Volume 1, Issue XII, December 2022, **No. 30, pp. 345-359**

Submitted 5/11/2022

Final peer review 28/11/2022

Online Publication 12/12/2022

Available Online at http://www.ijortacs.com

IMPROVING THE BOTTLE CAPPING SYSTEM WITH AN ADAPTIVE MODEL PREDICTIVE CONTROLLER

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Abstract

This work is aimed at* improving the bottle capping system with an adaptive model predictive controller. *To achieve this, first, a robust pneumatic frictional force model was developed considering damping and stiffness coefficients of microscopic deformations of the piston surfaces which were mainly responsible for object positioning inaccuracies. To deal with this, an Adaptive Model Predictive Controller (AMPC) model was developed and used to control the linear time-invariant behavior of the pneumatic actuator and then updated the control response with the Kalman filter. This was guided by qualitative methodology and the system implementation was achieved with Simulink. The result showed that the response time to friction was 4.02ms. The AMPC was integrated into the plant model and tested using a tenfold cross-validation technique. The result showed that static friction was 33.32N and coulomb friction 2.71N. To improve the validity of the work, the AMPC was compared with data on friction collected from a conventional pneumatic system. The result showed that 24.57% of static friction was reduced and 29.9% of coulomb friction was reduced, and this is the improvement achieved in the control of both static and coulomb friction of the pneumatic system.

Keywords: Precision, AMPC, Response Time, Kalman filter, Static Friction, Coulomb Friction

I. INTRODUCTION

The rate of experiencing improperly capped drinks in the brewery industries has resulted in so much loss to both consumers and brewers. This has been traced to the use of hydraulic actuator which lacks the adequate precision required in sensitive operations. This precision inadequacy is caused by friction, air compressibility, and time delay in the hydraulic actuator system (Todmal et al., 2016). Though it is capable of exerting adequate force during the capping operation, its precision cannot be guaranteed. This gives rise to so many improperly capped drinks,resulting in avoidable losses. Loss of revenue and the inability to meet production targets are some of the direct consequences. Additionally, the health hazards resulting from contamination due to exposure to improperly capped beverage bottles are serious health threats. To obviate these conditions, an Adaptive Model Predictive Controller is proposed to improve the bottle capping system by synchronizing the process. Its application will ultimately result in improving the bottle capping system (Xiaokang et al., 2019). The aim of this research is to improve the bottle capping system with an adaptive model predictive controller. This will be achieved in this research by developing an adaptive MPC model which will coordinate the process design parameters of bottle filling and capping operations and provide a reliable, affordable, and automated process control system that improved the quality of production in the manufacturing companies.

II. SYSTEMATIC LITERATURE REVIEW

Author	**Technique**	**Work done**	**Research gap/Limitation**
Emhemed et al. (2016)	Model Predictive Control (MPC)	The method of modified predictive control was based on the control matrix formulation which was combined with an optimized move suppression coefficient.	MPC can be made adaptive
Pereida and Schoellig (2018)	Adaptive Model Predictive Control	A higher-level based model predictive controller with a reference plant model was used to update the optimal reference input based on a cost functionwhile taking into account input and state constraints.	MPC provided better control efficiency than a PLC
Xiaokang et al (2019)	Adaptive Model Predictive Control.	In the research, the adaptive MPC was designed by combining an adaptive updating law for estimated parameters and a multiply constrained MPC for the estimated system.	Better than normal MPC and PLC.
Todmal et al (2016)	Programmable logic controller (PLC)	The study used indexing conveyor belts, three-way self-centering grippers, a three-jaw chuck (bottle holding fixture), and an infrared level detection sensor to design the industry 4.0 system for the brewery industry.	Can be improved with MPC
Gandhi et al (2015)	Programmable logic controller	The study used PLC to design an optimized process control system, for the bottle filling and capping process.	Can be improved with MPC

Prajapati et al (2019)	Programming Logic Control	The study developed a process control system using a DC motor, conveyor, PLC, sensors, pneumatic actuator, etc.	Can be improved with MPC
Vishwanath et al (2019)	PLC	The study used an electric motor, conveyor belt, sensor, and pneumatic system to design a process control system for the bottle capping and filling process	Can be improved with MPC

III. METHODOLOGY

The methodology employed a qualitative approach which makes use of open-source information from related works, analyzes them, and draws logical conclusions from them. The approach was also used for the research design, as the nonlinear model of the actuator was developed considering theimpact of friction on the positioning and control capping of bottles. Their nonlinearities were identified as a multi-constraint and approximated using Kalman filter-based adaptive MPC. This was implemented on the actuator system using Simulink and tested for results and analysis.

