2011 4th International Conference on Mechatronics (ICOM), 17-19 May 2011, Kuala Lumpur, Malaysia

Study of Fuzzy Controller to control vertical position of an air-cushion tracked vehicle

Altab Hossain
Department of Mechanical Engineering
[a]International Islamic University Malaysia (IIUM)
[b]University Selangor (UNISEL), Malaysia
E-mail: altab75@unisel.edu.my

Ataur Rahman
Department of Mechanical Engineering
International Islamic University Malaysia (IIUM)
Kuala Lumpur, Malaysia
E-mail: arat@iium.edu.my

A. K. M. Mohiuddin
Department of Mechanical Engineering
International Islamic University Malaysia (IIUM)
Kuala Lumpur, Malaysia
E-mail: mohiuddin@iium.edu.my

Abstract—**This paper presents the fuzzy logic control system of an air-cushion tracked vehicle (ACTV) operating on swamp peat terrain. Vehicle vertical position is maintained by using an inflated air-cushion system attached with the vehicle. It is desired that the vehicle vertical position be maintained at a desired position so that vehicle obtains sufficient traction control and to propel the driving system. To accomplish this task, it is required that the error between the actual position and the desired position equal to zero, and the differential position rate also be equal to zero. Therefore, the main purpose of this study is to develop an appropriate control strategy for an air-cushion system by using fuzzy logic expert system. Air-cushion system is controlled by the electronic proportional control valve and fuzzy logic controller (FLC) with associating the output signal of the distance (height) measuring sensor attached with the vehicle. In this control scheme the fundamental goal is to employ the fuzzy logic expert system to set the fuzzy rules and to actuate the electronic proportional valve in order to obtain appropriate valve control actions. Experimental values are taken in the laboratory for control system testing to investigate the relationship between vehicle vertical position and air-cushion system.**

Keywords- air-cushion; vertical position; driving system; fuzzy logic controller

I. INTRODUCTION

The agricultural mechanization on off-road is mainly restricted by terrain low trafficability and high water table. Therefore, transportation operation on off-road terrain are greatly emphasized to design and develop the vehicles with high crossing ability, good tractive performance and move on swamp peat terrain. Many research works have been carried out and different types of prototypes on tracked vehicle on off-road terrain have been introduced [1-3]. However, most of the vehicles are wheeled vehicles, tracked vehicles and air-cushion semi-tracked vehicles. It is found that the wheel vehicle system is not effective in soft terrain rather it is efficient on hard dry and flat or slightly sloping areas. With increasing demands to the wide application of off-road vehicles over swamp peat terrain such as agriculture, forestry, construction and the military, there is an urgent need for the air-cushion system to increase vehicle floatation capacity with partially support the vehicle load. Systematic studies of the principles underlying the transportation development of off-road vehicles on low bearing capacity swamp peat terrain, therefore, have attracted considerable interest to develop an air-cushion tracked vehicle due its reduced fuel consumption [4]. Although, this vehicle has been shown effective to move on low bearing capacity of soil, some problems have been incurred during the operation on the field due to the controlling problem of the air-cushion system. In order to maintain the vehicle mobility on soft and wet terrain, the control system is an important criterion for the vehicle operating on any undulating surfaces [5]. It is reported that the main problem for most previous fully track and fully tyre-wheeled air-cushion vehicles is the fixed and unadjustable height of the vehicle body relative to the driving mechanism. Furthermore, the air-cushion system of the existing semi-tracked air-cushion vehicle (STACV) is fixed in such a way that it always slides with the movement of the vehicle which may result excessive power consumption, load distribution problem between the track and air cushion system and hence increased the vehicle maintenance costs. To solve the adjustable problem of the STACV body's vertical position during traversing a new type of changeable air passage between upper plenum chamber and lower cushion chamber is introduced [6]. Vehicle body is controlled by using a pitch controller combined with the evaluation of power consumption. However, it is evaluated by using Matlab/Simulink for virtual STACV model only. Therefore, the small scale air-cushion tracked vehicle [4] has been modified and the air-cushion system has been more precisely

978-1-61284-437-4/11/$26.00 ©2011 IEEE

controlled by applying Fuzzy Logic Controller (FLC) during operation by maintaining the volume flow rate of air through the electronic proportional control valve and continuously monitored by the pressure sensor attached with the cushion chamber and distance measuring sensor attached with the vehicle chassis.

