A GENETIC ALGORITHM FOR TORQUE OPTIMIZATION OF AUTONOMOUS VEHICLES IN HIGH INCLINED TERRAINS

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Abstract— In this paper, a strategy based on genetic algorithms for mechanical torque optimization is implemented. The work is based on an electric 4WD (four-wheel drive) vehicle. This configuration is interesting as it can be generalized for mobile robots, off-road vehicles or even electrical wheelchairs. A multi-objective criterion is used. In usual applications, high velocities are desired to the trajectory accomplishment and, simultaneously, a stable movement have to be executed, even in terrains with high inclinations. Hence, to guarantee the stability in high inclined plans is the main challenge in this work. The fitness function here used consists in evaluate torques for a simplified dynamic model, while electrical, geometrical and mechanical vehicle characteristics are restricted. The results show interesting information about the systems behaviour, as the maximum inclinations that the vehicle can rise and the possible torques that can be executed to accomplish a trajectory in a maximum velocity. Simulations of a theoretical model and experimental tests developed in a mobile robot assure the results.

Keywords— Genetic algorithms, torque optimization, stability analysis, mobile robots.

Resumo— Neste paper, uma estratégia baseada em algoritmos genéticos para otimização de torque é implementada. O trabalho é baseado em um veículo elétrico com tração independente em quatro rodas. Esta configuração é interessante, visto que pode ser generalizada para robôs móveis, veículos off-road ou mesmo cadeiras de rodas elétricas. Um critério de decisão multiobjetivo é utilizado. Em aplicações comuns, deseja-se combinar elevadas velocidades para se cumprir a trajetória com a execução de movimentos estáveis, e isso mesmo em terrenos com elevadas inclinações. Portanto, garantir a estabilidade em planos inclinados consiste no maior desafio deste trabalho. A função objetivo aqui utilizada consiste em avaliar os torques para um modelo dinâmico simplificado, enquanto características elétricas, geométricas e mecânicas do veículo são restringidas. Os resultados mostram informações interessantes acerca do comportamento do sistema, como a inclinação máxima que o veículo é capaz de subir e os possíveis torques a serem executados para se estabelecer determinada trajetória em máxima velocidade. Simulações a partir de um modelo teórico e testes experimentais realizados em um robô móvel asseguram esses resultados.

Palavras-chave— Algoritmos genéticos, otimização de torque, análise de estabilidade, robôs móveis.

1 Introduction

Several are the developments related to autonomous vehicles during the last decades. Transport, mining, inspection, handling in dangerous tasks or even humanitarian tasks are some attributions of these machines (Simeón and Dacre-Wright, 1993; Tarokh et al., 1999; Caltabiano et al., 2004; Hamid et al., 2016; Stückler et al., 2016). Therefore, diverse challenges arose in electrical, computational and mechanical fields. In this work, the problem of mechanical stability is investigated.

When dealing with mobile-wheeled robots, the stability problem is usually linked to terrain or vehicle characteristics. A movement in sandy soil, for instance, is unstable if the vehicle can not control its velocity or orientation. Similar problem occurs if the robot is in high velocity and fall over when the vehicle loses its control capability (Iagnemma and Dubowsky, 2004).

Even initial researches in this area were related to spatial exploration, that still demands innovative solutions for the stability problem (Owaki and Ishiguro, 2017), actually the development of techniques for analysis and control of stability is making headway in new areas, as in civil construction (Vähä et al., 2013). However, sources of mechanical instability are innumerous and the methodologies to face these problems might be specially addressed. Here, the stability problem is related to the control of dragster and sliding effects. These effects are related to the robot equilibrium and are intensified in two cases: in terrains with high inclinations or when the vehicle is submitted to very high accelerations. If both conditions are satisfied, a criterion to optimize the vehicle behavior must be stablished.

The stability problem is not an exclusivity of mobile robots. Commercial cars also face this problem in specific cases. Fig. 1 shows an off-road vehicle climbing a ramp. According to Papadopoulos (2000) theory, the equilibrium can be obtained if the resultant force (R) projection does not intercept the plan defined by the contact points of the four wheels in the soil. This force is resultant of the vehicle weight, that acts in vertical direction, and the vehicle accelerations in the terrain direction.

