MODELING OF RESISTANT FORCES FOR AN INSPECTION MINI-ROBOT IN A TILTED LAND AND ON A CURVED MOTION

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Abstract: *In this paper there are presented two constructive aspects of a novel tracked mini caterpillar autonomous robot for patrol and inspection. There are analyzed the resistant forces that appear when the robot navigates on a tilt plane and also the resistant forces on each track when the robot is performing a curbed motion.*

Keywords*: autonomous robot, tracked vehicle, tilt plane, curbed motion.*

1. INTRODUCTION

We proposed to design a mini-robot mechanical structure with 4 wheels, 2 motor wheels and 2 passive wheels covered by two sets of caterpillars made by double toothed belt. The designed wheels are also toothed.

The minirobot is starting from a point in space considered to have the coordinates (0,0) and navigates towards a given set of point. The coordinates of this points are given by the user [1].

In his path, the minirobot can detect any values of temperature, gas/smoke concentration, luminosity and sound level that is exceeding the programed interval. In each case of these situations, the minirobot signals and transmit an alarm message to a command center through a Bluetooth wireless communication device [1].

The designed structural functional method for inspection in closed premises is presented in figure 2.

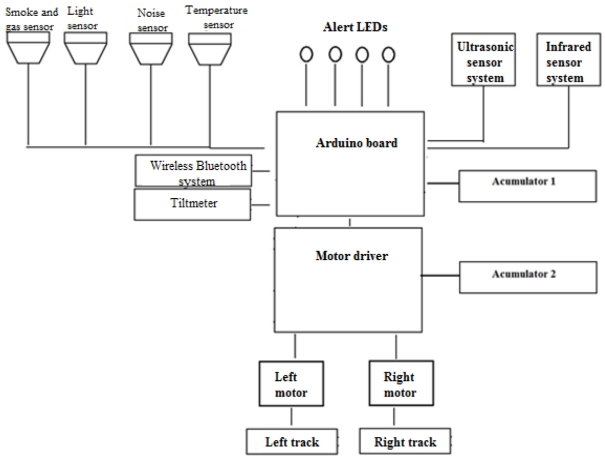

Figure 1. Structural conception of the minirobot

There were designed two sensor system for detecting the obstacles that can appear in the minirobot path:

- An ultrasonic sensorial system formed by 2 ultrasonic sensors that are using triangulation to determine the position and angle where an obstacle is place related to the minirobot;
- An infrared mobile platform where the infrared sensor is mounter on the platform and a stepper motor is angular rotating the platform.

These sensor systems are integrated together with a sensor fusion method (Fuzzy Logic) based on their tested characteristics [2].

The navigation method of the minirobot is a methodology based on potential field's algorithm. The input data in the algorithm are the minirobot position (obtained in real time due to odometry), the obstacles position and the target points. The output data are the actuators orientation and speed.

In order to design the command structure we need to choose the necessary characteristics of the motors.

For choosing the motors we made mechanical calculation in 2 cases. We analyzed the resistant forces that appear when the robot navigates on a tilt plane [3] and also the resistant forces on each track when the robot is performing a curbed motion.

2. RESISTANT FORCES ON A TILTED PLANE

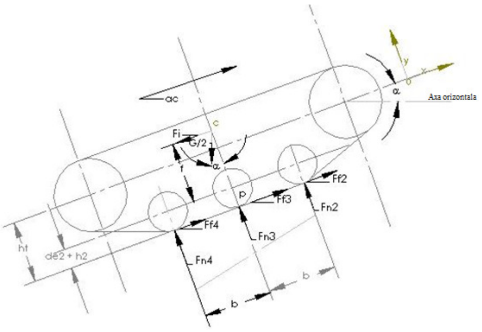

Figure 2. Global load in dynamic state

The parameters of the minirobot are:

- α = tilt angle;
- a_c = robot acceleration;
- C = center of gravity;
- F_{f2} , F_{f3} , F_{f4} = Friction forces correspondent to the 3 contact wheels with the soil;
- f = distance from the center of gravity to the contact wheels with the soil axis;

- F_{n2} , F_{n3} , F_{n4} = normal forces corresponding with the wheels 2,3,4 at contact with soil;
- F_i = inertial force with the application in center of gravity (c);
- $F_i = ma_c$;
- m = mass of the robot;
- v = moving speed.

We can write the equilibrium equations taken into account that there are two tracks [3].

$$2(F_{n2}+F_{n3}+F_{n4}) = G\cos\alpha \qquad -\mathit{on}\ X\ \mathit{axis} \quad (1)$$

$$2\left(F_{f2}+F_{f3}+F_{f4}\right) = G\sin\alpha + F_i \qquad -\mathit{on}\ Y\ \mathit{axis} \quad (2)$$

Related to the point P situated on the symmetry axis, we can write the equilibrium equations of the moments.

$$(F_i + G\sin\alpha)h_t = 2(F_{n4}b - F_{n2}b) \qquad (3)$$

The system formed by equations 1, 2 and 3 is indeterminate (number of unknowns is bigger that the number of equations) and from the mechanical point of view is a static undetermined system.

