Autonomous line-follower with fuzzy control

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***Abstract*—The aim of the paper is to shown a construction of an autonomous vehicle using fuzzy logic. The vehicle was designed as line-follower. The task of control system is to move a vehicle in such way that it follows a black line marked on the white floor. The vehicle consists of two wheels in the front and a support at the back. The system control is based on input signals from six optical sensors measuring the intensity of light reflected by the floor. Fuzzy logic control algorithm is implemented in ATmega328 microcontroller placed on Arduino board. The work concludes observations, the description of the difficulties encountered in the construction of the device and possible modifications.**

Keywords—autonomouse vehicle, line-follower, fuzzy control, microcontroller

I. Introduction

Actually, a new trend in vehicle construction is observed. Complicated electronic equipment is introduced in vehicle electrical systems. Such devices as radio, CD and DVD players are now standard equipment and sometimes a television in exclusive cars. New accessory is introduced as GPS, road maps, cameras used for registration of road situation. Some vehicles can furthermore update their maps based on sensory input. Moreover, new equipment is applied to facilitate driving of the car. Special sensors and systems are used for automatic parking. Next step will be autodriver similar as autopilot in aviation. At the TED 2011 conference in Long Beach a car was demonstrated with autodriver under Google mark. Also, it was announced self-driving car project in 2010 to make driving safer, more enjoyable, and more efficient. The constructors show a video with audio captions. They write “Having safely completed over 200,000 miles of computer-led driving, we wanted to share one of our favorite moments. Here is a man, who joined us for a special drive on a carefully programmed route to experience being behind the wheel in a whole new way. We organized this test as a technical experiment, but we think it's also a promising look at what autonomous technology may one day deliver if rigorous technology and safety standards can be met.”

Numerous major companies and research organizations have developed working prototype automated vehicles, including Google, Continental Automotive Systems, Bosch, Nissan, Toyota, Audi and Oxford University. In June 2011, the state of Nevada was the first jurisdiction in the United States to pass a law concerning the operation of autonomous cars. The Nevada Department of Motor Vehicles issued the first license for a self-driving car in May 2012.

II. Task of the vehicle and additional assumptions

The most of autodriver systems are built using video camera or sometimes radar systems as source of information. The authors of this paper suggest other idea. The assumption is introduced that such type of vehicle will be used in magazines or supermarkets for transport of articles. On the dark flour a white lines will be paint or made using white terracotta panels. (or inversely – the white flour and a black lines) The task of the vehicle is to follow the lines. Such type of vehicle is known as line-follower.

The infrared reflectance sensors were chosen as a source of information about the vehicle position. The Pololu QTR-1A reflectance sensors were used. The sensor carries a single infrared LED and phototransistor pair. Six reflectance sensors are placed under the vehicle floor. Only forward and rotation movement is assumed, thus the sensors are placed at the front and sides of the vehicle.

It is assumed that fuzzy logic control system will be applied. Such systems are effective, easy to implementation and they do not require exact knowledge of system dynamics. They only require general knowledge about control rules, not accurate information from system.

In order to diminish the cost of mechanical construction two wheels are used at vehicle front and a constant support in the place of rear wheel. In real applications this third wheel will be added. Such replacement does not change the control rules because only two front wheels are connected to the motors.

Nowadays exist some useful platforms for building control systems. The Arduino system is chosen. Arduino is an open-source electronics prototyping platform based on flexible, easy-to-use hardware and software. It's intended for artists, designers, hobbyists, and anyone interested in creating interactive objects or environments. The Arduino system is getting more popular because of the ease of use and versatility. Appropriate connection of Arduino components allows to construct a control circuit DC motors, can provide a platform to games or GPS receiver.

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III. Details of Construction

A. General description

As it was mentioned before the vehicle has two wheels propeled by two motors. The motors are controlled in difference way. During rotation the velocity of one wheel rises and second diminishes. Such kind of movement allows turn the vehicle in place practically without forward velocity. In the model maximal angle of rotation allowed in one control order is limited to 90^0 on account of sensors positions. The sensors are placed in such a way to form "Christmas tree" and are called A0, A1, A2, A3, A4, A5 and A6 (see Fig. 1).

