# *LOGICAL DESCRIPTION OF HUMAN GAIT*

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## Introduction

This paper deals with the design fundamentals of a real time controller for an active exoskeleton. Such an orthotic device has been proposed for the rehabilitation of certain classes of paralyzed persons /1, 2/. The exoskeleton with active joints is attached to the lower extremities of the patient. The missing biological signals for the control of locomotion are supplied externally to the actuators of the exoskeleton. The whole system is supervised by the patient regarding the start - stop signals, speed, direction of the motion and stability function.

Real time control of locomotion, excluding the postural function, involves six joints of lower extremities. Only two of them, the knee joints, are one degree of freedom actuators. Evidently, the real time control of such multivariable, nonlinear mechanical plant of variable structure is a challenging problem to the control engineer.

The essential condition for a practical solution of real time control of a multivariable system is the reduction of dimensionality. The general method used for that purpose in all large systems involves the division of control tasks among several levels. The same approach has been proposed in control of anthropomorphic robots and active braces for lower extremities. as well /3/.

Further reduction of dimensionality of the locomotion function can be achieved by using the logical (Boolean) description of the control task instead of differential equations of motion. The difference in the amount of information to be processed by the gait controller in both cases is essential. Instead of continuous data processing logical control is applied only at discrete instances. Naturally, the logical description of the locomotion process does not contain full information about system dynamics but this can be added at the lower control level so that it does not affect the task of the main controller. Thus, by applying the multilevel control and logical description of locomotion the real time control of the multivariable nonlinear system becomes feasible even in the rehabilitation field.

The emphasis of this paper is on the methodology by which the logical description of the human gait is derived based on the recorded data. It will be shown how logical variables are obtained from the dynamic records of joint motions in normal and handicapped persons. Once the logical description is available, it is a routine matter to design the finite state controller for biped locomotion.

As pointed out, the active exoskeleton is going to be used for the rehabilitation of patients having neuromuscular deficiencies of lower extremities. Since these patients are able to control to a large extent the upper half of the body, the stability problem is not considered here.

Description of the Control Task

The idea of using logical description of locomotion in animal and man is not new /4, 5/. Biped locomotion has been considered in that light as well /6/. However, in the previous considerations the mathematical models of the discrete controller were derived by observations of natural motions and by deducation.

The starting hypothesis has been that the control of each joint can be reduced to that of an elementary finite automaton having only four states: direct rotation, reverse rotation, loose state, locked state.

The direct and reverse rotation of the joint depends evidently on the sign of the tangent to the corresponding angle-time curve. The change in the tangent sign corresponds to the switch from direct to reverse rotation.

The locked state corresponds to the continuous zero tangent rate.

The free joint state is identified by using energy consideration. Namely, in the free joint state potential energy is transformed into kinetic energy. The free joint states in the hip and ankle serve also as rotation points for direct and reverse pendulum motions of the legs.

The free joint state is not imperative in control of locomotion. Eliminating this means increased power consumption. However, in this specific application the free joint states are necessary for other reasons. If in certain positions the joint is not allowed to rotate freely the servo motor may be exposed to mechanical overload. This occurs, for example, when the ground is reached with locked ankle or when standing with locked ankles.

The methodology proposed here relies directly on angular records of joint motions collected from the biological system. the records were obtained from normal and handicapped persons while walking on level ground. However, the methodology applies to any other form of locomotion (climbing the stairs, running).

The following records were used for the derivation of logical equations of biped locomotion:

*Continuous variables*

hip angle

knee angle

ankle angle

All angles were recorded as a function of continuous independent variable (time).

*Discrete variables*

heel-ground contact

tip (toe)- ground contact

middle of the sole-ground contact

crutch-ground contact (if used)

When several discrete variables were simultaneously present on one recording channel different logical states were recognized by means of modulation. Figure 1 explains the meaning of amplitude modulated records.

A complete record of a locomotion cycle is shown in Figure 2. This sample belongs to a patient recovering from complicated leg fractures. He is still using crutches although he may be able to walk without them in the future.

## Derivation of Discrete Variables

The locomotion controller must be used for the following tasks:

to recognize: a) different forms of safe standing,

b) patients intention to initiate the gait starting with left or right leg,

c) the allowed state transition of the joints,

d) patients intention to maintain locomotion.

