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MATHEMATICAL MODELING AND EXPERIMENTAL IDENTIFICATION OF BACKLASH NONLINEARITY IN PROTOTYPE OF A ROBOT GANTRY WITH ELECTRIC DRIVE AND BALL SCREW TRANSMISSION

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Abstract. *The objectiveof this work is to present a methodology for the experimental identification of the backlash nonlinearity in the Gantry robot prototype with transmission by ball screw and elastic coupling on the electric drive gearbox for alternating current and frequency inverter. The use of robots is associated with productivity, quality and safety so that robots Gantry types have specific applications in load handling tasks (robot winch), laser cutting and machining. The development of robots with lower cost construction forms often require the use of flexible couplings (which allows linear and angular misalignments) as well as lower manufacturing cost components that have a feature off. However these constructive aspects may adversely affect the robot's performance in accurately positioning tasks. The backlash limits the performance and control of mechanical systems causing delays and oscillations, which explains the importance of identifying it. Furthermore, the backlash is a static characteristic present in reversing movement which prevents the coupling between the dynamic and increases the order of the dynamic system. The contribution of this work is the mathematical modeling of robot Gantry prototype with and without nonlinearity of backlash and a methodological proposal for identifying the nonlinear characteristic of backlash in the elastic coupling and the transmission axis ball screw of a prototype robotic manipulator low cost.*

Keywords: *mathematical modeling, backlash nonlinearity, Gantry robot, Construction of prototype*

1. INTRODUCTION

Historically the robots come from the perspective of assist humans in repetitive activities, unhealthy and great physical effort (Gomes, 2000). According to ISO 10218 (*apud* Romano, 2002), a robot is a machine with base manipulative fixed or not, multifunctional, easy programming and reprogramming, automatically controlled, widely used in industry for the good relationship between productivity and maintenance as well as high accuracy.

Industrial robots are characterized by integration between the mechanical mechanisms, actuators, sensors, control unit and power and effectors (Romano, 2002). The continue process of developing robotic systems improved functionality and adaptability of portico robots (or Gantry) in demanding industrial automation environment, making Gantry robots were employed in different areas to perform various functions, including most importantly winch robot, laser cutting machines and CNC machining. The main advantages are: productivity, quality, safety, adaptable (Shang and Cong, 2014). Research on robots Gantry type, are concerned especially with the development of high-precision strategies control and for high speed, which, combined with the great forces that parallel manipulator of this kind can translate, it becomes very difficult (Shang and Cong, 2014).

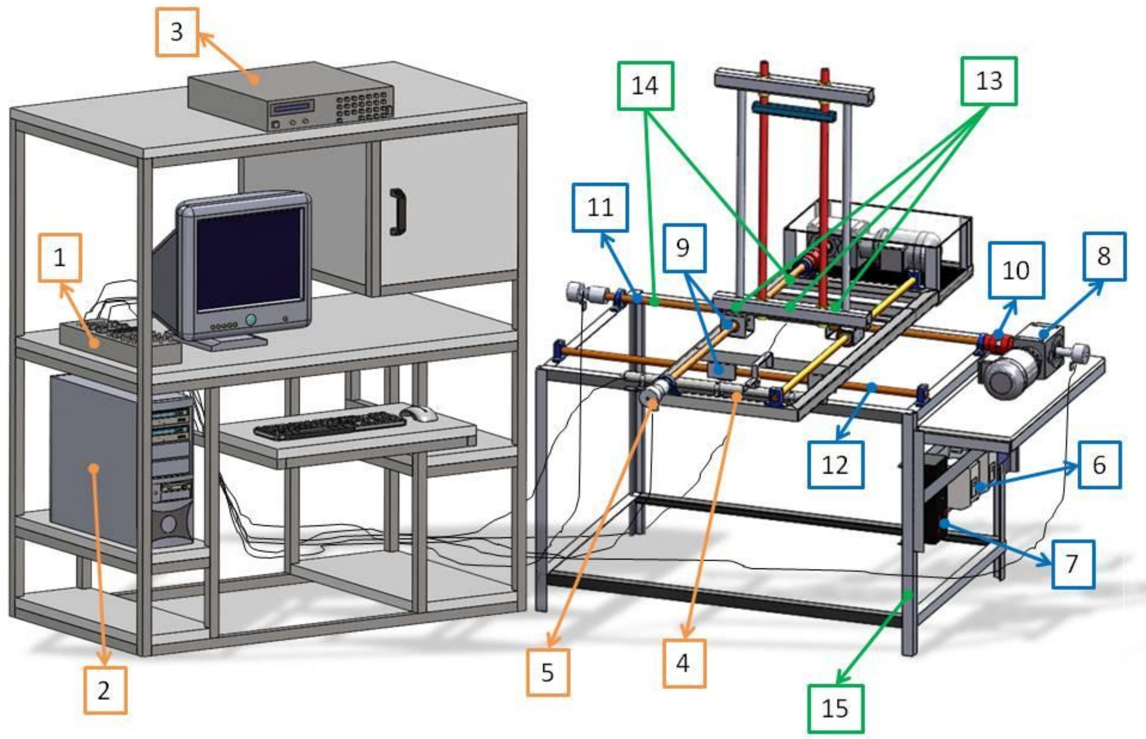
The backlash is the main source of positioning error and impacts and their lessening/compensation is the most effective way to improve positioning accuracy and avoid the impact (Yang, Yan and Han, 2015). Despite the various robot applications, the models that describe its dynamics do not yet have the required accuracy which affects directly the accuracy of their functions. Mathematical models are very important for predicting system behavior (Slotine and Li, 1991). Besides, certain nonlinearities, such as the backlash, are few studies while theoretical and experimental research so that control systems where such nonlinearities considered is a theoretical and experimental problem open and studies in this area are of great relevance to applications (Tao and Kokotović, 1995).