In the transportation area, many logical systems have been designed for controlling the vehicle components. Fuzzy logic control, a relatively new, intelligent, knowledge based control technique performs exceptionally well in non linear, complex and even in system where no precise mathematical model [7]. Fuzzy logic provides an inference morphology that emulates human expert knowledge and experience in terms of linguistic variables [8]. Therefore, this work presents the fuzzy logic expert system (FLES) model, comprising the control rules and describes the corresponding inference systems based on fuzzy rules [9]. The aim of this study is to construct of fuzzy knowledge-based model with Mamdani approach for controlling vertical position of an air-cushion tracked vehicle. A comparative performance analysis of this model, by sampling data collected from the operation, is used to validate the models.

II. METHODOLOGY

The use of mathematical models with control parameters in air-cushion system for tracked vehicle operating on swamp terrain which involve various types of uncertainties and vague phenomena raises the problems how accurately they reflect reality. Hence it is natural to look for different methodologies. In this regard, the fuzzy logic expert system (FLES) for automotive engineering is extended to vehicle dynamics, in particular to an air-cushion-terrain system. The control objective of the air-cushion pressure system management is to regulate volume flow rate through the change in valve position by using a fuzzy logic controller (FLC). Fig.1 illustrates the basic scheme for vehicle vertical position control (i.e., sinkage control) during sinking due to the low bearing capacity swamp peat terrain. In this figure, two valves control the inlet and outlet flow rate, respectively. A distance sensor is mounted at the vehicle chassis frame to measure the vehicle vertical position (vehicle center of gravity, h_{cg} is considered as 21 cm) from which the vehicle sinkage is calculated. It is desired that the vehicle vertical position be maintained at a desired position so that vehicle obtains sufficient traction control. To accomplish this task, it is required that the error between the actual position and the desired position equal to zero, and the differential position rate also be equal to zero. Therefore, for this control system an appropriate control strategy has been developed to actuate the microprocessor controlled electronic proportional valve in order to obtain appropriate valve control actions.

A. Structure of the Control System

A cushion pressure control system with fuzzy logic controller is designed to realize the cushion pressure targets and thus minimize the total power consumption based on the sinkage [10]. It has the advantage of fuzzy controller being simple (relations between input and output variables can be explained in a linguistic-based rule base), robust (performance is not depending on training and new input variables and rules can be easily added) and not requiring precise mathematical model [8-9]. In the control system of the vehicle, position (vehicle vertical distance) h is selected as controlled variable, and air flow rate Q as regulated variable through the change in valve position. The block diagram of the developed control system is shown in Fig. 2. Based on the difference between measured value (h) and reference value (h_r), the position is controlled by a regulation variable, i.e., flow rate Q. Hence, the resultant deviation, i.e., position error (PE), e and differential position or rate of position error (RPE) $\dot{e}$ are continuously measured in operation.

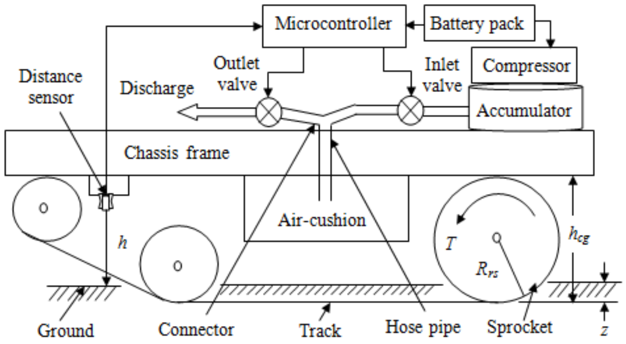


Figure 1. Vehicle vertical position control system.

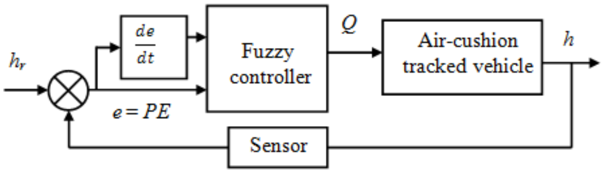


Figure 2. Block diagram of the control system.

