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CONSTRUCTION AND CONTROL PID OF DELTA PARALLEL ROBOT

Alexander Patrick Chaves de Sena

Federal Institute of Education, Science and Technology of Pernambuco, Department of Mechanical Engineering, Caruaru, Brazil
e-mail: alexander.sena@caruaru.ifpe.edu.br

Anderson Vinícius de S. Silva

Federal Institute of Education, Science and Technology of Pernambuco, Department of Mechanical Engineering, Caruaru, Brazil
e-mail: vini1708@hotmail.com

Asafe dos Santos Silva

Federal Institute of Education, Science and Technology of Pernambuco, Department of Mechanical Engineering, Caruaru, Brazil
e-mail: asafemusic15@gmail.com

Abstract. *This present paper proposes the construction and the PID position control of a prototype with parallel kinematic structure, robot type delta linear with three degrees of freedom. The physical structure was built on recycled materials, open-source architecture controller and software, and low-cost actuators. The set is driven by current motors with PWM technique, interfaced by power driver circuits, which receive control signals from a microcontroller embedded system. It was studied a mathematical model to associate the coordinates of the moving cars and the final effector. A PID controller has been tested and validated for linear drive cars with good positioning results. The Ziegler-Nichols tuning method was used to implement the controller. The robotic system went through phases of development and experimental testing of its mechanical system, interface circuits, embedded system and programming. For this, a supervisory program was created that allowed visualization of the outputs and inputs through graphs plotted in real time, besides allowing the adjustment of the constants also in real time.*

Keywords: *prototype, PID controller, parallel architecture, mathematical modeling, delta robot.*

1. INTRODUCTION

Parallel architectures are of great interest because they have good rigidity associated with positioning accuracy, with a higher load capacity than traditional serial architectures. In addition, these devices can operate at high speeds without the same levels of inertial problems as serial architectures (Carvalho and Ceccarelli, 1999). When compared to the serial structures, the parallels have smaller work space in relation to the total volume of the structure, however, it can be installed on the workstation, not taking up space on the factory floor. Recently some papers have been published describing the use of parallel architecture for robot design, such as: Chiang, Lin and Hou (2011); Riaño, Peña and Pardo (2014) and Lin, Luo and Lin (2015).

The delta structure presents the second generation of parallel robots, because the actuators are fixed at the base and the moving elements are "light" (Deblaise, 2006). Due to the increasing need to increase production, the pharmaceutical and packaging industries have generally adopted the Delta robots in their lines because of their characteristic of high efficiency in the pick-and-place tasks. The mobile platform of the delta has three degrees of freedom, always moving parallel to the base, because the three links connect with the fixed base. The linear delta (also known as Linapod) has three linear actuators fixed to the fixed base allowing to maintain the same characteristics of the traditional delta, increasing the working space in one direction (Gonçalves, 2009).

The kinematics of parallel mechanisms is fundamentally different from the kinematics of the serial mechanisms. Each parallel architecture has particular kinematic characteristics making it difficult to apply generalist equations. Obtaining the kinematic equations of the parallel mechanisms requires the analysis of each chain, relating the ligaments with the mobile platform and the fixed base (Filho, 2006).

Mathematical modeling is an essential task for position control, and consists of calculating the coordinates of the mechanism joints corresponding to a specific configuration of the effector (position and orientation). The possibility of parallel robots operating with high accelerations and high accuracy generated the need for the development of high performance control systems (Filho, 2006). These controllers require the solution of the dynamic equations of the

machine in real time (Merlet, 2000). Some researchers dedicated to the dynamic analysis of parallel structures, such as: Knapp and Cobet (2000); Filho (2006) and Stan *et. al.* (2011).

2. METHODOLOGY

The development methodology prioritized reliability, functionality and cost optimization. The design of the prototype was structured in some steps, as presented in Fig. (1).