So, the objective of this paper is to present the methodology for the experimental identification of the backlash nonlinearity in the Gantry robot prototype with transmission by ball screw and elastic coupling on the electric drive gearbox for alternating current and frequency inverter. For this, are presented four sections. At first this is some constructive aspects of robotic joint built. The next section presents the mathematical modeling of the backlash. In the subsequent sections are presented to identify of the backlash and the conclusions and future prospects for this work.

2. ROBOT GANTRY PROTOTYPE

For the experimental identification has been built an experimental stand (Fig. 1) with a robotic joint of a Gantry robot electrically powered by alternate current gear motor (AC) and the frequency inverter, with ball screw transmission which is connected to the gearbox shaft by a elastic coupling.

Figure 1. Design Robot Gantry
Source: the author.

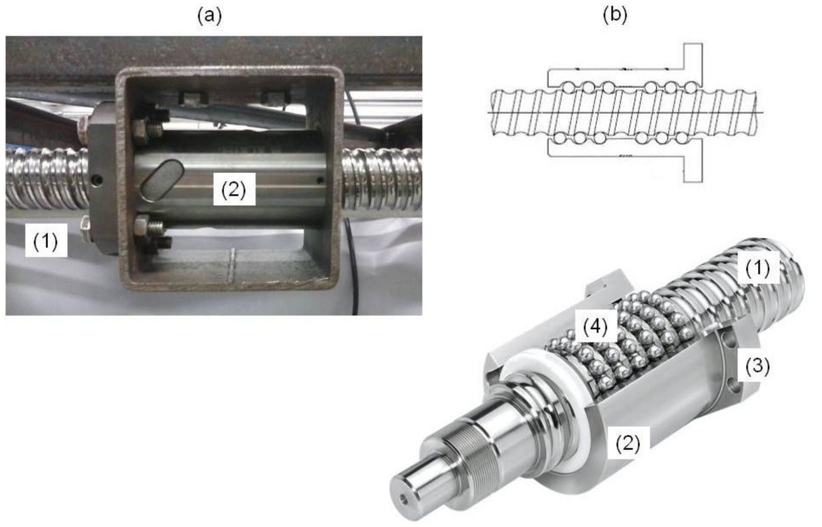


Control		Actuation		Mechanism	
11	dSPACE	6	Frequency Inverter	13	Links
22	Microcomputer	7	Command box	14	Joint
33	Power supply	8	Gearmotor CA	15	Stand
44	Displacement Transducer	9	Ball nuts		
55	Endoder	10	Elastic coupling		
		11	Axis screw		
		12	Axis smooth		

The cartesian structure means in linear displacement (given which is a prismatic joint) of one link in relation to the previous. The nut moves on the axis screw from angular displacement caused by torques applied by AC gearmotor on the axis.The angular and linear displacement signals are captured by sensors installed that sent for the board acquisition and control dSPACE 1104 with interface with Simulink/Matlab through ControlDesk.

