alternative and easily deal with the complex system or process [12],[13] are the reasons why the latter approach is selected to be employed.

In system identification, there are a few structure of model that can be utilized to represent the system [14]. Recently, researchers have shown an increased interest of using block-oriented or block-structured nonlinear model in modeling the system. A block-oriented nonlinear model is a model that consist a series of blocks that represent both memoryless nonlinearity and linear dynamic of the system based on input and output measurement of the system [15]. Extensive review revealed that a Hammerstein model is among the block-oriented nonlinear model of choice for modeling any system [16]-[20] and studies in [21]-[23] proved that a Hammerstein model can also be used to model the pneumatic actuator system.

Basically, a Hammerstein model consists of a static nonlinear block and linear dynamic block in cascade. In this study, the static nonlinear block of Hammerstein model will be represented by a deadzone of the pneumatic valve, while the linear block will be represented by a dynamic element of the system. Previously studies on modeling the nonlinear system using Hammerstein model also reported that a recursive and iterative algorithm is often a choice to be used as a parameter estimator for the model [16]-[18],[20]. Iterative algorithm is often used in off-line estimation, while recursive algorithm is often used in on-line estimation [20]. Based on the reviews, this study proposes a Hammerstein model as a new model for a pneumatic system utilized in this study and Recursive Least Square (RLS) algorithm as the parameter estimator for the developed Hammerstein model.

This rest of the paper is organized as follows: The IPA system operations and its components are described in Section 2. The methodology and procedures in modeling the IPA system using system identification approach, and the simulation and experimental results based on the new developed model are discussed in Section 3, and the overall findings are concluded in Section 4.

II. MATERIAL AND METHOD

The pneumatic actuator system, namely the Intelligent Pneumatic Actuator (IPA) system utilized in this study is classified as the linear double-acting cylinder type with 0.01mm position accuracy. The system is equipped with five main components (as illustrated in Fig. 1); the pressure sensor, optical sensor, laser stripe rod, on/off valves, and Programmable System on Chip (PSoC) control board. Each of these components has their own function in ensuring the IPA system works well, and each of them is interconnected with each other.

In this study, two valves have been used for controlling the IPA positioning system. Both valves were used to control the inlet and outlet air of the cylinder, and a Pulse Width Modulator (PWM) signal was used to drive these valves. The PWM signal will behave according to the current pressure readings given by the pressure sensor and current position readings given by the optical sensor. While the PSoC control board will act as the "brain" to control the whole operation of IPA system. The system is said to be so-called "intelligent" since it integrates actuator, microprocessor and sensors together in one system [24].

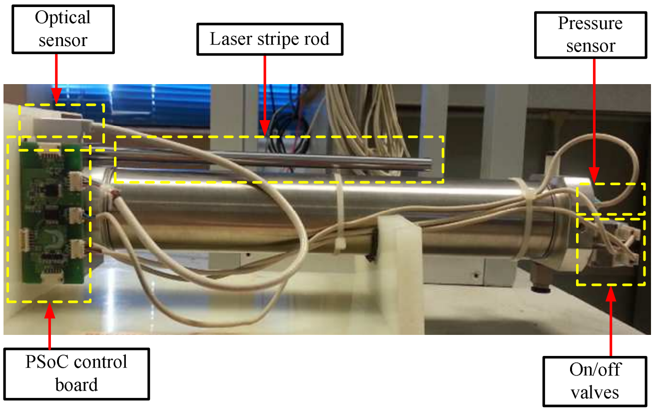

Fig. 1 The IPA system

System identification has been employed as a modeling approach to represent the IPA system utilized in this study. System identification concept can be as simple as a "blind" approach using black-box model concept to obtain a linear and nonlinear model of the system/framework in view of measured exploratory information. Generally, modeling of the system using system identification approach will go through these four accompanying procedures:

A. Experimental Design and Data Collection

For the technique and procedures utilized for designing the experiment, the previous research in [25]-[28] were referred. The components used during the process of collecting data have been listed in Table 1 and the IPA system's specifications have been described in Table 2.

