Actor model approach to control stability of an articulated vehicle

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Abstract. The paper presents an application of actor model to control braking torques on wheels of an articulated vehicle in an untripped rollover manoeuvre. The numerical model of the articulated vehicle and dynamic optimisation have been used to calculate appropriate braking torques for each wheel in order to restore stability. The optimisation problem requires the equations of motion to be integrated at each optimisation step and its time-consuming. Therefore, parallel computing with using actor model system has been proposed. Actor model system has been implemented in genetic algorithm. In the paper, formulation of genetic algorithm with actor system and results obtained from dynamic optimisation have been presented and compared.

Keywords: actor model, genetic algorithm, parallel computing, dynamic optimisation, articulated vehicle

1 Introduction

The dynamic optimisation of sophisticated physical systems like multibody system, articulated vehicle is time-consuming task. Improvement of the optimisation calculation time is a subject of many papers [1, 2, 3]. Parallel and distributed systems are often used in order to improve the efficiency of calculations [1, 2, 4]. Some of the algorithms allow to split computational effort on separate threads, processes or cluster's nodes in a natural way. The approach used in order to formulate model of the system and implementation of the optimization process are not without significance. Currently, the development of computer hardware and software allow to release from the monolithic architecture to micro-services approach in which part of the business logic can be separately processed and those parts can communicate with each other [5]. These modifications allow to significantly reduce the time of calculation by parallel processing and provide high scalability of the system. One of the ways such implementation of the system and calculations is actor model approach [4, 6, 7]. The actor model for concurrent and parallel programming is gaining popular due to its high level of abstraction and its ability to make efficient use of multicore and multiprocessor machines. Implementing applications on top of those primitives has proven challenging and error-prone. Additionally, mutex-based implementations can cause queueing and unmindful access to (even distinct) data from separate threads in parallel can lead to false sharing: both

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decreasing performance significantly, up to the point that an application actually runs slower when adding more cores. The actor model describes calculation process as a result of interaction between active objects (actors). Actors interact with each other by asynchronous messages passing. Each actor can process the received message according to implemented behavior, forward a message to other actor or wait for a new message. It exists many actor model implementations like Akka, Akka.NET, CAF, Theron [8, 9]. Each one has embedded queue system and allows to implement well known architectonic (e.g. CQRS) and design patterns (e.g. chain of responsibility). Some of actor model systems can deployed in cloud systems like Amazon Web Services or Microsoft Azure.

In this paper genetic algorithm with actor model approach has been presented. During optimisation cornering manoeuvre of the articulated vehicle has been considered. The aim of the optimisation calculations is maintaining stability of vehicle and preventing before its rollover during manoeuvre. Rollover accidents of articulated vehicles are especially violent and cause greater damage and injury than other accidents. Many systems help in preventing vehicle rollovers, as they can automatically adjust the braking pattern for each wheel, possibly giving the driver greater control [3, 10, 11, 12]. Presented method is based on the control of braking torques in the case of losing the stability. Braking torques patterns, which have to be applied to each wheel of the vehicle, are obtained by solving an optimisation task.

2 Mathematical model

The model of the articulated vehicle was formulated as a system of rigid bodies contains of a tractor, a fifth wheel and a semi-trailer. It is assumed that the tractor is a rigid body, which motion has been described by means of six generalized coordinates (fig. 1) which can be written in the following form:

$$\tilde{\mathbf{q}}_T^{(1)} = [x^{(1)} \quad y^{(1)} \quad z^{(1)} \quad \psi^{(1)} \quad \theta^{(1)} \quad \varphi^{(1)}]^T \tag{1}$$

where: $x^{(1)}, y^{(1)}, z^{(1)}$ - translational components of the tractor,
$\psi^{(1)}$, $\theta^{(1)}, \varphi^{(1)}$ - rotational components of the tractor.

