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Vorwort

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Berichterstattung heißt hier Dokumentation des Transfers aktueller Ergebnisse aus mathematischer Forschungs- und Entwicklungsarbeit in industrielle Anwendungen und Softwareprodukte – und umgekehrt, denn Probleme der Praxis generieren neue interessante mathematische Fragestellungen.

Prof. Dr. Dieter Prätzel-Wolters
Institutsleiter

Kaiserslautern, im Juni 2001

The 1st Joint International Conference on Multibody System Dynamics
May 25–27, 2010, Lappeenranta, Finland

Real-Time Simulation of Multibody-Systems for On-Board Applications

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ABSTRACT

Simulation of multibody systems (mbs) is an inherent part in developing and design of complex mechanical systems. Moreover, simulation during operation gained in importance in the recent years, e.g. for HIL-, MIL- or monitoring applications. In this paper we discuss the numerical simulation of multibody systems on different platforms. The main section of this paper deals with the simulation of an established truck model [9] on different platforms, one microcontroller and two real-time processor boards. Additional to numerical C-code the latter platforms provide the possibility to build the model with a commercial mbs tool, which is also investigated. A survey of different ways of generating code and equations of mbs models is given and discussed concerning handling, possible limitations as well as performance.

The presented benchmarks are processed under terms of on-board real time applications. A further important restriction, caused by the real-time requirement, is a fixed integration step size. Whence, carefully chosen numerical integration algorithms are necessary, especially in the case of closed loops in the model. We investigate linearly-implicit time integration methods with fixed step size, so-called Rosenbrock methods, and compare them with respect to their accuracy and performance on the tested processors.

The paper gives an overview of significant characteristics to regard, like model type (DAE, ODE), choice of solver and attended time for simulation, when pursuing the intention of a mbs simulation on an on-board platform.

Keywords: multibody system simulation, real-time simulation, on-board simulation, Rosenbrock methods

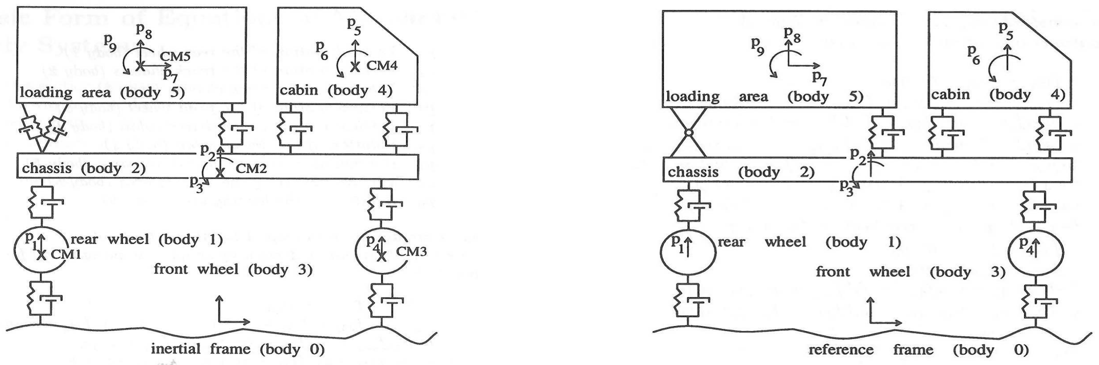
1 INTRODUCTION

The real-time simulation demand implicates limitations regarding step size, simulation time and therefore model complexity, choice of integration method and simulation platform. For most applications these dependencies are neither linear nor straightforward.

The result of one integration step is required in an *a priori* defined time interval to guarantee real-time, which claims for fixed integration step sizes [8, 13]. A further limitation regarding the choice of solver is given by the fact, that on-board platforms generally have a comparable weak performance and lower memory capacity than standard pcs.

For many practical applications the system is too stiff for efficient integration methods like the explicit Euler method, which often is favored for real-time applications. Then it is more suitable to consider them as constraint systems, which are described with so-called differential algebraic equations (DAE), and integrate them with adequate solver techniques. In this paper both approaches are pursued, integrating DAEs and ODEs (ordinary differential equations) with stable solver techniques with fixed step size (sect. 3).