In order to derive the logical description of the recor-

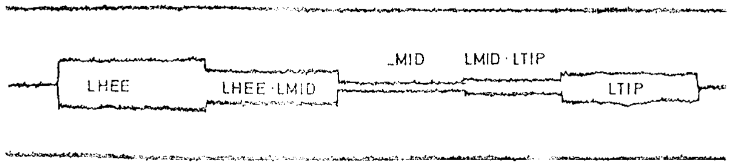


**Fig. 1.** Amplitude modulation of logical signals

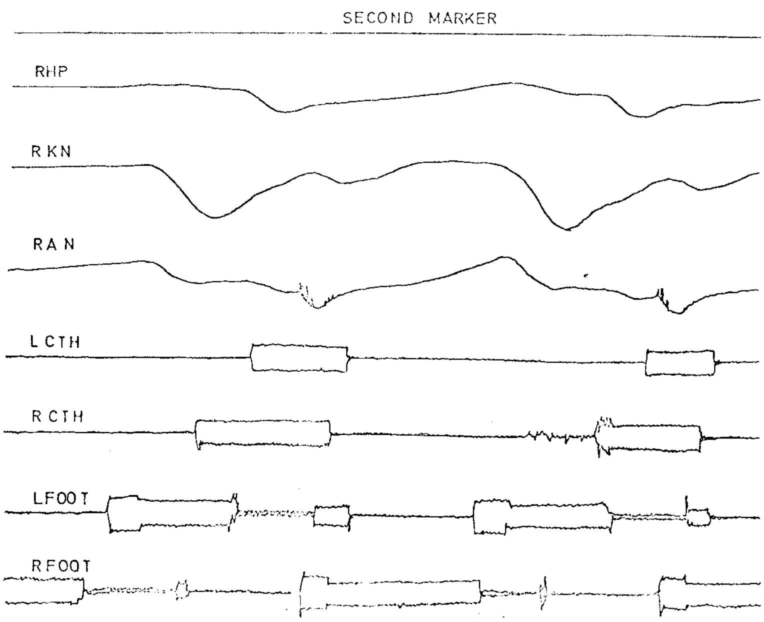


**Fig. 2.** Record of gait

ded gait, dynamic properties of the gait must be assigned to a complete set of logical variables. Logical properties of support are assigned to a set of eight variables. They are coded as four character words of the general form: abbb;

a - can be L(eft) or R(ight) and refers to the body side,

bbb - can be:

HEE - heel-ground contact

MID - middle of the stole - ground contact

TIP - toes-ground contact,

CTH - crutch ground contact.

The support function is described by Boolean algebra defined over the set of two constants (0, 1). Therefore, the support variables abbb can have the values:

1 - the nody part refered to by the variable is used as a support,

0 - the body part refered to by the variable is not used as a support.

The crutches, if used, are assumed to be the part of the body in locomotion.

Logical properties of joint dynamics, as previously defined, are assigned to the complete set of 36 variables. Variables are coded as six character words of the form: accddd,

a - can be L or R,

cc - refer to the joint and can be:

HP - hip joint,

KN - knee joint,

AN - ankle joint,

ddd - refer to the joint state and can be:

LCK - joint is locked,

RLL - joint is loose, performs as a frictionless bearing,

FWD - joint is forced to move forward. It means that the extremity part which follows the joint moves in direction of the locomotion.

BCK - joint is forced to move backwards. It means that the extremity part which follows the joint moves in direction opposite to locomotion.

MAX - joint has reached the final position in FWD direction

MIN - joint has reached the final position in BCK direction.

The following operator will be used in logical expressions:

+ - inclusive disjunction,

. - conjunction,

(-) - negation.

Logical Pattern of Gait

The logical pattern of gait was derived under the hypothesis that the patient's intentions concerning locomotion can be recognized by the support logic. Taking one person into account the sequence of support logic was recognized for each step in the run. These sequences differed slightly from step to step due to redundant information. The common support logic sequence has been obtained by correlation. This common sequence is found in any recorded step of the same person.

This approach allows to establish an interesting fact which was intuitively known. Namely, the common support sequence contained in each step stands in one-to-one correspondence with the instants of joint state transitions. On the basis of this correspondence the flow chart of the locomotion controller can by synthesized as shown later in the example.