IV. SYSTEM MODELING

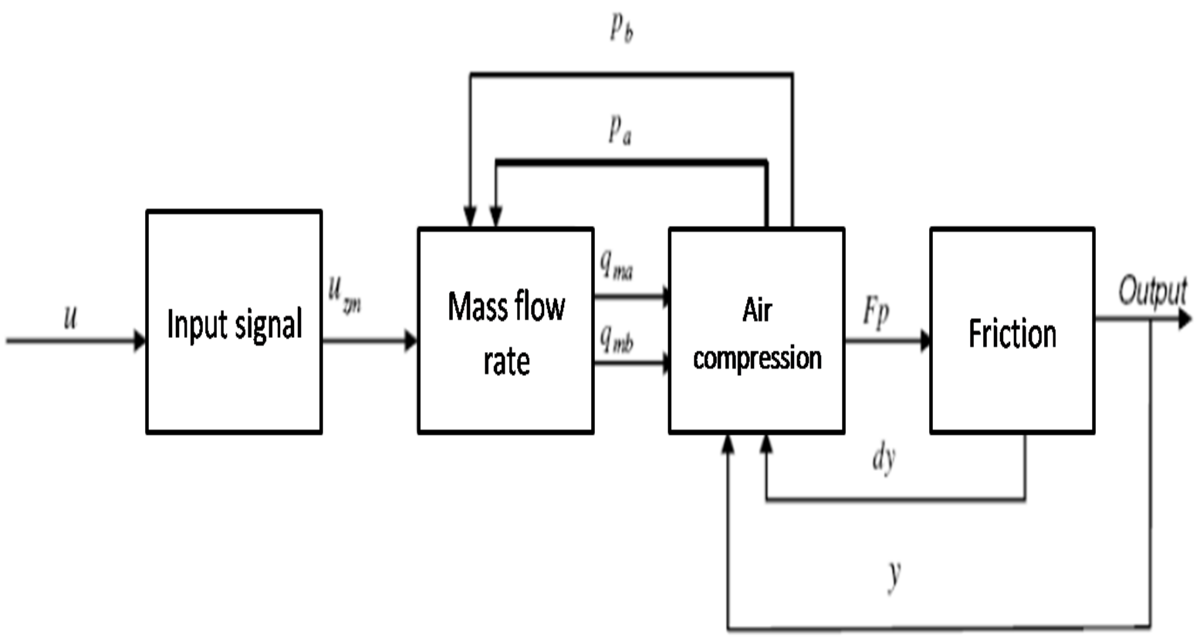

Figure1: Nonlinear modeling diagram of the pneumatic actuator

The modeling diagram in figure 1 shows how the three nonlinear parameters act on the input signal of the pneumatic actuator to affect the output, which is positioned and stability of the object (Bottle). The mathematical model of the nonlinear frictional (F_p) effect on the pneumatic actuator is presented using the relationship between the static frictional force coefficients which are static friction, viscous damping coefficient, Coulomb friction, and Stribeck velocity as shown in figure 2;

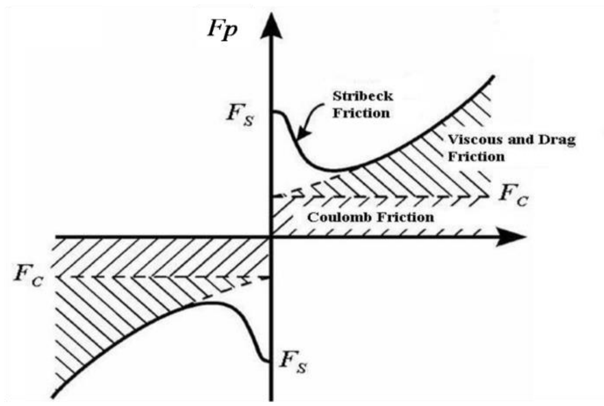

Figure2: frictional force characteristics coefficients (Carlo et al., 2010).

Carlo et al. (2010) defined the frictional force of a pneumatic actuator as given in equation1;

$$F_p = F_c + Bv + (F_s - F_c)e^{-\left[\frac{v}{y_s}\right]^{\delta}} \quad 1.0$$

Where B is the viscous damping coefficient, y_s is Stribeck velocity, F_c is the Coulomb friction, as $^{\delta}=2$; F_s is static friction, and $^{\delta}$ is an exponent of arbitrary constant presented by Carlo et al. (2020).

However, in a case where precise control or a more complex control strategy is required to achieve precise trajectory tracking and position control. Equation1 is improved considering damping and stiffness coefficients of microscopic deformations of surface disparities, presenting the improved F_p as shown in equation2;

$$F_p = \alpha_0 . z + \alpha_1 . \frac{dz}{dt} + \alpha_2 . y \quad 2.0$$

Where: α_0 is the stiffness coefficient of microscopic deformation; z is the average deflection between the surfaces of the cylinders; $\alpha_1$is the damping coefficient with respect to dz/dt; $\alpha_2$is viscous friction coefficient (B); y is velocity between the contact surfaces.

V. Development of the Adaptive Model Predictive Controller (AMPC)

MPC has the ability to approximate time series linear time-invariant dynamic systems like a pneumatic actuator, however, in real time this approximation is not always précised as there are prediction errors. This has made the MPC not appropriate in the time series approximation of high nonlinear tine invariant systems. This has made the MPC not reliable for the precision control of pneumatic actuator which suffers from issues of friction, and mass flow rate among other nonlinear parameters.