By observing Fig. 1 (a), the resultant is inside the described plan. In this case, the vehicle develops a stable movement. Fig. 1 (b) shows a movement on which the front wheels of the vehicle starts to lose contact with the terrain. If this instability is not controlled, the vehicle will enter in the Fig. 1 (c) posture. In this case, normal forces between the front wheels and the soil are inexistent.

The example shown in Fig. 1 is interesting, as it is possible to observe that interaction wheel-terrain is an important, even often neglected, aspect in robot system modelling. Two are the principal problems when dealing with the wheel-terrain interaction: the terrain roughness and the terrain inclination. A different approach can be used to solve each problem.

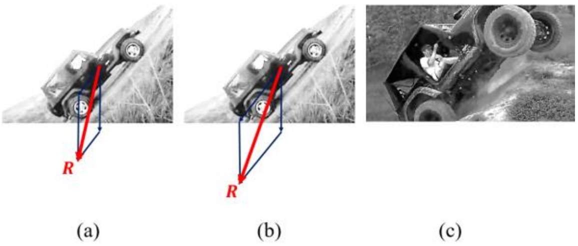

Figure 1. (a) stable movement, (b) unstable movement, (c) lose of normal force in frontal wheels

Silva et al. (2008) considered to solve the 2D mechanical problem in an algebraic way. The authors developed an online technique to control the torque in robots with four actuated wheels. This approach is very useful to avoid instability in vehicles if there is a previous knowledge of the terrain characteristics.

However, according to Le et al. (1997), it would be useful to find a solution that does not depends of previous knowledge of terrain characteristics. Moreover, it would be interesting to develop a strategy that can be adaptable to diverse vehicle configurations, as vehicles with six or more wheels. Finally, a strategy that permits the vehicle control even in an instable condition.

By considering a terrain with no previously known geometrical characteristics and a vehicle with n pairs of wheels equipped with and Inertial Measurement Unit, the development of an intelligent system can be useful. Garg and Kumar (2002) adopted a genetic algorithm to minimize the torque in robotic manipulators. Here, the objective is to optimize the torque to accomplish a desired trajectory in a minimal time and in stable conditions.

2 Dynamical Model

The fundamental basis of this work is to optimize the dynamical equations that describes the movement of a vehicle – a mobile robot – in inclined plans. As stated, the goal is the obtaining of high vehicle velocities but with controlled accelerations. These accelerations can not permit the system instability. Terrain and vehicle characteristics are restrictions for the problem.

Usually, algebraic formulations are sufficient approaches to the problematic here faced, as done by Silva et al. (2004). However, genetic algorithms can be used as an alternative to solve the equations, if an online programming is not required. The first step to model the dynamics of a vehicle is to distinguish correctly the problem's parameters. The terrain dependent properties, *i.e.*, geometrical and physical characteristics, can be previously gave by the user or the vehicle sensors. The vehicle kinematics varies and it have to be set according to the terrain characteristics. The vehicle geometrical and inertial properties, however, are constants: chassis and wheels as considered one rigid body, as the mass and the inertial parameters are concentrated in the vehicle center of mass. The terrain is considered rigid and without roughness. These simplifications are done for initial tests and analysis.

By considering a two-dimensional model of a vehicle with 4 wheels in a ramp, as shown in Fig. 2, it is possible to study initial system requirements. Generalized coordinates x, y and α are used to describe the movements in two reference systems. Fig. 2 also displays the distribution of the robot weight (W) between two wheels. The reactions in the contact points A and B are, respectively, F_{n_A} and F_{n_B}. These normal forces, when multiplied by a friction coefficient (μ), originate frictions forces F_{f_A} and F_{f_B}. The absence of roughs implies in a movement with friction forces parallel to the robot chassis. The constant inclination does not permit the development of centripetal accelerations.

The equilibrium conditions are set by Eq. (1) and (2). These conditions originates Eq. (3), (4) and (5). As it is possible to observe, there are three equations and four unknown variables: F_{f_A} F_{f_B}, F_{N_A} and F_{N_B}. It means that an infinite set of solutions can be obtained. However, to avoid the dragster effect, a condition can be used as a restriction: the normal forces must be higher than zero to guarantee the contact with the terrain. Moreover, according to Silva et al. (2004), the relations presented in Eq. (6) and (7) must be preserved to avoid the sliding effect. The parameter μ denotes a maximum limit for the friction coefficient while a movement is being executed. If the relations of forces are higher than this value, the wheels start to slid, resulting in instability.

