CONTROL LAW IMPLEMENTATION FOR MULTI-ISO: A TRAINING MACHINE FOR LOWER LIMBS

S. Moughamir, N. Manamanni, J. Zaytoon and L. Afilal
Université de Reims Champagne Ardenne
Laboratoire d’Automatique et de Micro-électronique
LAM, Faculté des Sciences - Moulin de la housse BP 1039 51687 Reims Cedex 2

Abstract. This paper presents the control system of a machine for training and rehabilitation of lower limbs. This system is based on the execution of a sequence of switching (position, speed and force) control laws corresponding to the required training configuration. Some illustrative training results are also discussed.

Keywords- Rehabilitation machine, training machine, fuzzy logic control, switching control laws, weight machine.

I. INTRODUCTION

Multi-ISO (Fig. 1) is a computer-controlled machine for training and rehabilitation of the lower limbs. This machine, which is destined for medicine and sports, is the result of a joint project involving the Laboratoire d’Automatique et de Microélectronique (Reims-France) and the company Myosoft (Bellegarde-France). Multi-ISO is based on original concepts that provide significant improvements over existing machines, including precise rehabilitation adapted to user needs, and dedicated training possibilities to improve physical performance and autonomy.

The architecture of Multi-ISO (Fig. 2) comprises a software and control part, a mechanical part, and an electronic part. The functioning principle consists in applying a torque delivered by a brushless motor to one (or both) lower limb(s). This motoring action allows the user to attain a nominal force of 200 deca Newtons (daN) at the ends of the limbs and a speed of 400°/sec under maximum load. Six other motors, not shown in Fig. 2, are also used to position the seat, either manually or automatically to a memorized position, so as to suit the needs and the morphology of the current user [1].

Multi-ISO can carry out different training configurations whose importance in medicine and sports are discussed in [1]. Seven training modes (Isokinetic, Steering, Isometric, Isotonic, Physiokinetic, Stretching, and Assisted) are implemented, and some of them are original and were developed specifically for Multi-ISO [2]. The specific training sessions, defined by a physiotherapist with the help of a domain-specific man-machine interface, are translated into a corresponding switching sequence of force, position or speed control laws that perform the required movement patterns. Training results are stored in a database to be subsequently processed. The control system comprises a PC-based supervisory module that handles the organization and the coordination of the activities involved in the training sessions, and a micro-controller-based module implementing the switching control laws.

This paper presents the control system of Multi-ISO; the synthesis of the switching control laws will be particularly emphasised. Some training results are given to illustrate the efficiency of the control system, despite the simplicity of the implemented control laws.

II. CONTROL SYSTEM OF MULTI-ISO

The control system of Multi-ISO (Fig. 3) belongs to the class of switching systems, which is a sub-class of hybrid dynamical systems. The established medical specifications
<table>
<thead>
<tr>
<th><strong>Title and Subtitle</strong></th>
<th>Control Law Implementation for Multi-ISO: A Training Machine for Lower Limbs</th>
<th><strong>Contract Number</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Author(s)</strong></td>
<td></td>
<td><strong>Grant Number</strong></td>
</tr>
<tr>
<td><strong>Performing Organization Name(s) and Address(es)</strong></td>
<td>Universite de Reims Champagne Ardenne Laboratoire d’automatique et de Micro-electronique LAM, Faculte des Sciences - Moulin de la housse BP 1039 51687 Reims Cedex 2 France</td>
<td><strong>Program Element Number</strong></td>
</tr>
<tr>
<td><strong>Sponsoring/Monitoring Agency Name(s) and Address(es)</strong></td>
<td>US Army Research, Development &amp; Standardization Group (UK) PSC 802 Box 15 FPO AE 09499-1500</td>
<td><strong>Performing Organization Report Number</strong></td>
</tr>
<tr>
<td><strong>Distribution/Availability Statement</strong></td>
<td>Approved for public release, distribution unlimited</td>
<td><strong>Sponsor/Monitoring Acronym(s)</strong></td>
</tr>
<tr>
<td><strong>Supplementary Notes</strong></td>
<td>Papers from 23rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society, October 25-28, 2001, held in Istanbul, Turkey. See also ADM001351 for entire conference on cd-rom.</td>
<td><strong>Sponsor/Monitoring Report Number(s)</strong></td>
</tr>
<tr>
<td><strong>Abstract</strong></td>
<td></td>
<td><strong>Subject Terms</strong></td>
</tr>
<tr>
<td><strong>Report Classification</strong></td>
<td>unclassified</td>
<td><strong>Classification of this page</strong></td>
</tr>
<tr>
<td><strong>Classification of Abstract</strong></td>
<td>unclassified</td>
<td><strong>Limitation of Abstract</strong></td>
</tr>
<tr>
<td><strong>Number of Pages</strong></td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>
[1,2] have shown that three control laws (position, velocity, and force) are required to carry out the different movements. The switching sequence between these control laws depends on the nature of the exercise to be realized, the angular position of knees, and the patient's force.