Logical analysis of the gait of several normal and handicapped persons revealed properties most probably common to any human gait. The following two properties for walking on level ground have been established so far.

The relation:

LHEE.LTIP + RHEE.RTIP = 0

represents an identical truth for biped locomotion. It means that toes and the heel of a leg can never be in contact with the ground simultaneously.

The next relation:

LMID + RMID = 1

is another identical truth. It means that a biped must be supported at least by one middle of the sole when walking on level ground.

The gait controller in this approach is in fact an asynchronous finite state machine. The state transition of this controller depend only on ternimal joint angle values and the support logic. Consequently, the parameter variations influencing the system dynamics between the terminal positions cannot influence the execution of the locomotion programme.

Dynamic Level

So far nothing has been said about the control of trajectories. Since the controller is not controlling the trajectories between the state changes the system is dynamically undefined. In order to define the dynamics of locomotion one has to introduce optimal criteria for the selection of desired transitions.

In our case it is convenient to use "bang-bang" control so that the changes in the state of the controller correspond to the changes of the joint states. With highly damped joint motions small errors will occur between the desired and actual angle values. This is even of less importance since the system is highly insensitive to disturbances.

Suboptimal control of the joint trajectories may affect the aesthetics of the gait. However, in the case of handicapped persons the greatest importance must be laid on the repeatability of locomotion cycles and insensitivity to disturbances. The asynchronous approach makes possible to a large extent the decoupling of leg motions from the position of the upper part of the body. The locomotion cycle can be executed even if the upper part of the body is extremely bent provided that stability is maintained by the use of crutches.

Example

The following example is given to illustrate the complete procedure of logical description of human gait. Figure 2 represents the record of one full locomotion cycle. The man involved is a patient using two crutches with the so-called "parallel quadrupedal" walk.

Figure 2 consists of two parts. The discrete variables presented at the bottom describe actually the support function of the feet and of the crutches.

Figure 3 shows the location of the treshold pressure elements on the sole.

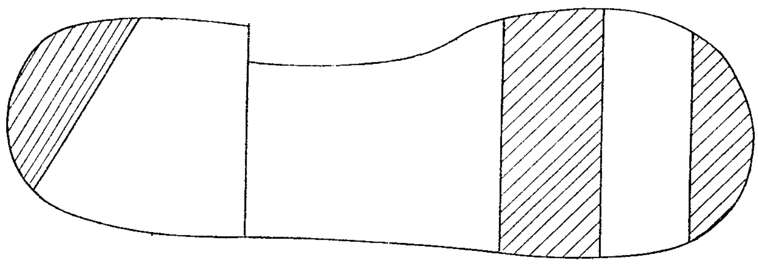

**Fig. 3.** Pressure sensors location

The upper part of Figure 2 contains the trajectories of the joint angles. The symbols are used according to the previously introduced code for logical variables.

In Figure 4 the common logical pattern of gait is superimposed on the support signals. For the patient considered the common logical pattern consists of eight phases.

The upper part of Figure 4 shows the joint dynamics divided into logical states. Symbols are used according to the previously described six character code. The first three characters are missing because they can be reproduced easily from the diagram. The time lag observed between the instants of support logic changes and the instants of logic state changes is due to delays present in any dynamic system. However, the basic pattern described in terms of logical expression remains the same for any gait cycle.

Only the first of the eight phases of the common logical pattern are presented in Figure 4, in order to save space. The rest can be easily obtained by further application of the same procedure.

So far only tasks c) and d) mentioned previously have been solved. The complete control of locomotion requires the tasks a) and b) to be solved.

The records were also used to analyse the different ways of safe standing. The patient involved displays eight distinct ways of safe standing. In other words, the logical expression of safe standing is:

(LCTH + RCTH).LTIP.RTIP.LMID.RMID.(LHEE + RHEE).

If the logical expression has to value 1 the controller assumes that the patient has intention to stay in a stand-still position.