TABLE I
LIST OF COMPONENTS USED FOR DATA COLLECTION

Component	Model	Quantity	Remarks
Actuator (Double Acting)	KOGANEI-HA: Twinport Cylinders	1	
Optical Sensor	AEDR-8300	1	Counter Input
Pressure Sensor	KOGANEI: PSU-EM-S	1	Analog Input
Valves (On/Off)	KOGANEI: EB10ES1-PS-6W	2	Analog Output

TABLE II
THE IPA SYSTEM'S SPECIFICATIONS

Parameters	Value	Remarks
Actuator Diameter	40mm	
Rod Diameter	16mm	
Rod Stroke	200mm	
Maximum Force (At 0.6MPa)	120N	
Ambient Force	0N	
Specific Heat Ratio	1.4	ISO 6358
Temperature	294.5K	ISO 6358

2000 measurements of input and output data with sampling time (T_s) 0.01s were collected from real-time experiment. The data contains 2000 data points of signal applied to the valves (input data) and 2000 measurements of the position signal (output data). The signal applied to the valves is a continuous step signal with amplitude ±255, and specially designed for the on/off valves of IPA system. While the output signals represent the position of IPA's stroke in mm. The plot of input and output data are shown in Fig. 2.

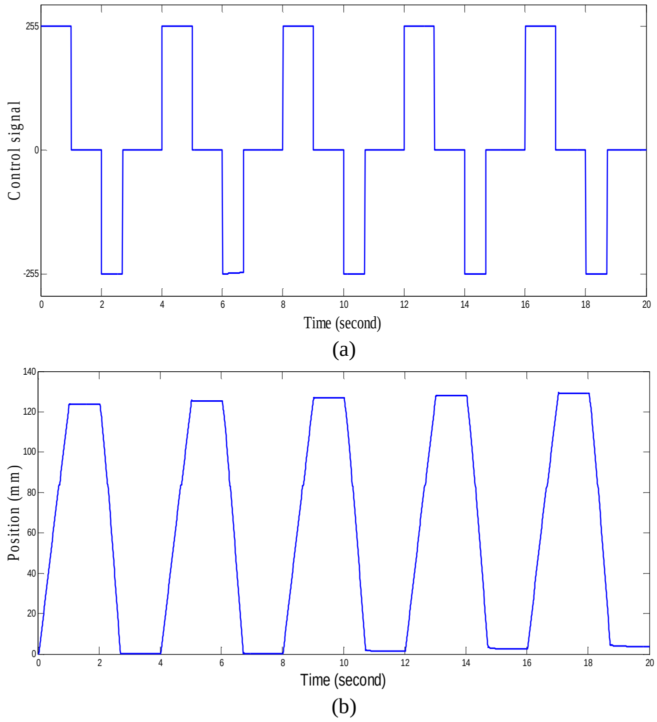

Fig. 2 The plot of collected data from real-time experiment: (a) input, (b) output

B. Model Structure Selection

In this study, the Hammerstein model or so-called a block-oriented or block-structured model was used in order to represent the real IPA system. The basic structure of a Hammerstein model consists of a static nonlinear block and linear dynamic block in cascade, as illustrated in Fig. 3. In this study, the static nonlinear block was represented by a nonlinear deadzone of the IPA valve, while the linear block was represented by a linear dynamic of IPA system itself. $u(k)$, $x(k)$, $e(k)$ and $y(k)$ represents the input, internal variable, noise and output signals, respectively.

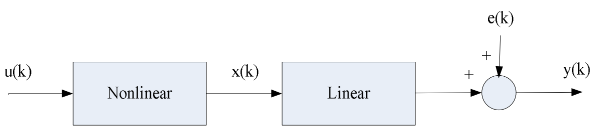

Fig. 3 The basic structure of a Hammerstein model

As previously described, a valve deadzone of IPA system will be considered as a nonlinearity block of the Hammerstein model proposed in this study. A nonlinear valve deadzone in IPA system can be described as a situation where the cylinder stroke does not give any response (extend or retract) for a given range of input voltage to the valve, until the input voltage reaches a particular value. The analytical expression of the valve deadzone for IPA system utilized in this study was referred from [21],[29] and can be expressed as Equation (1), while its graphical representation can be illustrated as in Fig. 4.