That is why we adopt the hypothesis [3]:

$$F_{n2} + F_{n4} = 2F_{n3} \qquad (4)$$

Considering a uniform increase of the normal forces.

Introducing (4) in (1) results:

$$6F_{n3} = G\cos\alpha \qquad (5)$$

So

$$F_{n3} = \frac{G\cos\alpha}{6} \qquad (6)$$

We consider $F_f = F_{f1} + F_{f2} + F_{f3}$ - equivalent with the necessary tracking force on one track for overcome the friction forces.

Relation 2 becomes:

$$2F_f = G\sin\alpha + F_i \qquad (7)$$

So $$F_f = \frac{G\sin\alpha + Fi}{2} \qquad (8)$$

$$F_i = ma_c \qquad (9)$$

And $$F_{i=}\frac{G}{g}a_c \qquad (10)$$

$$F_{f(\alpha,ac)} = \frac{G\sin\alpha + \frac{G}{g}a_c}{2} \qquad (11)$$

From relation 2 results:

$$F_{n4} - F_{n2} = \frac{(F_i + G\sin\alpha)}{2b}h_t = \frac{F_t h_t}{b} \qquad (12)$$

$$F_{n4} - F_{n2} = \frac{F_t(\alpha,a_c)h_t}{b} \qquad (13)$$

And together with relation 3:

$$F_{n4} - F_{n2} = 2F_{n3} \qquad (14)$$

By summing: $$2F_{n4} = 2F_{n3} + \frac{F_t(\alpha,a_c)h_t}{b} \qquad (15)$$

And also: $$F_{n4} = F_{n3} + \frac{F_t(\alpha,a_c)h_t}{2b} \qquad (16)$$

$$F_{n2} = 2Fn_3 - F_{n4} = 2Fn_3 - \ Fn_3 - \frac{F_t h_t}{2b} = F_{n3} \qquad (17)$$

$$\begin{cases} F_{n2} = F_{n3(\alpha)} - \dfrac{F_t ht}{2b} = F_{n3(\alpha)} - \dfrac{F_{t(\alpha,a_c)}h_t}{2b} \\ F_{n4} = F_{n3(\alpha)} + \dfrac{F_{t(\alpha,a_c)}h_t}{2b} \end{cases} \qquad (18)$$

G = 30N –weight of the robot

$$h_t = e + \frac{d_{e2}}{2} + \frac{h}{2} \qquad (19)$$

$$F_{n3} = \frac{G\cos\alpha}{6} \qquad (20)$$

From relation 19 results h_t=34.05

$$F_{f(a,ac)} = \frac{G\sin(\alpha) + \frac{G}{g}a_c}{2} = \frac{G}{2}(\sin\alpha + ga_c) \qquad (21)$$

$$F_{n2(\alpha,a_c)=}F_{n3} - Ff_{(\alpha,a_c)}\frac{h_t}{2b} \qquad (22)$$

$$F_{n4(\alpha,a_c)=}F_{n3} + Ff_{(\alpha,a_c)}\frac{h_t}{2b} \qquad (23)$$

The traction force T_4 necessary for the movement of the robot considering the parameters α and a_c is:

$$T4_{(\alpha,a_c)} = F_{f(\alpha,a_c)} = \frac{G}{2}(\sin\alpha + \frac{a_c}{g}) \qquad (24)$$

Taking into account the equation 24 we made simulation for various values of tilt angle of the path (α) and accelerations (a_c).The results are presented in table 1.

Table 1. Necessary traction force depending on the angle of the path and the imposed acceleration of the minirobot

Tilt angle of the path (α)	Imposed acceleration of the minirobot (a_c)	Necessary traction force (T_4)
10^0	0.2 m/s^2	2.1 N
10^0	0.3 m/s^2	2.4 N
10^0	0.4 m/s^2	3.1 N
20^0	0.2 m/s^2	3.9 N
20^0	0.3 m/s^2	4.1 N
20^0	0.4 m/s^2	4.4 N
30^0	0.2 m/s^2	5.5 N
30^0	0.3 m/s^2	5.9 N
30^0	0.4 m/s^2	6.1 N

3. RESISTANT FORCES ON A CURBED MOTION

The forces that act over the robot when performing a curbed motion are presented in figure 2.

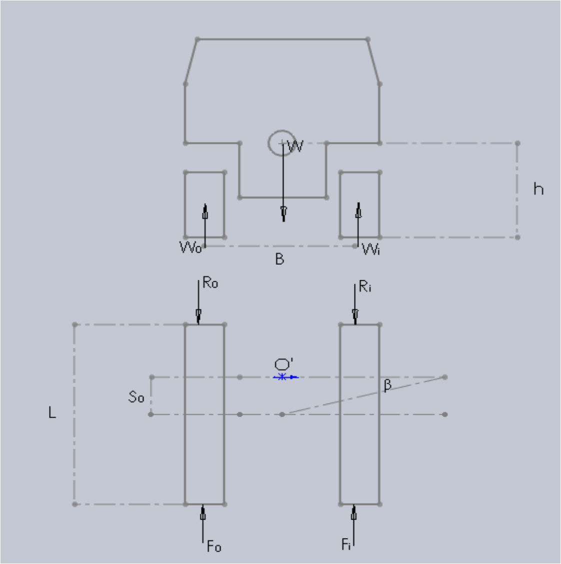

Figure. 3
The forces that act on a vehicle during a curbed motion

Considering the Wong equations [4], the inner and outer tracks forces can be calculated through the equations:

$$F_o = R_o + CF_{long} + \frac{M_r}{B} \qquad (25)$$

$$F_i = R_i + CF_{long} - \frac{M_r}{B} \qquad (26)$$

Where the parameters are:
R_o,R_i are the resistant forces of a longitudinal motion;
CF_{long} - the longitudinal component of the centrifugal force;
M_r - the resistant moment on a curbed motion;
B - the distance between the tracks.