B. Implementation of Fuzzy Logic Controller

For implementation of fuzzy values into the system by using FLES, position error (e) and rate of position error ($\dot{e}$) are used as input parameters and flow rate (Q) is used as output parameter. PE and RPE, respectively, are fuzzy variables of e and $\dot{e}$. For fuzzification of these factors the linguistic variables large negative error (LNE), small negative error (SNE), zero error (ZE), small positive error (SPE), and large positive error (LPE) are used for the position error (PE) and large negative rate of error (LNRE), small negative rate of error (SNRE), zero rate of error (ZRE), small positive rate of error (SPRE), and large positive rate of error (LPRE) are used for the rate of position error (RPE) as the input parameters. Similarly, the linguistic variables large negative open (LNO), small negative open (SNO), leave alone (LA), small positive open (SPO), and large positive open (LPO) are used for the flow rate (Q) as output parameter. The logical AND is

TABLE I. INFERENCE RULES OF CONTROLLER PARAMETERS

Rules	**Input variables**		**Output variable**
	PE	*RPE*	*Q*
1	LNE	LNRE	LNO
-----	-----	-----	-----
6	SNE	LNRE	SNO
-----	-----	-----	-----
10	SNE	LPRE	SNO
-----	-----	-----	-----
14	ZE	SPRE	LA
-----	-----	-----	-----
25	LPE	LPRE	LPO

implemented with the minimum operator, the aggregation method is maximum, and the center of gravity defuzzification method is used [9]. Based on the previous studies [11-12], the triangular shape membership functions are used in this study for both input and output variables because of their accuracy. The units of the used factors are: PE (cm), RPE (cm/s) and Q (%). For the two inputs and one output, a fuzzy associated memory or decision (also called decision rule) is formed as regulation rules. Total of 25 rules are formed. Parts of the developed fuzzy rules are shown in Table I. Once the inputs are fuzzified, the fuzzy inference system (FIS) refers to a set of user defined if-then rules to decide on a fuzzy output.

The first block inside the FLES is fuzzification, which converts each piece of input data to degrees of membership in one or several membership functions. Fuzzification of the position error (*PE*), rate of position error (*RPE*) and flow rate (*Q*) are made by aid follows functions. These formulas are determined by using measurement values.

$$PE(i_1)=\left\{\begin{array}{ll} i_1; & -6\le i_1\le 6 \\ 0; & otherwise \end{array}\right\}. \quad (1)$$

$$RPE(i_2)=\left\{\begin{array}{ll} i_2; & -1.5\le i_2\le 1.5 \\ 0; & otherwise \end{array}\right\}. \quad (2)$$

$$Q(o_1)=\left\{\begin{array}{ll} o_1; & -100\le o_1\le 100 \\ 0; & otherwise \end{array}\right\}. \quad (3)$$

where i_1 is the first input variable (PE), i_2 is the second input variable (RPE), and o_1 is the first output variable (Q). Prototype triangular fuzzy sets for the fuzzy variables, namely, position error (PE), rate of position error (RPE), and flow rate (Q) are set up using MATLAB FUZZY Toolbox. The membership values obtained from the above formulae are shown in the Figs. 3-5. The degree of PE is measured in cm from -6 to 6, RPE is measured in cm/s from -1.5 to 1.5, and Q is measured in percentage (%) from -100 to 100, respectively. These membership functions assist in changing numeric variables into linguistic terms. To illustrate the fuzzification process, linguistic expressions and membership functions of position error (PE) obtained from the developed rules and above formula are presented analytically for ZE and SPE. Similarly, the linguistic expressions and membership functions of other parameters could be calculated accordingly. The notation i_1 indicates the system input (for this case PE) and it has its membership function values that can be computed for all fuzzy sets as follows:

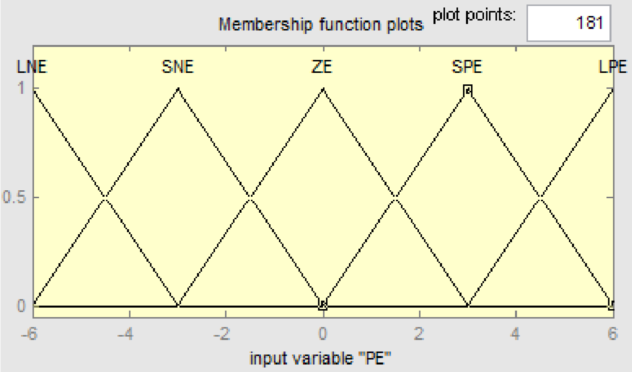


Figure 3. Prototype membership functions of input variable PE.