Due to the fact that modelling as C-code is impractical for many industrial projects and to guarantee the application to more complex system like 3D models e.g., we additionally pursue the way of modelling mbs models with commercial software tools, exemplarily with SIMPACK [3] and SimMechanics [4] (4.2.2 and 4.2.3), and simulate them on on-board platforms.



(a) ODE (b) DAE

Figure 1. Truck model [9]

2 BENCHMARK TRUCK MODEL

A mbs model of a planar truck with 9 degrees of freedom, [9], is implemented for benchmarking purposes. The truck is excited by a vertical road profile. Between wheels and chassis are pneumatic springs, i.e., the model includes non-linear spring-characteristics.

The truck model was built in two versions: an unconstrained and a constrained one. In the former, the trailer is mounted to the chassis by three springs, two of them are replaced by a constraint for the second version, cf. Fig. 1.

The equations of motion of the unconstrained truck model are given as a nonlinear system of ordinary differential equations (ODE)

$$\begin{aligned} \dot{q} &= v \\ M\dot{v} &= f(t,q,v,u), \end{aligned} \tag{1}$$

where $q, v \in \mathbb{R}^9$ denote the positions and velocities respectively, and $u \in \mathbb{R}$ denotes the excitation vector, the vertical road profile in this case. The dot above a symbol denotes the derivative with respect to time t. f represents the vector of applied forces and the mass and inertia matrix M of the truck model is constant and diagonal.

The considered constrained truck model (in redundant coordinates) leads to a system of differential algebraic equations:

$$\begin{aligned} \dot{q} &= v \\ M\dot{v} &= f(t,q,v,u) - G(q)^T\lambda \\ 0 &= g(q), \end{aligned} \tag{2}$$

where the last algebraic equation describes the constraint on position level. The additional constraint-forces, $G(p)^T\lambda$ with $G(p) := \frac{\partial g}{\partial p}$, ensure, that the constraint is satisfied. In the present model g is a function $g : \mathbb{R}^9 \to \mathbb{R}^2$ and consequently $G(p) \in \mathbb{R}^{2\times 9}$ and $\lambda \in \mathbb{R}^2$. In [9] eqns. (1) and (2) are given more detailed.

3 INTEGRATION METHODS

In this section the integration schemes, which are used for the presented benchmarking analysis, are briefly sketched.

3.1 ODE Time Integration

An essential real-time requirement is, that the equations of motion are solved fast enough and in an a priori defined fixed time. This may lead to explicit integration schemes with a fixed step size. Indeed, in many application the simple one-step explicit Euler-scheme is used. However, many elements of a typical mbs, such as springs, bushings can lead to very stiff ODEs. But for those types of equation explicit integration schemes are not suitable, since they would require too small step sizes or completely fail. On the other hand, implicit methods that do not need such small step sizes are based on nonlinear equations and their numerical solution in an a priori defined time cannot be guaranteed. Therefore, they do not fit the real-time requirement either. A compromise, which avoids both the small step sizes and the nonlinear equations, are so-called Rosenbrock methods. They can be interpreted as an application of one Newton-iteration to the nonlinear equations that arise in an implicit Runge-Kutta scheme, see [11] for a detailed derivation of these methods. Adapted to the special structure of the equations of motion of a mbs, a general *s-stage Rosenbrock* method with fixed step size h applied to the ODE (1) is given by the formulas:

$$
\begin{aligned}
\left(\begin{pmatrix} \mathbb{1} & 0 \\ 0 & M \end{pmatrix} - h \cdot \gamma \cdot J_n\right)\begin{bmatrix} (k_q)_i \\ (k_v)_i \end{bmatrix} &= \begin{bmatrix} V_i \\ f(T_i, Q_i, V_i, u(T_i)) \end{bmatrix} + h \cdot J_n \sum_{j=1}^{i-1} \gamma_{ij} \begin{bmatrix} (k_q)_i \\ (k_v)_i \end{bmatrix} \\
&\quad + h^2 \cdot \sum_{j=1}^{i-1} \gamma_{ij} \begin{bmatrix} 0 \\ \frac{\partial f}{\partial u}\frac{\partial u}{\partial t} + \frac{\partial f}{\partial t} \end{bmatrix} \qquad , i = 1, .., s \\
Q_i = q_n + h \cdot \sum_{j=1}^{i-1} \alpha_{ij}(k_q)_j, \quad V_i &= v_n + h \cdot \sum_{j=1}^{i-1} \alpha_{ij}(k_v)_j, \quad T_i = t_n + h \cdot \sum_{j=1}^{i-1} \alpha_{ij}, \\
q_{n+1} &= q_n + h \cdot \sum_{i=1}^{s} b_i \cdot (k_q)_i, \\
v_{n+1} &= v_n + h \cdot \sum_{i=1}^{s} b_i \cdot (k_v)_i.
\end{aligned} \tag{3}
$$

The Jacobian matrix J_n has the structure

$$
J_n := \begin{pmatrix} 0 & \mathbb{1} \\ \frac{\partial f}{\partial q} & \frac{\partial f}{\partial v} \end{pmatrix}\Bigg|_{(q_n, v_n, u(t_n))} \tag{4}
$$

The method is uniquely determined by the coefficients $((\alpha_{ij}), (\gamma_{ij}), (b_i), \gamma)$. The crucial feature of these methods is, that for each stage only a linear equation has to be solved and this can be achieved within an a priori known time. Nevertheless, with suitable chosen coefficients, the methods provide stability properties as they are typical from fully implicit schemes, cf. [11, 5].

For our benchmarking purposes we apply two methods of this class to the ODE (1): the first one is the linearly-implicit Euler-method. This is a 1-stage method and its coefficients are given by:

$$
\gamma = 1, \qquad b_1 = 1. \tag{5}
$$

The method is of order $p = 1$ and $A - stable$.

The second method, we consider, is based on the $4 - stage\ GRK4T$-algorithm by Kaps and Rentrop [12], which has proven to be a good choice for stiff MBS. It is of order $p = 4$ and is $A(89.3°) - stable$.

3.2 DAE Time Integration

For the DAE-case, eq. (2), we restrict ourselves to the linearly-implicit Euler-method.

The DAE as it is given in eq. (2) with the constraint equation on position level is a DAE of index 3, whose numerical solution under real-time conditions is merely not to realize. Therefore, it is a commonly used approach to reduce the index at most by one by replacing the constraint equation by its first time-derivative,

$$
0 = \frac{d}{dt}g(q) = \frac{\partial g}{\partial q}(q)\dot{q} = G(q)v, \tag{6}
$$

the constraint on velocity level, yielding an index-2-DAE. However, this procedure brings up the well-known drift-off effect in the constraint, i.e., a violation of the constraint equation, [11]. This effect is of course more severe when using a low-order integration method such as the linearly-implicit Euler-method. To overcome this drawback two stabilization techniques are applied and compared.

We make one modification in the integration formulas: calculating the position coordinates explicitly by setting

$$k_q = v_n \Rightarrow q_{n+1} = q_n + hv_n. \tag{7}$$

Taking into account, that the constraint on velocity level has to be fulfilled in the new integration step, i.e.,

$$0 = G(q_{n+1})v_{n+1}, \tag{8}$$

the linearly-implicit Euler-scheme for the DAE-case is given by

$$\begin{aligned} q_{n+1} &= q_n + hv_n, \\ \begin{pmatrix} M - h\frac{\partial f}{\partial q} - h^2\frac{\partial f}{\partial v} & G(q_n)^T \\ G(q_{n+1}) & 0 \end{pmatrix} \begin{bmatrix} k_v \\ \lambda \end{bmatrix} &= \begin{bmatrix} f(q_n, v_n, u(t_n)) + h\frac{\partial f}{\partial q}v_n \\ -(1/h)G(q_{n+1})v_n \end{bmatrix}, \\ v_{n+1} &= v_n + hk_v. \end{aligned} \tag{9}$$