To address this problem an Adaptive MPC was developed. This AMPC has the ability to blend with the varying operating condition of the prediction model. This is achieved using the fixed MPC model developed with the pneumatic actuator model and then allows the parameters to change at the nominal operating point and update with the Kalman filter. The pneumatic actuator model is therefore identified by the MPC as a linear time-invariant (LTI) model as shown in the equations below (Pereida and Schoellig,2018);

$$x(k+1) = Ax(k) + B_u u(k) + B_v v(k) + B_d d(k) \quad 3.0$$

$$y(k) = C_x(k) + D_d v(k) + D_d d(k) \quad 4.0$$

Where the matrices A, B_u, B_v, B_d, C, D_v, and D_d are the pneumatic actuator parameter (Frictions in equation2) which can be varied with time. The other variables are;

k=time (i.e the control interval)

u= manipulated input adjustable by the MPC

x= plant model states
v= measured disturbance inputs
d=unmeasured disturbance inputs
y=output

The models in equations3 and4 presented the LTI and the nonlinear output parameters. Consequently, the AMPC includes nominal operating points to apply the LTI model in equation1. This is because as time of the plant model changes, the control parameters use the nominal points to update itself with the plant. The plant model in terms of nominal condition is presented as equation5 and6;

$$x(k+1) = \breve{x} + A(x(k) - \breve{x}) + B(u_i(k) - \breve{u_\iota}) + \widetilde{\Delta x} \quad 5.0$$

$$y(k) = \breve{y} + C(x(k) - \breve{x}) + D(u_i(k) - \breve{u_\iota}) \quad 6.0$$

Where the parameters to be updated are A, B, C and D. While u_i is the combined plant input made up of u, v and d variables respectively in the equation4.

The nominal conditions updated are;
$\breve{x}$= nominal state
$\widetilde{\Delta x}$ = nominal state increment
$\breve{u_\iota}$= nominal input
$\breve{y}$=nominal output

So far, the model in the equation3 and4 presents the LIT and the nonlinear output parameters. The equation5 and6 presented the parameters for the update and the time of update interval using nominal points.

The Kalman Filter

To perform the update, the AMPC uses a Kalman filter to adjust the gain of the controller at each control interval to maintain steady state with the updated plant model. The Kalman based LTI model is presented in the equations below;

$$L_k = \left(A_k P_{k|k-1} C_{m,k}^T + N\right)(C_{m,k} P_{k|k-1} C_{m,k}^T + R)^{-1} \quad 7.0$$

$$M_k = P_{k|k-1} C_{m,k}^T (C_{mk} P_{k|k-1} C_{m,k}^T + R)^{-1} \quad 8.0$$

$$P_{k+1|k} = A_k P_{k|k-1} A_k^T - (A_k P_{k|k-1} C_{m,k}^T + N)\, L_k^T + Q \quad 9.0$$

Where L_k and M_k are gain matrices, Q, R and N are covariance matrices constant defined in the MPC state estimation. A_k and C_k are state space parameters of the controller state defined as the traditional MPC, but affected by the plant update at (k) time. $P_{k|k-1}$ Is the error estimated covariance at k time based on time series information available at k-1. The flow chart of the AMPC is presented in figure8;

Response time model of the Controller

The model presented the general equation for the response time of the controller using the step input. The model is presented as;

$$b(t) = b_i + \left(b_f - b_i\right)[1 - e^{-t/n}) \quad 10.0$$

Where b_i is the initial plant output and input signal; b_f is the finalpredicted output from the dynamic actuator transfer function, t is the time, n is the system order which in this case is a second order system.

The System Flow Chart

The flow chart in figure 3 presented the adaptive model predictive controller developed and showed how the plant model in figure 1 was identified as a linear time invariant system in equation3 with their nonlinear output which are constraints model of friction in the equation2 of the pneumatic actuators are controlled using a reference set point computed with the mean matrices of the MPC parameters using the nominal plant model in equation6. The output constraints are updated using Kalman filter from the input parameters and the updated gain in equation7 and8 are given as the controlled output signal to drive the plant, while the error in the equation9 is returned for optimization.