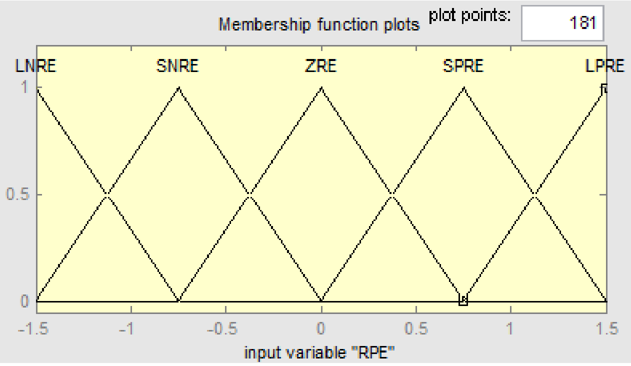


Figure 4. Prototype membership functions of input variable RPE.

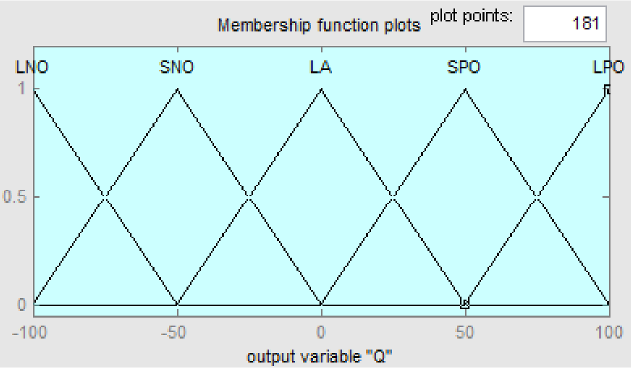


Figure 5. Prototype membership functions of input variable Q.

$$\mu_{ZE}(i_1)=\left\{\begin{array}{ll}\frac{i_1-(-3)}{3}; & -3\le i_1\le 0\\ \frac{3-i_1}{3}; & 0\le i_1\le 3\\ 0; & i_1\rangle 3\end{array}\right\}. \quad (4)$$

$$\mu_{SPE}(i_1)=\left\{\begin{array}{ll}\frac{i_1-0}{3}; & 0\le i_1\le 3\\ \frac{6-i_1}{3}; & 3\le i_1\le 6\\ 0; & i_1\rangle 6\end{array}\right\}. \quad (5)$$

In defuzzification stage, truth degrees (μ) of the rules are determined for the each rule by aid of the min and then by taking max between working rules. Due to its popularity, the "center of gravity" (COG) defuzzification method is used for combining the recommendations represented by the implied fuzzy sets from all the rules [11]. The output membership values are multiplied by their corresponding singleton values and then are divided by the sum of membership values to compute Q^{crisp} as follows:

$$Q^{crisp}=\frac{\sum_i b_i\mu_{(i)}}{\sum_i \mu_{(i)}}. \quad (6)$$

where b_i is the position of the singleton in the i th universe, and $\mu_{(i)}$ is equal to the firing strength of truth values of rule i.

C. Statistical Methods for Comparison

The predictive ability of the developed system has been investigated according to mathematical and statistical methods (7-9). In order to establish the relative error (ε) of structure, the subsequent equation is used:

$$\varepsilon=\sum_{i=1}^{n}\left|\frac{y_i-\hat{y}_i}{y_i}\right|\frac{100\%}{n}. \quad (7)$$

Root means squared (RMS) of the system is calculated by the following equation:

$$RMS=\sqrt{\frac{\sum_{i=1}^{n}\left(y_i-\hat{y}_i\right)^2}{n}}. \quad (8)$$

In addition, goodness of fit (η) of the predicted system is calculated by the following equation:

$$\eta=\sqrt{1-\frac{\sum_{i=1}^{n}\left(y_i-\hat{y}_i\right)^2}{\sum_{i=1}^{n}(y_i-\bar{y})^2}}. \quad (9)$$

where n is the number of interpretations, y_i is the measured value, $\hat{y}_i$ is the predicted value, and $\bar{y}$ is the mean of measured value. The relative error provides the difference between the predicted and measured values and it is necessary to attain zero. RMS should be small as close as 0 for good accuracy of prediction. The goodness of fit also provides the ability of the developed system and its highest value is 1.

