the dynamics of functional motions.

Thinking in terms of reflex arcs control, interesting solutions to above problems have been found. In an early paper, the hint was made that minimum effort motor control implies maximum use of free joint states involved in functional motions[8]. In other words, it requires maximization of ballistic segments of joint trajectories. By rephrasing the minimum effort principle of motor control in this way, it was not difficult to identify articial reflex arcs which assure adaptive terminal angle control of joints.

Adaptive step length control requires that the joint terminal angles (flexion, extension) become functions of power supply P to motor units. In principle, such functions could be obtained by numerical optimization methods writing down state space equations of the given man-machine multivariable system. But it would take a lot of efforts and biomechanic measurements to derive the desired relation. Instead, a non-numerical approach, bypassing above inconveniences has been successfully applied.

In the first place, there is no need to derive minimum effort trajectories of the hip and the knee in the swing phase in terms of explicit solutions. An implicit optimal solution is quite satisfactory provided that the terminal angles within which the respective joint is in free (zero rigidity) state can be determined by reflex arcs. In other words, we need to detect by reflex arcs the initial and the end point of the ballistic segment of the swing phase trajectory when dealing with locomotion, for instance. Two singular points of the swing trajectory are relevant for implicit optimization in this case. In order to avoid undesired ground contact, the initial point of the ballistic segment of the knee trajectory must occur in the vicinity of the vertical line. In other words, the free state of the knee joint begins when the two legs, rotating around the hip in opposite directions, become aligned. Let us remind that this attitude can be detected in several ways. Either with the help of the vertical sensor, or by measuring the maximum angular speed of the hip in the swing phase. The end point of the swing phase is determined by implicit solution of following equations

$$M_1^h(P,\Psi) + M_2^h(\Psi) + M_3^h = 0$$

$$M_1^k(P,\alpha) + M_2^k(\alpha) + M_3^k = 0$$

where $M_1(P,\cdot)$ represents the driving moment due to power input preceding the free joint state and to inertial forces of the system, $M_2(\cdot)$ corresponds to nonlinear damping, including limiters of joint rotation, and M_3 covers all resistive moments. Since we are interested in implicit optimization of hip and knee trajectories in the swing phase, the explicit form of M_2 and M_3 is not needed. The end point of a ballistic segment belonging to the minimum effort joint trajectory in the swing phase can be implicitly recognized by $\dot{\Psi}=0$, $\dot{\alpha}=0$. At that angle value, the available rotational energy of the free leg is consumed acting against nonlinear damping and other resistive moments.

This fact suggests following rule based control for adaptive step length in terms of minimum energy optimization

Knee:	sensory input	joint state
	$\dot{\alpha} = 0$	locked
Hip:	sensory input	joint state
	$\dot{\Psi} = 0$	locked

By adding these rules to the control data base, the flexion terminal angle of the hip Ψ_t^f becomes a state dependent parameter: $\Psi_t^f = f^{-1}(P)$. However, the explicit relation $\Psi_t^f = f^{-1}(P)$ is not needed since we are dealing with its implicit form $f(\Psi_t^f, P) = 0$ at $\dot{\Psi} = 0$, $\dot{\alpha} = 0$.

In order to test the validity of dynamic control by reflex arcs, a terminal device in the form of artificial leg was linked to the computer. The device is shown in Fig. 4. It consists of two cybernetic actuators attached to the hip and the knee, each having four discrete states (flexion, extension, free, locked). The reflex arcs control in Fig. 2 was applied to this artificial leg. Terminal angles of active joints were not taken as fixed parameters but as adaptive variables. The step length adaptivity was tested with respect to variable voltage supply to cybernetic actuators. Evidently, the reduced power supply causes slower system response which, on his side, affects the step length via variable hip terminal angles.

Hybrid Assistive System

Another test of reflex arcs control was conducted in the following way. In the past, the two main lines of research in rehabilitative engineering - the functional stimulation and externally powered assistive systems - have followed their own ways. A bridge between the two trends in rehabilitation of handicapped with motor defficiencies was not easy to establish since, among other things, the control of orthotic devices relied essentially on numerical methods. However, the functional stimulation relies on evocation of remaining internal reflex patterns.

External control by reflex arcs offers the possibility to combine functional stimulation and active orthoses. The starting point in the design of artificial reflex arcs control is the transfer of knowledge from the man to the machine. Equations of motion are not the primary target of such a control. Having this in mind, it was natural to ask the question if external and internal reflex arcs control could be combined into hybrid systems with rehabilitative potential superior to each of the two methods taken by itself. Such hybrid systems should take maximum advantage of the remaining neuromuscular activity of the handicapped by supporting and extending it in the case of need by assistive devices with external reflex arcs.

Systematic exploration of the rehabilitative potential of hybrid systems is still at its very beginning . A pioneering experiment about the feasibility of hybrid systems has been conceived in the following way. Paralyzed patients capable to stand and walk under functional stimulation have been selected for feasibility studies of hybrid systems. In addition to functional stimulation, the patient was fitted with active orthoses on both legs. The active element of the orthoses was the knee joint with two discrete states: free and locked. Flexion and extension was controled by functional stimulation.

The basic control program for each leg consisted of four rules derived from the table in Fig. 2:

extension by functional stimulation
flexion by functional stimulation
knee locked by external reflex arc (extended knee)
knee free by external reflex arc (heel off).

