Smart Climbing Mirror Cleaning Robot Using Hybrid Fuzzy-PID Control based on Pneumatic System

Songkran Kantawong[1], Member

ABSTRACT

This paper presents the combination of an intelligent fuzzy logic control and robotic technologies for developing an exterior climbing mirror cleaning robot based on pneumatic system in the advance fields of high building mirror cleaning robot technology. The typical pneumatic system is controlled by ON/OFF directional valve control that gives usually uncertain response both in the terms of position and velocity control and also low accuracy in the moving and holding force control because of its nonlinearity and uncertainty of pneumatic system. The fuzzy logic with proportional plus derivative plus integral control (fuzzy-PID) presented in this paper will improve the drawbacks and weak points of the ON/OFF valve control such that it becomes a continuous valve control which enhances the overall performance of the system in the same time. The stability of climbing robot that is moving along any slope angles of mirror glass surface depends on the holding force, suction cup parameters and pneumatic piston cylinder control that must be suitably designed and mainly realized. More safety factors for high air-pressure supply in the case of high building include winding force, gravity force and other environmental effects. The experimental results show that the fuzzy-PID control with pneumatic solenoid and directional valves control gives more satisfactory responses in the terms of settling time and steadystate error. The significant improvement of the position response and nonlinear or dynamic performance of pneumatic piston system is carried out both in Matlab simulation program and tests at laboratory room. The results are better than ON/OFF valve control and conventional PID control. Finally, the robot can climb very well on any slope angles of mirror surface that are less than 90 degree while the cleaning mechanism can work well as design concept. The future work will further improve the system performance of climbing robot for more safety, stability and reliability in the case of vertical slope situation that depends on the wet glass surface and more winding force effect.

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[1] The author is with Department of Electronics and Telecommunication Engineering, Faculty of Engineering, Bangkok University, Thailand., E-mail: krankantawong@gmail.com

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1. INTRODUCTION

The pneumatic system is one of the most typically applications in an automatic manufacturing systems that are especially use in the field of air pressure control, because it reasonably costs and trades off between low cost and high cost of modern technologies when compared to a general electric motor that is more complicated to modify and adjust its motion control and that offers also more expensive installation and maintenance costs with large energy consumption. A major challenge is the development on an automatic exterior high building cleaning system that has been studied for many years ago but rarely seen especially in a manufacturing system. In order to extend the capabilities of an exterior mirror cleaning system, this research conducts to improve the position control performance of pneumatic piston cylinders and suction cup system that both usually used ON/OFF directional valve control [1] with fuzzy- PID control. In order to compensate or eliminate the nonlinear characteristic of pneumatic actuator [2] by a continuous valve control [3]-[4], both position and velocity of the pneumatic pistons [5] are controlled by the fuzzy-PID controller such that the target position is reached correctly along any slope angles of mirror surface measured by position sensors and angular ones. The prototype mechanism module of this climbing robot for cleaning mirror and their system are shown in figure 1 and 2 respectively.

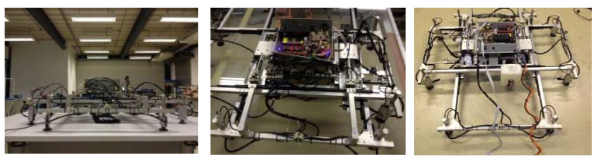

Fig.1: *The prototype module of a cleaning robot climbing exterior mirror with pneumatic piston control system.*

The system performances are evaluated through Matlab simulation program and experimental tests in the laboratory room. The remainder of the paper is organized as follows: Section II describes the

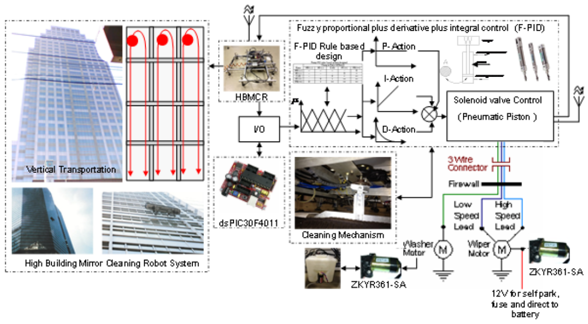

Fig.2: The block diagram of the proposed system.

mechanical module of the robot designed by the solid work program. The mechanical structure of the robot with the controlled pneumatic piston is proposed in section III. Section IV describes the fuzzy-PID control system. The experimental results are shown in section V, followed by the conclusion in section VI.

2. MECHANICAL MODULE FOR THE ROBOT

The mechanical module for the robot based on pneumatic control system is created by the solid work program under version 201.

2.1 Mechanical Module Design for the Robot

The all-around views of the mechanical module for the robot are shown in figures 3 and 4.

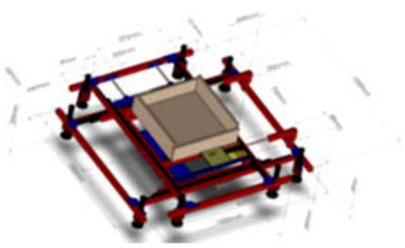

Fig.3: The isometric view of the mechanical module for the robot.