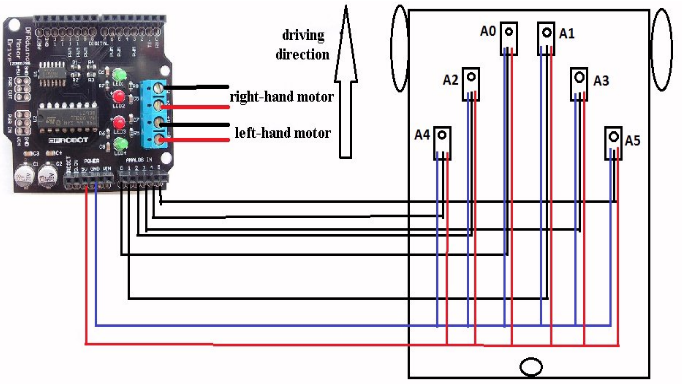

Fig. 1. Positions of sensors and driving chart.

The left side of Fig. 1 shows a module DFRduino Motor Drive Shield. It is 2-channel actuator motor driver used for controlling direct current motors. It supplies voltage 6-12V and allows turn motors in both directions - forward and backward. Pulse width modulation (PWM) is used for driving [1]. Thanks to special pins DFRduino Motor Drive Shield can be straight connected to Arduino Uno board which is responsible for the movement of the vehicle. The structure of complete system is shown in Fig. 4.

TABLE I. USED COMPONENTS

No.	Name	Quantity
1	Arduino Uno R3	1
2	DFrobot Motor Shield 2x1A	1
3	QTR-1A infra red reflectance sensor	6
4	Motor PM-02-DS 6V/180RPM	2
5	Wheels 65x26mm	2
6	Battery 1100mAh 4.1Wh Li-Polymer 3.7V 5.0x37.5x59.0mm	2

B. Arduino board

The Arduino Uno R3 is a microcontroller board based on the ATmega328. It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz ceramic resonator, a USB connection, a power jack, an ICSP header, and a reset button. It contains 32 KB Flash Memory of which 0.5 KB used by bootloader, 2 KB SRAM, 1 KB EEPROM. Moreover, it has 10 bits A/C converter, which allows 1024 resolution (quantization steps). Thus, it contains everything needed to support the microcontroller. It can be simply connect to a computer with a USB cable or power it with a AC-to-DC adapter or battery to get started [2]. Arduino has its own open-source programming language basing on C/C++. The compilation of a program, prepared on computer PC, is done using Arduino IDE and implemented on the Arduino board. The board is shown in Fig. 2.

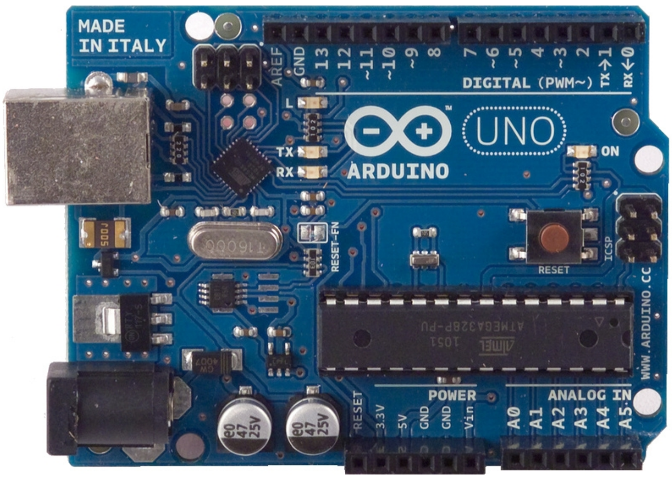

Fig. 2. The Arduino Uno R3 board.

C. Sensors

The QTR-1A infrared reflectance sensors are applied. They require an analog input to take readings. The sensor carries a single infrared LED and phototransistor pair. The phototransistor is connected to a pull-up resistor to form a voltage divider that produces an analog voltage output between 0 V and VIN (which is typically 5 V) as a function of the reflected IR. Lower output voltage is an indication of greater reflection [3]. The sensor is shown in Fig. 3.

