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INTELLIGENT AIR-CUSHION SYSTEM OF SWAMP PEAT VEHICLE CONTROL: FUZZY LOGIC TECHNIQUE

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ABSTRACT

This paper describes the fuzzy logic to control the intelligent air-cushion system of swamp peat vehicle. Focusing on optimizing the total power consumption of the vehicle, two main issues were studied in this paper. First, a theoretical model is developed to minimize total power consumption of the vehicle. Second, a control scheme is proposed to achieve the control targets and to minimize the power consumption by using a fuzzy logic controller. Compared with traditional approach, fuzzy logic approach is more efficient for the representation, manipulation and utilization. Therefore, the primary purpose of this work was to investigate the relationship between total power consumption, clearance height and cushion pressure, and to illustrate how fuzzy logic technique might play an important role in prediction of total power consumption. All experimental values were collected from the field test using a developed prototype hybrid electrical air-cushion tracked vehicle.

Keywords: Swamp Peat, Power Consumption, Fuzzy Logic, Cushion Pressure.

1. INTRODUCTION

With increasing demands to the wide application of off-road vehicles over soft terrain and swamp peat such as agriculture, forestry, construction and the military, there is a need to increase the knowledge about intelligent air-cushion system of swamp peat vehicle. The performance of air-cushion tracked vehicles travelling in a straight motion with uniform ground pressure distribution is well understood. However, prepared or unprepared tracks inherently have uneven profile for situations of vehicles travelling on deformable road surfaces. The vehicle responses during off-road operation are dependent on the road conditions and vehicle parameters such as clearance height, road roughness, vehicle speed, vehicle weight, and air-cushion pressure [1-3]. Many research works have been carried out and different types of vehicles are introduced to solve the transportation problems on moderate peat terrain [4-6]. But still no one offers any vehicle on low bearing capacity swamp peat terrain in Malaysia. The proposed vehicle could be useful for transporting the palm oil fresh fruit bunches over the swamp peat. A hybrid vehicle which combines intelligent air-cushion system with a driving mechanism has been proven to be an efficient solution for a heavy duty vehicle on severe working conditions [7]. The use of commercial intelligent air-cushion tracked vehicles to test the vehicle parameters is limited due to the difficulties in varying parameters as well as the control of the air-cushion pressure. A small scale hybrid electrical air-cushion tracked vehicle (HEACTV) was therefore developed based on low bearing capacity of peat swamp [8]. The study has been focused based on the bearing capacity of the peat swamps in Sarawak that has been found as 7.7 kN/m^2 and it has poor trafficability due to the presence of submerged and undecomposed and partially decomposed materials. Other important properties are the very high ground water table, and low bulk density [9-11].

The mobility of the vehicle, cushion pressure and sinkage by vehicle effect on swamp terrain, are complex process with many other factors. For this reason, mathematical models have been introduced to understand the terrain nature and mechanics of track-terrain interaction and the interaction of air-cushion supporting system-terrain [12]. The air-cushion system of this vehicle was designed in such a way that it would not slide on the terrain with the vehicle movement. It only supports the partial load of the vehicle once the vehicle sinkage is closed to 70 mm and makes the vehicle ground contact pressure 7 kN/m^2. The additional thrust (or tractive effort) is provided to the vehicle by using a propeller to overcome the drag motion resistance of the air-cushion system. As the terrain is unprepared, the air-cushion system was protected by using a novel design supporting system.

2. STRUCTURE SKETCH OF VEHICLE

The vehicle comprised mainly with full track system, air-cushion and air-cushion propulsion system, DC motors, two propellers, a battery pack, and a small engine are shown in Fig. 1. The full segmented rubber track mechanism is used as driving system to overcome traveling resistance, and the flexible skirt air-cushion as vehicle body to support vehicle partial weight. The air-cushion pressure is provided by a single compressor to lift the vehicle. Since the total vehicle load is partly supported by the air-cushion system and partly by the driving (also called propulsion system) system, the required total power for the vehicle includes two parts, i.e., the power for propulsion system and the power for lifting system (air-cushion system). Thus, it is important to reduce the total required power consumption that significantly affects transportation efficiency. A fuzzy logic controller is needed to maintain the vehicle in the optimum operation condition that optimizes the total power consumption of the vehicle by using properly selected control parameters. Therefore, an intelligent air-cushion system for a swamp peat vehicle is developed and theoretical analysis is carried out.