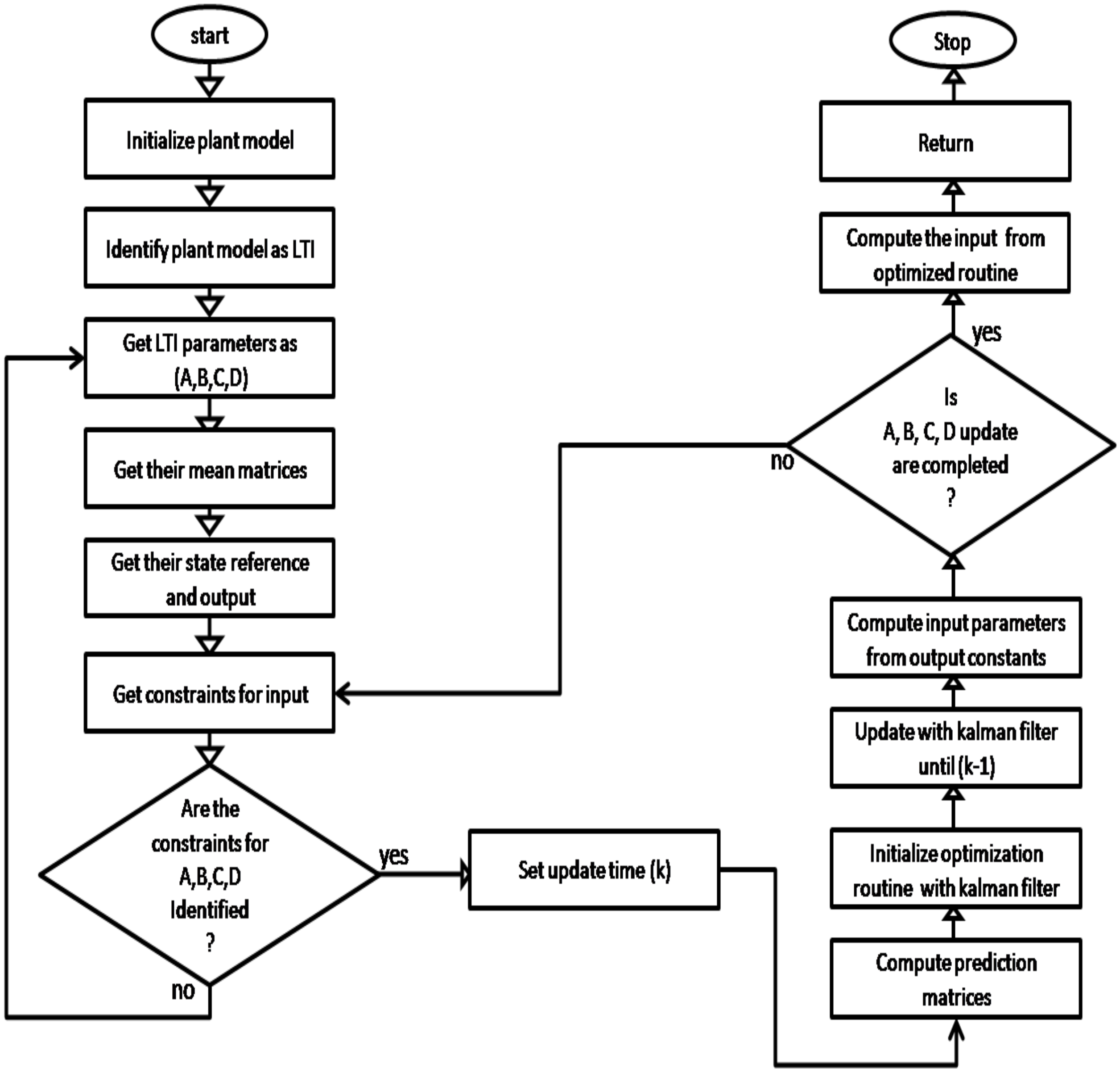

Figure3: Flow chart of the Adaptive Model Predictive Controller

VI. SYSTEM IMPLEMENTATION

The models developed were implemented using the mathematical models developed, modeling diagrams designed, control system toolbox and optimization toolbox in Simulink. The pneumatic actuators plant model in figure1 was used to implement the plant model which is a nonlinear time invariant system due to friction as presented in equation3. The AMPC in the model in figure3 was used to control these nonlinear parameters to achieve a precisely controlled pneumatic actuator system. The Simulink model was presented in figure3;

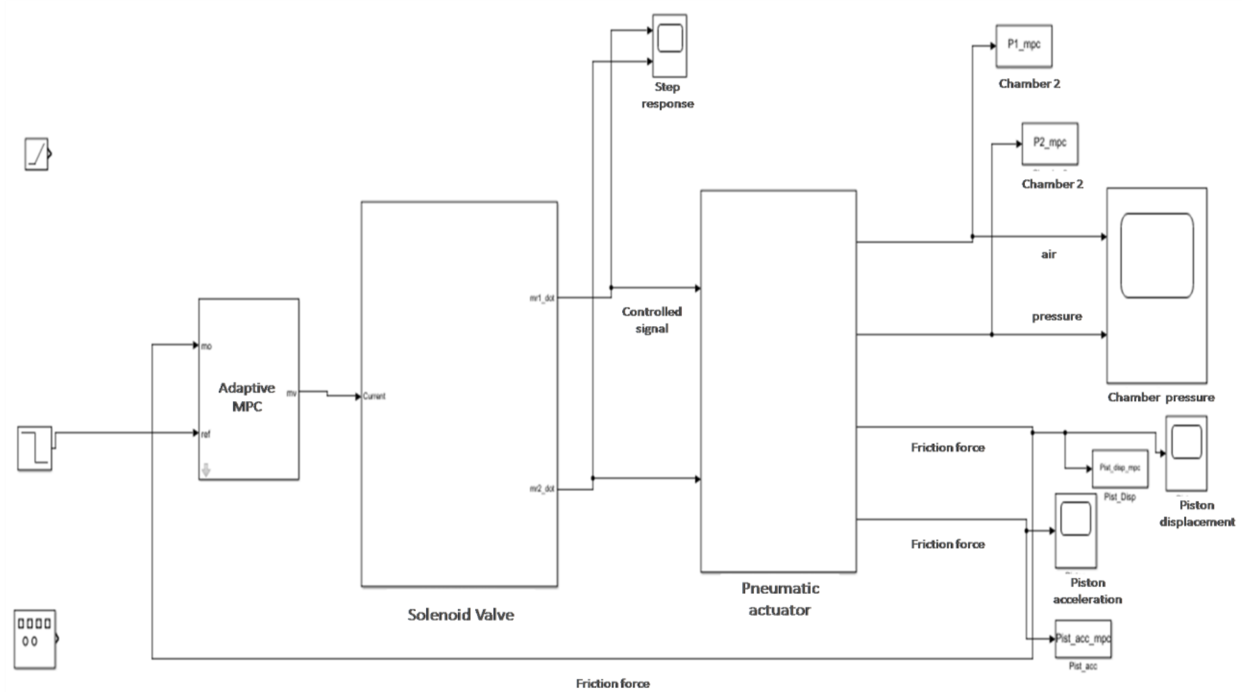

Figure3: Simulink model of the AMPC controlled pneumatic actuator

The figure3 presented the Simulink model of the AMPC controlled pneumatic actuator. The source codes for the implementation are in the appendix A, while the simulation parameters which were collected from the testbed and used to develop the Simulink are presented in table1;

