EXPERIMENTAL ROBOTICS FOR TRAINING AND MANUFACTURING

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Abstract. *The research and development (R&D) of two anthropomorphic robots are presented. These are 5 degree of freedom (DOF) arms. The main R&D guidelines conducted to these remarkable milestones:*

- *The task is to incorporate the maximum added value to the project: the native idea, the design and the construction.*
- *The project is a real feasibility study conducted to looking for the local industry facilities in response to these innovative "mechatronics" requirements.*
- *Following the "learning by doing " paradigm, a knowledge transfer from lab to the graduate university classroom was made.*
- *These two robots are the work-piece manipulators for an also experimental manufacturing flexible cell.*

In order to acquire a deep knowledge about these manipulators, it was mandatory to analyze, design, develop and test the following activities and subjects :

- *CAD design and Cam manufacturing of mechanical devices.*
- *Main parts are manufactured from high strength aluminum. .*
- *Four-contacts bearings are used in all rotating axis.*
- *Synchronic pulleys and helical gears gave the mechanical join reductions.*
- *PWM drivers implemented with H power mosfets.*
- *DC. servomotor digital PD and PID control loop.*
- *Denavit-Hartenberg kinematics and direct–inverse geometric analysis.*
- *Immerse 3 D real time virtual reality simulation and interactive 3D representation.*
- *Neural-net dynamics modeling and control analysis.*

Contributed to this Project students, graduates, professors and technicians from the National Universities of Córdoba, Technological of Córdoba (UTN), San Luis, and Cuyo, and also many SME from Córdoba, Argentina.

Keywords. *Robotics, mechatronics, simulation, digital control, flexible manufacturing.*

1.INTRODUCTION.

The main R&D Project is a flexible manufacturing cell named "Celflex". Figure 1 shows the cell layout with the CNC mill and the two robots. According to Apóstoli [1] [2] [3], the Project Leader (PL) decided to incorporate the maximum added value to the project. The first job was to simulate the interactions between machines and parts by means of a real time Petri Nets (PN) circuit implemented with Cmos electronics devices. Later on, Trombotto [4] and Maidana designed and built the PN control based on a multi input-output 82192L (PPI 8255) digital card and a program written in C. But quickly arose the need to manipulate the parts with a *real arm* with at least a 1 meter length, in order to place the rough pieces into the mills and get out the finished ones. So the RSA-1 was born.

5 axes RSA-2 4 axes CNC ELINON I mill 5 axes RSA-1

Figure 1. “Celflex“ experimental manufacturing cell

2. ROBOTICS DEVELOPMENT

2.1 RSA-1 Arm

The RSA-1 robot has 5 degree of freedom (DOF) and synchronous drive belts and pulleys for synchronous transmission of rotations, with XL and L models used. Step motors are driven with unipolar (SAA1027) and bipolar (couple 297/298) power mode. Three controls were designed and built: one Motorola 6800 microprocessor based, a PIC micro-controller based and a ISA 8255 standard board with a C written program and a “S” control shape for smooth start and stop. Morán [(5)] and Abate brought outstanding contributions to the mechanical, electromechanical and electronics designs and developments.

The RSA-1 body was built around a standard aluminum laminated and coated rectangular tube. Joining together side by side two of them makes the final arm. Figure 1. At the rotational joins, pairs of conical bearings were used. The arm has, at its rear, a 22 kg lead counterweight. The two fingers have a pneumatic gripper, which was designed an built with a basic Cad/Cam environment.

Apóstoli [(6)] and Abate made the theoretical study with the direct and inverse geometrical analysis which was calculated with a Basic program and the Autocad 9 drawing, and also implemented the Denavit-Hartenberg transformation with MathCad 4. A mechanical emulator arm with 1:1 ratio to RSA-1 for training purposes at the classroom was built.

This arm had extensive tests and finally could reliable handled cylindrical parts from the storage to the Elinon I mill and vice versa. It was shown *working* in many fairs, congresses and conferences in Buenos Aires and Cordoba cities and earned the 1995 Province of Cordoba Government industrial prize.

This simple device laid the robotics basis and brought the team own experiences, validating at lab the theoretical kinematics algorithms fundamentals that one can find in a dozen of robotics classical books. But we always remember the Stanford Arm robot designed an built by Paul. It could confirm the classical paradigm *: ”learning by doing”*. At the blackboard and around the PC simulation environment one can display many theories, but one always can find heavy gaps with the practices acquired at lab.

2.2 RSA-2 Arm

The experiences earned with the RSA-1 development were applied to a new technological robot named RSA-2. This is also an anthropomorphic arm, but is intended for benchmark tests and continuous advanced application on mechanical devices, power electronics, control algorithms and simulation facilities. Figure 1.