$$x(k) = \begin{cases} m_l[u(k) - b_l] & ; u(k) \leq b_l \\ 0 & ; b_l < u(k) < b_r \\ m_r[u(k) - b_r] & ; u(k) \geq b_r \end{cases} \quad (1)$$

where b_l and b_r are the deadzone points, m_l and m_r the corresponding segment slopes, $u(k)$ and $x(k)$ the input and output signals of the nonlinear valve deadzone.

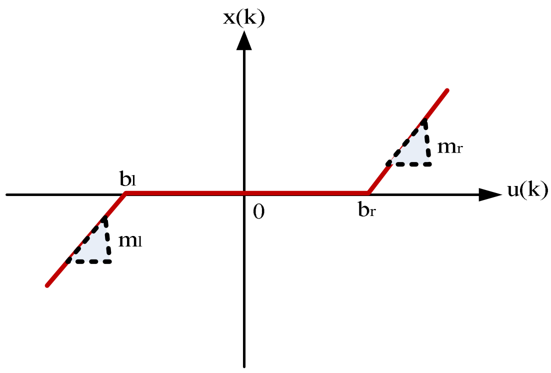

Fig. 4 A graphical representation of the valve deadzone for IPA system

In this study, an auxiliary function called as switching function expressed in Equation (2) and Equation (3) was introduced in order to write the behavior of the deadzone in Equation (1) so that it is linear in parameter [21].

$$x_l(k) = \begin{cases} 1 & ; u(k) \leq b_l \\ 0 & ; u(k) > b_l \end{cases} \quad (2)$$

$$x_r(k) = \begin{cases} 1 & ; u(k) \geq b_r \\ 0 & ; u(k) < b_r \end{cases} \quad (3)$$

Thus, the deadzone equation (Equation (1)) can be represented as Equation (4).

$$x(k) = x_l(k)[m_l[u(k) - b_l]] + x_r(k)[m_r[u(k) - b_r]] \quad (4)$$

In this study, the linear block of the Hammerstein model (illustrated in Fig. 3) is represented by a linear dynamic of IPA system and a third order Auto-Regressive with Exogenous input (ARX) has been considered as a model structure in order to describe the system. Thus, the linear part of the Hammerstein model represented in a discrete-time ARX model structure can be written as Equation (5).

$$y(k) = z^{-d}\frac{B(z)}{A(z)}x(k) + e(k) \quad (5)$$

where,

$A(z) = 1 + a_1 z^{-1} + a_2 z^{-2} + \cdots + a_{n_a} z^{-n_a}$, and
$B(z) = b_0 + b_1 z^{-1} + b_2 z^{-2} + \cdots + b_{n_b} z^{-n_b}$

where n_a is the number of system poles, n_b the number of system zeros, d the pure delay system, and z^{-1} is the shift operator. So, $x(k) z^{-d} = x(k-d)$.

Equation (5) can also be written in the form of summations as in Equation (6).

$$y(k) = \sum_{i=0}^{n_b} b_i x(k-d-i) - \sum_{j=1}^{n_a} a_j y(k-j) + \sum_{j=1}^{n_a} a_j e(k-j) + e(k) \quad (6)$$

Substituting Equation (4) into Equation (6) gives Equation (7).

$$y(k) = \sum_{i=0}^{n_b} b_i \begin{Bmatrix} x_l(k-d-i) m_l[u(k-d-i)] \\ +x_r(k-d-i) m_r[u(k-d-i) - b_r] \end{Bmatrix} - \sum_{j=1}^{n_a} a_j y(k-j) + \sum_{j=1}^{n_a} a_j e(k-j) + e(k) \quad (7)$$

Then, the complete Hammerstein model for IPA system written in regression equation can be expressed as Equation (8).