III. RESULTS AND DISCUSSIONS

A. Control Surface of the Fuzzy Controller

Fuzzy logic controller has been developed based on position error (PE) and rate of position error (RPE). The final output (Q) of the fuzzy logic controller is verified by using MATLAB fuzzy toolbox. Using MATLAB the fuzzy control surface is developed as shown in Fig. 6. It may serve as visual depiction of how fuzzy logic expert system operates dynamically over time. This is the mesh plot of the example relationship between position error (PE) and rate of position error (RPE) on the input side and controller output flow rate (Q) on the output side.

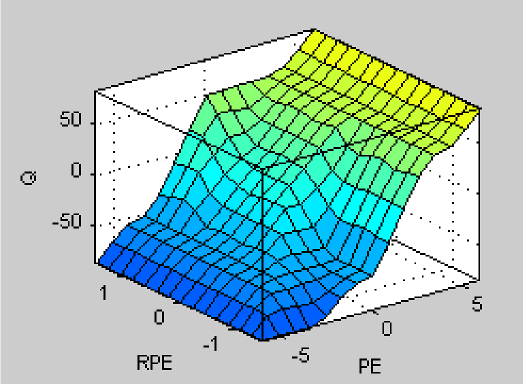


Figure 6. Control surface of the fuzzy controller.

The surface plot depicts the impacts of position error and rate of position error parameters on the flow rate. It shows that as the vehicle position error and rate of position error increase positively, there is concomitant increase in flow rate through the change in valve position as expected. The flow rate reaches the apex when the position error and rate of position error both reach their respective maximum level. This control surface displays the range of possible defuzzified values for all possible inputs of PE and RPE. For example, if PE is -3.15 cm and RPE is 0.46 cm/s, then the crisp output (Q) can be obtained as approximately 54% opening position of inlet valve. The plot is used to check the rules and the membership functions and to see if they are appropriate and whether modifications are necessary to improve the output. If necessary, the rule base for the fuzzy sets is modified until the output curves are desired. When a satisfactory system is achieved, the fuzzy program is converted to machine language (or other real time code) and downloaded into a microprocessor controller. The microprocessor then runs the machine or the system based on the fuzzy intelligent program.

B. Simulation Results of Control System

A Fuzzy logic controller is designed to simulate the fuzzy logic expert system once it has been verified with the rule viewer. The Fuzzy logic controller block in Simulink has two inputs: PE and RPE, respectively, and one output: Q. Fig. 7 shows the finalized Fuzzy logic controller with all the sources and sinks connected to it. Since the load distribution affects the total power consumption significantly, so position (h) of the vehicle is used as controlled variable in the control system of air-cushion tracked vehicle. Using MATLAB SIMULINK, the Fuzzy logic controller shows the output result of flow rate (Q) as -28.25 based on two inputs of position error (PE) and rate of position error (RPE) as -1.717 and 0.3997, respectively, which can be observed using three display results of the control systems. It is noticed that the inlet valve needs to be open 28.25% with outlet valve in closed position.