Table1 Simulation parameters

Parameters	**Values**
Gear motor voltage	12V DC
Load current	9.5A
Torque	10kg
Speed	30rpm
Run time of operation	7s
Conveyor drive voltage max	5V
Sensor resistance	1kilo ohm
Sensor voltage	5V
Speed of conveyor with bottle inertia	0.06m/s
Actuator diameter	25mm
Stroke	500

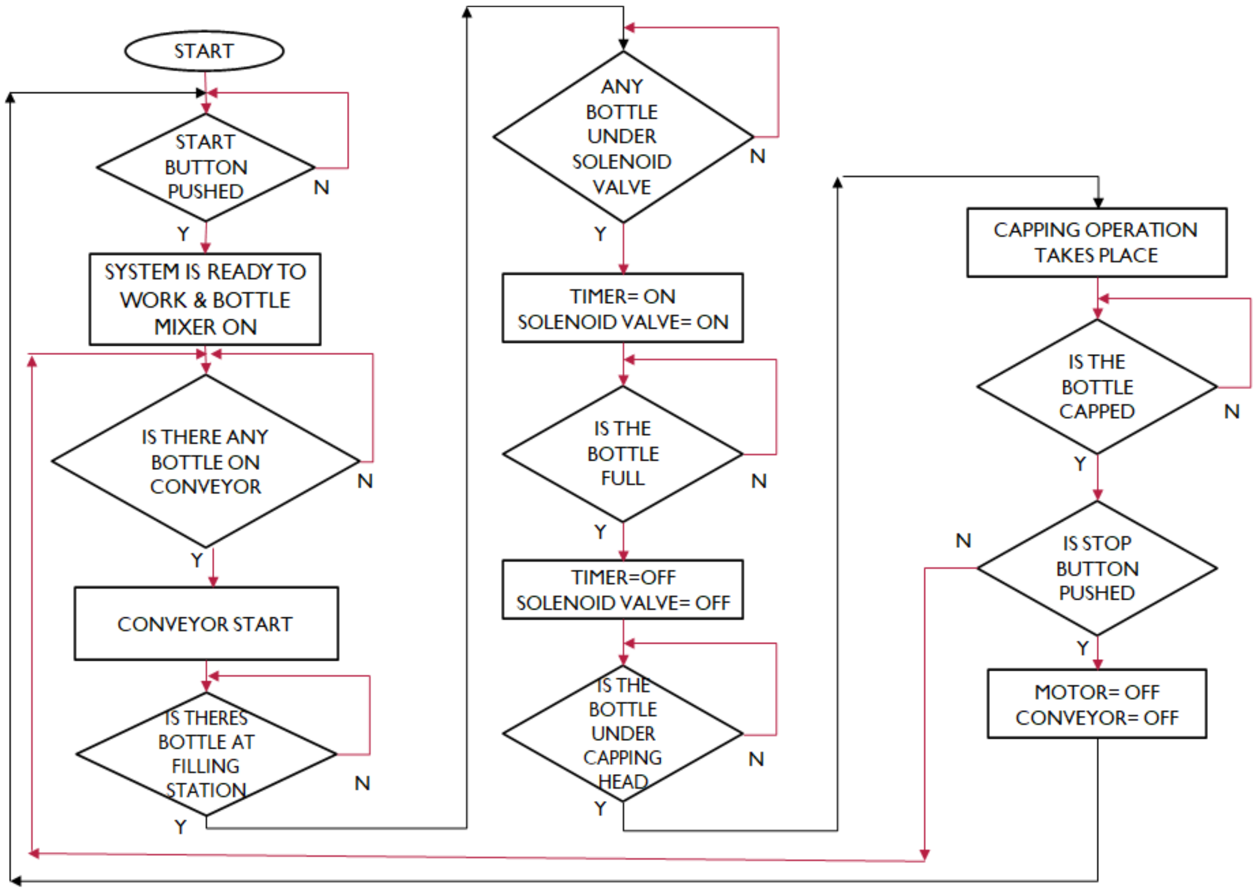

Figure4: System flow chart for filling and capping of bottles

The figure4 presented the data flow chart of the system operation. When the machine is on via the start button, the mixer which is a tank with the ethanol spirit to fill the bottle is activated and then IR sensor is used to detect if bottles are on the conveyor for filling, these conveyors, powered by the pneumatic actuators and gear motor, move the bottles to the tank in the précised position for filling. If the bottle is positioned, the solenoid valve is open and the bottle is filled until the level sensor detects the specified desired level (full) and then the filling process stops. When this occurs, the conveyor moves the bottle again to the capping section where they are capped and conveyed for packing.