With a better budget coming from the BID-Conicet # 83 Project, it was possible to buy original materials and spare parts for the new arm. At the lab, now we had a brand new American 3 axes CNC Mill, and the team wrote the postprocessor between the Teksoft Cam and the CNC control. So we were able to integrate a Cad/Cam environment. Apóstoli [7] designed the robot model and later on Novillo [8] and Conforto transferred the hand drawings to Autocad 14 and 2000. Figure 2.

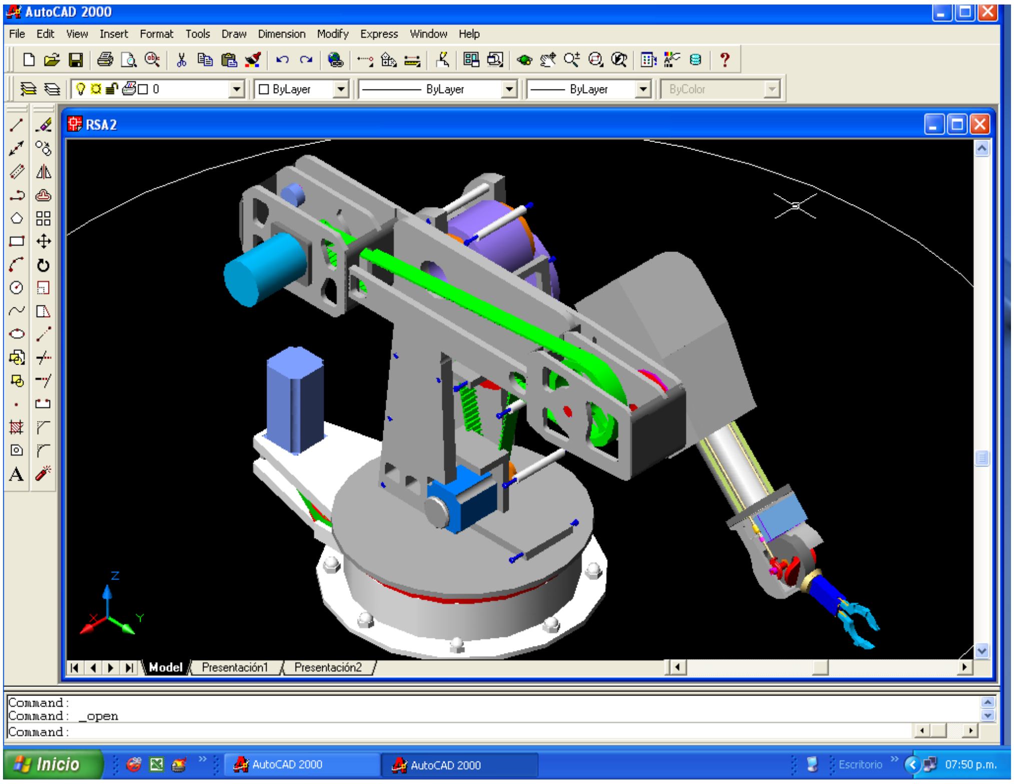

Figure 2. RSA-2 with Autocad 2000 3D rendered design

The RSA-2 main body was CNC manufactured from high strength aluminum 2024 (130 HB) and 7075 (150 HB) used for highly structural components.The joint shafts were built with grounded SAE 4140 and a special chrome-nickel-molybdenum Böhler V820 steel with carbonitriding process. U.S.A. Kaydon Reali-Slim X four contacts series bearings are used in all rotating axes, e.g.: a KG 140XPO 14 inches diameter in the base axis, embracing the cylindrical helix gear with 400 mm. diameter , 200 teeth and 30º helix angle. The bearing circular aluminum supports were manufactured with the CNC Mill RS-274 standard program (code G02,G03). Synchronous pulleys and drive belts (T10 with steel core)) together with cylindrical helical gears gave the mechanical joint reduction, e.g.: the base has a 100:1 ratio reduction (10.000 to 1 decoupled inertia) and the forearm a 20:1 ratio.

Several motors were tested, e.g.: high torque step motors Superior Electric KML092 and KML093 , 8.16 Nm torque (USA); DC brushless servomotors 8.4 Nm torque CMU BLQ64P (Italy); DC Pancake Kollmorgen F9M4R 70W (USA); DC Leeson M1120040 1/7 HP (USA) and DC motor 24V 2000 RPM 150 watts Remssi (Argentine). Due to a well balance performance-price ratio these 150w DC motors (with and IDEC 600 lines encoder at end rear axis) were adopted.