The first stabilization technique to avoid the drift-off effect is based on the Baumgarte-approach [6]: replacing the constraint on velocity level by a linear combination of the constraints on velocity and position level, i.e.,

$$0 = G(q_{n+1})v_{n+1} + \alpha g(q_{n+1}), \tag{10}$$

with $\alpha \approx 1/h$. The right-hand-side of eq. (9) has to be modified correspondingly.

The second stabilization technique can be interpreted as an application of the Gear-Gupta-Leimkuhler-formulation (GGL) [10]. In that approach the new position coordinate, q_{n+1}, is obtained by the solution of the equation

$$\begin{aligned} M\frac{q_{n+1} - q_n}{h} &= Mv_n - G^T(q_n)\eta \\ 0 &= g(q_{n+1}), \end{aligned} \tag{11}$$

with additional multipliers η. The numerical solution has to be calculated by an iterative algorithm. To guarantee real-time capability, the number of iterations must be fixed. For most calculations, one iteration step is sufficient. With the solution q_{n+1} the new velocities, v_{n+1}, are obtained by the solution of the linear system in (9) as before.

For a more detailed analysis of higher order integration methods and non-iterative stabilization-techniques for real-time purposes we refer to [5], see [7] for considerations concerning matters of stability.

3.3 Implementation

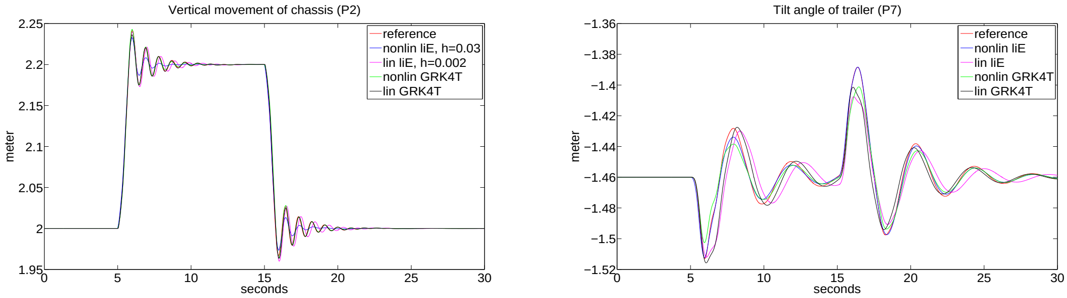
All tested integration methods have been handcoded in C. These solver routines have been incorporated into the platform dependent, generated code for the equations of motion of the truck model, which has required some involved modifications both on the solver side as well as on the MBS side, see sect. 4 for details.

For the Jacobian matrix J_n we have used a partitioned approximation: $\frac{\partial f}{\partial q}(q_0, v_0, u(t_0))$ has been computed once before integration in a preprocessing step, whereas $\frac{\partial f}{\partial v}$ as well as $\frac{\partial f}{\partial u}$ and $\frac{\partial f}{\partial q}k_q$ are calculated at each integration step by forward differences and the last one as directional derivative to reduce computation time.

To solve eq. (11) for the GGL-stabilization we have applied only one iteration step of a simple Newton-algorithm.

4 SIMULATION RESULTS

For all simulations the planar truck model has been exited by a bump excitation. The results are analyzed for a simulation time of 100s, in which the truck is excited by three bumps of the height of 0.2m. To make



(a) Vertical movement chassis

(b) Tilt angle trailer

Figure 2. Simulation results on microcontroller

a conclusion on the accuracy of a simulation result, the residuals

$$err_i = ref_i - q_i, i = 1, \dots, 9 \tag{12}$$

are compared. Thereby ref_i is the reference solution for the nine degrees of freedom of the truck model.