The choice of transmission in robotic systems is linked to the type of task that will be performed. On the robots Gantry type are very much used transmission screw and nut type (power screw) as shown in Fig. 2, which show advantages for stability, efficiency, accuracy, durability, and cost (Shimada *et al.*, 2013) but disadvantages especially related with dynamic variations and vibrations (Hanifzadegan and Nagamune, 2015).

Figure 2. Ball Screw: (a) Adopted at the Experimental Stand; (b) Schematic Design and Main Components - (1) Screw (2) Nuts, (3) Flange (4) Balls
Source: the author.



Other decisive factor is the choice of the drive. They must contemplate the need for the project (appropriate to each utility robot), initial costs and maintenance. The industry, in general, uses three types of drive and combinations thereof: pneumatic, hydraulic and electric.

In systems driven by electric motors advantages are the low variance of speed (though low, this factor very difficult the use of AC motors over to DC even if they are more expensive and require more maintenance and care) high current startup, process efficiency, shorter cycle times (better dynamic response) and less maintenance with the main disadvantages the high cost and slow starts and stops caused by acceleration and deceleration ramps of the motor (Garcia-Valdovinos and Parra-See, 2003).

Most of these problems have been corrected through of own electronics and especially the development frequency inverters. The frequency inverters combined with the improvement in AC geared motors provided great energy saving, given its better use, and a direct result improvements in the process and production costs, and the elimination of initial peak current and reducing equipment maintenance (Amirabadi *et al.*, 2014).

3. MATHEMATICAL MODELING OF BACKLASH

The backlash is important nonlinearity to be understood, modeled and compensated by limiting the performance and control of mechanical systems. The backlash limits severely the performance causing delays, oscillations and inaccuracies and is common in many components (such as actuators and mechanical connections) (Tao and Kokotović, 1995). The presence of this nonlinearity occurs in mechanical systems in which the motor is not directly connected to the moved (Nordin, 2000).

There is the presence of at least two backlashes on the robot: one elastic coupling and one in the nut. If discarded the backlash in the elastic coupling the angular displacement applied to the axis motor (θ_m) is the same to the angular displacement performed by the screw (θ).

For the nonlinearity of the backlash in the nut, the relationship between the linear displacement and angular displacement of the screw would be described by Eq. 1.

$$y = \frac{p}{2\pi}\theta \tag{1}$$

This equation indicates a direct and proportional relationship between the linear displacement (y) and angular displacement (θ), which depend only on the screw step. That is, a full angular displacement of $2\pi\ rad$ corresponds to a linear displacement of one step p in the screw.

The backlash is a non-differentiable characteristic (to be not continuous, described by discrete equations). Given the existence of backlash the dynamic equations of robotic joint cannot be combined being coupled by a mathematical relationship with discretized time is the relationship between the linear displacement of the prismatic joint (y) and the angular displacement (θ) in the presence of backlash, described by Eq. 2 (Tao and Kokotović, 1995).

$$y = \begin{cases} m(\theta(t) - c_l) & se\ \theta(t) \leq v_l \\ m(\theta(t) - c_r) & se\ \theta(t) \geq v_r \\ y(t-1) & se\ v_l < \theta(t) < v_r \end{cases} \tag{2}$$

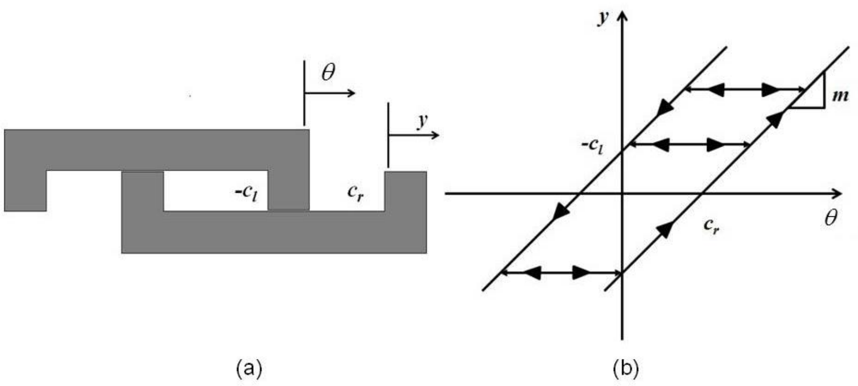
where m, $c_l(< 0)$ and c_r are the constant parameters of backlash nonlinearity on the screw, and the expressions v_l and v_r are given by Eq. 3 and Eq. 4.

$$v_l = \frac{y(t-1)}{m} + c_l \tag{3}$$

$$v_r = \frac{y(t-1)}{m} + c_r \tag{4}$$

In the Fig. 3, shows the schematic design of nonlinearity of the backlash and the graphic representation.