Fig. 3. Hybrid structure of the control system of Multi-Iso.

The sequential controller is based on hierarchical specifications given in terms of Statecharts [3] formalism. The established specifications, which are presented in an accompanying paper [4], are generic and hence they can be used for any training machine for the lower limbs.

The switching control scheme depicted in Fig. 4 shows the three control laws: velocity ($L_v$), force ($L_f$) and position ($L_p$). The activation of these control laws depends on the variable $i$ ($i \in \{1,2,3\}$) delivered by the discrete controller. Given the nonlinear model [1] of Multi-Iso and the uncertainty related to its parameters, a fuzzy velocity control law has been used as an inner control loop for the switching system. The inner control loop guarantees the asymptotic stability of the system. Hence, when a switching sequence of control laws occurs, the applied control law ($L_f$ or $L_p$) generates a velocity reference, $\omega_{ref}$, and the system remains stable thanks to the inner control loop.

Fig. 4. Switching control scheme.

In order to guarantee the continuity of the control variable, $\omega_f$, when switching between the control laws, a practical solution based on the use of a numerical filter was developed to guarantee a smooth behaviour of the system (a law switching frequency), and, by consequence, to ensure the user comfort. The value of the parameter $\alpha_f$, which conditions the filter bandwidth, is fixed experimentally for each user and, generally speaking, this value is small for training sessions and large in the case of rehabilitation exercises.

A. Velocity control law

Essentially used during Isokinetic and Steering training or rehabilitation modes, the main goal of the velocity control law is to guarantee a constant velocity without static error in order to avoid the drift of the moving part of the machine when the reference is zero. To meet these requirements, it is necessary to set up an easy to implement controller that takes model non-linearities into account. Furthermore, the control should be robust towards the model variations induced essentially by the man-machine mechanical interactions. Consequently, a fuzzy-logic controller [1] was used with the classical four-module structure depicted in Fig. 5 [5].

![Fig. 5. Fuzzy controller for velocity control $L_v$.](image)

Five fuzzy sets were used for each of the variables $e$, $\Delta e$ and $u$. For ease of implementation, the membership functions for the error signal, $e$, were chosen with triangular shapes and saturation, whereas those related to error variation, $\Delta e$, and output, $u$, were chosen with simple triangular shapes. The inference rules were established on the basis of the practical knowledge of the behaviour of the machine in view of obtaining an error and an error variation of zero. The fuzzy controller output, $u$, is obtained by using the MAX-MIN composition method as well as the centre-of-gravity method to guarantee a uniform influence of each rule during the defuzzification [6].

Unlike the classical techniques used in robotics, which introduce several feedbacks (non-linear compensation of the gravity plus the velocity feedback), the implementation of the fuzzy controller is rather simple because it only uses one feedback reaction. The implemented controller achieves a zero steady-state velocity error and compensates the effects of the potential energy and the force applied by the user. The controller is tuned to obtain a short rise time relatively to the reaction time of high-level sportsmen, which is equal to $125 ms \pm 20\%$ [7]. The machine can, therefore, be used in extreme training conditions. Moreover, the controller was shown to be robust towards parametric disturbance due, for example, to the adaptation of the patient’s seat configuration.

B. Position control law

The position control law is used in the Isometric training mode where the patient needs to apply a maximal force around a fixed number of positions determined by the physiotherapist. On the other hand, this law is applied near the extreme positions of training movements to realize a smooth deceleration towards the final position. Position control is implemented by feeding the output of a proportional controller to the velocity control loop. This simple and easy-to-implement solution guarantees a zero steady-state position error without overshoots.

C. Force control law

This control law, which is used during the Isotonic, Physiokinetic, Stretching, Assisted, and free movements, is original because its objective is not to maintain or to follow a
desired reference (as is the case for the position and velocit
control laws), but to simulate a variable mechanical load. The
load imposed by the simulated weight machine can be chosen
to meet the required medical specifications, and hence to 'provide' a machine adapted to the user needs. Thus, the aim
of the force control law is to make Multi-Iso behave like a
classical weight (training) machine, while avoiding the
drawbacks of these machines, such as the losses caused by
the transmission system and the impossibility to train the
limb both in extension (upward movement) and flexion (downward movement) at the same time.

The dynamical model of an ideal weight machine (Fig. 6)
can be expressed as follows:

\[ J_0 \omega_{ref} = F_{ref} \cdot l - F \cdot l - f_0 \cdot \omega_{ref} \]
\[ F_{ref} = M \cdot g \]

where \( l \) is the length between the point of effort application
and the rotational axis; \( f_0 \) and \( J_0 \) represent, respectively, the
viscous friction and the inertia of the moving part. A
particular tuning of these parameters gives a specific reference model, and, consequently, a specific weight
machine, tailored for a given user needs. The force \( F_{ref} \) due
to the load \( M \), represents the desired force to be applied b
the patient to balance the system.