VII. RESULTS OF SIMULATION

This section presented the results of the pneumatic actuator simulated with AMPC. The result presented the controlled static and coulomb frictional forces produced during the displacement cylindrical chambers as shown in figure 5;

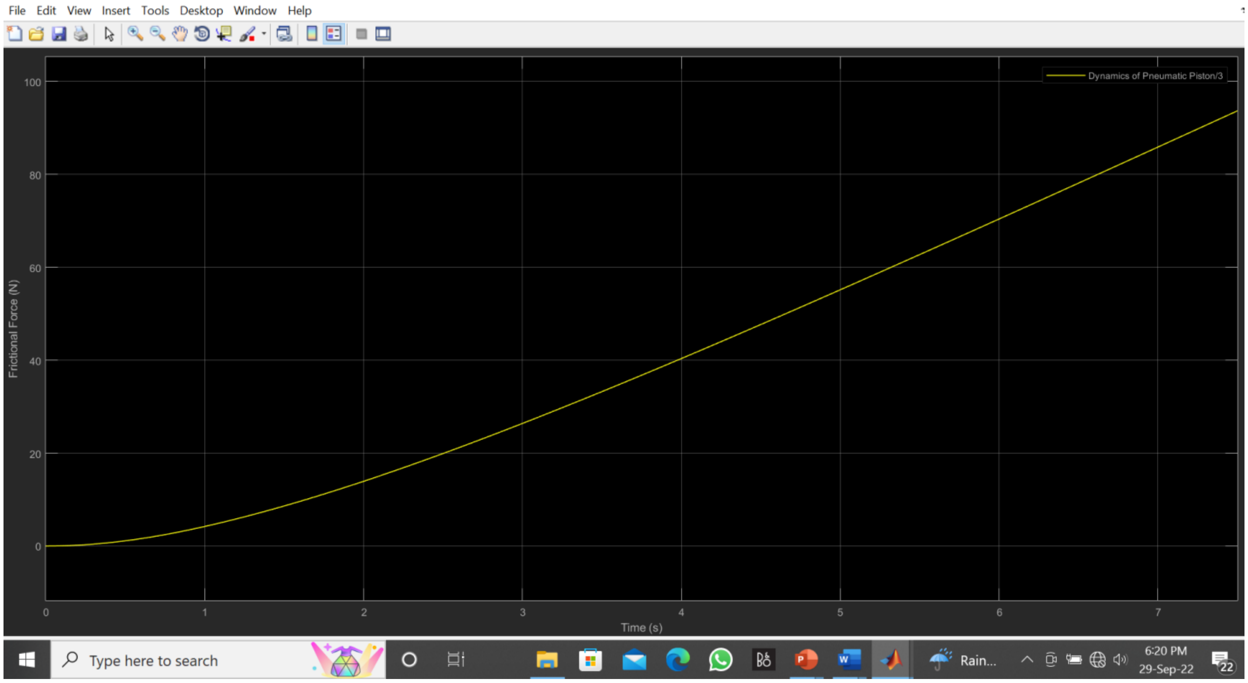

Figure5: Result of the controlled static friction

The result presented in figure5 presented the static friction force of the pneumatic actuator. The result was measured using the pneumatic frictional model in equation2 which shows the controlled static friction coefficient behavior during the technical process. During this process, the AMPC detects this static frictional signal as an LTI modeling equation3 with the constraint's parameter identified in equation4. These parameters are updated at dynamic conditions (i.e.) as the piston displaces to produce variation between Fc and Fc) using the equation5 which is the nominal points for the update and the controlled output in equation6. The update was done using the Kalman filter and thecontroller gain is in the equation7 and8 with the error in equation9. From the result, it was observed that the average F_s value is 36.83N as against 41.51N in the characterized PLC controlled pneumatic actuator. The result showed that the static frictional force was reduced and hence improved the précised positioning of bottles on the conveyor system. The next result presented the coulomb frictional force on the pneumatic cylinder. This friction occurs as the cylindrical chamber of the actuator displaces itself for the conveyor to move. The result is presented in figure6;