Mármol [9] and Apóstoli also designed and built the DC servomotor power drivers implemented with the Motorola 33035 PWM and the IR 2110 chips driving upper and lower gates of a H bridge power low Rd Mosfet, enabling to supply up to 40 amps. at 100 VCC. Concerning with sampled digital loop control Mármol [10], Pedroni and Apóstoli also made the first trial to design a basic PD control around the Hewllett-Packard HCTL-1100. It is a FIR (Finite Impulse Response) filter and has 24 bits of resolution, 64 minimal microseconds sampled time and can control DC servomotors with encoder inputs, step and brushless motors. In order to test the digital loop, and previously to connect it to the real robot, a servomechanism bench was designed and built by Jorge [11], Brizuela and Apóstoli. For programming the PD filter, a PC ISA printed circuit with three HCTL-1100 was designed with Protel and assembled, and a Visual Basic program was written with an interactive screen enabling: 1) to choose the 4 filter parameters: gain, pole, zero and sampling time; 2) to set the desired position and 3) to reed the max. velocity and acceleration. First, the servo loop was analyzed and simulated with Matlab-Simulink. Later on testing the forearm, with these PD filter parameters: gain 63.75, zero 0.9023, pole 0.9961 and sampling time 2048 microseconds, we got 0.33 seconds required to reach the final position inside the 5% band with 2500 input pulses. So, the forearm velocity is 56.81 º/sec. and the static error is 0,0075º per each pulse.

Cacciavillani [12] and Gavilán made the second trial in order to implement a PID digital filter control with the Motorola DSP 56F805EVM device. Figure 3.

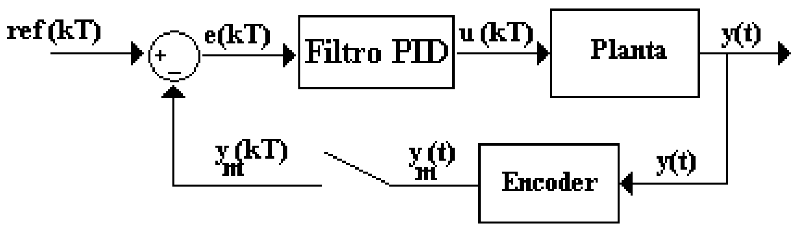

Figure 3. Digital servo loop

The PID filter has the following Z transform function:

$$\frac{K(z-c_1)(z-c_2)}{z(z-1)} \qquad 1)$$

A Windows 98 SE was the O.S. for programming the Motorola DSP with Core Warrior software and Linux Mandrake 9.0 O.S. helps to set the QT Graphic Interface Designer. An interactive screen was also developed , and setting the following PID parameters to: T=10 msec; velocity controls: Kp=2.037e+002, Td=3.96 e-004 sec, Ti=6.297 e-004 sec.; position controls: Kp=1.267e+004, Td=4.99 e-004 sec, Ti=5.005 e-004 sec; with 80,000 encoder lines of final position , we obtained on the base # 1 axis (the heaviest, of course): overshoot = 7%, establishment time = 3 sec and stationary error = <1%.

In conclusion, a PID filter promises a better theoretical performance because of null permanent error. In this case the last DSP generation (in 2004) by its novel technology, encouraged young students to develop a brand new digital control. But after a deep insight among performance versus price, we adopted the basic PD HCTL-1100 because of: a) its low price (45 U$S each) and lower computer requirements: an old PC Pentium 120 Mhz is enough to bring outstanding results for this experimental RSA-2 robot, b) ordinary Visual Basic programming, not a proprietary one. c) standard printed circuit with sockets for easy and cheap device replacements, mandatory in a development site under budget constrictions and not quickly access to up to date technology.

2.3. Modeling and Simulation

A friendly GUI operator for programming the RSA-1 arm was developed by Artola [13] et al. Written in C, on the screen the programmer can set the 5 angle rotations or the TCP and can obtain de direct and inverse transformation, together with a wire or solid geometric 3D representation.

Intended for graduate academic training and applying the Roboworks kit (from Robotics Laboratory-Austin University, U.S.A.) to the arm solid parts, Apóstoli [14], Distefano and Iriarte developed a 3D RSA-2. geometric visualization. Figure 4. The operator can rotate each join with a selected key, or receive an outdoor data base for a unison 5 axes movement (like a movie) in order to integrate a “telerobotics” environment through a 2.5 G bits wide band Internet link with another PC which has the direct and inverse program designed by Pedroni [15]. Figure 5.