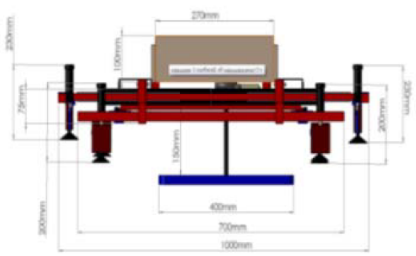

Fig.4: The front view of the mechanical module for the robot.

2.2 Module Design for Suction Cups

The eight suction cups are supported by pneumatic piston cylinders which each acts as a choke absorber. They are shown in figures 5 and 6. The robot uses a half of total suction cups for each step of movements over the mirror surface. It is able to move along the two axes comprising forward or backward direction in the horizontal axis and upward or downward direction in the vertical axis. This means that when the robot is moving in each step, the four suction cups only are used to suck up the mirror surface while the other four suction cups are reserved into a free or standby mode. In the case of any emergency that may occur such as increasing of winding force, wet surface, reduction in air pressure supply or severe vibration, the above free mode can arise immediately and offers more safety in order to work.

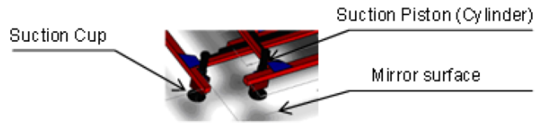

Fig.5: Mechanical module for suction cups.

Each of four suction cups is controlled by one mini vacuum pump of type VAD-M5L that in turn regulates the air pressure being produced by the main compressor air supply of rated 4-6 bar as shown in figure 6.

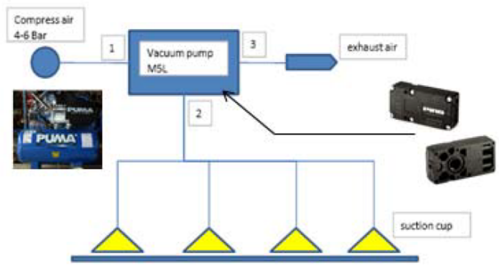

Fig.6: The diagram of suction cups controlled by mini vacuum pump of type VAD-M5L [6] being produced by the main compressor air supply.

2.3 Mechanical Module Design for Cleaning

The mechanical module for cleaning is installed below the robot base and jointed to thin metal sheet with aluminium bars for stronger support. The rest are composed of water tank for wash and the 24 V_{DC} wiper motor connected to the cleaning clothes through clamp rod as shown in figure 7.

3. MECHANICAL DESIGN FOR THE REAL ROBOT

The mechanical structure for the real robot is shown in figure 8. It has the total weight about 13kg

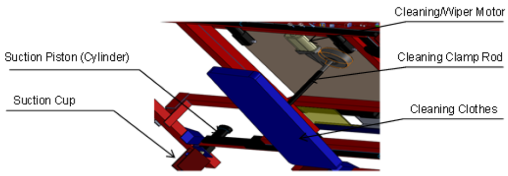

Fig.7: *Mechanical module for cleaning.*

with the dimension of 1.0 m length, 1.0 m width as well as 0.2 m height and is made of aluminium. Additionally, the pneumatic equipment is installed on it.

3.1 Mechanical Module for the Real Robot

The mechanical module for the robot is composed of five main parts as described below.

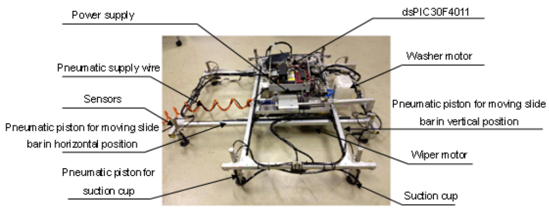

Fig.8: *Mechanical structure design for the real robot.*

The first part is the air compressor rated at 4-8 bar with one mini vacuum pump of type VAD-5ML. The second part is the pneumatic piston systems being composed of suction cups and piston cylinders traveling guide rail in both the vertical and horizontal axes. The third part is the dsPIC30F4011 microcontroller and the battery power that supplies DC power. The fourth part is the mechanical system for cleaning. It is composed of the DC wiper motor, the water tank for washer and cleaning cloths. The final part is the remote control for long distance, sensors and supporters that keep more safety.

3.2 Design of Suction Cups Modules

The design of suction cups always reflects the performance of them. Types, shapes, material and dimensions of the suction cups assure the suitable holding force for sucking up the mirror surface and releasing them from it. The holding force applied from a suction cup depends on its effective diameter being evaluated by both equations (1) and (2). The first equation is derived from the movable suction cups dependent upon the design concept on this module and the second equation is taken from the specification datasheet of the mini vacuum pump (VAD-M5L) as described below.