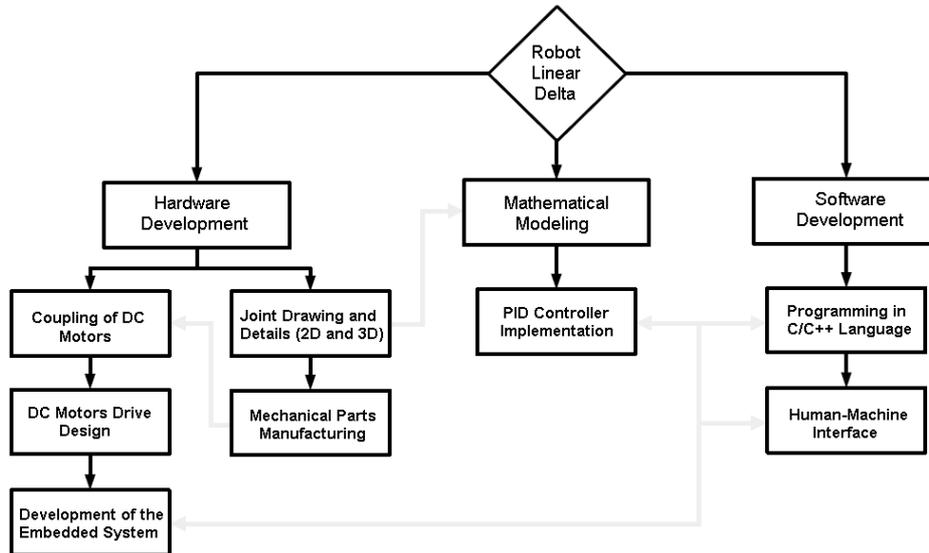


Figure 1. Methodology for Delta robot design. Source: Adapted from Lin, Luo and Lin (2015).

2.1 Experimental Assembly

Initially, a CAD design of the robot was developed in SolidEdge™ software to collect information about its characteristics, such as dimensions, movement and materials for fabrication. Linear positioning systems were removed from automatic IBM server doors (scrap), having a useful 450 mm stroke, and ABS structure. The ball screw is SFU1605 standard ball with BK/BF1 machined ends, in other words, the ball screw has a pitch of 5 mm, a diameter of 16 mm and an axial play of approximately 1 mm. In Fig. (2) the electromechanical assembly is presented.



Figure 2. Electromechanical assembly of the Delta robot. Source: Own authorship.

The spindle screws are supported on high-speed rolling bearings at the ends, and the transmission of the motor to the ball screw occurs by 5 mm wide toothed belt and aluminum pulleys. The nut is plastic type recirculating ball type C7.

To guide the nut were assembled low cost linear ball guides coupled by means of a piece denominated in this work "tnut support". The coupling of the encoder to the motor shaft was performed by machining a part called "encoder support". The physical structure was assembled by means of extruded rectangular aluminum profiles of type L0423 (80x25mm), 1.2 mm thick and 90 cm high. M12 threaded rods were used to join the square profiles by means of trizetas, as well as the whole structure was welded. The drive rods were manufactured with three M6 threaded rods and twelve brass rod end (female).

The embedded system is composed of basic software and hardware with PIC18F4550 and USB interface. The set is an open architecture, without the need to remove the microcontroller for firmware upgrade. The system has an HMI interface and the numerical control is carried out by means of a numeric keypad and viewed on a 16x2 I2C LCD display. The operation of the prototype for the user should be simple, objective and being developed in Language C in MPLAB X IDE[®]. In order, to ensure that the robot recognizes the initial position and does not exceed the joint operating limits, end-of-stroke sensors were used to establish the starting position at the same time as interrupting the signal sent to the motors. In the system, when the key is closed the microcontroller will identify a downward edge, logic high level down, through a previously configured external interrupt. When this event occurs, the program will zero the position count, representing the starting point. Microcontrollers in general have a very low current to power the DC motor. To perform the control of the motor, a PWM-controlled power board was used, where its circuit was made from the H-Bridge system. This board has the following features: power from 6VDC to 24VDC, 7A (continuous) and 15A (peak) output current, PWM power adjustment from 0 to 100%, digital polarity reversal, electric brake, power suppression motor peak, external direction and speed signal inputs isolated by opto-couplers. Three motors DC (three axis linear delta robot) with high speed and 24VDC and 3A, were used to drive the ball screws, which in turn converted the rotational motion to linear. Position sensors were selected and mounted on the structure to perform feedback for control. The Incremental Encoder (6 mm axis) is 400 pulses/revolution, which allows the calculation of linear position in two output bits (5VDC). The displaced length in millimeters is given by an association between the number of pulses and the pitch of the spindle. In Fig. (3) a schematic of the embedded system is presented.