$$y(k) = \varphi^T(k)\hat{\theta} + e(k) \quad (8)$$

where the regressor vector,

$$\varphi^T(k) = \begin{bmatrix} x_l(k-d)u(k-d), -x_l(k-d), \\ x_r(k-d)u(k-d), -x_r(k-d), \\ -y(k-1), \cdots, -y(k-n_a), \\ x(k-d-1), \cdots, x(k-d-n_b) \end{bmatrix}.$$

and the parameter vector,

$$\hat{\theta} = \begin{bmatrix} b_0 m_l, b_0 m_l b_l, b_0 m_r, b_0 m_r b_r, \\ a_1, \cdots, a_{n_a}, b_1, \cdots, b_{n_b} \end{bmatrix}^T$$

C. Parameter Estimation

In parameter estimation procedure, the mathematical model estimated by a particular estimation technique is measured in term of how accurate the model prediction output compared to the actual or measured output. In this study, the Recursive Least Square (RLS) algorithm will be used to determine the coefficients or parameters of the Hammerstein model. The RLS algorithm has been considered to be utilized in this study since it can provide faster convergence speed/rate and control performance, and it also does not exhibit the eigenvalues spread problem. The RLS algorithm employed in order to estimate the regression equation (Equation (8)) are listed as in Equation (9) to Equation (12).

$$\hat{\theta}(k) = \hat{\theta}(k-1) + L(k)\varepsilon(k) \quad (9)$$

where,

$$L(k) = \frac{P(k-1)\varphi(k)}{\rho + \varphi^T(k)P(k-1)\varphi(k)} \quad (10)$$

$$\varepsilon(k) = y(k) - \varphi^T(k)\hat{\theta}(k-1) \quad (11)$$

$$P(k) = \frac{1}{\rho}[P(k-1) - L(k)\varphi^T(k)P(k-1)] \quad (12)$$

where L is the least squares weighting factor, P the matrix that is proportional to the variance of the previous estimates, ρ the forgetting factor, ε the current estimation error, $\hat{\theta}$ the parameter vector, φ the information vector, and y the output vector.

D. Model Validation

In model validation, the validity between the measured and developed Hammerstein model under a validation requirement was checked in order verify that the identified Hammerstein model represents IPA system adequately. In this study, the Akaike's Model Validity Criterion was employed and the model was validated based on poles location, best fit, loss function and final prediction error. Observing the location of the poles of the system is highly necessary since it provides the information about the system's stability. The developed Hammerstein model is said to be stable if it manage to keep the location of the poles of the linear model in the range of -1 to 1 (unit circle). Besides, the developed Hammerstein model is also considered acceptable if it manage to provide the model with higher best fit, lower loss function and lower final prediction error. The equation used to determine the percentage of best fit, loss function and final prediction error can be represented as in Equation (13), Equation (14) and Equation (15), respectively.

$$Bestfit(\%) = \left(1 - \frac{|y - \hat{y}|}{|y - \bar{y}|}\right) \times 100 \quad (13)$$

where y is the measured output, $\hat{y}$ the estimated output and $\bar{y}$ the mean value of the measured output.

$$V(\hat{\theta}) = \frac{1}{N}\sum_{k=1}^{N}\frac{1}{2}\varepsilon^2{}_k \quad (14)$$

where,
$\varepsilon_k(\hat{\theta}) = y_k - \varphi^T{}_k(\hat{\theta})$

where N is the number of data points and ε the estimation error.

$$FPE = \frac{N+p}{N-p}V(\hat{\theta}) \quad (15)$$

where p is the number of parameters in the model, N the number of data points and V the loss function.

III. RESULTS AND DISCUSSION

This study presents a new modeling for Intelligent Pneumatic Actuator (IPA) system using nonlinear system identification approach. The aim of this study is to model the entire IPA system using Hammerstein model and estimate all the parameters of the model using a Recursive Least Square (RLS) algorithm. Table 3 shows the estimated parameter values for Hammerstein model obtained using RLS algorithm.