To satisfy the equilibrium conditions in the lateral direction, the IRC must be at an s_0 distance through the central line of the soil contact area of the tracks (AC from figure 2) [4].

S_0 is calculated with the next equation

$$s_0 = \frac{lV^2}{2\mu_t g R'} cos\beta = \frac{la_y}{2\mu_t g} cos\beta \qquad (27)$$

where:
l is the track length;
V - the longitudinal speed of the vehicle;
a_y -the centrifugal acceleration of the vehicle (V^2/R');
R' - the curbed motion radius;
μ_t - the lateral resisting coefficient.

Taking into account that R' is larger than l, so that B is very small and we can consider cos (β) = 0

Therefore equation 27 is becoming:

$$s_0 = \frac{la_y}{2\mu_t g} \qquad (28)$$

Because of the displacement of the instantaneous rotation center (s_0), the resistive moment (M_r) has two components [4]:

- the lateral resisting moment related to 0';
- the centrifugal moment related to 0'.

So the longitudinal movement resistances for the inner and outer track will be [4]:

$$R_o = (\frac{W}{2} + \frac{hWa_y}{Bg})\mu_r \qquad (29)$$

$$R_i = (\frac{W}{2} - \frac{hWa_y}{Bg})\mu_r \qquad (30)$$

And results [4]: (31)

$$F_o = \left(\frac{W}{2} + \frac{hWa_y}{Bg}\right)\mu_r + \frac{Wa_y s_0}{2gR\prime} + \frac{\mu_t Wl}{4}(1 - \left(\frac{a_y}{g\mu_t}\right)^2)$$

$$F_i = \left(\frac{W}{2} - \frac{hWa_y}{Bg}\right)\mu_r + \frac{Wa_y s_0}{2gR\prime} - \frac{\mu_t Wl}{4}(1 - \left(\frac{a_y}{g\mu_t}\right)^2)$$

(32)

The parameters for our designed minirobot are:

W= 30 N (weigh of the minirobot);
h=0.03 m (high of the center of mass);
a_y=0.03 m/s^2 (centrifugal acceleration);
B=0.22 m (distance between the tracks);
g=9.80 m/s^2 (gravity acceleration);
u_r=0.23; (coefficient for resisting longitudinal movement)
u_t=0.72 (coefficient for resisting lateral movement);
l=0.17 m (length of the tracks);
v=0.25 m/s (movement speed of the minirobot).

Taking into account the equations 31 and 32 we made a simulation introducing the designed minirobot constructive data, for finding the inner and outer forces depending on various values of curbed motion radius and cubed motion angle .The results are presented in table 2.

Table 2. Inner and outer tracks depending on the curbed motion radius and curbed motion angle

Curbed motion radius	Curbed motion angle	Inner track force (F_i)	Outer track force (F_0)
0.40 m	25^0	1.1 N	2.8 N
0.40 m	35^0	1.3 N	2.9 N
0.40 m	45^0	1.5 N	3.1 N
0.30 m	25^0	1.4 N	3 N
0.30 m	35^0	1.6 N	3.2 N
0.30 m	45^0	1.8 N	3.4 N
0.20 m	25^0	1.4 N	3.1 N
0.20 m	35^0	1.7 N	3.4 N
0.20 m	45^0	2 N	3.7 N

4. CONCLUSIONS

In this paper, we presented the designed minirobot for inspection of closed premises, we presented two dynamics methods for calculating the necessary forces of the tracks in in two different scenarios, climbing a slope and performing a curbed motion.

We personalized the equations with the constructive data from our minirobot and we obtain final equations personalized for this case.

Furthermore, we made simulations for determining the necessary traction force depending on various values of tilt angle of the path (α) and accelerations (a_c) and also for finding the inner and outer forces depending on various values of curbed motion radius and cubed motion angle.

This performed simulations helps us to choose the necessary motors for controlling the minirobot.

For choosing the motors, we considered the difficult case scenario in every case: a tilt angle of the path of 30^0 with an acceleration of 0.4 m/s^2 and a curbed motion radius of 0.20 m with a curbed motion angle of 45^0. The forces for climbing a slope with 30 degrees an acceleration of 0.4 m/s^2 has been determined that it is bigger than the one necessary for performing a curbed motion at 45^0 degrees with a curbed motion radius of 0.20 m so further it was calculated the moment of the determined force and used for choosing the motors as a minimum necessary moment of the actuator.

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