Figure 3. Representation Backlash NonLinearity: (a) Schematic Design; (b) Graphic Model
Source: Tao and Kokotović (1995).



The model variables shown in Eq. 2, 3 and 4 are described in Tab 1.

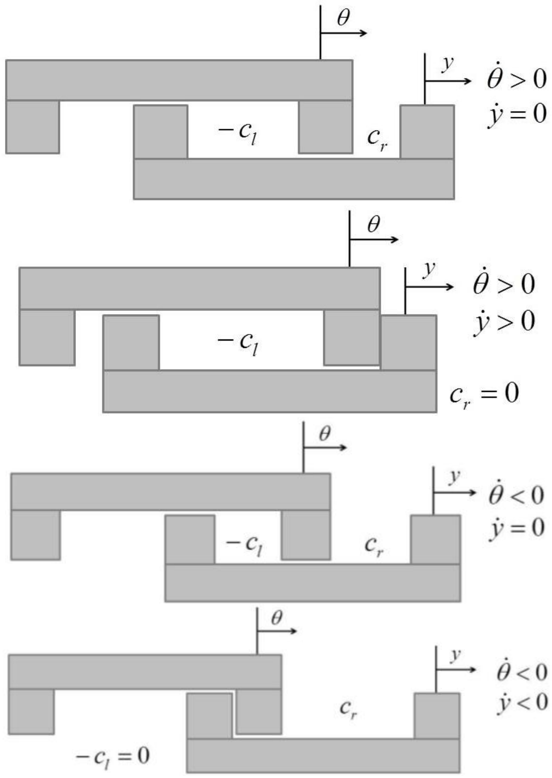
Table 1. Description of Parameters and Variables of Backlash Nonlinearity
Source: the author.

Parameter /	Description	Unit
θ	Angular displacement angle of the spindle (system input)	rad
y	Linear displacement of the prismatic joint (system output)	m
c_l	Initial position left side *(left)*	rad
c_r	Initial position right side *(right)*	rad
m	Gear ratio	m/rad
v_l and v_r	Projections functions	rad

4. EXPERIMENTAL IDENTIFICATION OF BACKLASH

In identification of the backlash was expanded the procedure described by Menuzzi (2011) from the acquisition of experimental data from the sidelines. Initially the robot is positioned in the zero referential. Then make the displacement to the negative direction slightly behind the point chosen to be the test beginning. Next, the robot is minimally moves to the opposite side in order to reset the backlash on the right. Therefore, the total backlash ends up being equal to itself off to the right. This procedure is schematized in the diagram of Fig. 4 below.

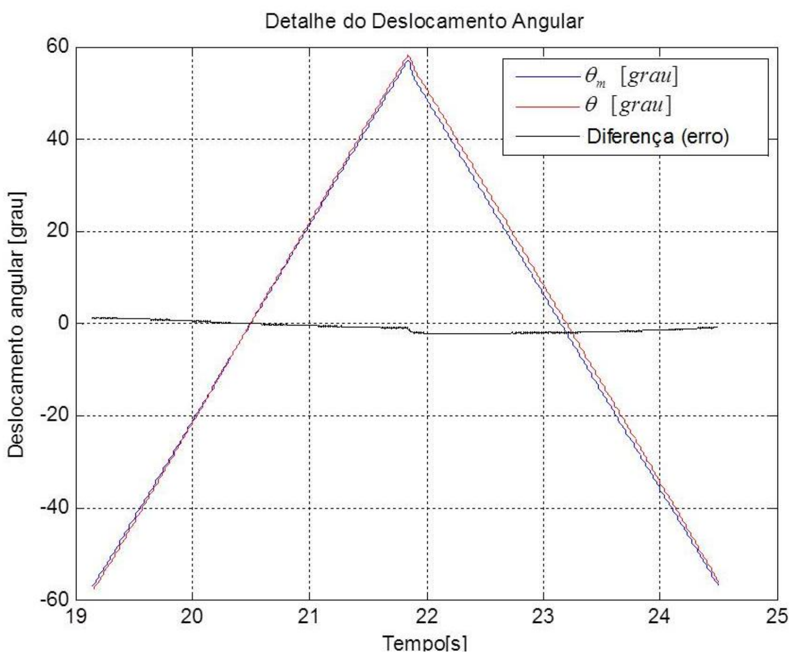
Figure 4. Procedure Diagram for the Backlash of Identification
Source:the author.