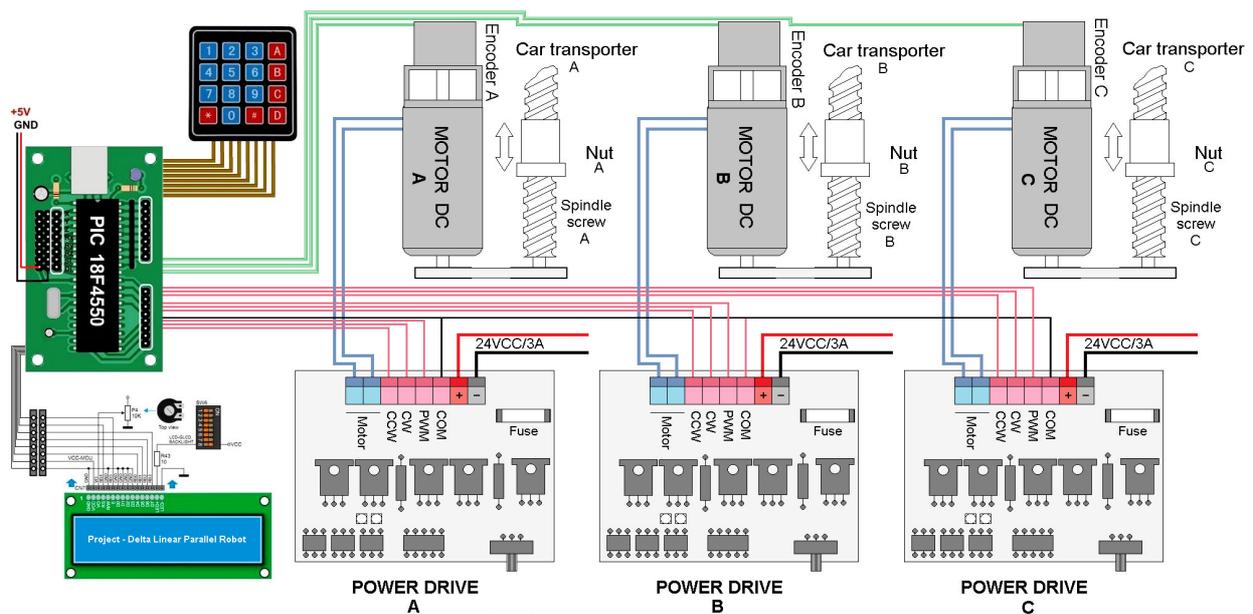


Figure 3. Schematic of embedded system. Source: Own authorship.

2.2 Mathematical modeling

Referring to Fig. (4) from points A_1 and A_2 , points B_1 and B_2 are positioned at 120° clockwise, while points C_1 and C_2 are at 240° . Representing the center of the tool installed in the effector as point F, the distance from the center of the effector to point A_1 , B_1 or C_1 is a value constant represented by OE, or "offset" of the effector. OF is the "offset" of the tool. By determining the coordinates of points A_1 , B_1 and C_1 by means of geometrical analysis, it is necessary to determine the points A_2 , B_2 , C_2 in relation to the z-axis.