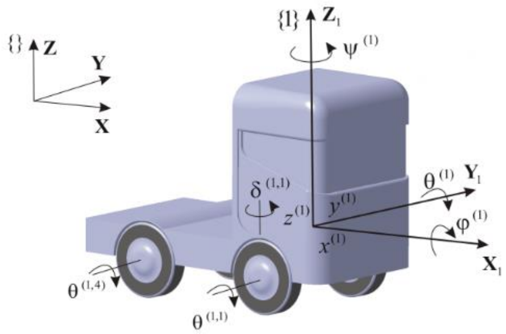


Fig. 1. The model of the articulated vehicle tractor

Wheels are connected with the tractor and each wheel has one degree of freedom $\theta^{(1,i)}, i = 1, \dots, 4$ and the generalized coordinates vector has the form:

$$\tilde{\mathbf{q}}_{TW}^{(1)} = [\theta^{(1,1)} \quad \theta^{(1,2)} \quad \theta^{(1,3)} \quad \theta^{(1,4)}]^T \tag{2}$$

It has been assumed that suspension stiffness has been reduced to contact point of a tire with a road. Therefore, vector of the generalized coordinates contains only front wheels steering angles $\delta^{(1,1)}$ and $\delta^{(1,2)}$:

$$\tilde{\mathbf{q}}_{TS}^{(1)} = [\delta^{(1,1)} \quad \delta^{(1,2)}]^T \tag{3}$$

Motion of the fifth wheel has been described by one degree of freedom (pitch angle $\theta^{(2)}$) in relation to the tractor (fig. 2).

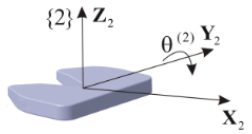


Fig. 2. The model of the articulated vehicle fifth wheel

Generalized coordinate of the fifth wheel is the component of the following vector:

$$\tilde{\mathbf{q}}_{F}^{(2)} = \left[\theta^{(2)}\right] \tag{4}$$

Semi-trailer (fig. 3) has one degree of freedom, inclination angle $\psi^{(3)}$, with respect to the fifth wheel and its generalized coordinates vector are given by:

$$\tilde{\mathbf{q}}_{S}^{(3)} = \left[\psi^{(3)}\right] \tag{5}$$

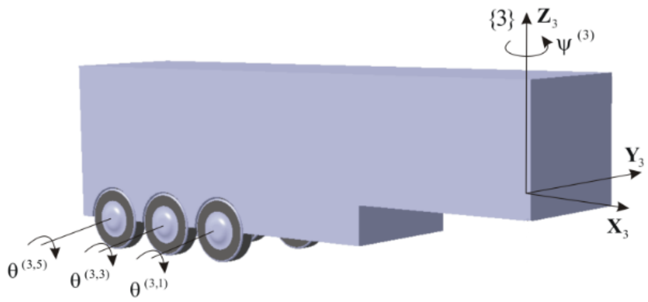


Fig. 3. The model of the articulated vehicle semi-trailer

The semi-trailer has six wheels (fig. 3) and each has one degree of freedom, $\theta^{(3,i)}, i = 1, \dots, 6$, which is component of the following vector generalized coordinates:

$$\tilde{\mathbf{q}}_{SW}^{(3)} = [\theta^{(3,1)} \quad \theta^{(3,2)} \quad \theta^{(3,3)} \quad \theta^{(3,4)} \quad \theta^{(3,5)} \quad \theta^{(3,6)}]^T \tag{6}$$

Equations of vehicle motion have been formulated using Lagrange equations of second kind and homogenous transformations [7]. It can be written in the following form [6, 13]:

$$\begin{aligned} \mathbf{A}\ddot{\mathbf{q}} + \mathbf{\Phi}_q \mathbf{r} &= \mathbf{f} \\ \mathbf{\Phi}_q^T \ddot{\mathbf{q}} &= \mathbf{w} \end{aligned} \tag{7}$$

where: $\mathbf{A} = \mathbf{A}(t, \mathbf{q})$ - mass matrix,

$\mathbf{f} = \mathbf{f}\left(t, \mathbf{q}, \dot{\mathbf{q}}, \mathbf{M}^{(1)}, \dots, \mathbf{M}^{(i)} \dots, \mathbf{M}^{(n_w)}\right)$ - vector of external, Coriolis and centrifugal forces,

$\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}}$ - displacement, velocity and acceleration vectors,

$\mathbf{M}^{(i)}$ - vector of discrete values of braking torques acting on the *i*-th wheel,

n_w - number of wheels,

$\mathbf{\Phi}_q$ - constraints matrix,

$\mathbf{r}$ - vector of constraint reactions,

$\mathbf{w}$ - vector of the right sides of the constraint equations.