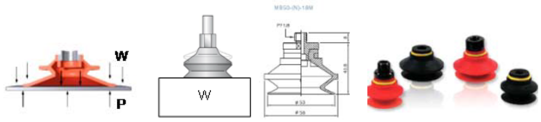

Fig.9: *Suction cup types and holding force action design.*

$$D = \sqrt{\frac{4 \times W \times t \times 1000}{\pi \times P \times n}} \qquad (1)$$

When D is the diameter of suction cup (mm) , n means the number of suction cups that actual hold on the mirror surface per one moving step, W means the weight of mobile robot ($13kg \times 9.81m/s^2 = 127.53N$) , P is the vacuum pressure (kPa) that assigned from the vacuum pump operating pressure at 4bar rated in figure 11 and t mean the safety factor that assigned from the total moveable suction cups per one step as $t = 4$. So the diameter of suction cup from (1) is equal to

$$D = \sqrt{\frac{4 \times 127.53N \times 4 \times 1000}{3.14 \times 68kPa \times 4}} = 48.87mm$$

The diameter of suction cup that is assigned from datasheet of mini vacuum pump type VAD-M5L is shown in equation (2).

$$D = 1.12 \times \sqrt{\frac{m \times S}{P_u \times n \times \mu}} \qquad (2)$$

Where m means the mass of mobile robot (kg) , P_u is the vacuum pressure (bar) of VAD-M5 in figure 11, n means the number of suction cups, S means the safety factor that normally used $S = 2$ and μ is mean the friction coefficient of glass surface approximate to 0.5 [6]. The diameter of suction cup that was computed from equation (2) shown below

$$D = 1.12 \times \sqrt{\frac{13kg \times 2}{0.68bar \times 4 \times 0.5}} = 48.9mm$$

The diameter of suction cup is selected as $D = 50mm$ that is suitable from (1) and (2) as model type MB50-(N)-18M and may be up to $D = 75mm$ for more safety with lower energy air pressure supply and practical to use. The pneumatic piston cylinders are used for this suction cup model type SPZ-16-80- P-A specified as $0.7Mpa, 7.1kg/m^2$ and 100PSI. The real suction cup mechanical system is shown in figure 11.

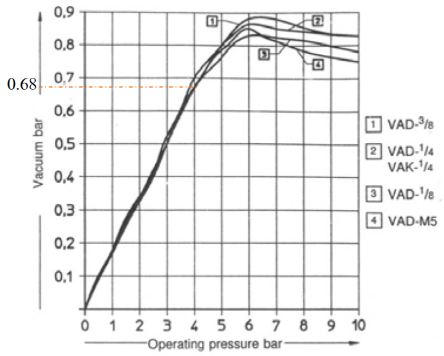

Fig.10: *Data sheet of vacuum pump operating pressure [7].*

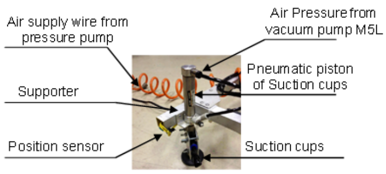

Fig.11: *Real robot suction cup mechanical structure design with pneumatic piston control.*

3.3 Design of Pneumatic Piston

The pneumatic piston design depends on the suction cups system design and traveling guide rails. The pneumatic pistons force is evaluated from the many important factors of the pneumatic system such as air pressure pump supply, the diameter of pneumatic piston, total weight of robot body and the length of piston cylinder. By Newtons second law, the mathematic model of the pneumatic piston is described below.

$$\sum F = F_n = F_{th} - F_R - Cx^{'} = mx^{''} \quad (3)$$

Where $F_n = k \times P \times An$ is the piston force (N) , F_{th} means the total force (N), F_R means the friction force (N) that usually approximate as $0.1F_{th}$, A is the cross section area of piston cylinder (cm^2), k is the adjustment factor $(k \approx 10)$ and C is the air damping constant $(C \approx 1.5 - 2Ns/m)$ that depend on an experiment, P means the working vacuum pressure $(4 - 8bar)$, m is the weight of pneumatic piston that coupling with the object and x is the displacement distance of pneumatic piston. The diameter (D) of pneumatic piston is evaluated from equation (5) and shown the real pneumatic cylinders in this system in figure 12.

$$F_n = F_{th} - F_R = 10 \times A \times P - 1 \times A \times P = \frac{9\pi D^2 P}{4} \quad (4)$$

$$D = \sqrt{\frac{4 \times F_n}{9 \times \pi \times P}} = \sqrt{\frac{4 \times 31.88N}{9 \times 3.14 \times 4bar}} = 10.6mm \quad (5)$$

Where $F_n = 127.53N/4 = 31.88N$ means the piston force per one pneumatic piston of each of suction cups at $P = 4bar$. In practical, the nearest larger size of the piston diameter that evaluated from (5) must be selected depend on the validity of manufacturing product types. So the pneumatic piston cylinder of this suction cup is selected as $D = 16mm$ and stroke length as $l = 80mm$ as type SPZ-16-80-P-A (FESTO product) where the pneumatic piston cylinder for traveling guide rail is selected as $D = 22mm$ and stroke length equal to $l = 200mm$ as type SPZ-22-200-P-A (FESTO product).

