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IMPROVING THE PRECISION OF ELECTRO-PNEUMATIC ACTUATOR BASED ROBOTIC BOTTLE CAPPER USING ADAPTIVE MODEL PREDICTIVE CONTROL

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Abstract

This paper on improving the precision of electro-pneumatic actuator based robotic bottle capper using Adaptive Model Predictive Control is focused on solving the frictional force challenges that are encountered in an automated bottle capping machine. To actualize this task, the pneumatic actuator systems, pneumatic actuator control systems like programmable logic controllers, model predictive control, adaptive model predictive control techniques, and several research works which adopted these techniques for improving the precision of the robotic bottle capper were reviewed. In this paper, the adaptive model predictive control technique was proposed to improve the system because of its ability to continually update and redesign its model predictive control strategy before a new control action is applied. The result of this study shows that the adaptive model predictive control technique has the highest performance accuracy of 94.30% when compared with other techniques.

Keywords: Programmable Logic Controller; Model Predictive Control; Bottle Capper; Precision

1. INTRODUCTION

Pneumatic actuators are one of the most used industrial equipment in the world today due to the numerous advantages they have, such as affordability, efficiency, temperature flexibility, and high power-to-weight ratio, among others. One of the major applications of this pneumatic system is in the automatic transportation of objects and motion control applications as in the brewery industries, pharmaceutical industries, and beverage industries, among a host of others. However, improving the performance of their close-loop-based precise position control has remained a major challenge and is actively a research area in control system engineering.

According to Haitao et al. (2019), the pneumatic actuator system is highly nonlinear due to the dynamics of air compression, frictional force variation, and the nonlinearity of mass flow rate, among others. Pedro et al. (2006) seconded the opinion that the main nonlinearity in the actuator system is the frictional force that exists between the contact surface and actuator seals. This causes nonlinearity in the position equilibrium and trajectory tracking error of the pneumatic actuators and has remained a major challenge to date.

Over time, many control system methods were proposed to stabilize nonlinear systems like the testbed actuator mechanism. They include dynamic feedback control, nonlinear control, feedforward control, predictive control, variable transformation, robust control, etc. (Luyben, 2018). However, the predictive control technique provided a better stability control approach when compared to the counterparts for complex nonlinear systems. This is because it can approximate the time-series behavior of the plant and make control decisions. One of the main controllers employed to achieve this objective is the Programmable Logic Controller (PLC).

According to Inyama and Agbaraji (2015), over 90% of the global industrial process control systems are designed with PLC. These PLCs are logic solvers which are used to automate the technical process and improve productivity. The PLC has some advantages such as affordability, availability, ease to use, and multi-ports compatibility among others, which make it popular for process design. However, they also have their limitations like delayed response time, overshoot, overheating, module failures, and electromagnetic interference among others, which make them not ideal to solve certain complex process control system problems like the case of pneumatic actuator control as discussed in (Dakre et al., 2015).

Recently, studies by (Haitao et al., 2019; Ashok et al., 2017) among others, proposed the use of Model Predictive Control (MPC) which has many advantages over the PLC, like optimal set point coordination control, ability to determine dynamics and static interactions between input, output, and other disturbance variables. However, MPC design is based on linear mathematical models which cannot be very efficient to guarantee precision control and dynamic stability of the pneumatic actuator attributed to complex nonlinear constraints already mentioned. To address these limitations of MPC, an adaptive MPC is proposed which uses a Kalman filter to adaptively control parameters with linear time-invariant behaviors like the pneumatic actuator at nominal operating points. This will provide a reliable, affordable, précised, and automated process control system that improved the quality of production in the manufacturing industries.

2. LITERATURE REVIEW

Nilesh et al. (2017) presented an improved bottle-filling operation using a multi-nozzle PLC system. This was achieved using a solenoid valve, nozzle, sensor, actuators, PLC, and conveyor system. The result showed drastic improvement in the cycle time to 87.40%, but despite the success still gives room for improvement.