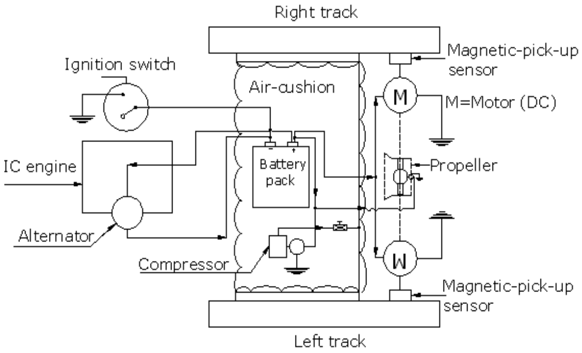

Fig 1. Structure sketch of the vehicle

Like many other real-world optimization, at present, various techniques exist in soft computing method. Based on the studies on wheeled air-cushion vehicles and semi-tracked air-cushion vehicles, an intelligent system using Fuzzy Logic was proposed to predict the power consumption. Fuzzy Logic, a relatively new, intelligent, knowledge based technique performs exceptionally well in non linear, complex systems [13-14].

This work presents the model of fuzzy system, comprising the control rules and term sets of variable, enabling to express vague human concepts using fuzzy sets and also describe the corresponding inference systems based on fuzzy rules [15]. In fuzzy rule-based systems, knowledge is represented by if–then rules. The aim of this study was the construction of fuzzy knowledge-based models for the prediction of the power consumption by controlling air cushion pressure of air-cushion tracked vehicle based on the Mamdani approach. A comparative performance analysis of this approach, by sampling data collected from the operation, was used to validate the fuzzy models.

3. THEORETICALL MODELS

When the vehicle with a constant load is subjected to external disturbances, such as uneven or slope of terrain surfaces, the clearance height of the vehicle and the required power on the tracks will change. However, the load distribution between driving system and air cushion pressure also changes, and thus total power requirement changes. Hence, in order to find an optimal range of load distribution which is corresponding to minimum power requirements, the cushion pressure needs to be controlled within optimal range.

The total power requirement P of the vehicle includes the power for air cushion system P_c and the power for driving system (propulsion system) P_d, which is given by:

$$P = P_c + P_d \tag{1}$$

where P_c is the power consumed by air-cushion used to support the weight of the vehicle body in W and P_d is the power consumed by driving system (propulsion system) in W used to overcome the traveling resistance and maintain normal driving state.

3.1 Model of Motion Resistance

In this study, the vehicle is designed mainly as a low speed heavy-duty off road vehicle. Based on established mathematical model, and assuming the vehicle on a level terrain surface, the motion resistances from aerodynamics and track belly drag component in the computations of the total motion resistance can be ignored. Hence, the total resistance R_t can be assumed to only contain the motion resistance of the vehicle due to terrain compaction R_c, inner resistance R_{in}, and the dragging motion resistance R_{drag}.

In a particular soil condition, the compaction resistance R_c in N is given by [12],

$$R_c = 2B\left(\frac{k_p z^2}{2} + \frac{4}{3D_{htc}} m_m z^3\right) \tag{2}$$

In the above Eqs., p' is the normal pressure of the vehicle in N/m^2 and z is the sinkage in m, m_m is the surface mat stiffness in N/m^3, k_p is the underlying peat stiffness in N/m^3, D_{htc} is the track hydraulic diameter in m when air cushion touches the ground, A_C is the air-cushion effective area, W is the total weight of the vehicle in N, W_t is the weight supported by the two tracks (weight of driving system or weight supported by propulsion system) in N, and p'_o is the cushion pressure in N/m^2.