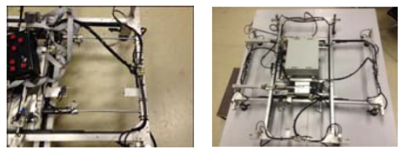

Fig.12: *Real pneumatic piston cylinder of guide rail control.*

3.4 Waste Air consumption of Pneumatic Piston Cylinder

The waste air consumption of two pneumatic piston cylinders [7] was evaluated from the equation (6).

$$Q = 2 \times S \times n \times q \quad (6)$$

Where Q means the waste air consumption (l/min), S is the stroke length of piston cylinder (cm), q is the waste air consumption of the piston stroke length per 1 cm. (l/min)that can be found from figure 13. For $D = 16mm$ of piston cylinder of suction cup control at the maximum pressure rated of 8 bars and n is the round working time of piston cylinder per minute. When $S = 8cm$, $n = 1$ and $q = 0.018l/cm$, the waste air consumption that was computed from equation (6) shown below

$$Q = 2 \times 8cm \times 1 \times 0.018l/cm = 0.288l/min$$

For more precious calculation, the waste air leakage between the head and the end of piston cylinder and air supply valve control must be compensate about 20 percent, so the waste air consumption equal $Q = 1.2 \times 0.288l$/min $= 0.3456l$/min per one piston cylinder. For the piston cylinder of traveling guide rail of $D = 22mm$ can be calculated the waste air consumption from the linear iteration process about $Q = 1.2 \times 2 \times 20cm \times 1 \times 0.0334l/cm = 1.6032l$/minper one pneumatic piston cylinder.

Cyl. Dia.	Operating pressure in bar									
	1	2	3	4	5	6	7	8	9	10
	Air consumption in l/cm. Of cylinder stroke									
8	0.0009	0.0015	0.002	0.0024	0.0029	0.0034	0.0039	0.0044	0.0049	0.0054
10	0.0015	0.0023	0.0031	0.0038	0.0046	0.0053	0.0061	0.0069	0.0076	0.0084
12	0.002	0.003	0.004	0.006	0.007	0.008	0.009	0.010	0.011	0.012
16	0.004	0.006	0.008	0.010	0.011	0.014	0.016	0.018	0.020	0.022
18	0.005	0.007	0.010	0.012	0.015	0.017	0.020	0.022	0.025	0.027
20	0.006	0.009	0.012	0.015	0.018	0.021	0.024	0.027	0.031	0.034
25	0.010	0.014	0.019	0.024	0.029	0.033	0.038	0.043	0.048	0.052
32	0.016	0.024	0.031	0.039	0.047	0.055	0.063	0.070	0.078	0.086
40	0.025	0.037	0.049	0.061	0.073	0.085	0.097	0.110	0.122	0.135
50	0.039	0.058	0.077	0.096	0.115	0.134	0.153	0.172	0.191	0.21

Fig.13: *Air consumption of piston cylinder stroke [7].*

3.5 Waste Air Consumption of Suction Cup Control

The volume of air flow that generates the vacuum is important key for the suction force rate. So, the waste air consumption of suction cups that was controlled by mini vacuum pump type VAD-M5 is found in figure 14. The maximum of operating pressure rated point at 8 bars is equal to $20l/$ min of air consumption rate that can be supply for four suction cups. So, each of suction cups has the maximum air consumption equal to $5l/$ min that cover for waste air consumption of one piston cylinder control at $0.3456l/$ min and allowed by the typical value [7] that the suction rate of suction cup diameter up to 60mm is not more that $8.3l/$ min .

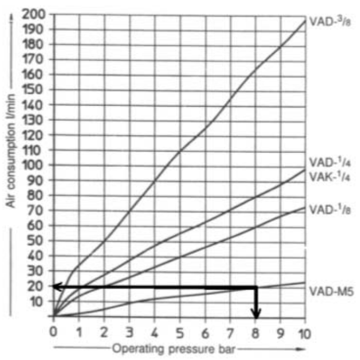

Fig.14: *Air consumption of vacuum pump [7].*

3.6 Pneumatic Piston Valve Control

The pneumatic piston valve control should be designing to support for the total air consumption of all of the pneumatic piston cylinders and suction cups that are described above, so the six solenoid valves (Y1 to Y6) control type 5/2 specified for total air consumption about $80l/\mathrm{min}$ as shown in figure 15.

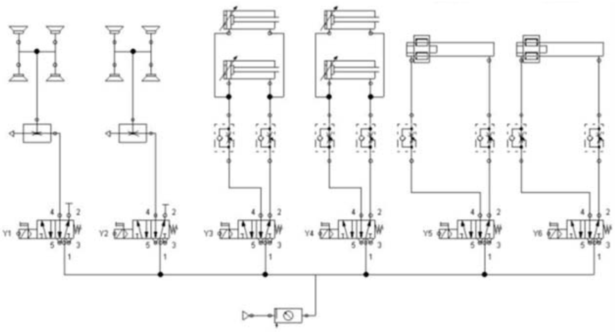

Fig.15: *Diagram of pneumatic piston valve control.*

In figure 15, the solenoid valve Y1 and Y2 are controlled for two mini vacuum pumps type VAD-M5 that must be support for waste air consumption about $Q = 40l/\mathrm{min}$. Where Y3 and Y4 are controlled for piston cylinders of travelling guide rails that must be support for waste air consumption about $Q = 4 \times 1.6032l/\mathrm{min} = 6.4128l/\mathrm{min}$ .Finally, Y5 and Y6 are piston cylinders of suction cups controlled that must be support for waste air consumption about $Q = 2 \times 0.3456l/\mathrm{min} = 0.6912l/\mathrm{min}$.