Offordile et al. (2021) presented an enhanced precision electro-pneumatic actuator robotic system for bottle capping using a fuzzy logic controller. The study was done by developing a fuzzy set of rules which improves the precision of bottle capping in the brewery industry. This was done using the Simulink tool, control system tool, fuzzy logic tool, and Simulink. The result achieved a 3.1% increase when compared to the PLC-based characterized system.

Behrad et al (2020) presented a position control and force allocation algorithm for a hybrid pneumatic electrical linear actuator. In the study, a model predictive controller was developed and used to design a pneumatic-based collaborative robot. The result when tested showed that the MPC was able to reduce the root mean square error by 59%, the mean electric actuator force by 36%, and the pneumatic actuator force by 24%.

Anug et al. (2015) presented research on PLC-based automated bottle filling and capping with metal can ejector and SCADA. In the research, a PLC-based process design was modeled for the filling and capping of bottles. The aim is to solve the problem of delay time, experienced in the traditional method which employed human resources and is cost-intensive. The result showed that the PLC-based process design improved the automation of the technical process, but suffers delays in the position control of the pneumatic actuator.

Lakshmeesha et al. (2018) presented an automatic bottle-filling and capping machine based on an Arduino controller. The study implemented a small-scale automation system for manufacturing industries to save the cost of production. This was achieved using the proposed Arduino which has been identified as an alternative to PLC and cheap.

Zar and Tin (2019) presented PLC based automated bottling filling and capping system. The study used an inductive sensor, ladder logic diagram, PLC, and DC motor among others to develop a process design for a bottle capping system. The result when tested showed that the new system developed was able to automate the technical process. However, PLC suffers issues of delayed response time which affect the precision control of pneumatic actuators.

Jitendra (2020) presented an autonomous bottling-filling machine adding to the accuracy and precision along with the rejection mechanism. The study used a microcontroller to design the process control system which improves flow rate control, delay rectification, counting of bottles, and rejection criteria among others. The result when tested showed that despite the success the controller still needs improvement in its precision control of pneumatic actuators.

Siti et al. (2017) presented an enhanced position control for the pneumatic system by the application constraints in the MPC algorithm. In the study, an MPC algorithm was developed using a mathematical model and then implemented for the control of pneumatic systems. The result showed that the MPC was able to improve the precision control of bottle positioning, compared to the PLC type. This MPC will be localized in this study for the Nigerian breweries.

Pankaj et al. (2019) presented an automatic bottle filling and capping system using PLC. The study used proximity sensors, PLC controllers, and pneumatic sensors among other necessary process design components to model an automatic system for the automation of bottle filling and capping. The result showed that the PLC improves the efficiency of production when compared to the conventional process of manufacturing which used manual labour. The result however shows further that the PLC has issues with the position control of bottles via the control of solenoid and pneumatic systems.

Liton et al. (2019) presented research on automatic bottle-filling systems using PLC-based controllers. The study was aimed at developing a simple and cost-effective automatic bottle filing system using PLC. This was done using sensors, actuators, dc motor, conveyor, and the proposed control system. The result showed that the developed system is cost-effective and can be affordable for small-scale water production-based industries.

Best et al., (2016) presented a study on model predictive control for pneumatically actuated soft robots. This study the adaptive model predictive control for improving the performance of the pneumatically actuated soft robot and developed other dynamic models and control methods to give the robot the ability toperform various tasks. The result of this study gave a performance accuracy of 90%.

Syed et al. (2020) presented research on the analysis and implementation of the distributed control system in process of bottle filling with MATLAB. In the study, the process control was designed with a PID controller and implemented with Simulink. The result showed that a cost-effective system for automatic filling and capping of the bottle was developed. The result when tested showed improved process automation efficiency but despite the success, there is still room for improvement.

