

# SENSORS USED FOR BIOMECHANICAL REHABILITATION OF THE PARAPLEGIC LEG

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**Abstract** — An orthosis is a device applied to a part of the body to correct deformity, improve function or to relieve the symptoms of disease. A new rehabilitation mechatronical device equipped with suitable inertial sensors is presented, which enables training of a leg affected by strokes or injuries, in coordination with the movements of the other, normal, leg. The main purpose is acquiring and implementation of an intelligent orthosis used for recovery training of the subject with neuromotor problems. It is destined especially to inferior and superior limbs joints recovery but performing the corresponding exercises will affect also the muscles. It will be conceived in a modular way (the mechanic module, the electronic module and the interface module). As it was demonstrated as well in the evaluation of the actual status, this project's subject is compliant with the European and world trends and priorities for developing robotics systems for medical recovery.

**Keywords** — Knee Joint, Medical Techniques Sensors, Rehabilitation.

## I. INTRODUCTION

As defined in the Rehabilitation Act of 1973, "Rehabilitation engineering" means the systematic application of engineering sciences to design, develop, adapt, test, evaluate, apply, and distribute technological solutions to problems confronted by individuals with disabilities in functional areas, such as mobility, communications, hearing, vision, and cognition, and in activities associated with employment, independent living, education, and integration into the community [1].

Rehabilitation technology means the systematic application of technologies, engineering methodologies, or scientific principles to meet the needs of, and address the barriers confronted by, individuals with disabilities in areas that include education, rehabilitation, employment, transportation, independent living, and recreation. The term includes rehabilitation engineering, assistive technology devices, and assistive technology services.

Novel lower-limb rehabilitation device equipped with suitable inertial sensors is presented, which enables training of a leg affected by strokes or injuries, in coordination with the movements of the other, normal,

leg. This simple degree-of-freedom (1-DOF) device can be included in the category of therapy robots.

As shown in [1], therapy robots have at least two main users simultaneously, the person with a disability who is receiving the therapy and the therapist who sets up and monitors the interaction with the robot. An important number of these devices are destined for upper-and lower-limbs movement therapy. A robot may be a good alternative to a physical or occupational therapist for the actual hands-on intervention for several reasons:

- 1) *once properly set up, an automated exercise machine can consistently apply therapy over long periods of time without tiring;*
- 2) *the robot's sensors can measure the work performed by the patient and quantify, to an extent perhaps not yet measurable by clinical scales, any recovery of function that may have occurred, which may be highly motivating for a person to continue with the therapy;*
- 3) *the robot may be able to engage the patient in types of therapy exercises that a therapist cannot do.*

Many attempts are made to develop new motion tracking systems to support the rehabilitation programme for patients at home, so that the burden and hospitals can be relieved, and inertial sensors seem to offer proper solutions for this goal.

Tao et al. introduce a real-time hybrid solution to articulate 3D arm motion tracking for home based rehabilitation by combining visual and inertial sensors. For inertial motion tracking a MT9 inertial sensor from Xsens has been used [2].

Zhou et al. in 2007 developed [3] a home based rehabilitation system equipped with body-mounted inertial sensors, able to provide measurements of upper limb motion. To estimate the position of the shoulder joint, a Lagrange based optimization technique has been used, which integrates the values of acceleration and the estimated value of rotation measured by two inertial sensor units. Each unit consists of a tri-axial accelerometer, a tri-axial gyroscope and a tri-axial magnetometer.

In 2005, Azevedo & Heliot use inertial micro-sensors which associate 3 accelerometers and 3 magnetometers in a minimal volume, to identify postural task transition,

as soon as possible after the patient makes a decision, in order to allow for optimal posture preparation and execution and compare the execution of the ongoing task with the reference pattern, in order to identify the current movement phase [4].

## II. REHABILITATION DEVICE STRUCTURE

### A. Role and configuration

The rehabilitation device proposed is a simple 1-DOF mechanism attached, with proper splints and straps, to the patient's leg, which must be trained due to movement and coordination problems, as effect of strokes or injuries. For simplicity, the device is considered as a rigid link pivoting about the knee joint and powered by a single actuator. The actuator is a DC geared motor with brushes, at 12 (V), with a nominal torque of 1.2 (Nm) and an output speed of up to 100 (rpm). An external gear between motor shaft and mobile element of the device amplifies the motor torque to 6 (Nm) at 20 (rpm). Adjustable switches mounted on the joint serve to limit rotation angles of the trained leg according to the therapy strategy and to avoid injuries due to machine failures.