Note that the backlash is present in at least two situations: the elastic coupling and in the nut and so the two will be identified. Had special attention to take up a trajectory that would allow a reversal of motion, considering that the backlash is present especially in these situations.

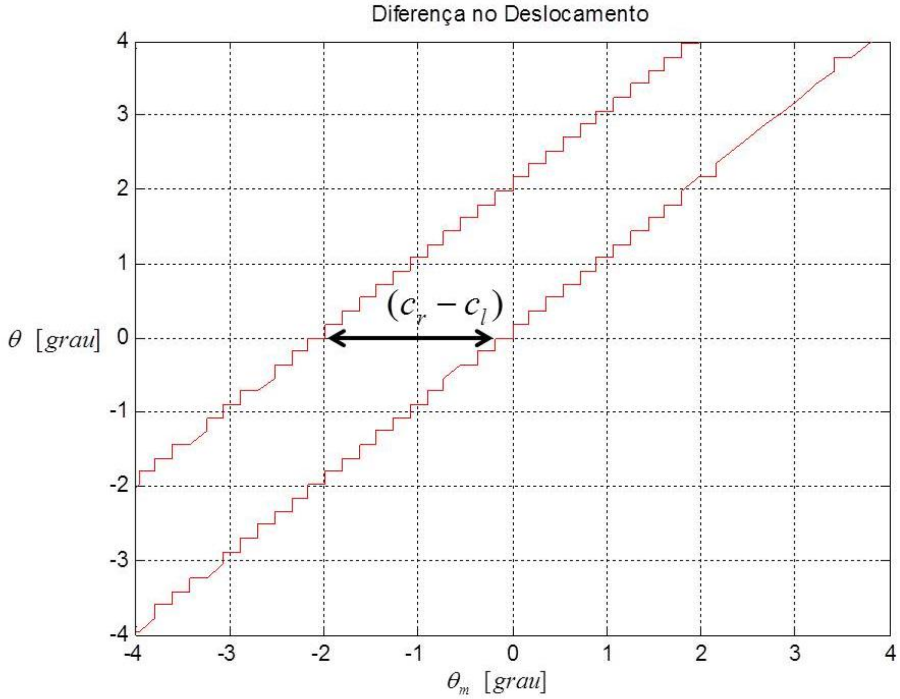
For the backlash in the coupling there is a difference between the angular displacement, that is the equal relationship between the displacement is not valid because existence the nonlinearity backlash as is shown in Fig. 5 .in one cycles of complete displacement performed.

Figure 5. Detail of the First Cycle Angular Motion Full
Source: the author.



The backlash is shown in the Fig. 6.

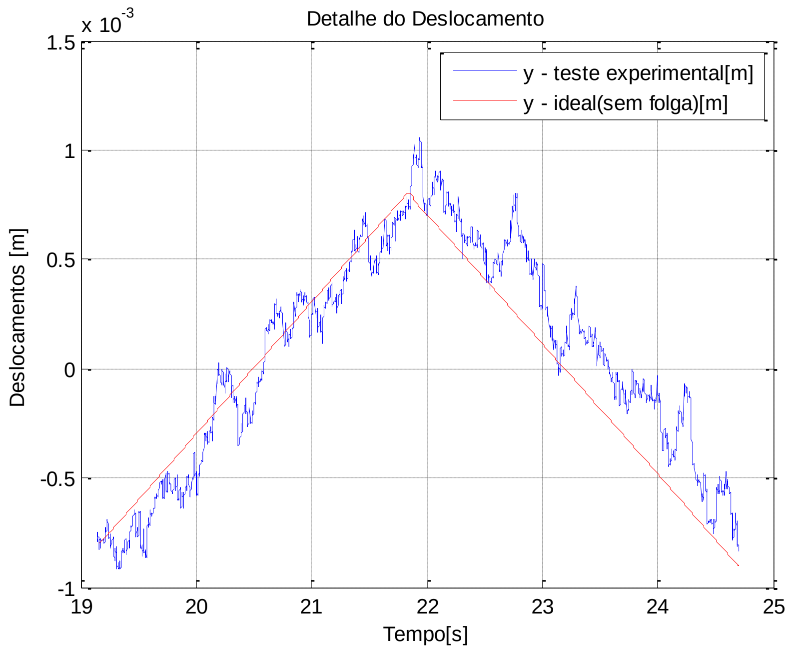
Figure 6. Backlash in Elastic Coupling
Source: the author.