Zeng and Barooah (2021) presented a study on the application of an adaptive model predictive control scheme for energy-efficient control of building HVAC systems. this study is aimed at developing a system that is independent in performing control operations in HVAC systems. the controller achieved an accuracy of 94.30%.

3. PNEUMATIC ACTUATOR SYSTEM

To develop the nonlinear model of the pneumatic actuator system, it is necessary to first describe the actuator model as a servo motor positioning control system using the relationship between the servo valve and cylindrical chambers as presented in figure 1. During the operation, the control parameter (u) energized the solenoid valve which triggers magnetic force on the valve spool resulting in displacement (Haitao et al., 2019). This process opens the orifice to connect one port to the supply pressure line while the other pots are connected to atmospheric pressure, resulting in the pressure variation between the cylinder chambers. When this occurs, force is produced to move the mass (M) in a displacement position of (y) based on the input signal. The schematic model of the pneumatic actuator is presented below;

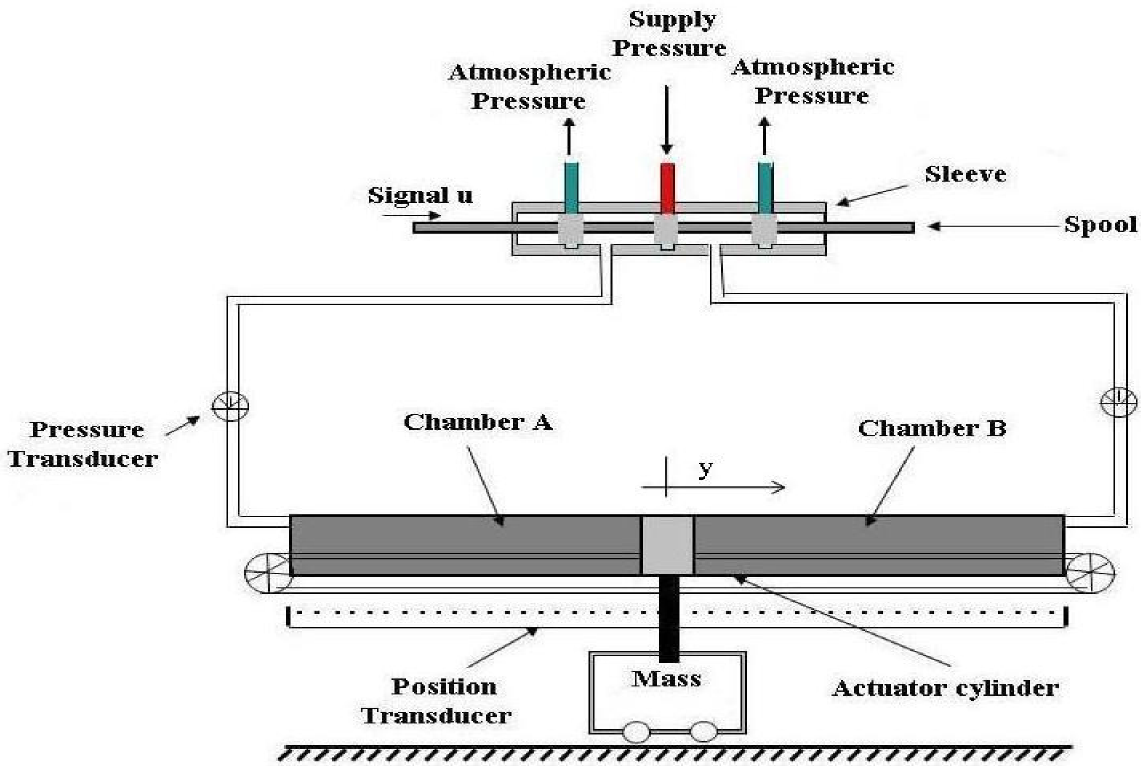

Figure 1: Schematic model of the pneumatic actuator (Carlo et al., 2010).