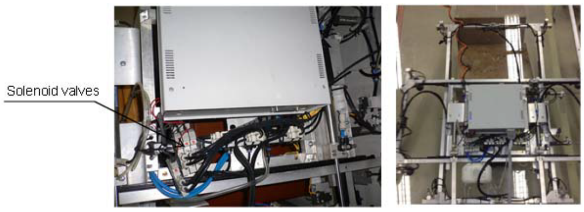

Fig.16: *Pneumatic piston valve control installation.*

3.7 Cleaning Mechanical Structure Design

The cleaning mechanical system is shown in figure 17 that composed of DC wiper motor type ZKYR361-SA rated as 24VDC, 0.5A, the washer water tank has volume as $1.644cm^3$. The cleaning area is formed as circular area that evaluated by $\pi r^2 = \pi(0.2)^2 = 0.1256m^2$ depended on the radius of cloth size as $0.2m$ for $0.16m$ high and $0.4m$ long area.

Fig.17: *Real robot cleaning mechanical structure design.*

3.8 Micro Controller Module Design

The dsPIC30F4011 is assigned for controlling the all of pneumatic cylinders system shown the control diagram in figure 18 and real installed in the robot body in figure 19.

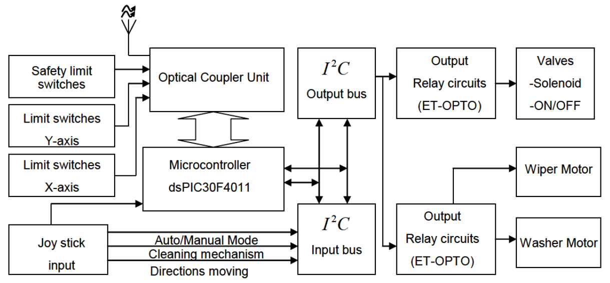

Fig.18: *Diagram of dsPIC30F4011 micro controller design.*

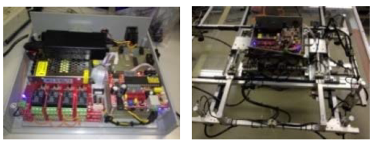

Fig.19: *dsPIC30F4011 micro controller installation module.*

4. FUZZY PROPORTIONAL PLUS INTEGRAL AND PLUS DERIVATIVE (F-PID) CONTROLLER DESIGN

In many researches were found that the conventional PID control is normally used for linear systematic control because of its linear controller characteristic, but the pneumatic is nonlinear system that has the uncertainty of its dynamic response [8] especially in the position control. The aims of fuzzy-PID controller is used to control the continuous directional valve controls to reach the target position and maintain the velocity of pneumatic piston of mirror cleaning robot for more accuracy, reduce the transient state response and any disturbance forces in a specific state, smoothly moving with more stability and can embody better behaviour of its dynamic response than the classical linear PID controller [9]-[10]. The performance of the system is necessary improved for more efficiency by well tuning method of the fuzzy controller that can be also more stable and more robustness [11]-[13]. The Coefficient Diagram Method (CDM) [14]-[16] is an algebraic approach applied to polynomial loop in the parameter space and widely used to tune the process control parameters which can give the good controller performance both in the transient state and steady state response. Not only the faster position target response and stabilize satisfactions, but the order of the controller is usually less than the process. After that the actual control parameters are found with fine tuning again in experimental tests until these control parameter results converge to the satisfied target position in the steady state response with not overshoot and practical to use in a real mirror cleaning situations.

4.1 Transfer function of pneumatic piston control

In the ON/OFF directional valve control, the open loop transfer function ($G_p(s)$) p between air pressure input ($P(s)$) and displacement output ($X(s)$) of pneumatic piston cylinder was derived from equation (3) is show in equation (7) to (8), while the pneumatic piston control diagram and closed loop system control are shown in figures 20 and 21.

$$G_p(s) = \frac{X(s)}{P(s)} = \frac{k_2 A}{ms^2 + C_S} \tag{7}$$

Where k_2 means the result of $F_{th} - F_R$ from equations (3)-(4). The diameter of pneumatic piston cylinder of suction cup is $D = 16mm$ and $m \approx 1kg$ means the mass of piston cylinder plus suction cup ($m_{MB50} \approx 0.02kg$), while $C \approx 1.5$ is the initial air damping constant, so the equation (7) can be evaluated below

$$G_p(s) = \frac{X(s)}{P(s)} = \frac{9 \times \pi(0.016/2)^2}{s^2 + 1.5s} = \frac{1}{54.51s^2 + 81.77s} \tag{8}$$