The details of the procedure which leads to formation of equation (2) with a description of elements in the matrix $\mathbf{A}$ and the vector $\mathbf{f}$ is presented in [6].

3 Formulation of the articulated vehicle optimisation problem

Articulated vehicles rollover is one of the most dangerous road manoeuvres. This situation happens mostly during the unforeseen lane-change manoeuvre [5] whilst cornering of the vehicle. Such manoeuvre has been performed when the preplanned vehicle trajectory would collide with an obstacle. When the obstacle is detected, the trajectory is translated to other traffic lane, as shown in fig. 4, in order to avoid collisions with the obstacle.

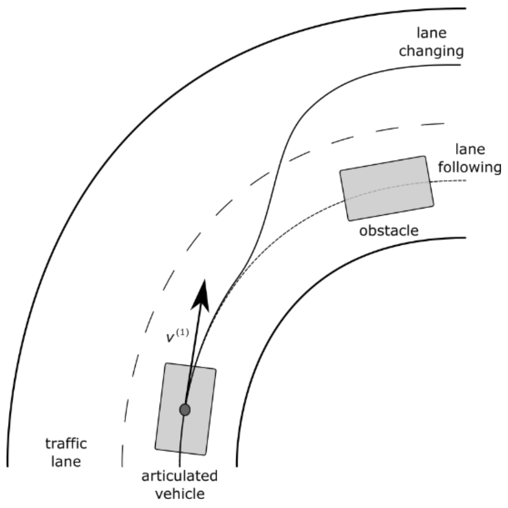


Fig. 4. Lane changing and lane following manoeuvre during cornering

Stability of the articulated vehicle can be restored by an appropriate control of braking torques applied to each wheel of the vehicle. Let us consider a vector of braking torque discrete values $\mathbf{M}^{(i)}$ of the *i*-th wheel. A continuous function $M^{(i)}(t)$ will be obtained using spline functions of the 3rd order. The vector of the decisive variables contains discrete values of the braking torques of wheels and can be written in the form:

$$\mathbf{M} = [\mathbf{M}^{(1)} \quad \dots \quad \mathbf{M}^{(i)} \quad \dots \quad \mathbf{M}^{(n_w)}]^T = \left(M_j\right)_{j=1,\dots,m} \tag{8}$$

where m – number of decisive variables.

$\mathbf{M}^{(i)} = \left(M_k^{(i)}\right)_{k=1,\dots,n}$,

n – number of discrete values of the braking moment.

In the presented problem, braking torques calculated for fixed initial vehicle velocity and the front wheels' steering angle have to fulfil the following conditions:

- the articulated vehicle cannot lose stability during the manoeuvre,
- longitudinal velocity loss has to be as small as possible,
- lateral displacement of the vehicle is limited by the standard road width.

Above assumptions are taken into account in the objective function and also in optimisation constraints. The stability conditions can be assured by minimizing the functional [8]:

$$\Omega(\mathbf{M}, \mathbf{q}, \dot{\mathbf{q}}) = \frac{1}{t_e}\left(C_1 \int_0^{t_e} \left(\varphi^{(1)}\right)^2 dt + C_2 \int_0^{t_e} (v_0 - v_e)^2 dt\right) \rightarrow \min \tag{9}$$

where: C_1, C_2 - empirical coefficients,

t_e - time of simulation,

v_0 - initial velocity,

$v_e = \sqrt{\left(\dot{x}^{(1)}(t_e)\right)^2 + \left(\dot{y}^{(1)}(t_e)\right)^2}$ - total final velocity of the tractor.

In the considered optimisation problem, inequality constraints can be written as follows:

$$[M_{min} - M_1 \quad \dots \quad M_{min} - M_i \quad \dots \quad M_{min} - M_m]^T \leq \mathbf{0} \tag{10}$$

$$[M_1 - M_{max} \quad \dots \quad M_i - M_{max} \quad \dots \quad M_m - M_{max}]^T \leq \mathbf{0} \tag{11}$$

where: M_{min}, M_{max} - acceptable minimal and maximal braking torque values.