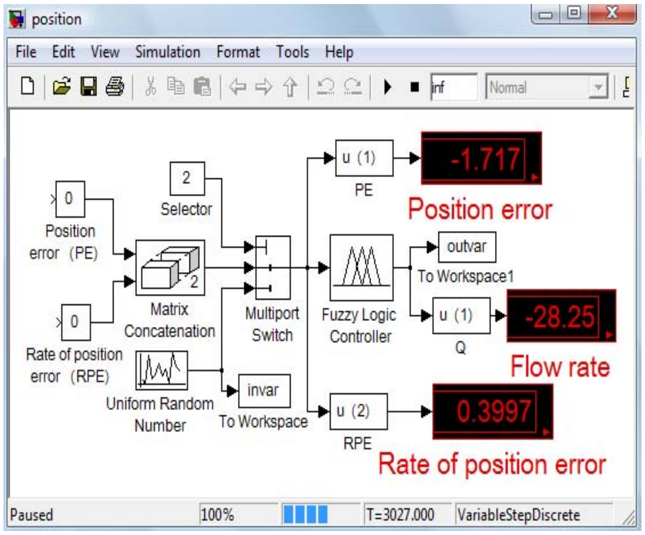
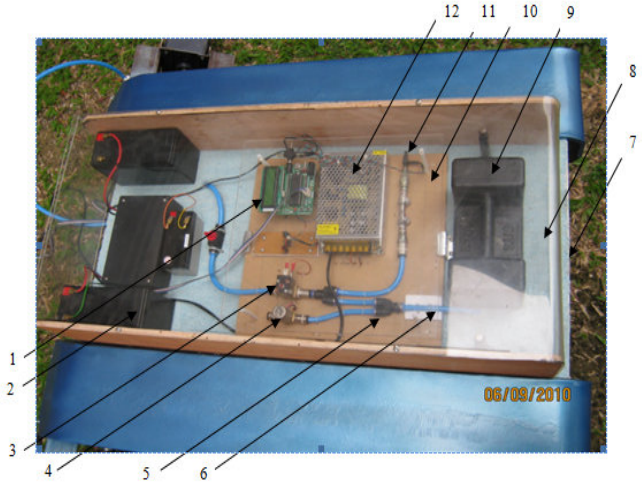


Figure 7. Fuzzy logic controller simulation.



Notation: 1-Micro controller, 2-Battery, 3-Inlet valve, 4-Outlet valve, 5-Connector, 6-Hose pipe connected to air-cushion, 7-Distance sensor, 8-Vehicle glass cover, 9-Counter balance weight, 10-Control board, 11-Pressure sensor, 12-Converter

Figure 8. Vehicle field testing with intelligent system.

C. Experimental Results of Control System

The field experiment is conducted on the terrain which is soft soil similar to swamp peat at the Faculty of Engineering, IIUM. The terrain used in testing is soft with small grass and little amount of water to make similar to swamp peat. During the control system testing, the distance sensor is attached with vehicle chassis frame and the reference height (vehicle vertical position) has been set as 15 cm based on the allowable vehicle sinkage of 7 cm as shown in Fig. 8. Sampling data collected from the operation are used to validate the fuzzy logic expert system models. Sample data is shown in table II.

TABLE II. COMPARISON BETWEEN ACTUAL AND PREDICTED DATA

Experimental data				**FLES data**
Distance	**Input variables**		**Output variable**	**Output**
h (cm)	***PE (cm)***	***RPE (cm/s)***	***Q (%)***	***Q (%)***
12.30	-2.69	1.08	25.50	32.50
11.84	-3.15	-0.46	56.06	50.20
12.57	-2.42	-0.62	41.97	42.80
11.53	-3.46	-1.03	63.92	51.30
10.29	-4.70	-1.23	76.27	61.70
9.05	-5.94	-1.24	97.60	82.50
11.76	-3.23	0.05	55.87	50.20
7.47	-7.52	0.11	100.00	94.00
11.96	-3.03	1.04	50.00	50.00
10.83	-4.16	-1.02	72.90	55.20
9.44	-5.55	-1.38	84.76	76.00
7.41	-7.58	-0.05	100.00	94.00

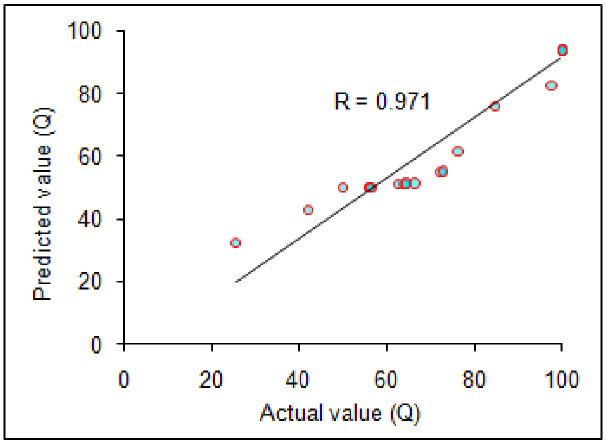


Figure 9. Correlation between actual and predicted values of flow rate.