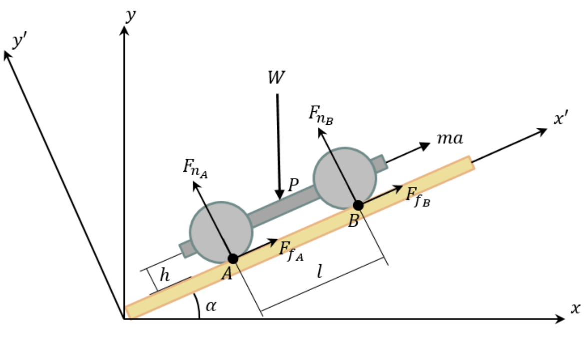

Figure 2. Simplified mechanical model

$$\Sigma F_x = ma_x \tag{1}$$

$$\Sigma F_y = \Sigma M_z^P = 0 \tag{2}$$

$$\begin{cases} F_{f_A}\cos(\alpha) + F_{f_B}\cos(\alpha) - F_{N_A}\sin(\alpha) - \\ -F_{N_B}\sin(\alpha) - macos(\alpha) = 0 & (3) \\ F_{f_A}\sin(\alpha) + F_{f_B}\sin(\alpha) + F_{N_A}\cos(\alpha) + \\ +F_{N_B}\cos(\alpha) + ma\sin(\alpha) - W = 0 & (4) \\ \dfrac{F_{N_A} l\cos(\alpha)}{2} - F_{N_B}\left(1 - \dfrac{l\cos(\alpha)}{2}\right) - \\ -F_{f_A}h - F_{f_B}h = 0 & (5) \end{cases}$$

$$\frac{\left|F_{f_A}\right|}{F_{N_A}} \leq \mu \tag{6}$$

$$\frac{\left|F_{f_B}\right|}{F_{N_B}} \leq \mu \tag{7}$$

It is important to notice that the normal forces are not controllable. In fact, only the friction forces are controlled and the torque transmitted to the wheels is responsible for this. The normal forces are obtained also according to the torque values. Eq. (8) shows the relations between torque and friction forces, where r is the wheel radius.

$$\tau = F_f r \tag{8}$$

3 Optimization Process

The system of equations (3), (4) and (5) have infinite torque values as a solution. However, the optimization problem was not considered until now. In fact, the multiple possible solutions should be coupled in a proper manner, to optimize a specific problem variable.

If the movement is made with the vehicle starting from a stationary condition and above the ramp, a coefficient of static friction μ_s is adopted in the beginning of the movement. If the vehicle is already in movement, a coefficient of dynamical friction μ_d is adopted. The μ_s value is empirical and depends on the terrain. In addition, the static friction is always larger than the dynamical friction. It means that the torque in a movement beginning from a stationary condition is larger than the torque in a movement starting from a known velocity. This information is important, because the solutions for the equations depend directly from the type of movement being executed.

Moreover, by admitting that the robot is stationary in a high inclination plane, some angles make it impossible the beginning of a movement. In this case, the wheels can skid continuously and the vehicle stays in the same point or lose its control. As a solution for this problem, it is a practice in off-road competitions, for instance, to starts a movement with high velocities before the vehicle achieve a point with high inclination. In this case, the pilot uses its intuition and technic to accomplish an adequate trajectory. For an autonomous vehicle, the same strategy can be adopted.

Here, the movement is made with the vehicle beginning from a stationary condition. In this case, optimal values of friction and normal forces can be obtained from a genetic algorithm with a specific objective function, such as time or power consumption reduction. In this work, the objective function is to maximize the vehicle stability, according to Papadopoulos (2000) theory, and the initial vehicle acceleration, with a view to improve the velocity as faster as possible and minimize the time spent on the trajectory accomplishment.

According to Fig. 3, it is possible to measure an angle β that is result of the interaction between the robot weight and the instantaneous acceleration. If the acceleration is disproportionally high, the dragster effect shown in Fig. 1(c) occurs. However, if the acceleration is very low, the vehicle velocity does not increase appropriately and the time spent on the trajectory is defected. Thus, an interesting strategy is to maintain the angle β as higher as possible, near a constant and empirically determined value. The value ε, shown in Fig. 3, is denominated minimal stability margin. This methodology, adapted from Papadopoulos and Rey (1996) formulation, is used to guarantee that the vehicle do not fall over. Thus, it is a condition to maintain the robot safety. The angle β is obtained according to Fig. 4 and shown in Eq. (9). The value dw is presented in Eq. (10).