The classical genetic algorithm and genetic algorithm with actor model approach method have been applied in order to solve formulated minimization problem [8, 9]. In the next paragraph genetic algorithm with actor model approach method will be presented in detail.

4 Actor model approach in genetic algorithm

Actors are objects which encapsulate state, behaviour and they can communicate exclusively by exchanging messages which are placed into the recipient's mailbox (fig. 5).

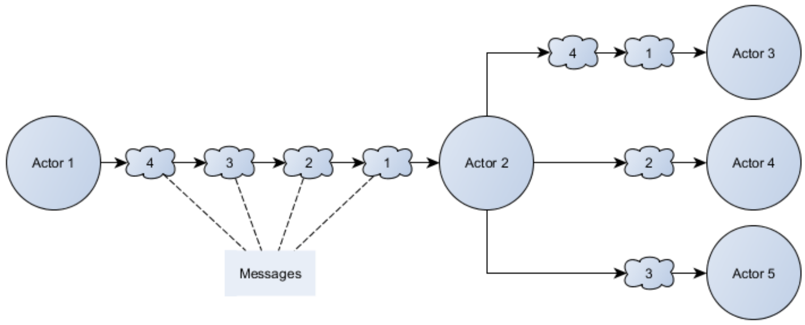


Fig. 5. Messages exchanging in actor model system

One actor can split up its tasks and delegate until they become small enough to be handled in one piece in order to build fault-tolerant, hierarchical system. Each actor can be treated as separate thread on one computer or it can be a process on machine in cluster of distributed systems. Such approach is therefore suitable for designing and development of a parallel and distributed information systems. Actor model basis on event-driven system in which actors process events and generate responses or more requests in asynchronous way and message passing is network transparent.

In this paper CAF framework has been applied in order to implement genetic algorithm with actor model approach. CAF allows to transparently connect actors running on different machines and operating systems via the network. It integrates multiple computing devices such as multi-core CPUs, GPGPUs, and even embedded hardware. In presented approach first actor (system) creates next actor (generation) which is responsible for managing genetic algorithm generations (fig. 6a). This actor produces many coworkers (crossover operators) which perform next operation in non-blocking and asynchronous way. Number of those child actors depends on number of individuals in population. When crossover operation is finished each actor produces new actor which is responsible for mutation operation. Individuals obtained from mutation are forwarded to actors which evaluate objective function value. This operation is time consuming because it is necessary to integrate dynamic equation of motion of the system. The main advantage of such approach is that the calculation of the objective function can be performed in parallel and non-blocking manner. The next actor waits until calculation of the objective function will be finished by all actors. It collects results and creates new parent's population according to natural selection rule. These steps are repeated until stop condition is not satisfied. Messages which are sent during one step of presented approach are shown in fig. 6b.