The motion resistance of the vehicle due to internal friction losses, deeply affected by the track and the speed of the vehicle, R_{in} in N is computed by [12]:

$$R_{in} = \left(\frac{W - W_{v(ac)}}{1000g}\right)\left[222 + 3v_t\right] \tag{3}$$

where v_t is the vehicle theoretical speed in m/s, g is the gravitational acceleration in m/s^2, W is the total weight of the vehicle in N, and $W_{v(ac)}$ is the weight supported by the air-cushion in N and is equal to $W_{v(ac)} = p'_o A_C$.

The drag motion resistance R_{drag} of the air-cushion system in N is calculated by [12],

$$R_{drag} = p'_0 A_C \tan\varphi \qquad (4)$$

Depending on Eqns. 2-4, the total travelling resistance R_t in N is,

$$R_t = R_c + R_{in} + R_{drag} \qquad (5)$$

3.2 Power Demand for Air-Cushion System

The power demand for air-cushion system P_c in W can be expressed by [1],

$$P_c = p'_0 Q = p'_0 h_c L_c D_c \left(\frac{2p'_o}{\rho}\right)^{\frac{1}{2}} \qquad (6)$$

Where Q is the volume flow of air from compressor in m^3/s, h_c is theoretical clearance height in m, L_c is the air-cushion perimeter in m, D_c is the discharge coefficient, ρ is the air density in kg/m^3 and p'_o is the cushion pressure in N/m^2.

3.3 Power Demand for Propulsion System

The power demand for propulsion system P_d in W can be expressed by,

$$P_d = R_t v_t = \left[2B\left(\frac{k_p z^2}{2} + \frac{4}{3D_{htc}} m_m z^3\right) + \left(\frac{W - W_{v(ac)}}{1000g}\right)[222 + 3v_t]\right] v_t + \left[p'_o A_C \tan\varphi\right] v_t \qquad (7)$$

Where R_t is the total travelling resistance in N, v_t is the vehicle theoretical speed in m/s, p'_o is the cushion pressure in N/m^2.

3.4 Total Power Consumption and Optimum State

Based on Eqs. (6) and (7), the total vehicle power requirement P is rewritten as below,

$$P = P_c + P_d \qquad (8)$$

In Eq. (8), P_c is mainly used to fully or partially support main proportion weight of the vehicle body, P_d is to overcome the vehicle travelling resistance and to maintain the normal driving state. For a particular soil condition, the existence of an optimal load distribution ratio, which results in minimum total power consumption for the vehicle, could be determined. So for Eq. (8), taking partial derivative of P with respect to p'_o and having resultant equation equal to zero, i.e.

$$\frac{\partial P}{\partial p'_0} = 0 \qquad (9)$$

The optimal cushion pressure p'_o can be calculated for given soil condition and vehicle speed.

4. CONTROLLER DESIGN

4.1 Structure of the Control System

Focusing on optimizing the total power consumption of the air-cushion track vehicle operating on some severe conditions, e.g., soft terrain, wet fields, swamp peat, many research works have been carried out [17]. However, for most air-cushion vehicles, the air from the cushion chamber is exhausted and wasted. Based on the previous studies on tracked air-cushion vehicles, air from the cushion chamber is fed back to the air accumulator which will reduce the power consumption of the air compressor. The diagram of the air-cushion pressure control system is shown in Fig. 2. In the diagram, controller determines the valve of air-cushion pressure based on the height and determines the value of the air-cushion pressure using pressure sensor and compares with calculated cushion pressure. Finally it takes decision by opening or closing solenoid valve. Distribution of vehicle load is controlled by Fuzzy Logic controller and is actually done by maintaining the inside pressure of the cushion based on the optimum power consumption by the vehicle.

At any instant the sinkage is measured by the high precision (1 mm resolution) distance measuring sensor. Then optimum pressure is determined based on the developed optimum pressure – sinkage relation and the pressure in the cushion chamber is controlled by the Fuzzy controller by maintaining solenoid valve and continuously monitored by the pressure sensor attached with the cushion chamber.