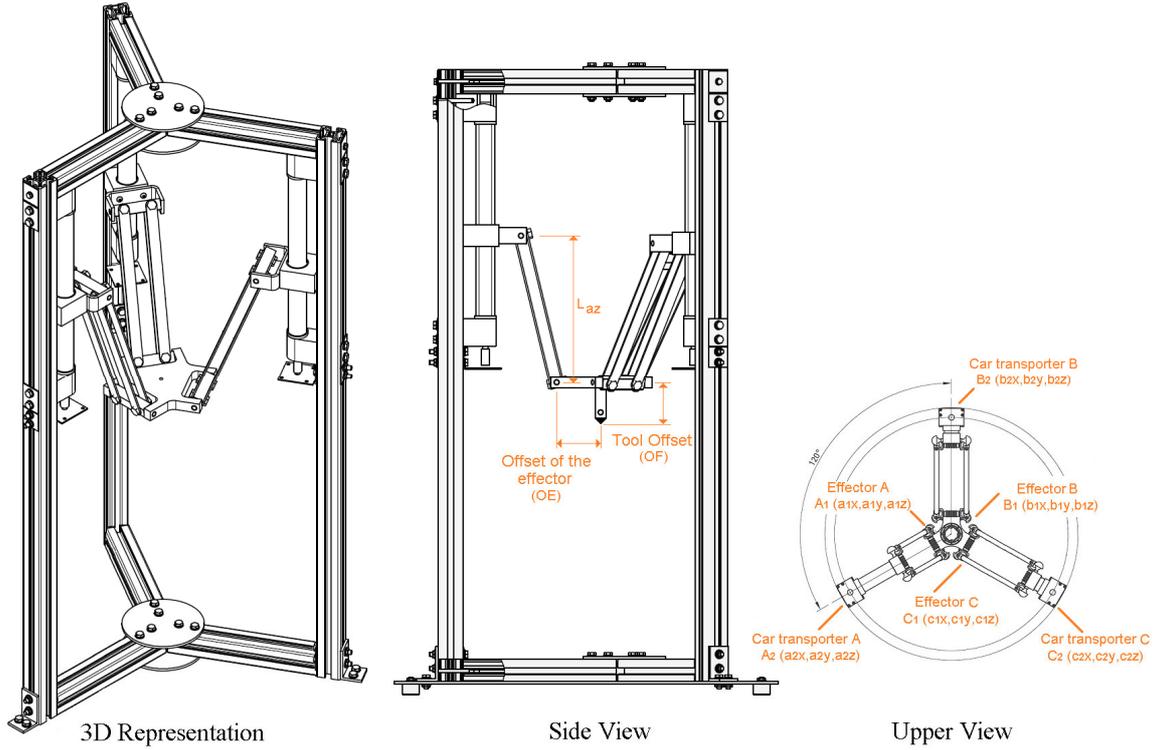


Figure 4. Fundamental elements for structure analysis. Source: Own authorship.

In this way, the size of the rod in the x-y plane and z-axis is projected. Applying the theorem of Pythagoras, it is observed by the projections of the rods:

$$L_{axy} = \sqrt{(a_{2x} - a_{1x})^2 + (a_{2y} - a_{1y})^2} \quad (1)$$

$$L_{bxy} = \sqrt{(b_{2x} - b_{1x})^2 + (b_{2y} - b_{1y})^2} \quad (2)$$

$$L_{cxy} = \sqrt{(c_{2x} - c_{1x})^2 + (c_{2y} - c_{1y})^2} \quad (3)$$

Next, a relation between the projections of the rods with respect to the z-axis is defined:

$$L_{az} = \sqrt{(L_a)^2 - (L_{axy})^2} \quad (4)$$

$$L_{bz} = \sqrt{(L_b)^2 - (L_{bxy})^2} \quad (5)$$

$$L_{cz} = \sqrt{(L_c)^2 - (L_{cxy})^2} \quad (6)$$

Finally, it is possible to obtain the position of the conveyors in relation to the base:

$$a_{2z} = f_z + OF + L_{az} \quad (7)$$

$$b_{2z} = f_z + OF + L_{bz} \quad (8)$$

$$c_{2z} = f_z + OF + L_{cz} \quad (9)$$

2.3 PID controller

The control of block diagram implemented is presented in Fig. (5). The expression of the discrete PID controller is presented in Eq. (10).