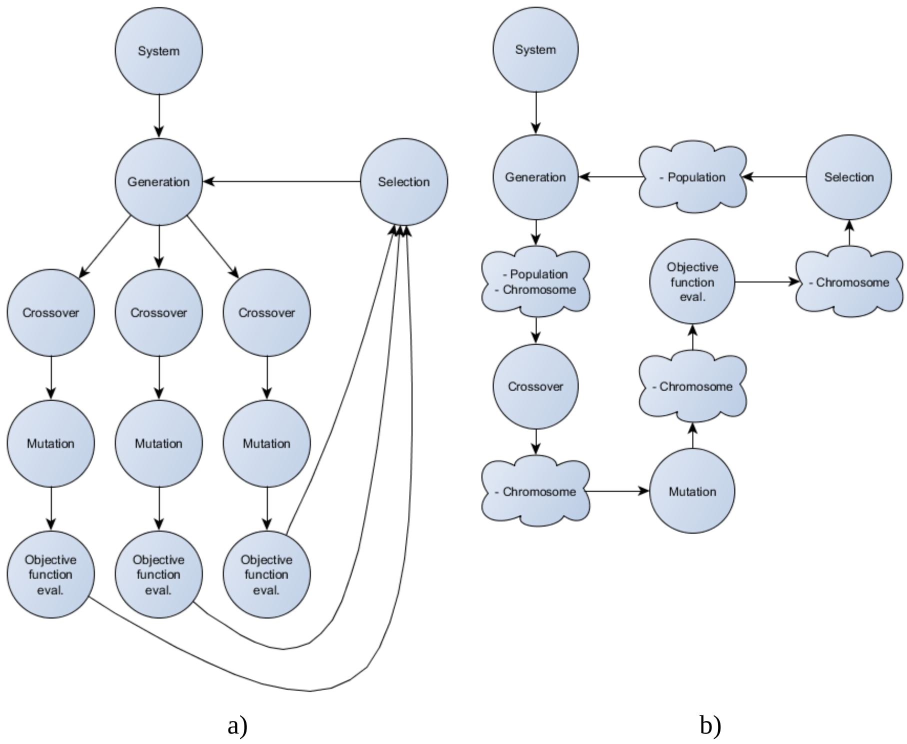


Fig. 6. Actors (a) and message flow between actors (b) in genetic algorithm

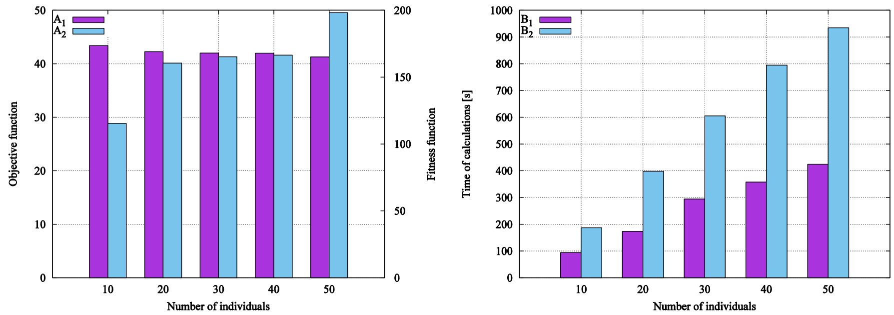
It is assumed real-number representation of genes in chromosomes and the following genetic operators have been used [14]: hybrid selection consists of natural selection combined with elitist selection, arithmetical one-point crossover, in which a new chromosome is a linear combination of two vectors and non-uniform mutation.

It can be concluded that application of actor model frameworks offers many facilities which provide abstraction layer for low-level operations such as: queuing messages, multithreading calculations, synchronization mechanisms and location transparency.

5 Numerical simulations

During simulations optimal braking torques have been calculated using classical genetic algorithm and its modification using actor model approach. It has been analysed lane change manoeuvre whilst cornering of the articulated vehicle. When the appropriate braking torques are not applied the rollover of the vehicle occurs. Additionally, when only the articulated vehicle cornering manoeuvre is considered the truck is stable. Lane change manoeuvre start at $t = 3\ [s]$ of simulation and in the same time additional braking torques have been applied. This torques are acted till the end of the simulation ($t_e = 6\ [s]$). It has been assumed that vehicle initial velocity $v_0 = 45\ [km/h]$. Physical parameters of the articulated vehicle have been taken from [3]. Interpolation of the braking torque has been performed for $m = 7$ interpolation nodes which are decisive variables in considered problem. Bulrish-Stoer-Deuflhard [15] method with adaptive step size has been used for integration equations of motion. Computing has been performed on Intel Core i5 2,6 GHz and 8 GB LPDDR3 1600 MHz RAM computer with OS X El Capitan.

Objective and fitness function values obtained for various number of individuals in the population (actors) using genetic algorithm with actor model approach have been presented in fig. 7a. Differences between time of optimisation calculations obtained for classical genetic algorithm and its modification with actor model can be seen in fig. 7b.



a) b)

Fig. 7. Values of the objective (A_1) and fitness (A_2) function obtained for various number of individuals (a), values of the optimisation calculations time (b) obtained for various number of individuals with actor model system (B_1) and with classical genetic algorithm approach (B_2)

As shown in fig. 7 differences between objective function or fitness function for various number of individuals are small. For further calculations it has been assumed thirty individuals in the population. Such number of individuals seems to be a good compromise between time and accuracy of calculations. When comparing the times of the calculation obtained for both analysed methods it can be noticed that optimisation time is significantly shorter in the case of a model actor approach regardless of the number of individuals in the population. Fig. 8a shows steering angle course of the articulated vehicle front wheels applied during simulations. Results obtained for the population of 30 individuals from optimisation using analysed in the paper modification of genetic algorithm are presented in fig. 3b, c. It shows courses of tractor roll angle and its trajectory. Figures present also results of simulations for lane following (cornering) manoeuvre (1) and those with the lane change manoeuvre before optimisation (2) and after optimisation (3). Courses of the optimal braking torques acting on the wheels $w_1, \ldots, w_6$ are shown in fig. 8d.