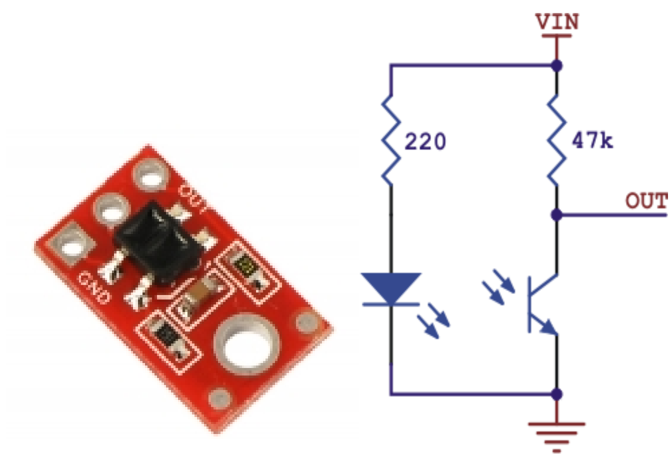

Fig. 3. The infra red reflectance sensor

D. Motors and wheels

The motor PM-02-DS is adapted to the vehicle. Motor attains 180 rpm without load when 6V is applied. The current without load is about 71 mA and short circuit current 470 mA at 6 V. It allows a torque 1.92 kg·cm. The kit with motor contains also gear 1:120.

E. Power supply

The construction of autonomous line-follower needs the power supply to move. The Arduino Uno board has a USB port, thanks to which possible is connection with computer. By USB is given 5V and it is not enough to properly movement of the vehicle. Because line-follower is autonomous vehicle, it needs external power supply. On the base of the line-follower are installed two batteries LP503759 1100 mAh Li-Polymer made by polish company called Batimex. Each of them gives the power supply of 3.7 V. They are connected in series, thus it gives 7.4 V, which is enough to smooth movement.

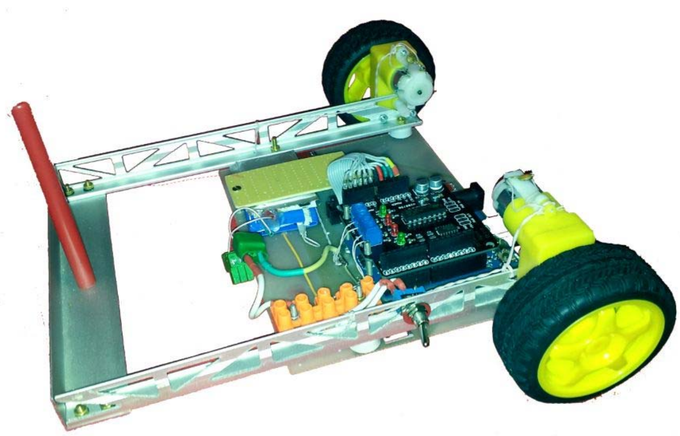

Fig. 4. The structure of complete system.

F. Connections on the vehicle

The vehicle is built from aluminum parts which is the light base, on which are located all the electric components and wires. The main part of the vehicle is Arduino Uno R3 board with microcontroller ATmega328. It is placed on the front of the car between two front wheels and motors. To the Arduino Uno board by special pins is connected DFRduino Motor Drive Shield (motor shield is located on Arduino Uno) which allows the movement of the vehicle. To its connected are two motors and six infrared reflectance sensors. Sensors are located on the base. To properly operate, taken holes in the base where are located the reflectance parts of sensors. Batteries are placed near Arduino Uno board and they are connected by wires to the switch, which is located on the right side of the vehicle.

IV. THE ALGORITHM

The autonomous line-follower, as it was mentioned on the previous paragraphs, is built in not conventional way. The control of the vehicle is based on fuzzy logic algorithms. In order to implement the project are developed appropriate linguistic variables with given values, fuzzy sets and membership functions, appropriate rules and proposals that have been used in the process of aggregation [4]. The appropriate method of defuzzification was used [5].

A. Linguistic variables

The linguistic variables have been developed for proper control of the vehicle. The values of the bands were determined by measuring the voltage values that returns the appropriate sensor for a given position. A black, matte tape glued to a large sheet of white paper has created. They mark the route designated for the vehicle.

The sensors can be located in different positions with respect to the tape. In the case when they are located above the tape, the tension returned to the analog output module of Motor Shield is in the range [4.7 V, 5 V]. When the position of the sensors is close to the border of the tape, the voltage decreases. The voltage changes from the upper limit, ie [4,7 V, 5V] to about 4V when they are on the edge of the tape, but still above the tape. If the sensors are moving away further from the tape - that is, their position is on the edge of the tape, but already not above them, the value of the voltage reaches a value of approximately 3.3 V. If the sensors are completely out of tape, then the voltage decreases sharply to the values less than 3.3 V, depending on the level of ambient light, it may reach the minimum value, which is 0V.