$$u(t) = K_p e(t) + u_i(kT) + K_i e(t)T + K_d \frac{e(t) - e(kt)}{T} \quad (10)$$

Where:

K_p is the coefficient proportional;

K_i is the coefficient integral;

K_d is the coefficient derivative;

T is the sampling period;

$e(t)$ is the current system error;

$e(kT)$ is the error in the instant before the current system;

$u_i(kT)$ is the value of the integral term in the instant before the current system;

$u(t)$ is the PID output.

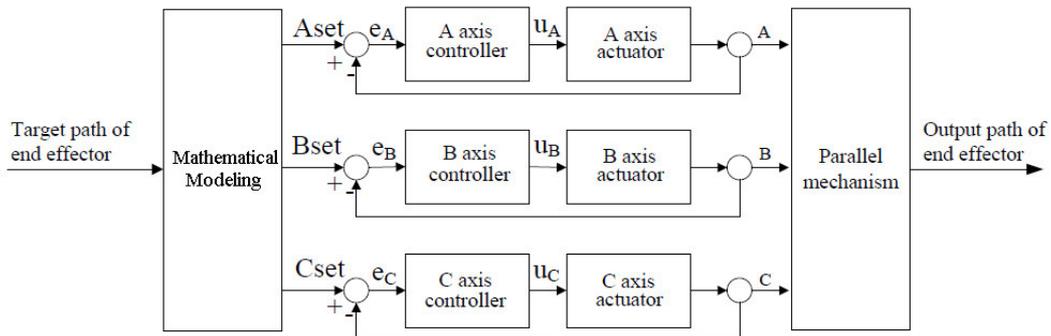


Figure 5. Control diagram of the parallel mechanism. Source: Own authorship.

3. EXPERIMENTAL RESULTS

One of the great difficulties in implementing a PID control is the experimental tuning of proportional, integral and derivative values. The Ziegler-Nichols tuning method was used for the implementation of the DC motor speed controller, and consequently the position control.

For this reason, a supervisory program was also created that allowed the visualization of the output and input through graphs plotted in real time, besides allowing the adjustment of the constants also in real time. This supervisor was programmed in the Java language (Fig.6), and communicates with the microcontroller via USB \leftrightarrow Serial protocols; for this the microcontroller must be connected to the computer via USB cable.