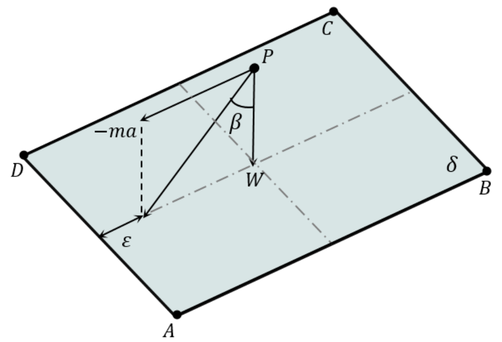

Figure 3. Vehicle stability diagram

$$\beta = atan\left(\frac{ma\cos(\alpha)}{W + dW}\right) \tag{9}$$

$$dW = ma\,cos(\alpha)\,tan(\alpha) \tag{10}$$

According to Eq. (9) and (10), the angle β depends directly of the vehicle acceleration. Thus, both β and a could be maximized as a function of only one variable. However, Eq. (9) permits values that promote the dragster effect in the vehicle. In fact, for higher inclinations, the minimal margin of stability can be overcame and the vehicle stability is negatively affected.

With a view to solve the unlimited values that β can assume, a maximum value of β can be specified. By using a similar scheme that the presented in Fig. 4 and considering the vehicle geometrical characteristics instead of the accelerations, Eq. (11) is found, where β_ε is the angle related to the minimal margin of stability. In this case, the condition of maximum acceleration can be coupled to the maximum stability, where the second one can be represented by the objective function shown in Eq. (12).

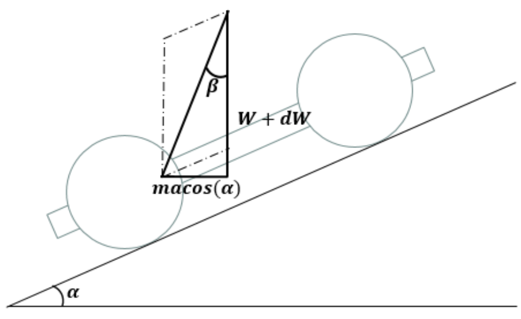

Figure 4. Obtaining of angle β

$$\beta_\varepsilon = atan\left(\frac{\left(\frac{l}{2} - \varepsilon\right)\cos(\alpha)}{h}\right) \qquad (11)$$

$$F1 = min(|\beta_\varepsilon - \beta|) \qquad (12)$$

4 Evolutionary Model

As stated, the present work is based in the solving of a multi-objective problem by means of genetic algorithms. The first objective function is to minimize the expression in Eq. (12). The angle β_ε is the value that β assumes in a distance ε from the stability margin, according to Fig. 3. The angle β is obtained as shown in Fig. 4. Both angles varies according to the terrain inclination angle, α. When the difference of these angles is minimized, the vehicle can execute a maximum acceleration that does not implies in instability. This maximum acceleration is obtained from the torques necessary to solve the dynamical model previously described, in Eq (3), (4) and (5).

The second objective function is inserted to guarantee the non-slippage condition, described in Eq. (6) and (7). In these equations, the only controllable variable is the force in the wheels. Thus, the objective here is to control the torques in order to maintain a stable movement. This objective cannot be considered a restriction because, for some angles, it is impossible to completely avoid the slippage, as it will be discussed hereafter. Mathematically, it can be represented in Eq. (13). The conditions of non-slippage can be used in a simple sum, as the values of normal forces, friction coefficients and torques are always positive.

$$F2 = min\left(\left|\frac{F_{f_A}}{F_{N_A}} - \mu\right| + \left|\frac{F_{f_B}}{F_{N_B}} - \mu\right|\right) \qquad (13)$$

The individuals used in the genetic algorithm are the torques generated in wheels A and B. In fact, both objectives can be expressed as a function of the torques and also the terrain inclination and friction coefficient. However, while the objectives of the problem are intrinsically mechanical, the main restrictions depends on the motor and its electrical characteristics. First, the maximum torques that the motors can provide to the wheels, that depends on the motors current. Second, the possible values of velocity that the vehicle can assume, that depends on the motors voltage. Finally, by considering that these parameters can instantaneously be overshot, a maximum power can also be set.