To better illustrate these situations, Fig. 5 shows the all possible sensor position relative to the black belt and a white sheet of paper.

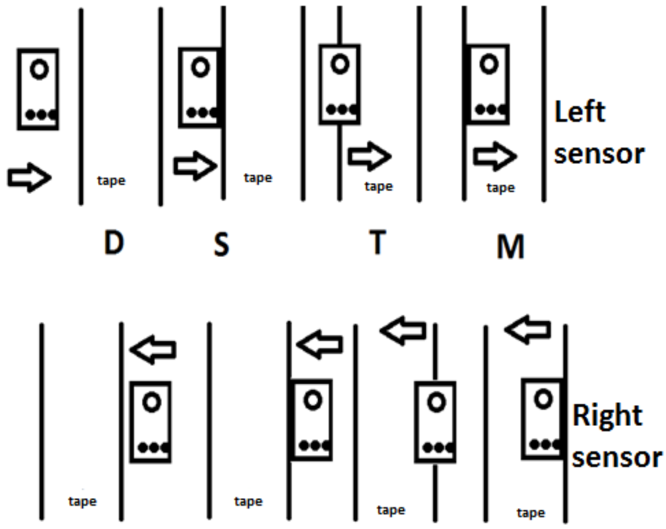

Fig. 5. Positions of sensors relative to the black tape

Linguistic variable, which is responsible for the value of reflection is called Reflection. The space of discourse for a Reflection takes the values in [0V, 5V], the whole input voltage range. It can take the following names (which are fuzzy sets): large (D), medium (S), little (T) and small (M). The way of generation of names for linguistic value Reflection is presented in Table 2.

TABLE II. VALUES OF LINGUISTIC VARIABLE REFLECTION

Name	Values	Shortcut
large	0V - 3.6V	D
medium	3V – 4.3V	S
little	3.6V – 4.85V	T
small	4.3V – 5V	M

Membership functions for each fuzzy set of the linguistic variable Reflection are shown in Fig. 6, where a = 0V, b = 3V, c = 3.6V, d = 4.3V, e = 4.85V and f = 5V.

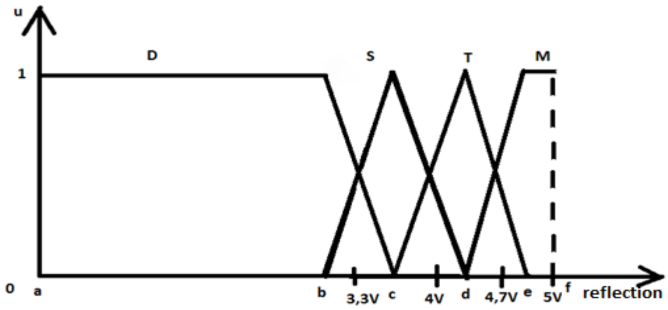

Fig. 6. Membership function of reflection

This linguistic variables concern each sensor, because when the calibration was carried out in the course of project execution, the same voltage values was obtained, depending on sensor location relative to the track. Therefore, each sensor is described by set of linguistic variables and the shapes of membership functions are the same for each sensor.

The second linguistic variable that has been designed to allow the vehicle was controlled using fuzzy logic is a variable Angle. It aims to define the angle movement of the vehicle, depending on its position relative to the path. Variable Angle determines the change in the angle drive and it is decision variable that is used in the defuzzification process.

TABLE III. VALUES OF LINGUISTIC VARIABLE ANGLE

Name	Values	Shortcut
left	[-90;-30]	L
slightly left	[-60;0]	LL
straight	[-30;30]	P
slightly right	[30;90]	P
right	[0,60]	LP

Because in the assembled vehicle the wheels are not torsional, driving angle is dependent on the speed of both wheels. That is to say if both wheels are spinning at the same speed, then the vehicle moves straight. If it has to turn right, then left wheel spins faster than the right. A similar situation occurs when turning left - right wheel rotates faster than the left. Space of linguistic variable Angle is [-90^o, 90^o]. Fuzzy sets of the variable Angle take the name: left, slightly left, right, slightly right and right. The rules generation of names of linguistic angle for a given angle drive in Table 3.