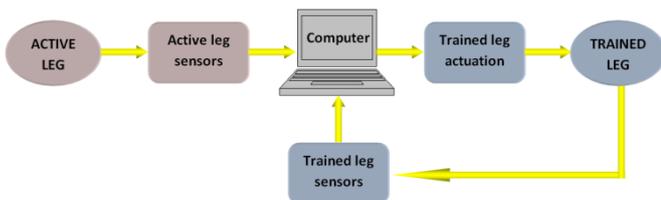


Fig.1. Block diagram of the device

The block diagram of the device is shown in Fig. 1 [5]. Sensors attached to the active leg measure accelerations, angular velocities and rotation angles of movements and the control computer commands the DC motor to assure a similar movement of the trained leg, based on the feedback from sensors attached to this leg.

### B. Sensor units used for prototype

Study of kinematics and dynamics of the two legs, the active and the trained, lead to following conclusions:

- 1) Both legs must be equipped with sensors able to measure movement angles in knee joints;
- 2) Angular velocity in sagittal plane of active and trained leg must be measured, in order to assure movements with same angular velocities in both legs;
- 3) Measure of accelerations in sagittal and frontal planes of both legs are useful for an efficient control.

Due to the fact that two MTx miniature three-degree-of-freedom (3-DOF) inertial sensor units from Xsens Motion Technologies were available in the laboratory, they have been used for experiments with the prototype device [5]. These sensor units provide drift-free 3D orientation as well as kinematic data: 3D acceleration (MEMS solid state sensors, capacitive readout), 3D rate gyro (MEMS solid state sensors, monolithic, beam structure, capacitive readout) and 3D earth-magnetic

field (magnetometer in thin film magneto resistive technology) and are excellent measurement units for orientation and kinematic data measurements of human body segments. One MTx unit has been attached using suitable straps to the shank of each leg, one mounted directly on the active leg and the other fixe on the mobile metallic element of the rehabilitation device.

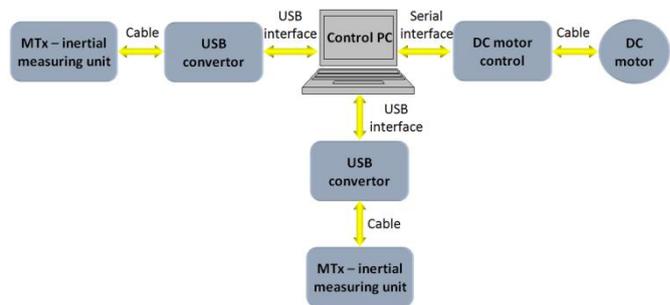


Fig. 2. Acquisition and control scheme of the prototype device

Fig. 2 presents the acquisition and control scheme of the prototype device, organized around a notebook PC computer: 2 USB interfaces connect the MTx sensor units, via USB converters and a USB/RS-232 converter allows communication with the DC motor control board. C++ software has been used to develop the acquisition and control program.

## III. SOLUTIONS FOR DISTRIBUTED SENSORS

MTx inertial measurement units were very useful in the development phase, because they allowed measurement of kinematic parameters in 3D space and comparison of knee angles directly measured and those computed using two other methods:

- 1) Integration of angular velocity in the sagittal plane;
- 2) Calculus of inclination using acceleration measured in frontal plane.

These sensor units are too complex and expensive for usual rehabilitation devices and, based on the experience gained; solutions have been developed and tested, based on simple, cheap acceleration and gyroscope sensors in MEMS technology [6].

### A. Acceleration sensors

Memsic 2125 acceleration sensor from Parallax Inc. has been used, because its simplicity, both from hardware and software point of view. This sensor, in MEMS technology, contains, internally, a small heater. This heater warms a "bubble" of air within the device. When gravitational forces act on the bubble, it moves and this movement is detected by very sensitive thermopiles (temperature sensors). On-board electronics convert the bubble position (relative to g-forces) into pulse outputs for the X and Y axes. Main characteristics:

- 1) Measure 0 to  $\pm 2$  (g) on either axis, with less than 1 (mg) resolution;
- 2) Simple, pulse (PWM) outputs of g-force for X and Y axis, requiring just two I/O pins.