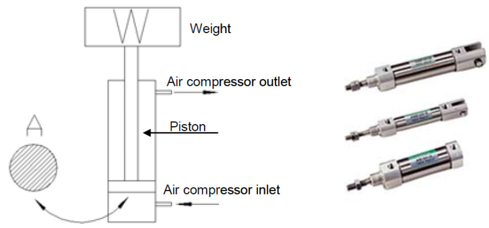

Fig.20: *Diagram of pneumatic piston cylinder actuator.*

4.2 Conventional PID Controller Design

The conventional PID controller is basically applied to control the nonlinear characteristic response of pneumatic piston cylinder and used the position sensing such as potentiometer with the filter circuit, amplifier unit or scaling unit to send the actual distance feedback to evaluate by the controller [17]. The closed loop control of PID controller ($G_c(s)$) c with pneumatic piston cylinder is assigned in figure 21 and equation (9), while the closed loop transfer function of the system ($G_{closed}(s)$) closed is shown in equation (10).

$$G_c(s) = K_p + K_i/s + K_d s \tag{9}$$

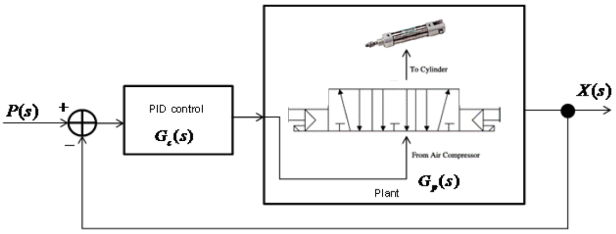

Fig.21: *PID closed loop control of pneumatic piston cylinder.*

$$G_{closed}(s) = \frac{G_c(s)}{54.51s^2 + 81.77s + G_c(s)} \quad (10)$$

For the conventional PID parameters are assigned as $k_p = 35, k_i = 58, k_d = 0.25$, while the initial closed loop transfer function is given as $G_{closed}(s) \approx \frac{0.001}{0.005s^2+0.065s+0.1001}$ is suitable evaluated by Matlab simulation in the first step.

4.3 Hybrid Fuzzy-PID Controller Design

The fuzzy-PID controller is created from the fuzzy-PI [18] and Fuzzy-PD as a parallel combination circuit or called a hybrid fuzzy-PID controller. The designed procedure concepts that widely used for hybrid fuzzy-PID controller are composed of the basically following step.

1) Build and initial tuning of conventional PID controller

2) Replace it with an equivalent linear fuzzy controller

3) Make the linear fuzzy-PID controller as nonlinear fuzzy-PID controller

4) Initial setting process of the fuzzy-PID controller by the CDM method

5) Fine-tuning the hybrid fuzzy-PID controller

6) Laboratory experimental testing and adjusting

7) Practical testing and correcting

The linguistic variables of fuzzy sets parameters are assigned with two inputs fuzzy sets based on trapezoidal and triangular membership functions of Mamdani in Max-Min interference method as error $e(t)$ sets and change in error sets $(de(t))$ that are shown in the general term of sub-fuzzy sets as NB (Negative Big), NS (Negative Small), Z (Zero), PS (Positive Small) and PB (Positive Big) in table 1, while the one output fuzzy set is find out to air pressure output. The error sets of the system is obtained by the different value between the target input and the actual output of the process, while the interference method is done by Max-Min algorithm by using the trapezoidal and triangular membership functions which the singleton values are used to verify the vertex of the fuzzy membership functions. The defuzzification algorithm is used the triangular membership function with COG method.

Table 1: *Fuzzy-PID Rule Based System Design.*

	Chang in Error($\triangle e$)				
Error(e)	***NB(−)***	***NS(-)***	***Z(0)***	***PS(+)***	***PB(++)***
NB(−)	−	−	−	−	0
NS(-)	−	−	-	0	+
Z(0)	−	-	0	+	++
PS(+)	-	0	+	++	++
PB(++)	0	+	++	++	++

The CDM transfer function is found in figure 22 and can be evaluated by the following step.

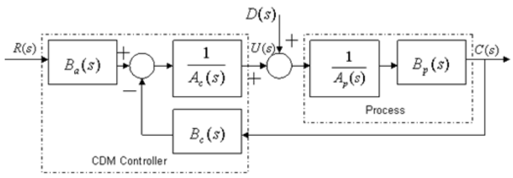

Fig.22: *The conventional closed loop control by CDM.*

For $A_p(s), B_p(s)$ are the process polynomials and $A_c(s), B_c(s), B_a(s)$ are the controller polynomials of CDM designed method.

$$\text{While } A_p(s) = p_k s^k + p_{k-1}s^{k-1} + \ldots + p_0 \quad (11)$$
$$B_p(s) = q_m s^m + q_{m-1}s^{m-1} + \ldots + q_0 \quad (12)$$
$$A_p(s) = p_k s^k + p_{k-1}s^{k-1} + \ldots + p_0 \quad (13)$$

Step 1: Conventional Transfer function designed.

$$\frac{X(s)}{P(s)} = \frac{C(s)}{R(s)} = \frac{G_p(s).G_c(s)}{1 + G_p(s).G_c(s)} \quad (14)$$

Let $P(s) = 1 + G_p(s).G_c(s)$

Step 2: Put the initial closed loop transfer function of the pneumatic piston in to the conventional PID transfer function.

$$\frac{C(s)}{R(s)} = \frac{0.001(k_p + k_i/s + k_d s)}{0.001(k_p + k_i/s + k_d s) + 0.05s^2 + 0.065s + 0.1001} \quad (15)$$

Step 3: Setting The CDM transfer function by undetermined coefficient.

$$P(s) = a_0\{[\sum_{i=2}^{n}\left(\prod_{j=1}^{i-1}\frac{1}{\gamma_{i-j}{}^{j}}\right)(\tau s)^i] + \tau s + 1\} \quad (16)$$

Where γ_i is stabilize index, τ is time constant, $t_i = 2.5\tau$ and $\gamma_{n-1} = \ldots = \gamma_3 = \gamma_2 = 2, \gamma_1 = 2.5$ for the stabilization criteria.