![Fig. 6. Model of a weight machine.](image)

Figure 7 depicts the established force control law, which
uses the previous model as a reference model. As in the case
of the position control law, the force control law re-utilizes
the velocity control loop; the reference model gives the
required velocity profile \( \omega_{ref} \) of the weight machine who
submitted to an external force. The main objective here is to
let the mobile part of Multi-Iso achieve the same velocity behaviour. Consequently, the velocity computed from the
reference model is used as desired input for the fuzzy velocity control loop.

![Fig. 7. Force control law.](image)

Many experimental tests were carried out to validate the
established force control law. Figure 8 depicts an experimental case with an imposed force, \( F_{ref} \) of 20 daN.
This result shows that the velocity of the machine, \( \omega \), closely
follows the required velocity profile, \( \omega_{ref} \). This case
Corresponds to an oscillatory force pattern, where the user
applies a force greater than, and then less than, the imposed
force.

![Fig. 8. Experimental results.](image)

### III. RESULTS

The following results illustrate the contribution of Multi-
Iso in the sports domain as well as the performance of its
control system and its adaptation capacity for each user.

Many training sessions was carried out by five
sportswomen who were students in the Sports Department of
the University of Reims. The value of the \( \alpha \) was fixed to adapt
Multi-Iso's dynamics to every user. These training sessions
followed a protocol devised by a physiotherapist to improve
the muscular force of the quadriceps, through the execution of
Isokinetic movement at a speed of 60°/s. The physical
exercises proposed here were carried out during a period of
three weeks with four training sessions per week. They
involved Concentri-type movement for a group of three
sportswomen, and simultaneous Concentric and Eccentric
movements for the other group of two.

Every session started with a warming-up phase of two
series comprising several repetitions. After a relaxation
period, a second phase, used for evaluation, involved three
series carried out with the sportswomen applying their
maximum force. This evaluation phase provides the curve of
average effort, which gives the work and power developed at
each session, and illustrates the progress of the force-peak
throughout the sessions. Next, the actual Isokinetic training
phase starts with two series of three repetitions each, then
four series of six repetitions, and, finally, one series of ten
repetitions.

The results of the most consistent sportswoman of each
group are presented in Figs. 9 and 10. Figure 9 shows, for
each week, the average values of the evaluation curves
related to the first sportswoman. The evolution of the effort
(Fig. 9a) shows an improvement of the force peak, going
from 80 daN in the first week to more than 120 daN in
the third. This training period resulted in an average progression
of 40% for the developed maximum force as well as a
widening of the application range of this force (Figs. 9a and
9b). These results are confirmed by the ‘fatigue’ curves (Fig.
10c) characterizing the physical endurance throughout a
series. An increase in force is noted throughout the three
weeks, as well as a flattening of these curves, reflecting a reduced muscular fatigue for the attained force level.

![Fatigue curves](image)

Fig. 9. Results of the Concentric training protocol.

The results for the second sportswoman reveal a significant increase in the effort curves (of the quadriceps) for both Concentric (Fig. 10a) and Eccentric (Fig. 10b) training. It can also be noted that the progress of the maximal force (Fig. 10c) is more significant in the Eccentric mode (40%) compared to the Concentric mode (25%). This observation confirms the findings of Albert [8]. Finally, the 'fatigue' curves, here characterizing the physical endurance throughout a series, are flattened throughout the three-weeks training period in the Concentric case (Fig. 10d). This implies an increase of the subject endurance for this training mode. On the other hand, the smoothness of the curves of Fig. 10e implies that the subject's performance was already high in the Eccentric mode.

V. CONCLUSION

This paper has presented the switching control system of Multi-Iso: a machine for training and rehabilitation of the lower limbs. This control system confers significant improvements to Multi-Iso over existing machines, including precise rehabilitation and dedicated training possibilities.

Current research work is related to the development of a fuzzy estimator for on-line adaptation of the filter bandwidth (parameter $\alpha$ of Fig. 4) to tailor the machine to the current user needs and physical state: comfort, sensations, fatigue and cardiac condition, etc. In parallel, another machine, based on identical concepts, is currently under development for training and rehabilitation of the upper limbs. The constraints imposed on the control system of this machine are far more severe than those related to Multi-Iso, due to the complexity of arm movements and the consequent safety constraints to be satisfied.

ACKNOWLEDGMENT

We would like to thank Dr. Louis Angelloz, the manager of the company Myosoft for supporting this work.

REFERENCES