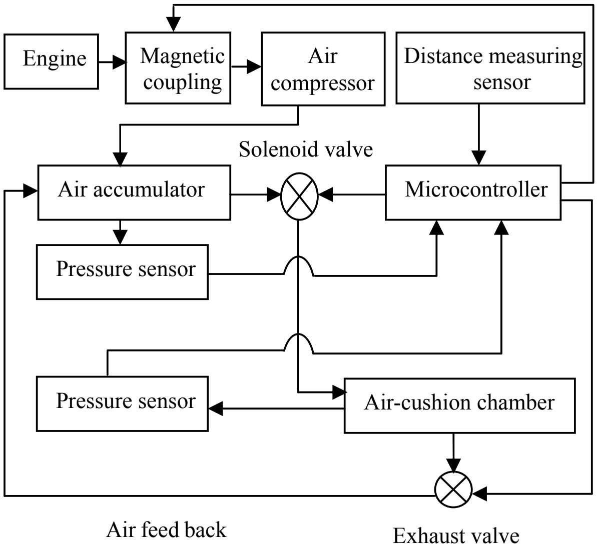

Fig 2. Control system diagram for air-cushion pressure.

4.2 Design of Fuzzy Logic Controller

There are a number of different techniques that would work here and therefore a design choice must be made. Some of the techniques require a relatively accurate model of the system in order to develop a satisfactory system. Fuzzy logic, on the other hand, does not require a model of the system. Instead, they rely on the knowledge of an expert for the particular system. Therefore, with all of this in mind, a Fuzzy Logic expert system is introduced for the prediction of total power consumption of the intelligent air cushion track vehicle. The main advantage of Fuzzy Logic is that it can be tuned and adapted if necessary, thus enhancing the degree of freedom of the system

[18]. For implementation of fuzzy values into the of ACTV by using Fuzzy expert system (FES), clearance height (CH) and cushion pressure (CP) were used as input parameters and total power consumption (PC) were used as output parameters. For fuzzification of these factors the linguistic variables very low (VL), low (L), medium (M), high (H), and very high (VH) were used for the inputs and output. The units of the used factors were: CH (m), CP (kPa), and PC (kW). With the fuzzy sets defined, it is possible to associate the fuzzy sets in the form of fuzzy rules. For the two inputs and one output, a fuzzy associated memory or decision (also called rule) table is developed as shown in Table 1.

Table 1: Rule base of fuzzy expert system.

Rules	Input variables		Output variable
	CH	CP	PC
Rule 1	VL	VL	VL
……..	……..	……..	……..
Rule 10	L	VH	H
……..	……..	……..	……..
Rule 15	M	VH	H
……..	……..	……..	……..
Rule 20	H	VH	M
……..	……..	……..	……..
Rule 25	VH	VH	M

The first block inside the fuzzy expert system (FES) is fuzzification, which converts each piece of input data to degrees of membership by a lookup in one or several membership functions. The fuzzification block thus matches the input data with the conditions of the rules to determine how well the condition of each rule matches that particular input instance. There is a degree of membership for each linguistic term that applies to that input variable. Fuzzifications of the used factors are made by aid follows functions. These formulas were determined by using measurement values.

$$CH(i_1)=\begin{Bmatrix} i_1;0.01\le i_1\le 0.03 \\ 0;otherwise \end{Bmatrix} \qquad (10)$$

$$CP(i_2)=\begin{Bmatrix} i_2;0.5\le i_2\le 4 \\ 0;otherwise \end{Bmatrix} \qquad (11)$$

$$PC(o_1)=\begin{Bmatrix} o_1;2\le o_1\le 10 \\ 0;otherwise \end{Bmatrix} \qquad (12)$$

Using MATLAB FUZZY Toolbox, prototype triangular fuzzy sets for the fuzzy variables, namely, clearance height (CH), cushion pressure (CP), and total power consumption (PC) are set up. The membership values used for the FES were obtained from above the formulas and are shown in the Fig. 3 (a), (b), and (c).

The determination of conclusion is taken when the rules that are applied to deciding what the power consumption to the plant (vehicle) should be. In defuzzification stage, truth degrees (μ) of the rules were determined for the each rule by aid of the min and then by taking max between working rules.