Step 4: Undetermined coefficient between conventional PID and CDM.

$$P(s) = a_0[\frac{\tau^3}{\gamma_1^2 \cdot \gamma_2}.s^3 + \frac{\tau^2}{\gamma_1}.s^2 + \tau s + 1] \quad (17)$$

$$P(s) = 0.00512a_0s^3 + 0.064a_0.s^2 + 0.4a_0s + a_0 \quad (18)$$

Step 5: Find the total parameters such as $k_p, k_i, k_dT_iandT_d$

$$s^3 : 0.05 = 0.00512a_0 \rightarrow a_0 = 0.9765 \quad (19)$$
$$s^2 : 0.01k_d + 0.06 = 0.064a_0 \rightarrow k_d = 0.25 \quad (20)$$
$$s^1 : 0.01k_p + 0.1001 = 0.4a_0 \rightarrow k_p = 29.0525 (21)$$
$$s^0 : 0.01k_i = a0 \rightarrow k_i = 97.65 \quad (22)$$

Step 6: Fine tuning of fuzzy PID with nonlinear control with trial and error of the following assumption criteria that

$$\text{Quadratic error: } I_1 = \int_0^t e(t)dt \quad (23)$$

$$\text{Normalize overshoot: } I_2 = \frac{y(t)_{\max} - r(t)}{r(t)} \quad (24)$$

Rise time: $I_3 \min(t/y(t)) = 90\%r(t)$
Setting time:

$$I_4 = \min(t/y(t)) \in [95\%r(t), 105\%r(t)] \quad (25)$$

An equivalent fuzzy-PID controller is designed in figure 23 and the control parameters that are derived from the initial setting parameters process by CDM method shown as following $k_p = 29.0525, k_i = 97.65, k_d = 0.25$.

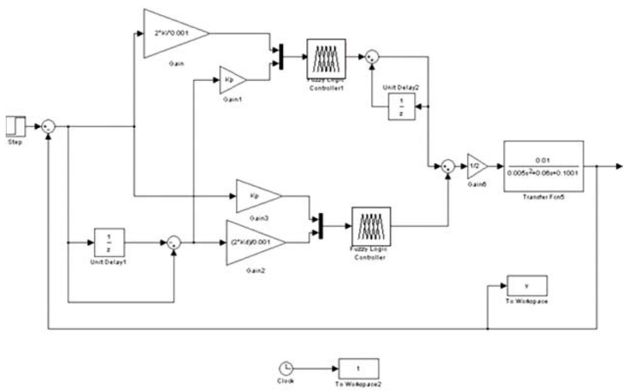

Fig.23: *Pneumatic piston control with hybrid fuzzy-PID controller.*

After simulation method [19], the fine control parameters have been tested for several system time responses for seeking an optimum values are received that $k_i = 58, k_p = 85, k_d = 25$ ($\%PO \leq 5\%$) that used for real testing in the laboratory room.

5. EXPERIMENTAL RESULTS

The performance of the robot system especially in the fuzzy-PID control is evaluated by the specification Pentium (R) 4 CPU 3.01 GHz with Matlab simulation program and Solid work simulation program version 2010. The real robot mechanisms are proved by mathematical analysis and real experimental tests were done in the laboratory room.

Table 2: *Comparing results of conventional PID and Fuzzy-PID control.*

No.	Components		
	Descriptions	*Type*	*Rated*
1	Main air pressure pump supply, 220VAC, 3 horse power, 2.2 kW, 2,850 rpm, air flow rate as 250 litre/minute, air pressure as 10kg/150 psi	PUMA	4-8bar
2	Vacuum pump mini with connection plate A, $D = 6mm$, Maximum vaccumn = 81kPa or 101.5psi, feed pressure as 0.38-0.6Mpa	VAD-M5L	55psi
3	Pneumatic piston cylinder of suction cup as $D = 16mm$, stroke length as $80mm$	SPZ-16-80-P-A	50-500 mm/sec
4	Pneumatic piston cylinder of traveling guide rail as $D = 22mm$, stroke length as $200mm$	SPZ-22-200-P-A	50-500 mm/sec
5	Suction cup (vacuum pad) diameter as $D = 50mm$	MB50-(N)-18M	> 6.5 kg/cup
6	Diameter of air pressure valve with variable speed control regulator $D = 6mm$	Solenoid valve	0-0.9 kg/cm^2
7	DC Wiper motor as 24VDC, 0.5A	ZKYR361-SA	$100rpm$
8	Cleaning Water Tank	Windshield washer	$1,664cm^3$
9	Micro controller control	dSPIC30F 4011	12C BUS