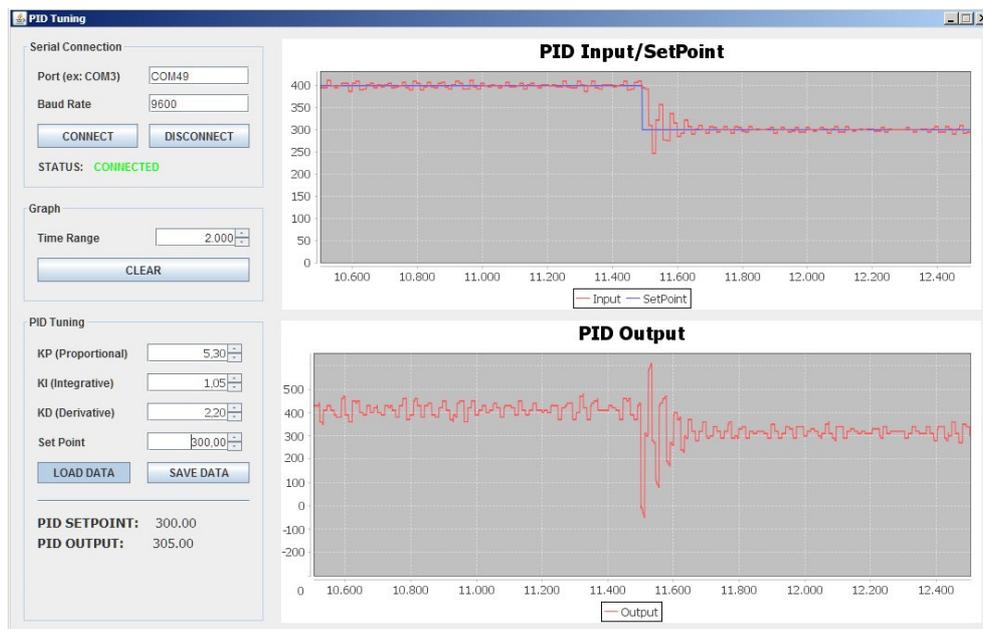


Figure 6. Supervisory for tuning by PID control. Source: Own authorship.

In Fig. (6) it is possible to observe the input and output signals of the controller, where the car A was located at 400 mm stroke and was moved to the 305 mm position, having a reference of 300 mm, that is, there was an error of 5 mm. The tuning of the controllers for this car that provided the best results determined as gains: $K_p = 5,3$; $K_i = 1,05$ and $K_D = 2,2$.

The experimental tests tested the performance of PID controllers for the positioning of conveyors A, B and C with operating voltages at 16VDC and 12VDC. The operating voltages were chosen for high speed and low positioning error. When the 24VDC operating voltage was used, errors greater than 5% of positioning were observed due to higher inertial effects. The results of the position control are presented in Tab. (1), using the operating voltages of 16VDC and 12VDC motors.

Table 1. Results of position control for the operating voltages of 16VDC and 12VDC motors. Source: Own Authorship.

Operating Voltage - 16VDC					Operating Voltage - 12VDC				
Input	Output	Error	Time	Speed	Input	Output	Error	Time	Speed
Car Transporter A					Car Transporter A				
325mm	324mm	0,31%	1,61s	201mm/s	335mm	336mm	0,30%	2,20s	153mm/s
260mm	258mm	0,77%	1,31s	197mm/s	280mm	279mm	0,36%	1,72s	162mm/s
140mm	139mm	0,71%	1,02s	136mm/s	135mm	134mm	0,74%	0,79s	170mm/s
40mm	39mm	2,50%	0,27s	144mm/s	65mm	64mm	1,54%	0,47s	136mm/s
Car Transporter B					Car Transporter B				
335mm	335mm	0,00%	1,34s	250mm/s	320mm	318mm	0,63%	1,84s	173mm/s
265mm	266mm	0,38%	1,00s	266mm/s	255mm	254mm	0,39%	1,51s	168mm/s
135mm	133mm	1,48%	1,24s	107mm/s	167mm	167mm	0,00%	0,94s	178mm/s
90mm	91mm	1,11%	0,29s	314mm/s	60mm	61mm	1,67%	0,38s	161mm/s
Car Transporter C					Car Transporter C				
365mm	362mm	0,82%	1,30s	278mm/s	325mm	326mm	0,31%	1,85s	176mm/s
240mm	239mm	0,42%	1,15s	208mm/s	255mm	256mm	0,39%	1,42s	180mm/s
180mm	179mm	0,56%	0,61s	293mm/s	155mm	157mm	1,29%	0,90s	174mm/s
90mm	92mm	2,22%	0,28s	329mm/s	50mm	51mm	2,00%	0,18s	283mm/s

4. CONCLUSION

The mechanical structure, although simple, met the specifications of the mathematical modeling so that the joint position control of the cars transporters A, B and C (position of the effector) is accurate. In this way, the structure must be well aligned and squared to ensure the angles of the cars. Simultaneously the mechanical assembly was performed the instrumentation of each positioning system with the coupling of encoders, as well as the drive system (power circuit) of the motor. A generalist "PID library" was conceived for any microcontroller, aiming at the implementation in PIC. Finally, a PID controller was tested and validated for each conveyor with a maximum positioning error of 2.50% for an operating voltage of 16VDC. In future work will be implemented a Fuzzy Mamdani type intelligent controller with the objective of minimizing the inertial effects.

5. ACKNOWLEDGEMENTS

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