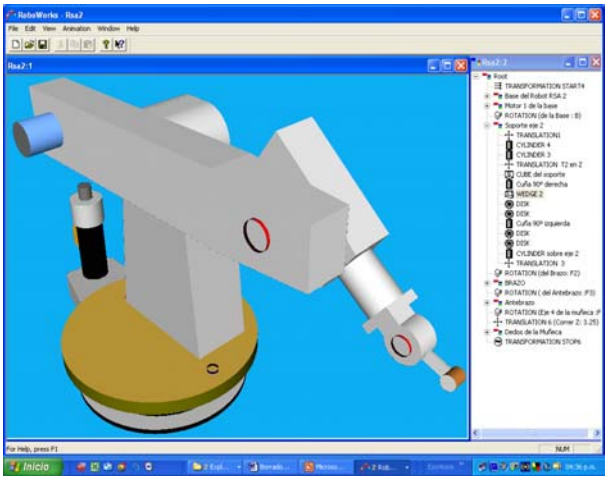

Figure 4. 3 D Roboworks RSA-2 visualization

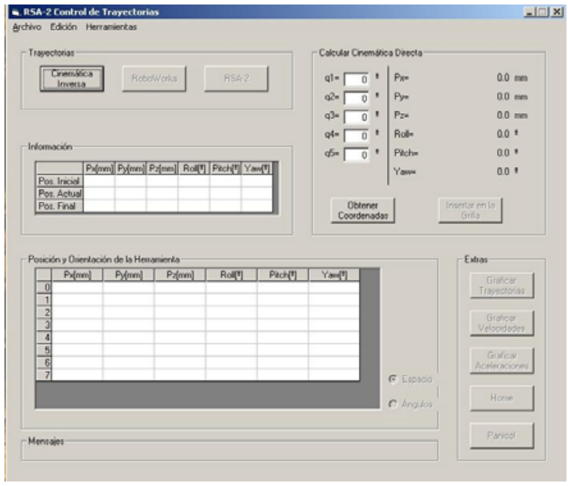

Figure 5. RSA-2 Screen programming

Luciano [16] designed a Virtual Reality environment for modeling, simulation and control in real time of the RSA-2 robot. Figure 6. Programmed with Clarion 1.5 and Borland C++ 4.0 and linked with Render Ware V 1.4 3D the interactive program allows a 3D immerse trip around the machines and the robot belonging to the “Celflex”. It also can program the robot tasks , even with a 1:1 aspect ratio and a rhythmic synchronism movement between the screen and the real robot.

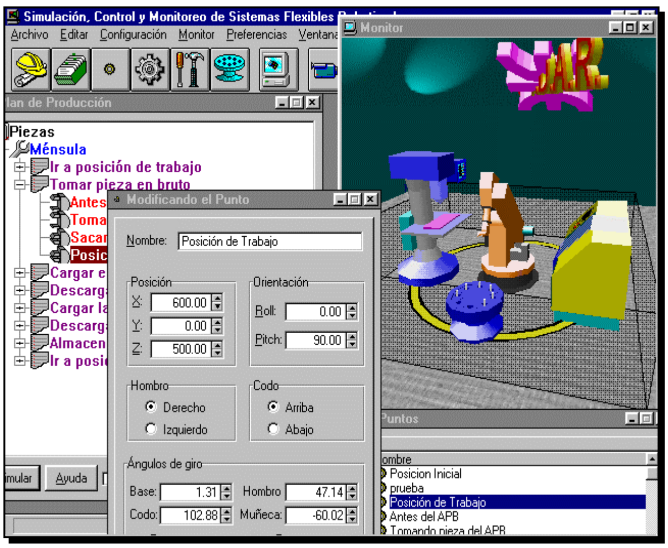

Figure 6. RSA-2 Virtual Reality programming

Artola [17] analyzed a neural net (NN) structure in order to learn the direct and inverse robotics dynamics. The Matlab 5.2 with the NN Toolbox 3.0 was applied and a simulation pattern was obtained with an on line learning. Later on, Artola [18] made a proposal on an adaptive controller with a Radial Basis Function. In order to minimize the convergence time a modular structure with 3 RBF in parallel was designed. The first tests of this model were carried out at the Böchun University (Germany) with a Matlab–Spar integrated benchmark environment.

Apóstoli [19] made the Celflex discrete event simulation with the program CACI Simfactory II.5. U.S.A.

Tamagnini [20], Trod [21] and González [22] developed the Celflex modeling, emulation and control with the real time expert system Gensym–G2 U.S.A.

These two robots gave us a strong knowledge for teaching the robotics bases, so we could transfer our lab jobs to the graduate engineering courses at the National University of Cuyo.
We also earned multidisciplinary "hands on" experiences inside a "mechatronics" environment, which were also transferred to the CNC machine tools projects.

As a general conclusion, we can point out that the project required a big effort to make the two robots operatives. But is the only way we know for bringing a solid knowledge about the subject, based on our own experiences gained with our own facilities in our country. It is a continuous learning process, gathering different theoretical and practical experiences from many sources, and it takes a lot of time, e.g.: we are working for more than 10 years and…. this is only the beginning.

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