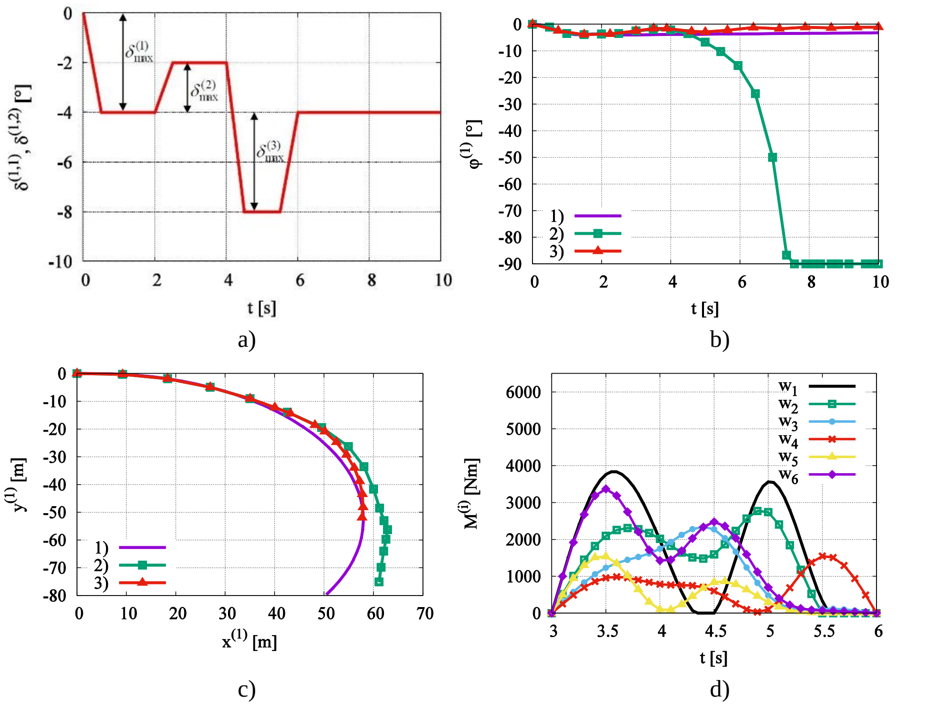


Fig. 8. Courses of: steering angle (a), the tractor roll angle (b), the tractor trajectory (c), optimal braking torques (d)

It can be seen that dynamic optimisation using actor model approach gives solution which allows articulated vehicle to maintain the stability during manoeuvre.

6 Conclusions

The articulated vehicle rollover is strongly associated with severe injury and fatalities in highway accidents. Stability can be achieved by an appropriate control of braking torques. In the paper, the problem of controlling brakes has been formulated as dynamic optimisation task. This task has been solved using classical genetic algorithm and its modification with using actor model approach. The long duration of the optimisation process results from the necessity of integrating equations of motion in each step. Actor model approach allows to reduce time of calculations by dividing computational effort into smaller tasks which are performed by single actor in asynchronous way. Results shows that time of calculations obtained for genetic algorithm with various number of individuals using actor model approach is averagely 50% shorter than the time obtained without this modification. It should be noted that the results have been obtained on a personal computer with a 4th core processor. According to the authors better results can be obtained on servers with larger number of cores or on computing cluster. Although the actor model approach is known since the 70s of the last century, but now it can be noticed that interest in this approach in application to modern business systems have been increased. This approach can be easily applied to scientific/numerical applications. In addition to the benefits mentioned previously, it can be obtained clear source code which is logically split into small atomic parts, well-designed object-oriented architectures and easy to maintain and extend.

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