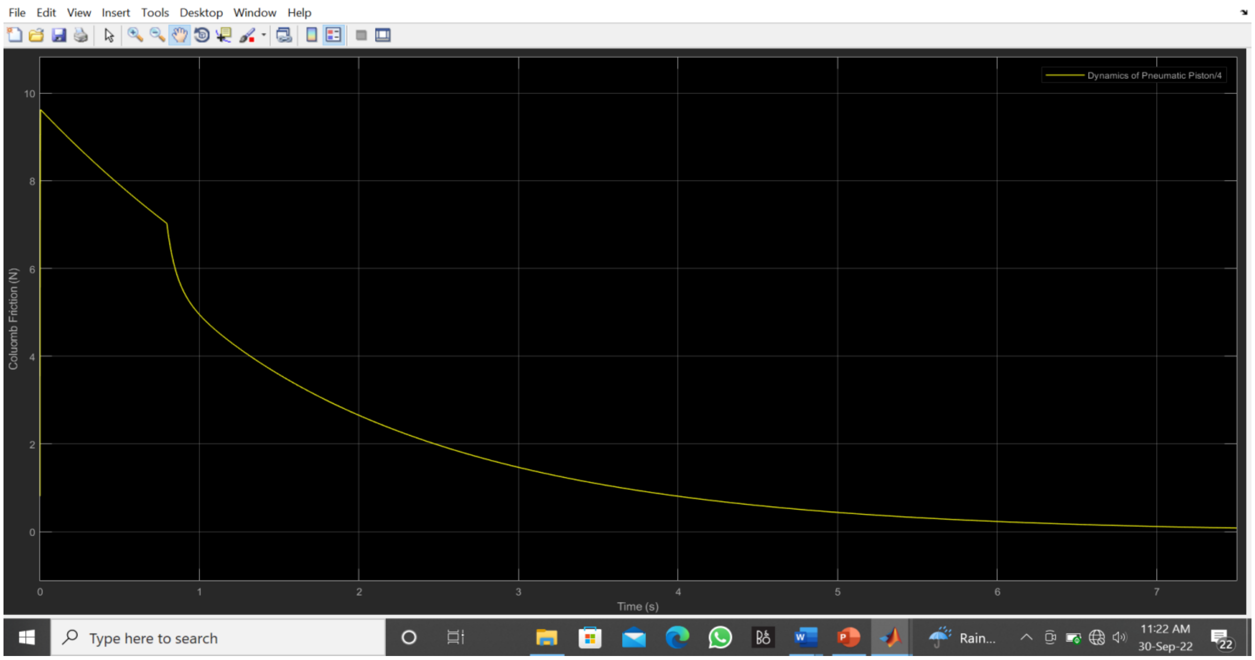

Figure6: Result of the controlled coulomb friction

From the result, it was observed that the average coulomb frictional force recorded for the pneumatic actuator is 2.25N as against 3.52N in the characterized. During this process, like the case of the static friction control process, the AMPC detects this coulomb frictional signal as an LTI modeling equation3 with the constraint's parameter identified in equation4. These parameters are updated at dynamic conditions (ie as the piston displaces to produce variation between Fc and Fc) using the equation5 which is the nominal points for the update and the controlled output in equation6. The update was done using the Kalman filter and the controller gain is in the equation7 and8 with the error in equation9. The implication of this result showed that the coulomb frictional force reduction in the new pneumatic actuator revealed improved position control performance of the bottles conveyed by the conveyor system for filling and capping.

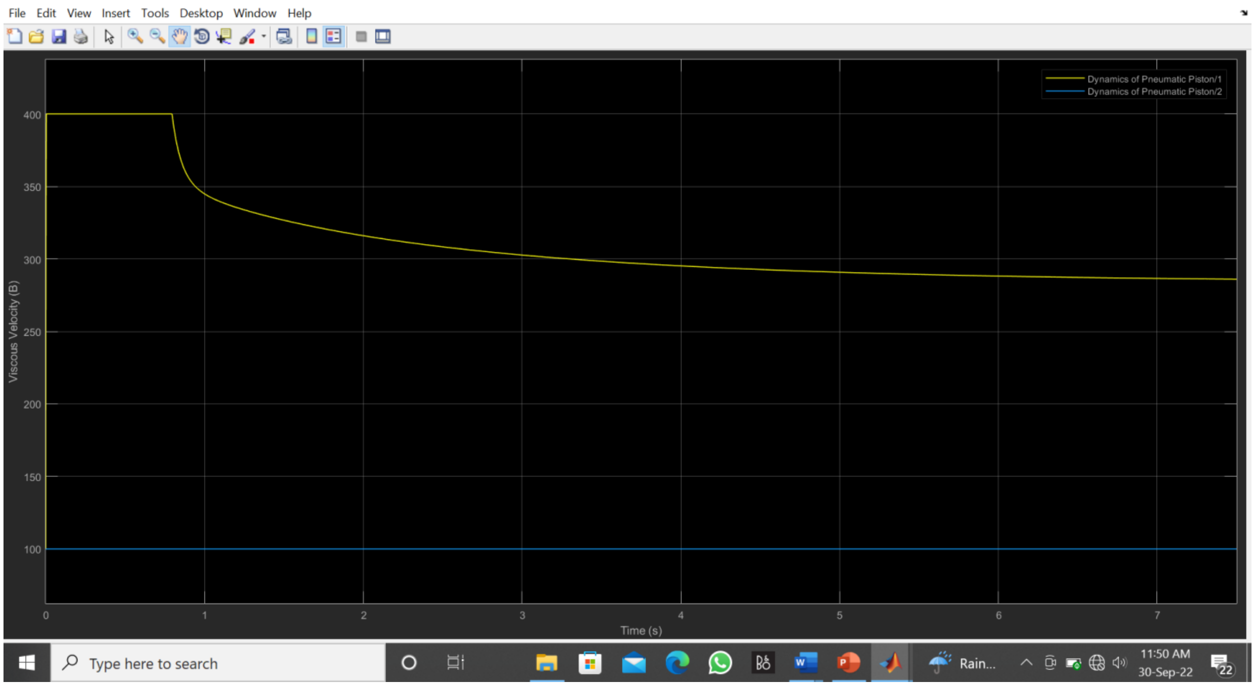

Figure7: The performance of the viscous velocity

From the result presented in the figure3 showing the viscous velocity of the two pneumatic cylindrical chambers as they convert the pressure to linear motion which drives the bottles to the solenoid valves, it was observe that the position of the chambers is controlled during the displacement process which is very good as this implied précised positioning of objects on the conveyor systems.

Validation of Results

This section used the tenfold cross validation model in equation11 to validate the result of the static and coulomb friction forces generated from the pneumatic actuator. The results are presented in the table2;

Table2: System Validation

Time (s)	Fs (N)	Fc (N)
0	00.00	0.00
1	31.57	2.09
2	34.50	2.11
3	36.04	2.13
4	36.90	2.17
5	36.02	2.22
6	36.70	2.25
7	37.05	2.29
8	37.40	2.31
9	37.03	2.38
10	37.30	2.41
Average	32.77	2.02

From the cross-validation result in the table2, the performance of the actuator was measured and it was observed that the average overall static frictional force is 32.77N while the coulomb frictional force is 2.02. From the analysis of Pedro et al. (2006) when the relationship between the static and coulomb friction are reduced, the behavior of the cylindrical chambers is improved, thus leading to the precise positioning of the bottles along the conveyor system.