A lot of experiments for determine inclination angles

with this type of sensors have been carried out by the author for mobile robots navigation [6].

Two sensors have been mounted adequately on the thigh and shank of each leg and connected to 4 available I/O ports of a microcontroller, one for each pulse output of g-force for x and y axis of a sensor.

### B. Gyro sensors

The basic operating element of a MEMS rate gyroscope is a flexing piezoelectric beam coupled to a sensing element [6]. The input voltage to the sensor is used to drive the piezoelectric element to resonance. Rotation about the axis of the beam induces a Coriolis force, proportional to the mass and angular velocity of the sensing element, which is detected by a capacitive element which seizes the Coriolis displacement of the vibrating beam. MEMS gyroscopes with integrated signal processing electronics in a single silicon piece are now widely available, but much of them require higher input voltages 12-16 (V) than those supported by standard acquisition systems. The ADXRS300 from Analog Devices has been used, because this chip includes circuitry with a charge pump to amplify the input voltage from 5 (V) to the required 12-16 (V). ADXRS300 is a  $\pm 300$  single axis rate gyro with signal conditioning. The output of a differential displacement capacitor is sent through demodulation stages included in circuitry on the chip, resulting in an analog voltage output, proportional to angular rate.

An ADXRS300 is mounted on the shank of each leg with the active (yaw) axis in sagittal plane.

Knee angles are computed by integration of angular velocities measured with gyro sensors. For safety they are compared with angles calculated using data from acceleration sensors.

### C. SMTx

Study and analysis of kinematics and dynamics of the two legs, one active and trained, led to the following conclusions [5]:

- 1) *The need to equip both legs with sensors to measure movements of the knee joint, i.e. the angle of travel.*
- 2) *The need to measure the angular velocity of the active leg movement and reaching a movement with a similar angular velocity of the leg resulted.*
- 3) *The need for acceleration measurement corresponding active leg movement and reaching a similar acceleration of the leg movements driven.*

For registration and monitoring of leg movement parameters (active and trained) XBus using a kit produced by XSens – Netherlands, consisting of four sensors XBus MTx and drive systems capable of simultaneously measuring the 3D acceleration, 3D rate of turn and 3D earth-magnetic field.

From the producer's documentation [7], it has been noted that this system was used by the following reasons: the MTx is an excellent measurement unit for orientation measurement of human body segments (the standard

version MTx has a full scale acceleration of 5g, full scales of 18 (g) are available as well); The MTx's provide drift-free 3D orientation as well as kinematic data; the Xbus Master enables ambulatory measurement of human motion; the Xbus Master can be connected to a PC or PDA via serial cable or wireless connection, where the data is logged or used in any real-time software application.

### D. The command and control module (ECCM)

It is composed of IMC500 microcontroller development system and the control module of DCMD (Fig. 3).

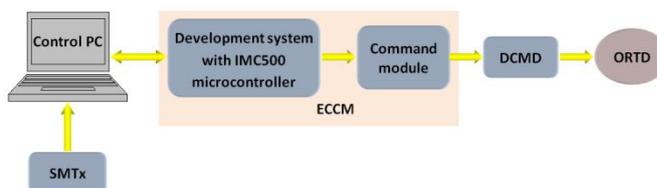


Fig. 3. The structure of the electronic command and control module

IMC500 development system is an 80C552 microcontroller system used to test prototype software command and control (Fig. 4).