With a population size of 50 individuals and a minimal value of 400 generations, the algorithm converges. Elitism is used in a proportion of 5% of the population. The crossover fraction is made in 80% of the individuals and the Pareto fraction in 35% of them. The results, as the analysis of the technique here applied, are shown in the next section of this paper.

5 Simulations and Experimental Analysis

The simulations are based on the parameter values of the real robot shown in Fig. 5. These values are presented in Table 1. The inclination angle α is a variable of the system and diverse analysis can be executed with different α values. Another entry of the genetic algorithm is the terrain friction coefficient. The initial velocity and the time of simulation are related to the operation. The other parameters are intrinsically geometrical or electrical and are not adjustable.

Figure 5. Robot adopted in simulations

Table 1. Parameters used in the Simulations.

Variable	Parameters		
	Description	***Value***	***Unit***
α	Inclination angle	*Var*	°
t	Time of simulation	*2*	*s*
v_o	Initial velocity	*0*	*m/s*
μ	Friction coefficient	*0.5*	-
r	Wheel radius	*0.07*	*m*
l	Length between axis	*0.19*	*m*
h	Robot height	*0.07*	*m*
m	Robot mass	*3.8*	*Kg*
P_{max}	Maximum power	*12*	*W*
E	Nominal voltage	*16*	*V*
I	Nominal current	*0.5*	*A*
I_{max}	Stall current	*5*	*A*
T_{max}	Maximum torque	*0.88*	*Nm*
v_{max}	Maximum linear velocity	*1,76*	*m/s*

Simulations were executed in MATLAB environment and using the Optimization Toolbox. The software uses a controlled elitist genetic algorithm, a variant of NSGA (Non-dominated Sorting Genetic Algorithm) II.

The first test was made for an inclination of 20° from the horizontal. The results related to the evolution can be observed in the Pareto front shown in Fig. 6. It is possible to observe that the objective 2 is reached and the objective 1, as expected, converges. The convergence occurs because the vehicle shown in Fig. 5 and used in the simulations is not capable to generate very high torques. Thus, it can not promote the dragster effect in 20° of inclination and the multiple-objective problem becomes a single optimization problem.

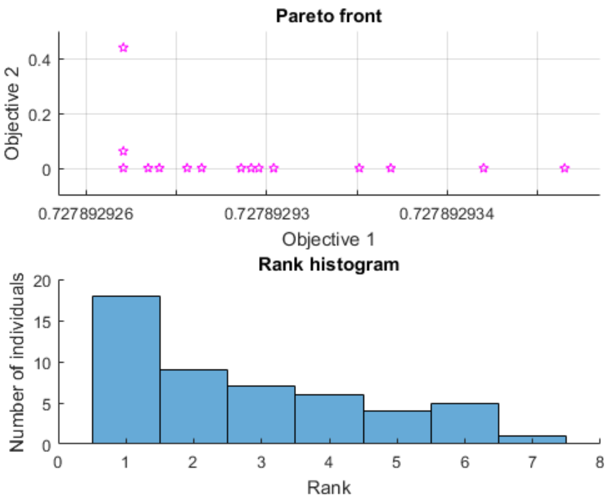

Figure 6. Performance of the optimization process

In this case, the optimal acceleration, according to the genetic algorithm result, is $1.76\ m/s^2$. In this condition, the necessary torque to be applied in wheels A and B are, respectively, $0.48\ Nm$ and $0.03\ Nm$. These values corresponds to an applied current of $2.75\ A$ in motor A and $0.18\ A$ in motor B. Also, with this acceleration, the vehicle velocity will present an ideal curve as denoted in Fig. 7.

It is also possible to notice that, in Fig. 7, the velocity does not reaches its maximum value. It happens because the maximum electrical power was limited to 12 W. Consequently, by considering a linear relation between wheel velocity and electrical tension, the maximum circuit voltage limits the maximum vehicle velocity.

As a conclusion, for an inclination of 20°, the vehicle can accomplish a stable trajectory and minimizing the time necessary to rise a ramp. However, if the vehicle can execute higher accelerations, it may lose the contact with the soil. In fact, the normal force in wheel B in the simulated case was really low, something about $0.8\ N$.

However, higher velocities can be reached if the torques are minimized or the maximum power is increased. In the first case, there is a risk of the robot do not accomplish the desired trajectory. In the second case, the motor should be monitored, to avoid permanent damages.