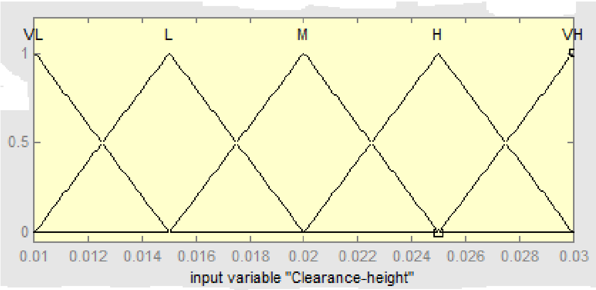

Fig 3 (a). Prototype membership functions for CH.

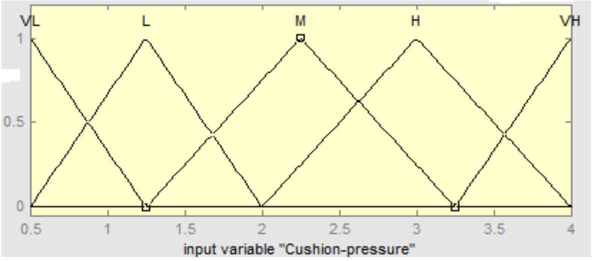

Fig 3 (b). Prototype membership functions for CP.

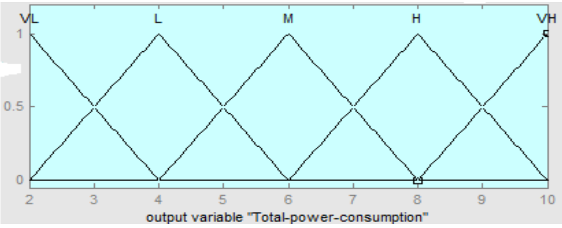

Fig 3 (c). Prototype membership functions for PC.

In this stage defuzzification operation is considered that is the final component of the fuzzy controller. Defuzzification operates on the implied fuzzy sets produced by the inference mechanism and combines their effects to provide the "most certain" controller output (plant input). Due to its popularity, the "center of gravity" (COG) defuzzification method is used for combing the recommendations from all the rules [15].

The output membership values are multiplied by their corresponding singleton values and then are divided by the sum of membership values.

$$output^{crisp}=\frac{\sum b_i\mu_i}{\sum \mu_i} \qquad (20)$$

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

In addition, the predictive ability of developed system was investigated according to mathematical and statistical methods. In order to determine the relative error (ε) of system, the following equation was used:

$$\varepsilon=\sum_{i=1}^{n}\left|\frac{y-\hat{y}}{y}\right|\frac{100\%}{n} \qquad (13)$$

Where n is the number of observations, y is the actual value, and $\hat{y}$ is the predicted value. The relative error gives the deviation between the predicted and experimental values and it is required to reach zero. In addition, goodness of fit (η) of predicted system was calculated by following equation:

$$\eta = \sqrt{1 - \frac{\sum_{i=1}^{n}\left(y - \hat{y}\right)^2}{\sum_{i=1}^{n}\left(y - \bar{y}\right)^2}} \qquad (14)$$

Where $\bar{y}$ is the mean of actual values. The goodness of fit also gives the ability of the developed system and its highest value is 1.

5. RESULTS AND DISCUSSIONS

5.1 Simulation Condition

To optimize the power consumption of HEACTV and some related physical and mechanical parameters about the HEACTV are shown in Table 2 and developed prototype is presented in Fig. 4 (photo). Steering of this vehicle was achieved by means of an individual switch of the DC motor with a power of 0.500 kW @ 2.94 Nm [8]. The dry weight of the vehicle was considered as 2.43 kN and it was designed mainly for operating a maximum load of 3.43 kN including a 1.00 kN payload over the swamp peat terrain. The total ground contact area of the vehicle was 1.052 m^2 including 0.544 m^2 of the air-cushion system. The vehicle was powered by a battery pack comprising eight (8) lead acid batteries, connected in parallel. The vehicle could travel 24 km powered of the single charging battery pack. A small IC Engine power of 2.5 kW @ 4000 rpm was installed on the vehicle to recharge the battery pack with the help of an alternator.

Table 2: Terrain and vehicle design parameters.