The shape of membership functions of fuzzy sets for particular linguistic variable Angle shows Fig. 7. The values are chosen in following way: k = -90, l = -60, m = -30, n = 0, 0 = 30, p = 60 and r = 90 (degrees).

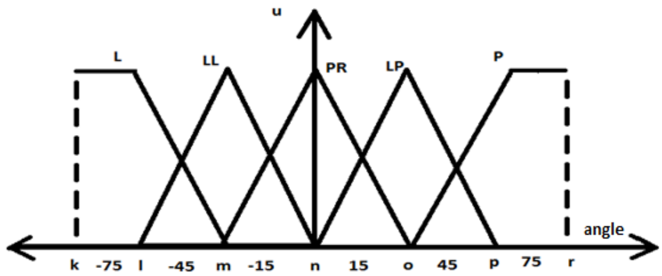

Fig. 7. Membership function of angle

B. Fuzzyfication

According to the definition, the fuzzification process involves the assignment of each not fuzzy point the degree of membership to a corresponding set or to fuzzy sets [6]. So this is a function that is different for each set and each interval specified in the established area (0V - 5V). Table IV shows the memberships (x-value of the voltage, u-membership value of reflection) - marking according to Fig. 6.

TABLE IV. FUZZYFICATION AND MEMBERSHIP FUNCTION OF REFLECTION

No.	reflection	
	Interval	Membership function
1	[a;b)	$u_1=1$
2	[b;c)	$u_2=(c-x)/(c-b)$ $u_3=(x-b)/(c-b)$
3	[c;d)	$u_4=(d-x)/(d-c)$ $u_5=(x-c)/(d-c)$
4	[d;e)	$u_6=(e-x)/(e-d)$ $u_7=(x-d)/(e-d)$
5	[e;f)	$u_8=1$

C. Rules and reasoning

After the selection and characterization of the relevant linguistic variables and fuzzy sets, in order to drive the vehicle, the appropriate rules must be created and approximate reasoning process be performed. The aggregation process is used to make all the rules [7].

R1: If A0 is D and A1 is not D and A2 is D and A3 is D and A4 is D and A5 is D then K is P

also

R2: If (A0 is S or A0 is T) and A1 is M and A2 is D and A3 is D and A4 is D and A5 is D then K is LP

also

R3: If A0 is not D and A1 is D and A2 is D and A3 is D and A4 is D and A5 is D then K is L

also

R4: If A0 is M and (A1 is S or A1 is T) and A2 is D and A3 is D and A4 is D and A5 is D then K is LL

also

R5: If A0 is M and A1 is M and A2 is D and A3 is D and A4 is D and A5 is D then K is PR

also

R6: If A0 is D and A1 is D and A2 is not D and A3 is D and A4 is not D and A5 is D then K is P

also

R7: If A0 is D and A1 is D and A2 is D and A3 is not D and A4 is D and A5 is not D then K is L

The word "also" denotes that rules are evaluated in parallel. The order of rules is not important. The project applies a popular Mamdani method for approximate deduction. This is called max-min method [8]. Depending on each rule, its weight is determined, and the decision (the set of angles). The weight of any rule is calculated as minimum of fuzzy memberships of the input values. Fig. 8 shows the procedure - values m_{c1} m_{c2}. The decision of the reasoning process is a fuzzy set, which consists of the sum (maximum) of two decisions (if two rules are active) - graph on the right in Fig. 8.

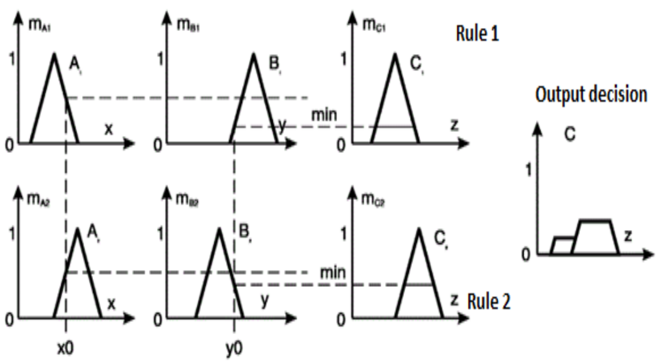

Fig. 8. Reasoning process

D. Deffuzification

The decision, which comes from the rules and reasoning process, is a fuzzy set or fuzzy sets. To get their representation in the crisp value (not fuzzy) the set of particular areas should be considered in defuzzification process. I the project is used a popular method, called high method, for defuzzification [9].