4.3 Result of AMPC Integration on the Pneumatic Actuator

Time (s)	Fs (N)	Fc (N)
0	00.00	00.00
1	09.02	13.50
2	20.52	07.20
3	21.12	07.12
4	23.54	06.90
5	24.22	06.38
6	24.57	06.35
7	26.92	05.37
8	27.55	03.55
9	27.82	03.60
10	28.62	03.20
11	29.02	02.90
12	29.55	02.70
13	30.72	02.35
14	31.19	02.00
15	31.55	01.92
16	31.69	01.87
17	32.52	01.70
18	35.32	01.50
19	38.54	01.44
20	39.55	0.73
21	39.97	0.65
22	42.52	0.51
23	43.82	0.20
24	44.30	0.12
25	45.55	0.08
26	46.64	0.05
27	47.29	0.04
28	49.52	0.03
29	53.30	0.02
30	56.52	0.01
Average	33.32	2.71

The result reported in the table3 presented the performance of the AMPC which was used to improve the test bed and evaluated. The performance showed that the average static friction is 33.32N and the coulomb friction is 2.71N. The implication of this result showed that the AMPC as able to control the nonlinear parameter model in equation2 which affects the position of bottles during the filling and capping process. The effect of the AMPC showed a reduced frictional force indicating better performance. The step response graph of the

AMPC controller is presented as shown in figure4;

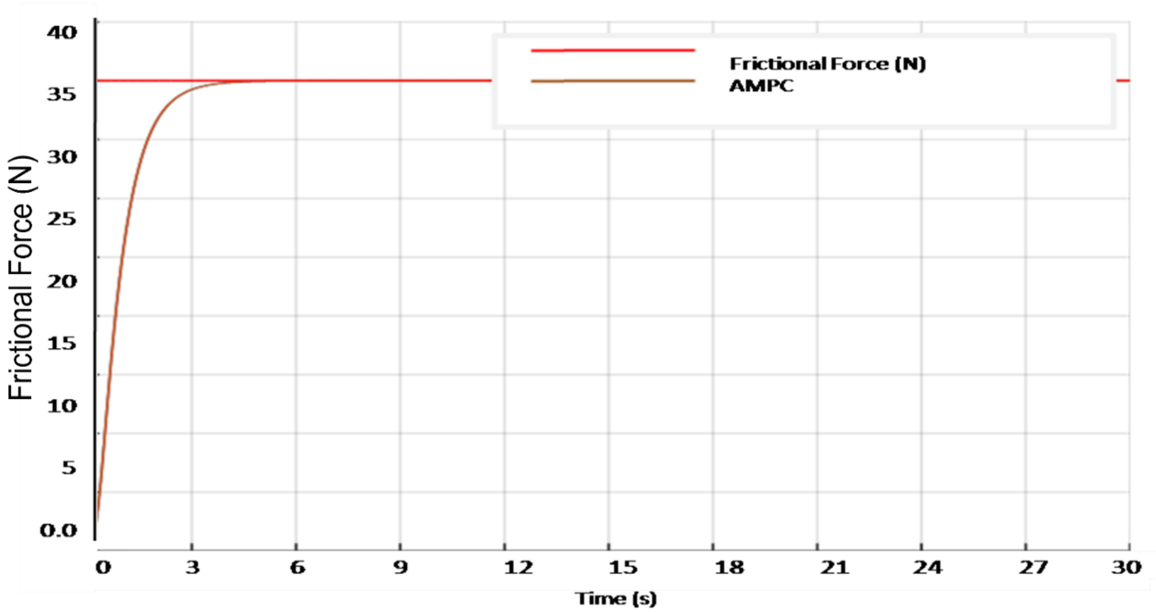

Figure4: Step response of the AMPC

From the result of the AMPC controller reported in figure4, the performance of the controller during the approximation of frictional force was measured. The result showed that the controller identified the friction from the displacement position of the pistons and then control it based on the reference set point computed in equation3 and update with Kalman filter with the gain in equation7 and8. The step respond result shows the time taken for the controller to detect and control the friction signal is at 4.02s better than the PLC with 12s. The result also shows that the no overshoot was recorded as the controller accurately controls the friction and ensures stability in the piston behaviors.

VIII. CONCLUSION

This study has successfully presented an improved process control system for bottle filling and capping. This was achieved by developing an adaptive MPC which identified the linear time-invariant model of the pneumatic actuator and then identified parameters whose behavior changes with time like the frictions which is the major focus of this work as literatures identified it as the main problem against precision control of pneumatic actuator. This problem was addressed using AMPC which used a Kalman filter to control and update MPC performance to guarantee precision positioning of bottles during the filing and capping process. The system was implemented and simulated with Simulink. The result showed that static friction was reduced from 41.51N to 33.32N. Coulomb friction reduced from 3.52N to 2.71N.

The AMPC was deployed on the test bed and then evaluated using comparative analysis and the result showed that static friction was reduced by 24.57% and coulomb friction reduced by 29.9%.

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