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An approach to the control of robotic assistive devices with highly nonlinear mechanical efficiency

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INTRODUCTION

The development of an assistive device[1] for the upper limb requires to solve many design problems, some of which are related to the coupling of a robotic device to the human arm and to the non isotropic behavior of the whole system. One of the working modes of the new active or passive assistive devices may require to reduce, or totally remove, the effects of the gravitational forces in order to restore the ability of a very weak arm to perform rather natural movements. This is a the task of some assistive home devices, included the one developed by the authors which and can be mounted on wheelchairs. In order to keep the apparatus easily adjustable and with acceptable sizes, electric motors and springs are often used to produce the counterbalancing torques at the joints of the devices. One of the most challenging question to be solved is related to the very nonlinear mechanical efficiency of the apparatus. The efficiency is affected by static, kinematic, and dynamical parameters of the biomechanical system. The approach to the solution of the rather general problem above mentioned has been developed and experimentally tested on a new assistive robotic device (Fig.1) consisting of an end-effector type structure connected to the human arm.

METHODS

Below we refer to the practical application to support the upper limb in motion, counter-balancing its weight.

To set up the software required to control the actuators while they are working to balance the gravity and the dissipative actions, both the human and the robotic arm must be mathematically modeled, including the major causes of resistance to motion.

In order to obtain programs easily manageable by the little microprocessors usually equipping the home assistive devices, some simplifications are required. In the model implemented, for the application described, the arm, chain of rigid bodies, has 3 dof at the shoulder and one at the elbow -shoulder displacement has been neglected because weak patients generally can't overcome the 90° arm abduction -. The wrist joint is not modeled because the arm is supported along the forearm. The stiffness of the patient natural joints have not been taken into account because only external and gravity actions must be removed with the "nongravity" working mode.

With the rigid bodies model, knowing the system position - given by the motors angles - it easy to compute the theoretical torques required at the active joints to balance the system weight. Because of the presence of not actuated d.o.f. of the limb, its position has been evaluated simply by a kinetostatic equilibrium, being the inertial term negligible for this, rather slow application.

The dissipative actions in the robotic arm are, on the contrary, too complex to be modeled precisely, on line and in real time, thus they have been evaluated off-line, experimentally, in order to build look-up tables that will be directly used by the motor control software. They have been evaluated for each actuator in all the possible working positions, all the permitted angular velocity and for some weights of the human arm. The look up tables (e.g. Fig.2) contains the values of the extra Current Intensity - corresponding to the required torque - needed by the electric actuator to balance the dissipative actions.

While most the other working modes of this kind of rehabilitative equipments can be driven in closed loop because they usually help the patient to follow a given task, for the non-gravity mode the hand target position or trajectory are unknown and the hand must not be kept in a position o at a given velocity or acceleration, therefore the system can only be driven in open loop.

Fig1; End-effector assistive device for the upper limb to be mounted on wheelchairs

The control must precisely balance gravity, spring forces and all the dissipative actions, therefore any minimal force exerted by the subject will perturb the equilibrium, producing movements that must not be counteracted by the control system.
If the described method can be used during the motion in one direction, it must be enhanced in order to be able to help the patient also at motion start or when the velocity may change sign. In these conditions, the direction of the extra torque needed to balance the friction is unknown if the will of the patient is also unknown.

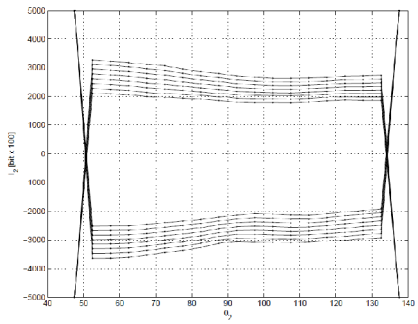

Fig 2: Plot, from a look-up table, of the torque (current) counterbalancing energy dissipation, at a joint(2), for some velocities ranging from 4 to 32 deg/s in both directions. The vertical lines at the right and left ends are due to two extra columns with opposite high currents used to stop the motion when it is going out of range.

The problem has been solved by adding to the motor control a cosinusoidal current, originating an harmonic torque varying between the two limit values of the static equilibrium in the two opposite directions. Thus, a minimum force added by the patient in any direction will produce the arm motion. As soon as the movement is detected the harmonic torque is replaced by the values extracted from the look-up tables.

RESULTS AND DISCUSSION

For the implemented non-gravity command strategy, the following figure (Fig.3a) shows the current path measured on an active joint(3) board, knowing the springs preload and the limb weight. The figure also includes (fig.3b,c) the resulting angular velocity and position of the joint(3).
To better understand the system behavior we focus the attention to a single joint.
We may notice that in all the zones with null velocity a cosinusoidal current is applied, it has equal frequency, in this case 3Hz, but different amplitudes because the resistance before motion varies depending on the position of the system. Applying a very light force (at t =14s) the joint start moving, as it happens when, from rest, an opposite light action is applied (t=20s) producing the opposite movement.
It is interesting to see how the system behave when the action direction changes (t=35s): at this point, in order to correctly counterbalance the dissipative terms, the diver changes rather instantaneously the sign of current values, and consequently the direction of the applied torque.

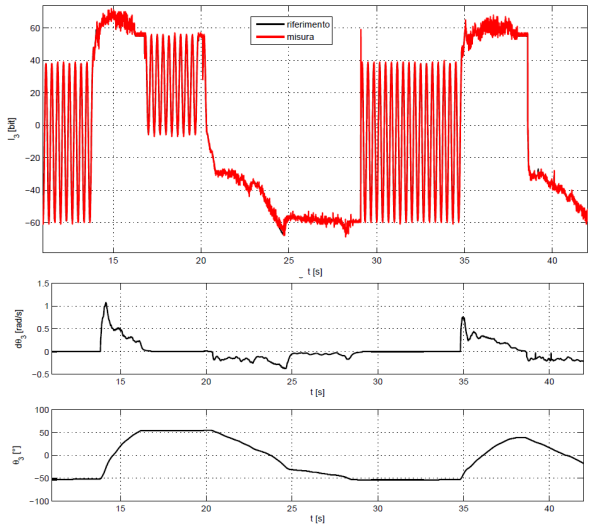

Fig 3; **a)** Tracking of the current generated by the control strategy on a joint(3); **b)** joint angular velocity; **c)** angular displacement

CONCLUSIONS

This work only concerns one of the working modes that can be implemented in a assistive/ rehabilitative home device for upper limb disabilities, which is an end-effector system because lighter and simpler of the exoskeletons types machines [2].
The results of the implementation of the non-gravity mode shows that, by means of look up tables built off-line, used by other models running on line, it is possible to counterbalance in near-real time all the actions that prevent the motion of a very weak the arm.
The problem related to the friction counterbalancement for incipient movements can be solved even sensor-less by imposing fluctuant torques.

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