TABLE III
HAMMERSTEIN MODEL PARAMETER VALUES

Block	Parameter	Estimated Value	Actual Value
Nonlinear (Valve Deadzone)	b_r	1.4120	1.4100
	b_l	-1.5010	-1.5000
	m_r	2.3810	2.3800
	m_l	3.4710	3.4600
Linear (Dynamic of IPA System)	a_1	-1.8200	-1.8690
	a_2	1.0010	0.9976
	a_3	-0.1808	-0.1284
	b_1	7.4980×10^{-4}	15.6700×10^{-4}

To confirm the acceptance of the developed Hammerstein model, the model has been validated according poles location of a linear ARX model, best fit, loss function and final prediction error. The estimated linear ARX model using RLS algorithm have resulted the entire poles lie inside a unit circle (0.9994, 0.4103±0.1121i), thus proved that the linear ARX model is stable. Meanwhile, the plot in Fig. 5 illustrates the output fittings between the developed Hammerstein model and previous linear ARX model (the model used in previous research) against the measured output (position).

It can be seen that both models produced a good fitting, however, Hammerstein model has managed to give a better fitting than linear ARX model. This indicates that the developed Hammerstein model successfully represents the real IPA system utilized in this study and the addition of nonlinear block (nonlinear valve deadzone) in the model very helpful to get a better model.

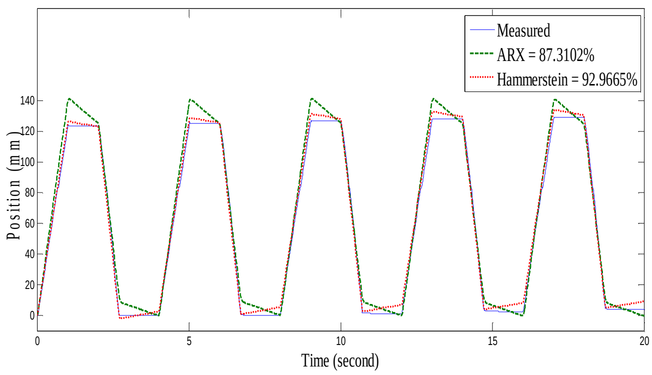

Fig. 5 The output fittings for a developed Hammerstein model and previous linear model

Apart from the 5.6563% improvement on fitting, the developed Hammerstein model also managed to reduce loss function and final prediction error by 3.5490×10^{-3} and 3.5439×10^{-3}, respectively. Summary of the best fit, loss function and final prediction error for both models are tabulated in Table 4.

TABLE IV
MODEL VALIDATION VALUES

Criteria	Model	
	Linear ARX	Hammerstein
Best Fit (%)	87.3102	92.9665
Loss Function	4.4000×10^{-3}	0.8510×10^{-3}
Final Prediction Error	4.4000×10^{-3}	0.8561×10^{-3}

Open-loop and closed-loop test were also conducted in order to test the functional reliability of the estimated Hammerstein model to represent the real IPA system. Fig. 6 show the corresponding responses between simulated Hammerstein model and real-time IPA system for open loop test. As seen in Fig. 6, the simulated Hammerstein model has managed to provide a response that is similar to the real IPA system.

Closed-loop test was also performed on the developed Hammerstein model in order to test its ability to control the IPA positioning system. In this study, a simple Proportional-Integral (PI) (K_p=14 and K_i=1) is used as a controller and the corresponding responses when the set-point to be reached is fixed and unfixed were compared. Fig. 7(a) and Fig. 7(b) illustrate the simulated and actual response of the IPA's stroke position for fixed and unfixed set-point, respectively. From both plots, it can be stated that Hammerstein model developed in this study can be used to represent the real IPA system, which the response from the simulation was better than the real-time experiment. This is because the simulation does not take into account other nonlinearity factors such as water leakage, friction, air compressibility, etc. as in the real-time experiment. The performance between developed Hammerstein model (simulated) and real IPA system (experiment) for fixed position were compared and summary of the data obtained are tabulated in Table 5.It can be seen from Table 5 that the experiment has provided a higher value for overshoot, steady-state error, rising time, and settling time than simulation. However, the results obtained from the experiment is still acceptable in this study as the overshoot and steady-state error are <10% and <2%, respectively.