Otherwise, the sensory inputs and sensory patterns affecting muscle activity and knee joint states were the same as in Fig. 2 (ground contact, knee angle, knee terminal angles).

Detailed description of the hybrid experiment is given in the reference[9]. At this point, we wanted only to draw the attention to the fact that a whole spectrum of man-machine systems under external and internal reflex arcs control may become an important new tool in the rehabilitation of the handicapped.

5. CONCLUSION

Non-numerical control methods in rehabilitation engineering have not been given due attention in the past. In this paper, a biologically oriented, non-numerical control philosophy for active orthoses and prostheses has been described. Essential features of the new approach are:

- Great evolutionary potential since it relies on knowledge transfer from the man to the machine.
- Easy integration of externally powered assistive systems into patient´s biological control mode.
- Development of hybrid systems combining the advantages of functional stimulation and of active assistive devices.

At this stage of research, the full potential of the artificial arcs control cannot be predicted. Such a control approach represents more a methodology how to shape the assistive and the hybrid systems to specific needs of each patient rather than a general deductive synthesis procedure.

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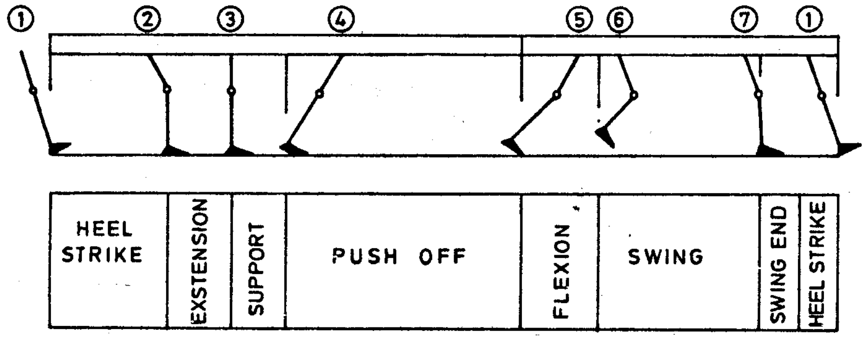
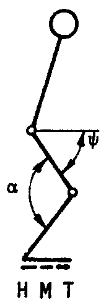


Fig. 1 Singular events within a locomotion cycle.

S - free joint, B - locked joint, F - flexion, E - extension

	PHASE	REFLEX ACTIVITY	SENSORY INPUT	SENSORY PATTERN	JOINT STATE	
					KNEE	HIP
1	Initial flexion	knee flexion	heel strike	H = 1	S	B
2	Extension following initial flex.	knee extension hip extension	shock absorbens terminal angle	α_t^P $\alpha \leq 180 - \alpha_t^P$	E	E
3	full support	locking	extended knee foot flat	M(H+T)=1 $\alpha \geq 180 - \Delta\alpha_0$ $90^0 + \Delta\psi \geq \psi \geq 90^0 - \Delta\psi$	B	S
4	push off	knee flexion hip extension	heel off	$\bar{T} + H + M = 0$	F	S
5		hip flexion (passive)	hip extension terminal angle	ψ_t^e	F	F
6	swing	knee flexion	foot off	H + M + T = 0	F	F
7		knee extension	knee flexion terminal angle	α_t^f	E	F
8		free hip	hip flexion terminal angle	ψ_t^f	E	S
9		knee locking	knee extension terminal angle	α_t^e	B	S
1	Initial flexion	knee flexion	heel strike	H = 1	S	B

Fig. 2 Reflex arcs data base for knee and hip control.



H-knee contact
M-middle foot contact
T-toe contact

α_t^f	knee flexion terminal angle	~ 120^0
α_t^e	knee extension terminal angle	~ 165^0
α_t^p	shock absorbens terminal angle	~ 10^0
$\Delta\alpha$	tolerance angle of extended knee	~ 7^0
ψ_t^f	hip flexion terminal angle	~ 50^0
ψ_t^e	hip extension terminal angle	~ 100^0
$\Delta\psi$	hip tolerance angle in standing	~ 5^0

Fig. 3 Sensory inputs and parameters for knee and hip control

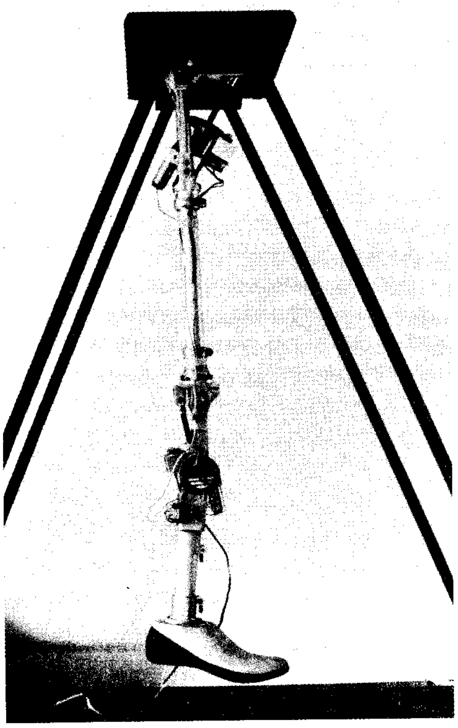


Fig. 4 Artifical leg with cybernetic actuators at the hip and the knee.