Figure 1 presented the model of the pneumatic actuator and how it operated. During this process, three main nonlinear parameters which are air compressibility, mass flow rate, and friction occur which affect the behaviour of the pneumatic actuator, thus leading to poor performance. Air compressibility is a nonlinear function that occurs as a result of the differential pressure between the valve and orifice and the model (Carlo et al., 2010). The mass flow rate (pressure dynamics) occurred as a result of the cylindrical size, as the small size of the cylinder increases pressure response and effect pneumatic behaviours (Carlo et al., 2010). Nonlinear friction on the other hand is the most important factor according to (Carlo et al., 2010). Friction is a nonlinear phenomenon that is very difficult to manage and control as its behaviour varies with time in the pneumatic actuator and also depends on unknown environmental factors like temperature, lubrication condition of the contact surface areas, etc.

3.1 Friction in Pneumatic Actuators

It is a very crucial practice to admit that the friction that occurs at the actuator of a system affects the performance and precision of the system. The nonlinearity of the actuator frictional force is the most complex in the position servo system of a pneumatic actuator. It leads to lots of mistakes in the control,it also makes the control of such position trajectory and position tracking difficult and erroneous.

The stick-slip movements and limit cycles around the desired position are both caused by frictional forces.

The frictional force between the counterparts and the seals in relative and constant sliding motion has a direct effect on the reliability, efficiency, seal/counter face ware, and skip-slip phenomenon of the actuator. This seal malfunction results in low sealing capability, high friction, and incorrect lubricating condition of the materials and geometry which leads to lower performance of the system (Haitao et al., 2019). Therefore, the reduction of this frictional force will improve the efficiency and performance of pneumatic components and gives the system a longer life span of service.

The importance of mitigating the rate of friction in pneumatic or hydraulic actuators cannot be overemphasized and has been duly considered by a wide range of researchers over the world. To achieve this, all the physical parameters both on the actuator and controllers are being considered and different methodologies have been adopted and analyzed to solve the challenge of both dynamic frictional force at a constant actuator velocity and dynamic frictional force in unsteady motion.

4. PNEUMATIC ACTUATOR CONTROL SYSTEM

This section discussed the various state-of-the-art actuator controllers adopted in this paper, the controllers include the programmable logic controller, model predictive control, and the adaptive model predictive controller. They are discussed as follows;

a. Programmable Logic Controller (PLC)

The PLC is a digital logic solver device that is a computer system employed for process control and industrial automation of electrochemical mechanical processes like the control of machines in the assembly lines of factory production. The PLC is used today in many industrial controls with multi-input and output ports which makes it compatible with the control of many plants at the same time. They are programmed with special software in ladder logic diagrams which required the knowledge of basic programming to configure (Kumar et al., 2019).

b. Model Predictive Control (MPC)

Model Predictive Control (MPC) is an advanced method of process control that is used the control the technical process while satisfying a set of constraints. The MPC relies on dynamic models of the process, most often linear empirical models obtained by system identification. The main advantage of MPC is the fact that it allows the current timeslot to be optimized while keeping future timeslots in the account (Wang et al., 2020). This is achieved by optimizing a finite time horizon, but only implementing the current timeslot and then optimizing again, repeatedly, thus differing from Linear-Quadratic Regulator (LQR). Furthermore, according to Ashok et al. (2017), the MPC can predict future events and take control actions accordingly. MPC is nearly universally implemented as digital control, although there is research into achieving faster response times with specially designed analog circuitry.

c. Adaptive Model Predictive Control

MPC is an advanced control strategy based on the optimization of an objective function within a specified horizon and has been recognized as the winning alternative for constrained multivariable control of industrial systems (Marshiana et al., 2019). However, the characteristics of many industrial systems are highly nonlinear and time-varying. Therefore, the algorithms obtained by MPC design techniques which are based on a linear mathematical model of the controlled process are not very efficient because these methods cannot guarantee stable control outside the range of the model validity.