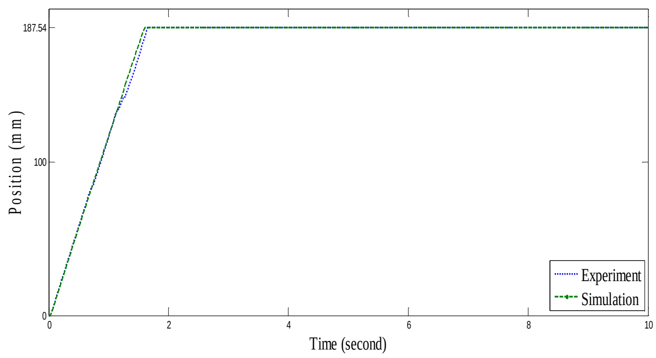

Fig. 6 Open-loop test

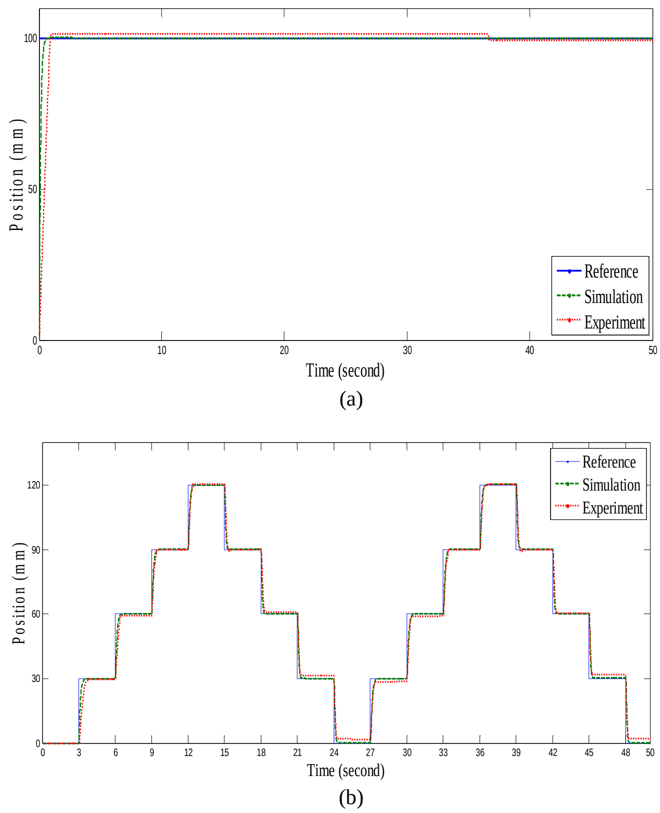

Fig. 7 Closed-loop test: (a) fixed set-point, (b) unfixed set-point

TABLE V
CLOSED-LOOP PERFORMANCES

Criteria	Closed-Loop	
	Hammerstein (Simulation)	**Real IPA (Experiment)**
Overshoot (OS)	0.1173mm	2.1849mm
Steady-State Error (e_{ss})	0.0037mm	0.6800mm
Rising Time (t_r)	0.2231s	0.6780s
Settling Time (t_s)	0.4194s	36.5939s

IV. CONCLUSION

This paper presents a new modeling of Intelligent Pneumatic Actuator (IPA) system using Hammerstein model based a Recursive Least Square (RLS) algorithm. An experimental approach, known as system identification technique was used to develop the model of IPA system used in this study. The nonlinear and linear block for a Hammerstein model was represented by valve deadzone and third-order ARX model for IPA system, respectively. The RLS algorithm was employed to estimate all the parameters for a Hammerstein model. Validation through Akaike's Model Validity Criterion shows that the developed Hammerstein model is acceptable as it managed to provide a higher fitness, lower loss function and lower final prediction error than the linear model developed before. Thus, shows that the model is good enough to represent the real IPA system utilized in this study. Besides that, the developed Hammerstein model also proved to be used as a model for the purpose of controlling the position of IPA system. Future study investigating the suitable controller to improve the transient response of the IPA positioning system, especially in real-time environment will be considered as the next stage of this study.

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