Table 3: *Comparing results of conventional PID and Fuzzy-PID control.*

Robot Operation (Rated speed)	Conventional PID	Hybrid-fuzzy PID (Present)
Rise time (s)	0.5	$\leq$ 0.05
Setting time (s)	1.0	$\leq$ 0.1
Steady state error (mm)	0.1-0.2	0
Suction cups time (s)	0.5-1.0	$\leq$ 0.5
Average climbing speed (m/s)	0.150	0.135
Average cleaning speed (rpm)	93.2	95.2
Wipe cleaning area (m^2)	0.1256	0.1256

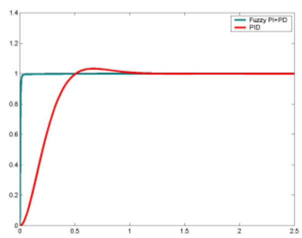

Fig.24: *The simulation result of fuzzy-PID controlled with pneumatic piston (Step response simulation with Matlab).*

The simulation result in figure 24 which plots between time (sec) and amplitude (unit step) response in horizontal and vertical axes respectively reveals that the fuzzy- PID control is given superior accuracy response than the conventional PID control both

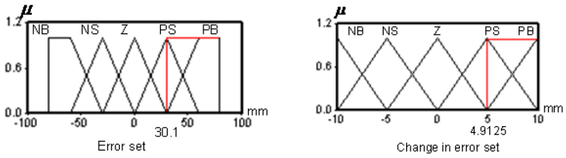

Fig.25: *The example results of fuzzy membership functions of error set and change in error set evaluation.*

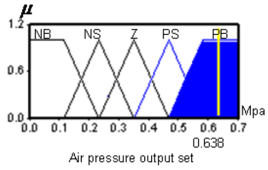

Fig.26: *The example result of fuzzy set output for air pressure evaluation.*

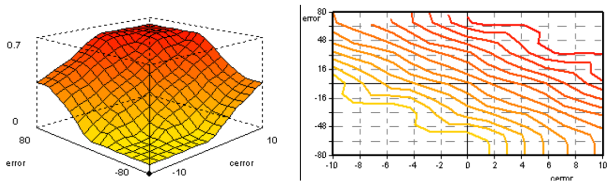

Fig.27: *The simulation results of fuzzy-PID controller in 3D surface and contour line control.*

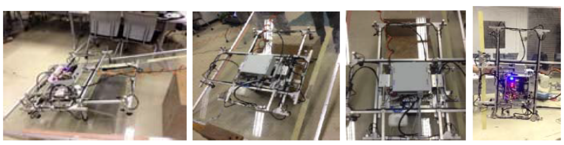

Fig.28: *The real experimental results in the laboratory room (slope at 30, 45, 60 and 90 degrees).*

in the transient state response with no overshoot and quicker reach to steady state response with non-steady state error of the desire target position. In figure 25-27, the desire outputs of air pressure in each of pneumatic pistons which are controlled by the fuzzy-PID controller are derived from the fuzzy set functions that must be suitable designed enough. The real experimental results are done in the laboratory room revealed that the robot can work well as design concept. In real place with any disturbances such as winding forces or raining effects, the control parameters are required for adjusting again in practical to use with more robustness control and disturbances compensated.

6. CONCLUSIONS

In this work, a fuzzy-PID control is applied to develop the mirror cleaning robot based on pneumatic piston system. The movement of the pneumatic piston and suction holding forces were controlled by hybrid fuzzy-PID to reach the desired position target, not limit only at the end of both sides of pneumatic piston cylinder that is relatively with the air pressure supply. The hybrid fuzzy-PID with CDM tuning method is selected to improve the position response and nonlinear performance of the pneumatic system with more accuracy which gave the most satisfied rising time, settling time and steady-state error for more robustness, stability, smoothly movement and safety to climb along the slop of the mirror surface of high building in the conditioning of nonlinear control. The room experimental results are revealed that the hybrid fuzzy-PID control gave the most satisfied performance than the conventional PID control in rise time; setting time and steady state error time response with more accuracy climb position and suction cup position. For further development, the practical robot must be improved for more efficiency in the terms of initial setting process, internal friction loss, piston inertia, winding force, raining effect and energy saving.

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Songkran Kantawong received his B.Eng. in Electronics Engineering from King Mongkuts Institute of Technology Ladkrabang (KMITL), Thailand in 1994 and received M.Eng. in Electrical Engineering (Telecommunication Engineering) from Chulalongkorn University (CU), Thailand in 2003. He is now a lecturer and an Associate Professor in the Department of Electrical and Electronics Engineering, Bangkok University, Thailand. His current research interests are wireless communication systems, RFID, image processing, pattern recognition, fuzzy and neural system, robotics technology, intelligent traffic system (ITS), energy saving, building automation system (BAS) and fire safety system. His researches are focused on advance research technology, application technology, manufacturing and robotic technologies.