Crisp output value (i.e. angle) is determined using the following formula:

$$z_0 = \frac{\sum_{i=1}^{n} z_i \cdot \max_z \left[\mu_{C_i'}(z)\right]}{\sum_{i=1}^{n} \max_z \left[\mu_{C_i'}(z)\right]} = \frac{\sum_{i=1}^{n} z_i \cdot w_i}{\sum_{i=1}^{n} w_i} \quad (1)$$

where $\mu_{C_i'}(z)$ are membership functions – trapezoids cutting on the w_i level, z_i are the means of the upper basis of trapezoids (formed during a process of fuzzy deduction), and w_i are weight coming from the appropriate rules. The situation is illustrated in Fig. 9.

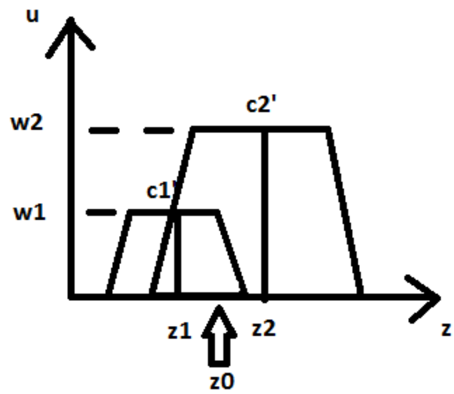

Fig. 9. Defuzzification process

E. Vehicle movement

Defuzzification process is used to obtain the crisp value of the angle of the vehicle. The value of the angle of drive depends on the speed of each wheel, because the wheels fitted in the structure are not torsional. Speed of rotation depends on the voltage, which is supplied to the engine in actual moment.

The value of the angle obtained after defuzzification must thus be converted into individual wheel speed. In course of the project, an experiment was conducted which allowed obtaining the appropriate relationship.

Each wheel during turning vehicle crosses a certain road. The difference between the paths on the total circulation allows the derivation of the following formula:

$$\frac{\Delta s}{2\pi r} = \frac{\alpha}{360} \quad (2)$$

where Δs is the difference of roads traveled by wheels, r is the distance between the wheels of a vehicle amounting to 22.2 cm, and α is a change in the angle of the vehicle.

Some measurements of velocity were performed. The results are shown in Fig. 10. The figure shows the distance traveled by wheel during one second depending on the voltage applied to the motor of vehicle. Obtained function is approximated by straight line. A mathematical formula was established.

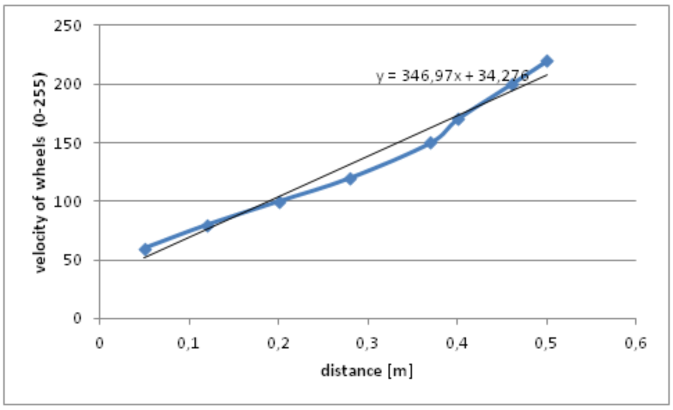

Fig. 10. Relation between velocity of wheels and distance

On the basis of the obtained formula and taking in consideration that rotation angle depends on the difference of the wheel speeds a following relation was given

$$V_r = \frac{\alpha \pi r}{180} \cdot 346.97 + 34.376 \qquad (3)$$

Because velocity between 0 and 50 set in program is not necessary (vehicle does not move), the final relation is:

$$V_r = 1.3437 \cdot \alpha \qquad (4)$$

The vehicle is controlled differentially, i.e. above differential speed depending on the angle is divided into two. One part of this value is added to the speed of one wheel and other part is subtracted from the speed of second wheel.

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