# Abstract

The backlash phenomenon occurs in the joints of industrial manipulators, significantly impacting the performance and functionality of the manipulator. As robots are widely employed in automated production sites, any deterioration in the robot's performance can adversely affect production, leading to economic losses for the company. A careful maintenance program can prevent this situation, and targeted interventions can be timely scheduled by monitoring the backlash status in the joint. But obtaining a measure of backlash is not simple; the sensors typically required for measuring backlash are not included in the equipment of a standard industrial manipulator. So technicians must resort to manual measurements or estimates derived from measurements of other quantities directly related to backlash (i.e., vibrations). This research work stems from an industrial demand for an automatic tool for measuring backlash based on the use of only the sensors available on the robot. The tool must be the core of a predictive maintenance algorithm to be implemented as a service on an IIoT (Industrial Internet of Things) platform.

In standard industrial manipulators, the only available sensors are the motor encoders, dedicated to measure motor shaft's speed and/or position and to provide closed-loop feedback to the robot controller. An encoder alone is not sufficient to measure the backlash. Backlash is an excess space that occurs between the teeth of mating gears, creating a discontinuity in the transmission of motion from the motor to the link. For a direct measurement of the backlash, two encoders are needed, one at the input (i.e., on the motor) and one at the output (i.e., on the link) of the joint. The state of the backlash in the joint is obtained differentially using the readings from the two encoders. With only one encoder available the only way to obtain information about backlash is to look for any disturbances that backlash may cause in the motor's operation. In some of the few available studies in the literature, it has been shown that in simple bench systems, under specific conditions that excite the phenomenon, backlash effects can be observed propagating through the mechanical structure up to the motor, where they can be recorded by the encoder. However, replicating the same conditions in industrial manipulators is exceedingly challenging. Even in those cases where it is possible, the signs of backlash propagated to the motor are inconspicuous, manifesting as minor disturbances superimposed on the primary and noisy motor position signal. Furthermore, other disturbances of different origins are also detected by the same sensor. These disturbances, coupled with noise, create difficulties in precisely identifying backlash in the encoder signal.

The research activities described in this thesis have demonstrated that it is not only possible to identify excitations in industrial manipulators that make backlash observable on the motor encoder, but also that the observed disturbance has recurrent and well-defined characteristics, allowing for a unique association with backlash. It is therefore possible to define a “signature”of backlash to be used for backlash identification. When the signature is detected within the signal of an encoder, it indicates the presence of backlash in the joint. Moreover, the amplitude of the signature is directly proportional to the magnitude of the backlash in the joint. Based on these findings, the problem of backlash estimation can be reduced to a fitting problem of a model to a signal.

The tools used include Matlab/Simulink, which was employed to develop a simulator for a robotic joint, allowing for in-depth analysis of the backlash phenomenon, and Python for running optimization algorithms based on evolutionary strategies. Additionally, a test bench was specifically developed, replicating a joint of a real industrial manipulator, and used for analyzing the phenomenon and generating simulated data.

The outcome of this work led to the development of a toolchain for backlash estimation, whose effectiveness was validated using both simulated and real-world data. A second phase of method validation was conducted on a real industrial manipulator, revealing strengths and potential areas of future improvement of the identified approach.