Parameters	Notations	Values	Units
Total vehicle load	W	3433.5	N
Length of track ground contact	L_t	1.00	m
Width of track ground contact	B_t	0.254	m
Length of the air-cushion,	L_{ac}	0.80	m
Width of the air-cushion	B_{ac}	0.68	m
Air cushion effective area	A_C	0.544	m^2
Air cushion perimeter	L_C	2.96	m
Vehicle theoretical velocity	v_t	2.78	m/s
Air density	ρ	1.20	kg/m^3
Surface mat stiffness	m_m	13590	N/m^3
Underlying peat stiffness	k_p	171540	N/m^3

Fig 4. Developed prototype of hybrid electrical air-cushion track vehicle [8].

5.2 Effect of Load Distribution on Total Power Consumption

The present study is focusing on load distribution (defined as the load transferred from the driving system to the air cushion system) for minimizing total power consumption. The effect of load distribution on the total power consumption for the hybrid electrical air-cushion tracked vehicle (HEACTV) are investigated.

Fig. 5 shows the relationship between load distribution ratio and total power consumption. From the Figure, it is observed that the load distribution ratio affects the total power consumption significantly as total power consumption linearly increases with the increase of load distribution ratio. The total power consumption is varied from 1.25 to 8.3 kW. Based on established theoretical model and the designed prototype, corresponding simulation and experimental results were carried out and an optimal load distribution ratio of 0.2 was obtained which could result in prediction of minimum power consumption of 3.5 kW and it was also supported by [8] for the vehicle loading condition of 3.43 kN.

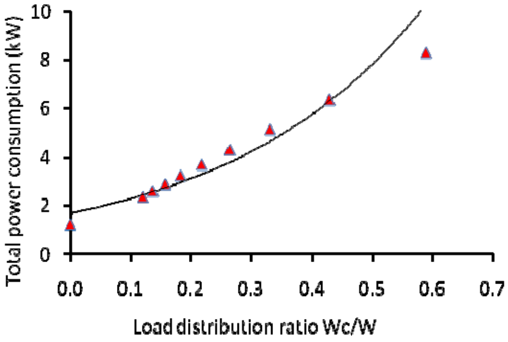

Fig 5. Effect of load distribution ratio on PC.

Fig. 6 shows the relationship between load distribution ratio and total power consumption for the actual and predicted (FES) values. For total power consumption, mean of actual and predicted values are 4.03 and 4.22 kW respectively. Furthermore, the correlation between actual and predicted values (from

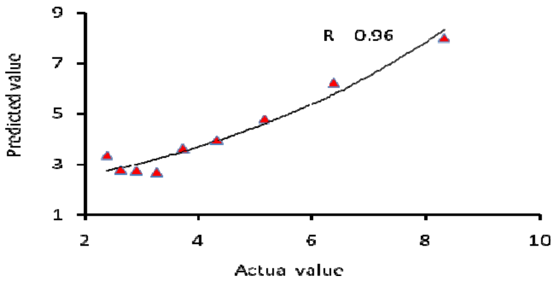

Fig 6. Correlation between actual and predicted values of total power consumption.

FES model) of total power consumption for different load distribution conditions also examined. The relationship is significant for all the parameters in different operating conditions. The correlation coefficient of total power consumption is found as 0.96. The mean relative error of actual and predicted value of total power consumption is found as 10.63 %. For the parameters tested and simulated, the relative error of predicted value is found to be equal to the acceptable limits (10%). The goodness of fit of prediction (from FES model) value of total power consumption is found as 0.97. The value is found to be close to 1.0 as expected.

6. Conclusion

This paper presents an adaptive approach based on the use of fuzzy logic for the prediction of total power consumption for the hybrid electrical air-cushion track vehicle in transportation efficiency and energy economy. In this study, according to evaluation criteria of predicted performances of developed fuzzy knowledge-based model was found to be valid. However, the conclusions drawn from this investigation are as follows:

(a) Load distribution could be controlled by taking cushion pressure as a control parameter using fuzzy logic controller.
(b) The developed model can be used as a reference for the full scale prototype which is being carried out.
(c) This system can be developed further by increasing the knowledge rules and by addition of Genetic-Fuzzy and Neuro-Fuzzy to the system.

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