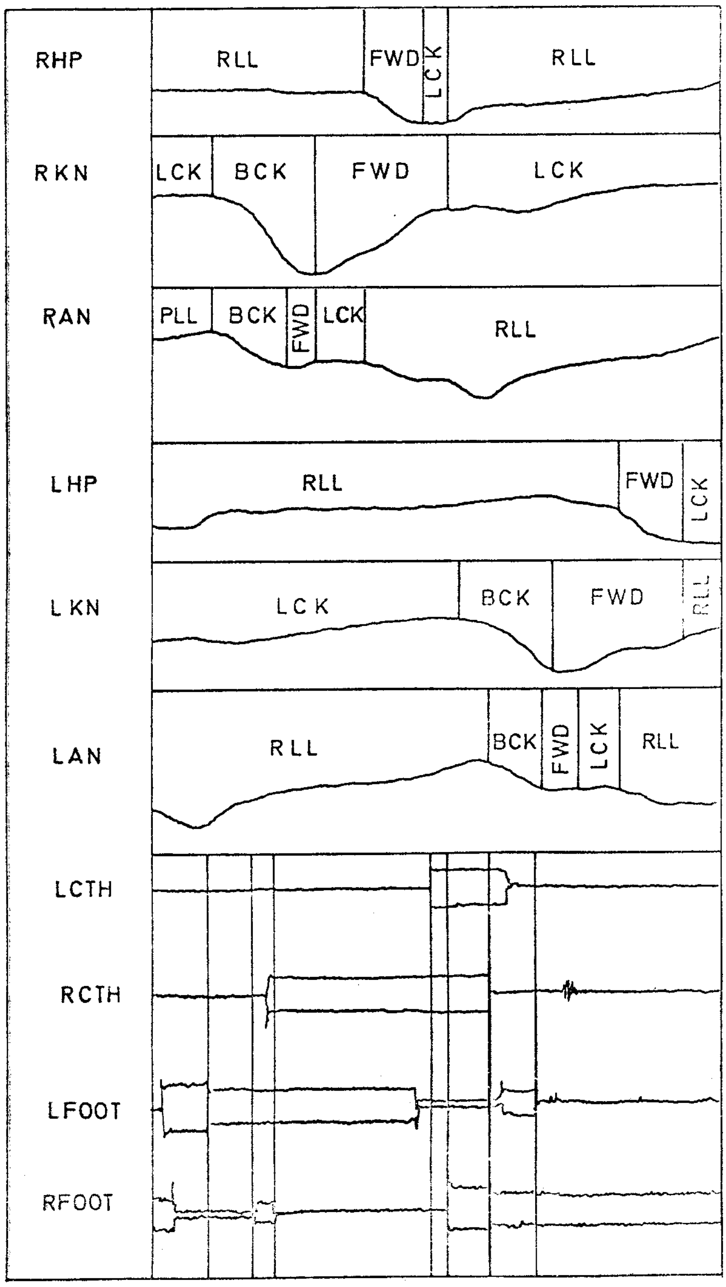


Fig. 4. Logical description of gait

Logical expression of a patient's intention to initiate the gait must also be recognized. The expression of these tasks are:

$$\overline{LCTH}.RCTH.(\overline{LTIP + RTIP}).LMID.RMID.\overline{LHEE}.RHEE \;;$$

if the above expression has the value 1 the controller assumes that the patient has an intention to initiate the gait starting with left leg,

$$LCTH.\overline{RCTH}.(\overline{LTIP + RTIP}).LMID.LHEE.\overline{RHEE};$$

if this expression has the value 1 the controller assumes that the patient has an intention to initiate the gait starting with the right leg.

The above expressions were simulated on a general purpose digital machine. The inputs to the machine were derived from various persons with preassure sensitive elements on the soles according to Figure 3. The simulated part of the gait controller never failed to recognize the intention of the man. Furthermore, the controller was able to detect postural malfunctions in the stand-still phase.

## Conclusion

Logical description of repetitive skeletal activities is a powerful method for reduction of dimensionality of the controller task. It can be applied to functions other than locomotion.

The advantage of this approach lies in the fact that it allows synthesis of a reliable controller for biological and dynamic plants. As pointed out the controller is highly insensitive to parameter variations. This feature is due to the fact that the main task of the controller is to periodically repeat the terminal joint values rather than to maintain the prescribed nominal dynamics of the system. A possible application of artificial locomotion is in the field of rehabilitation of persons having neuromuscular deficiences of lower extremities /1/.

The synthesis of a complete controller is more complex problem. It must deal with recognition of emergency situations, reliability, safe shut-downs. All these problems will be considered in a separate paper.

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