From Fig. 7, can estimate the center interspace $(c_r - c_l)$, as 1,8° (0,0314 rad). This backlash is generating a linear backlash $5 \cdot 10^{-5}\ m$ (given from the equation (9)).

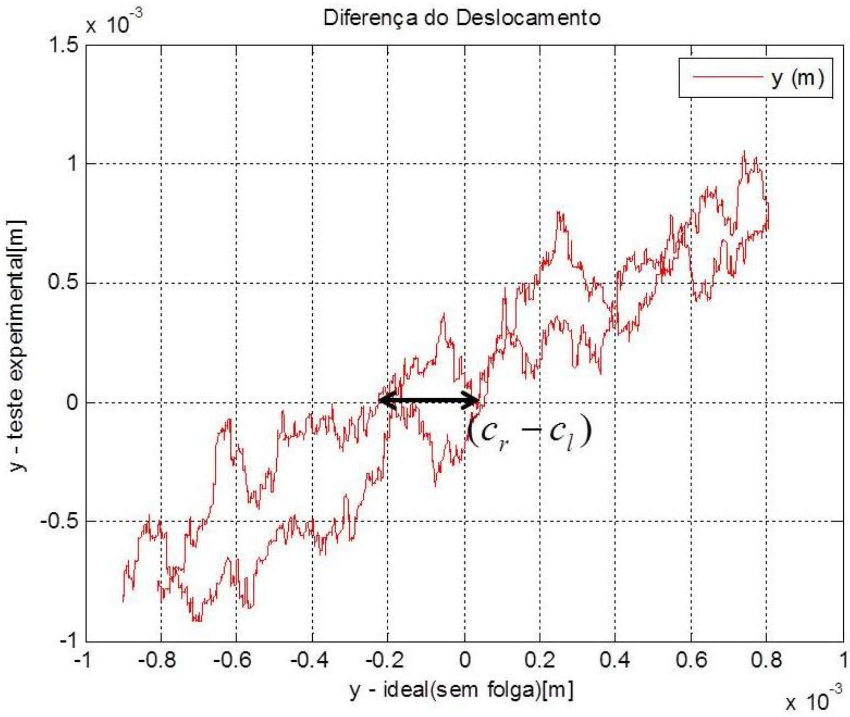
As the backlash in the nuts, the Fig 8 presents the simulation to verify the nonlinearity. For this was realized a full linear movement with motion reversal.

Figure 8. Detail of the First Cycle Linear Motion Full
Source: the author.



It perceives that there is a difference between the ideal linear displacement (according to equation (9)) and the experimentally obtained. The linear backlash is shown in Fig. 9.

Figure 9. Backlash in Nut
Source: the author.



From the Fig. 9, can also estimate the total backlash (center interspace ($c_r - c_l$)), as $1{,}825 \cdot 10^{-4} m$.

The very large fluctuations in the Fig. 8 and 9 are due to noise and vibration caused by the constitutive form of the robot.

5. CONCLUSIONS AND FUTURE PROSPECTS

The objective of this work presents a methodology for the experimental identification of the non-linearity of emu ma slack joint robotic type Gantry with transmission by screw ball and elastic coupling on the electric drive gearbox for alternating current and frequency inverter.

Built the experimental stand and modeled the backlash, making their identification for which it developed a methodology. The backlash estimated can be disregarded because showed very small compared to other nonlinearities such as friction, for example.

It is suggested to implement the dynamic model of backlash of the Gantry robot when for high precision applications such as prospects for continued research.

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8. RESPONSIBILITY NOTICE

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