For this reason, adaptive algorithms which would be based on a continuous model updating process and redesign of the MPC strategy before a new control action is applied to the real system would be the preferred ones. Up to now the development of such algorithms is very much restrained to systems with large sampling time because of their high computation time. However, the recent availability of inexpensive multi-core computers makes us rethink the possibility of developing adaptive MPC algorithms.

5. COMPARATIVE ANALYSIS

This section presents the analytical performance of the results obtained from practical experiments of the pneumatic actuator control devices applied in previous works. The result presented in this section justifies the proposal for the technique proposed in this paper.

According to the works Nilesh et al. (2017), Best et al., (2016), and Zeng and Barooah (2021) which were recorded as the best-performing studies adopting the respective techniques, the results of their performances are presented in table 1;

Table 1: Performance Results

Author	**Technique**	**Control Accuracy (%)**
Nilesh et al. (2017)	PLC	87.40
Best et al, (2016)	MPC	90.00
Zeng and Barooah(2021)	Adaptive-MPC	94.30

The results presented in table 1, the result will be analyzed and illustrated in figure 2;

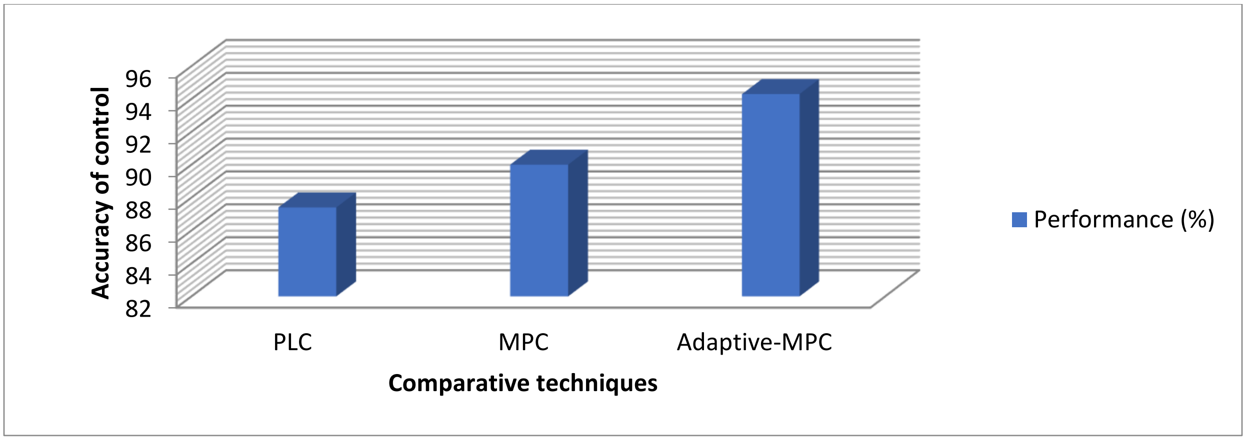

Figure 2: The Performance Analysis of the Techniques

From the image in figure 2, the level of accuracy for the different techniques reviewed in this paper is presented. From the analysis, it can be seen that the Adaptive-MPC technique has the highest level of performance. Meanwhile, the adaptiveMPC also has a wonderful performance in terms of overshooting control and reduction of energy use by 26.80%.

6. CONCLUSION

This study has successfully presented an improved process control system for bottle filling and capping. This work reviewed pneumatic actuator systems, pneumatic actuator control systems like programmable logic controllers, model predictive control and adaptive model predictive control techniques, and several other research works which adopted these techniques for improving the precision of the robotic bottle capper.This was achieved by adopting an adaptive MPC which identified the linear time-invariant model of the pneumatic actuator and then identified parameters whose behaviour changes with time like the frictions which is the major focus of this work as literature identified it as the main problem against precision control of the pneumatic actuator.The result of this study shows that the adaptive model predictive control technique has the highest performance accuracy of 94.30% among other techniques.

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