Another interesting result is that, with the genetic algorithm, it is possible to program the motors electrical voltages and currents for different initial conditions, also considering the inclined plan problem. As stated by Ridolfi et al. (2014), if an inertial measurement unit is used, it is possible to predict the system behavior. It is also possible to find a threshold for the vehicle inclinations, which can be useful in general tasks.

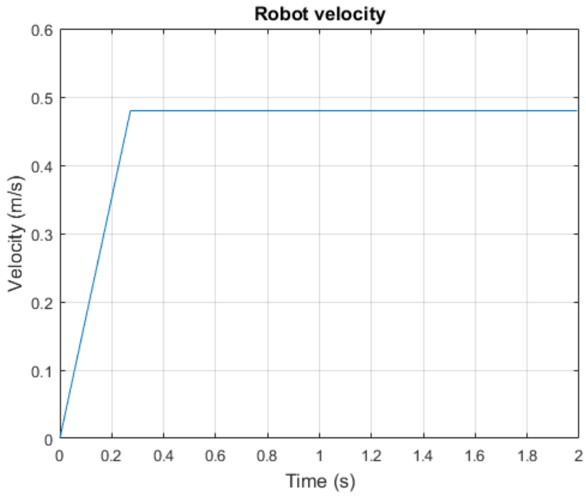

Figure 7. Velocity simulated curve: $\alpha = 20°$

By carrying out several analysis, it is possible to find a safe maximum inclination $\alpha = 38°$ for the simulated vehicle. For higher inclinations, normal forces in frontal wheels can disappear and the robot starts an unstable movement. In this case, the maximum velocity is lower than the previous one, as it is possible to observe in Fig. 8. The accelerations and electrical tensions also decreases, as it is necessary to develop higher torques, that reaches $0.68\ Nm$ in wheel A and $0.09\ Nm$ in B.

The genetic algorithm also give solutions for higher inclinations. However, these solutions should be carefully interpreted and well implemented. In fact, the maximum current gave in Table 1 cannot be exceeded, the absence of normal forces in frontal wheels can provoke loss of controllability and some values of acceleration generated by the algorithm can indicate that the inclinations turns the ramp impossible to be raised.

Experimental evaluations were executed with the mobile robot used in this work. A board of wood was used as ramp. Firstly, tests without the genetic algorithm results, *i.e.*, with maximum velocities and accelerations in the wheels, were performed. Later, some tests with the evolutionary model results were implemented.

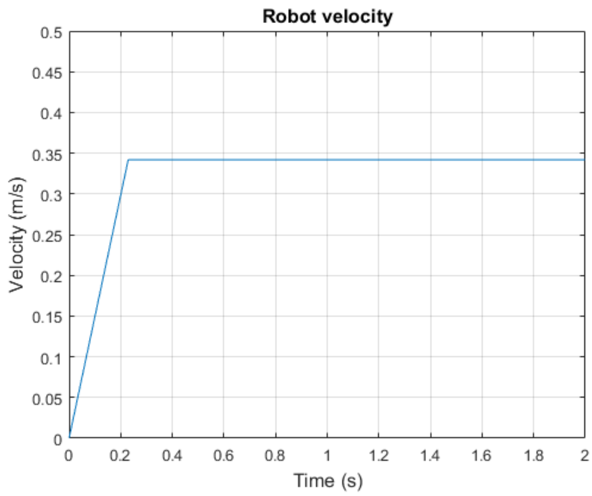

Figure 8. Velocity simulated curve: $\alpha = 38°$

For small angles, the results with and without the genetic algorithm are very similar. In fact, until 38°of inclination, stable movements were possible in all tests. Slow motion videos were used to verify the results and minimal differences were verified. However, for tests without genetic algorithm and in a ramp with 41° of inclination, the frontal wheels started to take off from the soil and a condition of instability was achieved. It does not happened in the tests with the genetic algorithm. Though, in both cases the programmed movements were accomplished.

For an inclination angle of 46°, the loss of contact became visual in the test without the genetic algorithm optimization, as it is possible to observe in Fig. 9. In this image, two subsequent frames were captured and is it possible to notice the difference in the contact with the ramp. In this case, the movement was not accomplished. Fig. 10 shows the initial and final positions of the robot in this case.

By using the same inclination, but with the results generated by the genetic algorithm, instability was also found. However, the set of velocities and accelerations permitted a better result. Fig. 11 shows the robot in three positions. The initial position is the same that the shown in Fig. 10. The intermediate position shows that the vehicle started to raise the ramp, as expected. However, the final position shows that the lack of stability let the robot without control.