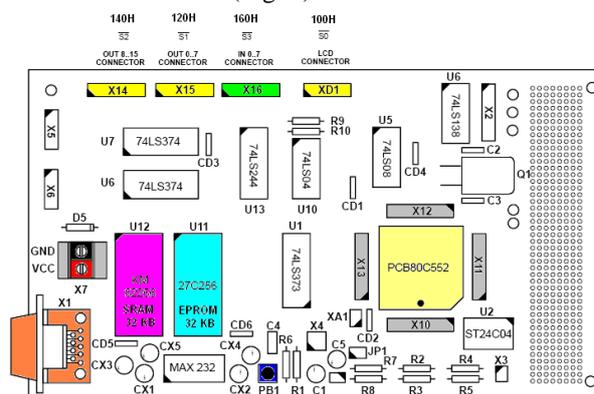


Fig. 4. The IMC500 development system

It has the following characteristics:

- 1) *External data memory (DATA MEMORY) is static RAM type, with capacity of 32 (kB). Memory address space occupied by data within the system development is between addresses 8000H and FFFFH;*
  - 1) *External program memory (PROGRAM MEMORY), EPROM type, with capacity of 32 (kB). Address space occupied by the external program memory development system, is between 0000h and 7FFFH. External memory contains the program's operating system or programs in their development phase contains a monitor program;*
  - 2) *RS-232 compatible serial interface;*
  - 3) *I<sup>2</sup>C serial bus (multi-master bus with arbitrary priorities and high-speed transmission – 100 (Kbytes/sec) in standard mode and 400 (Kbytes/sec) in fast mode - maximum serial clock frequency is 100 (kHz);*
  - 4) *Two parallel output ports, external 8-bit;*
  - 5) *1 parallel input port, external 8-bit;*

- 6) 8 inputs multiplexed to an analog-digital converter with 10 bit resolution, implemented in the structure's 80C552 microcontroller, featuring a conversion time of 50 machine cycles (approximately 50 ( $\mu$ s));
- 7) 8 outputs decoded port selection;
- 8) 2 outputs 8-bit analog-term modulated (PWM). By them integrating can get two digital-analog converters of 8 bits. One of these is used for DC motor control system design;
- 9) 3 16-bit timers;
- 10) A programmable watchdog (means of self-release programs for the wrongful execution because of disturbance or interference);
- 11) 15 interrupt lines, including 6 external lines;
- 12) Reset the placing under tension;
- 13) Connect directly from a liquid crystal display.

The role of IMC500 development system is as follows:

- 1) If so how independent articulated system for recovery, channel PWM DC motor control is programmed in real time the motion for the feature to be executed from a PC through a graphical user interface made Visual Basic.
- 2) When the working mode in conjunction with the patient's leg movements other channel PWM DC motor control is programmed in real time, corresponding values acquired from moving sensors, in order to perform the same movements or deviate that position adjustable value of software from a PC.

The command module of the DC motor drive contains a L298 circuit. For variable speed control using PWM signals (Pulse Width Modulation) generated by the microcontroller, which causes a change in motor supply voltage between 0 and 12 (V). The direction of rotation is changed by means of two digital outputs of the microcontroller system control unit affixed to the MCC. These elements allow you to change the default engine speed and angle of flexion or extension change and speed of movement of the member driven.

#### IV. OUR EXPERIMENTAL DEVICE

The system operates in the general case in which only one leg is affected. Thus, the unaffected leg in terms of locomotion will be called the "active leg" and one with various medical problems (especially paraplegic) will be called "trained leg".

The subject is seated comfortably in a sitting position, so feet do not touch the floor and allow the balance leg support surface without impeding movement.

Like any mechatronical product, the proposed system consists of three modules:

- 1) Mechanical part: orthotic device (ORTD) and the DC motor drive (DCMD);
- 2) Electronic part (command and control module - ECCM, inertial sensors - SMTx);
- 3) Software (programs in assembly language for microcontroller system, the higher-level language for communication with a PC and software configuration of

the sensors).

The operation of the system follows the steps:

- 1) Using inertial sensors to MTx XSens - Netherlands (unit of measurement parameters with very good performance for human body segments) recorded the motion parameters of the active leg.
- 2) Depending on the medical issues presented, it creates a recovery program for the affected leg mobility (trained). Make a database of more such programs preset active leg movement recording (healthy) versus time, the flexion and extension angles, and speed of movement.
- 3) The command and control module, using the prosthetic device to print a controlled motion rehabilitation programs previously established for the trained leg. Its movements are recorded (using the same sensors MTx) to be compared with the active leg movements and developments can be analyzed for its recovery.



Fig. 5. Experimental Prototyping

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