The results of the developed FLES have been compared with the experimental results. The mean of measured and predicted values (from FLES) on flow rate Q are 77.78 % and 70.29 %, respectively. The correlation between actual (measured) and predicted values (from FLES model) of air flow rate is shown in Fig. 9. The correlation coefficient of relationship is found as 0.971 which is significant in operation. Furthermore, the mean relative error of actual and predicted values from the FLES model on flow rate is found as 10.93 % which is almost equal to the acceptable limit of 10% [6]. The goodness of fit of the prediction values from the FLES model is found as 0.91 which is close to 1.0 as expected and hence shows the good performance of the controller and warrants the novelty of this work [12-13].

IV. CONCLUSION

In this paper, the fuzzy logic expert system is presented and described its implementation on air-cushion pressure control system for a swamp terrain vehicle. The control scheme for an air-cushion system is investigated based on the simulations and experiments. In this paper, a robust fuzzy knowledge based rules is developed to predict the fuzzy logic controller and finally it is compared with the experimental data. Both experimental and predicted results are found to be valid within the acceptable limits. However, the following conclusions are drawn from this study:

1. Taking vehicle position (height) from the ground as control variable, a control scheme is proposed and its feasibility is examined by simulations.
2. The correlation coefficient of relationship has been found as 0.971 which is significant in operation.
3. The mean relative error of actual and predicted values from the FLES model on flow rate has been found as 10.93% which is slightly above the acceptable limit of 10%.
4. The goodness of fit of the prediction values from the FLES model has been found as 0.91 which is close to 1.0 as expected.

ACKNOWLEDGMENT

The authors are grateful for the financial support provided by International Islamic University Malaysia (IIUM) for this project.

REFERENCES

[1] Bodin, A., Development of a tracked vehicle to study the influence of vehicle parameters on tractive performance in soft terrain, *Journal of Terramechanics*, 1999, **36** (1) 167-181.

[2] Luo, Z., Yu, F. and Chen, B.-C. Design of a novel semi-tracked air-cushion vehicle for soft terrain. *In. J. of Vehicle Design,* 2003, **31** (1) 112-123.

[3] Ataur, R., Azmi, Y., Zohadie, M., Desa, A. and Wan, I. Design and development of a segmented rubber tracked vehicle for Sepang peat terrain in Malaysia. *Int. J. Heavy Vehicle Systems*, 2005, **12** (3) 239-267.

[4] Rahman, A., Mohiuddin, A. K. M., Ismail, A. F., Yahya, A. and Hossain, A. Development of hybrid electrical air-cushion tracked vehicle for swamp peat. *Journal of Terramechanics*, 2010, **47** (1) 45-54.

[5] Wang, X., Luo, Z., Chen, B. C., Shi, Y. W. & Ning, S. J. (1999). Study on Automatic Control System of a Semi-Tracked Air-Cushion Vehicle. *Proceedings of the IEE International Conference on Vehicle Electronics,* China.

[6] Xie, D., Ma, C., Luo, Z. & Yu, F. (2008). Pitch control for a semi-track air-cushion vehicle based on optimal power consumption. *World Automotive Congress, (FISITA 2008)*, Germany, F2008-01-009, 14-19 September.

[7] Zadeh, L. A. (1973). Outline of a new approach to the analysis of complex systems and decision processes. *IEEE Trans. Systems, Man and Cybernetics*, *3*, 28-44.

[8] Gopal, M. (2009). Digital control and state variable methods: conventional and intelligent control systems. 3rd edition, Tata McGraw-Hill Education Pvt. Ltd.

[9] Carman, K. Prediction of soil compaction under pneumatic tyres using a fuzzy logic approach. *Journal of Terramechanics*, 2008, **45** (1) 103-108.

[10] Hossain, A., Rahman, A., and Mohiuddin, A. K. M. Load distribution for an intelligent air-cushion track vehicle based on optimal power consumption. *International Journal of Vehicle Systems Modelling and Testing*, 2010, **5** (2/3) 237-253.

[11] Passino, K. M. & Yurkovich, S. (1998). *Fuzzy control*. Addison-Wesely Longman, Inc. Menlo Park, California.

[12] Ivanov, V., Shyrokau, B., Augsburg, K. & Algin, V. (2010). Fuzzy evaluation of tyre-surface interaction parameters. *Journal of Terramechanics*, *47*, 113-130.

[13] Hossain, A., Rahman, A. and Mohiuddin, A. K. M. Cushion pressure control system for an intelligent air-cushion track vehicle. *Journal of Mechanical Science and Technology,* 2011, 25 (4) 1253-1260.