It is important to observe that, even this last result is not ideal, it shows the potential of the genetic algorithms in this kind of application. As the technique cannot be used online, a set of inclinations can be generated and implemented in the vehicle software. Moreover, the use of an inertial measurement unit can contribute to the control of the wheels velocity and the vehicle trajectory, avoiding the unwanted situation shown in Fig. 11.

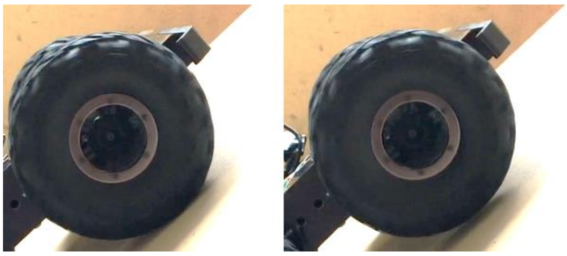

Figure 9. Loss of contact in test without use the genetic algorithm: $\alpha = 46°$

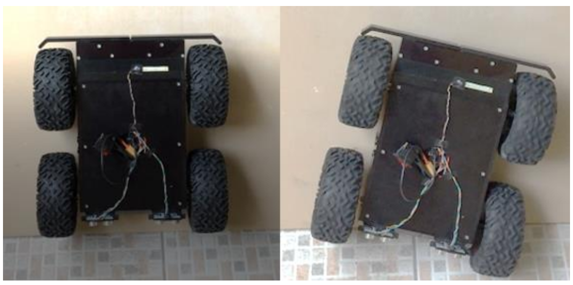

Figure 10. Initial and final position in test without genetic algorithms: $\alpha = 46°$

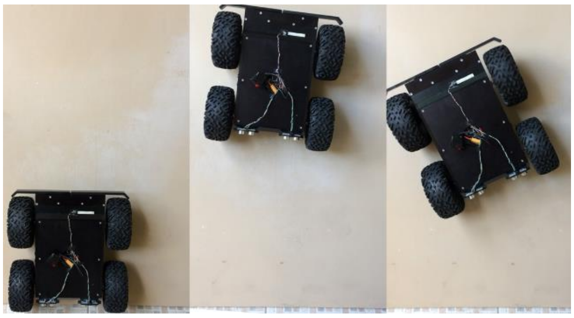

Figure 11. Initial, intermediary and final position in test with genetic algorithms: $\alpha = 46°$

Additionally, it is important to notice that the coefficient and parameters used in the simulations are approximations of the real parameters and coefficients. It means that a fine adjustment should be performed for different vehicle and situations. Additionally, a closed loop control should be performed, by using data from inertial sensors. Developments are also necessary in the mechanical model, such as to include the generated optimization process in tridimensional applications and in rough inclined terrains.

6 Conclusions

In this work, a genetic algorithm was used in the torque optimization of a 4WD vehicle in high inclined terrains. With two known variables, the terrain inclination and the friction coefficient, it was possible to verify the vehicle behavior in different situations and evaluate optimal task parameters. For this, a multi-objective strategy was used. The first objective was to maximize the vehicle accelerations and avoiding instability. The second objective was to do not permit that the robot loses its contact with the soil.

This work has interesting contributions. First, because it uses an intelligent technique in an operation that normally is applied with simplified and pure algebraic formulations. Traditional formulations are usually robust, but minimal changes in the conditions can provoke high modifications in the model. As the autonomous electrical vehicles and mobile robots are always interacting with different environments and in different situations, computational intelligence can be a way to simplify inherent problems.

Moreover, while the usual techniques need previous terrain characteristics to be simulated and implemented, the genetic algorithms demonstrated to be an interesting solution when the terrain inclination is unknown. In fact, they permit the knowledge of the maximum angles and velocities that the robot can rise only achieving data from specific sensors. They also can be used when the vehicle starts a trajectory from different initial conditions. The processing time is also reduced, as it is not necessary to make calculations during the programming execution, but only access data from a previously generated database.

However, as the method is not very robust, several improvements are necessary: a more detailed and complex mechanical model have to be applied, to assure a desired behavior in real world applications; a multiple sensor system can also be implemented, to provide better information for the control system and to guarantee a multitask autonomous vehicle operation.

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