For comparing performance the actual time for one integration step t_{step} is listed, although in section 4.2 all simulations are made with step size $h = 0.001$s.

4.1 Real-time Simulation on Microcontroller

With its 150MHz CPU the TriBoard TC1796 (TriCore) is the platform with the lowest performance but also the cheapest one, which is used for the presented benchmark tests. Because of its 32-bit architecture the simulation was made only with single precision numbers to optimize the performance.

Results are presented for the integration of ODEs (1) of the unconstrained model (Fig. 1 (a)) and compared to a reference solution $ref_i, i = 1, \dots 9$, which is integrated with a variable step size solver (RADAU5) on a standard pc.

Because of the comparable small performance of microcontroller, the integration of a linearization of the truck model is examined in addition.

As expected, the integration time of the linearized formulation is much smaller than for the nonlinear case, one integration step of the nonlinear model takes about 10 times longer than one step of the linearized model. This leads to more accurate simulation results than for the nonlinear model compared to a reference solution. The maximal L^2-norm of the residuals is about ten times smaller for the integration result with the linearly-implicit Euler method, e.g. Attention should be paid to the fact, that these simulations had been made with an increment $h > t_{step}$ to achieve real-time. This leads to the result, that for this test scenario the linearized model integrated with the 1-stage linearly-implicit Euler method and $h = 0.002s$ is more accurate than integrated with the 4-stage GRK4T method and $h = 0.008s$. And both approaches are better than integrating the nonlinear model whith adequate increments (cf. Tab. 1).

Model		liE	grk4t
non-linear	t_{step} [s] $\max\limits_i \|err_i\|_{L^2}$ [m]	$2.39 \cdot 10^{-2}$ $1.04 \cdot 10^{-2}$	$3.14 \cdot 10^{-2}$ $7.99 \cdot 10^{-3}$
linearized	t_{step} [s] $\max\limits_i \|err_i\|_{L^2}$ [m]	$1.76 \cdot 10^{-3}$ $3.62 \cdot 10^{-3}$	$6.66 \cdot 10^{-3}$ $5.64 \cdot 10^{-3}$

Table 1. Simulation results for unconstrained truck model on MCU

The simulation results for the first 30 seconds are shown exemplary for the vertical displacement of the chassis and the tilt angle of the trailer in Fig. 2.

4.2 Real-Time Simulation on Rapid Prototyping Boards

The real-time platform with the most performance used for the presented benchmarking is the DS1006 processor board of the company DSPACE, which is based on a 3.0 GHz processor with 256 MB RAM. The second real-time processor board is the MicroAutoBox of DSPACE, which has a 800 MHz CPU and a main memory of 8 MB RAM. [1]

These platforms allow including element libraries of commercial mbs software tools. In sections 4.2.2 and 4.2.3 the simulation of mbs models built with SIMPACK and SimMechanics on the DS1006 is discussed. All simulation results presented in the following are made with the step size $h = 0.001$s.

4.2.1 Numerical C-Code

The constrained and unconstrained MBS model is implemented as numerical C-code for this approach. To run them on rapid prototyping boards one has to recompile them with the dSpace X-compiler. For many applications additional simulation elements are required, e.g. data preparation for measured data or further control elements. In this case, it is suitable to include the C-code for the model and solver as a C-Mex S-function into a MATLAB Simulink model. Afterwards, the executable code is generated by the Real-Time Workshop [2].

The main results for simulating the constrained and unconstrained truck model are presented in Tab. 2. Every application was real-time capable with $h = 0.001$s. The effective integration time needed for one linear-implicit Euler step does not differ that much from t_{step} of GRK4T (for the ODE case). But the maximal L^2-norm of the residuals is about four times higher for the linearly-implicit Euler integration than for the GRK4T results.

Model		**ODE**		**DAE**		
Solver		li Euler	GRK4T	li Euler		
				unstab	BG	GGL
t_{step} [s]	MABX	$5.24 \cdot 10^{-4}$	$6.40 \cdot 10^{-4}$	$4.45 \cdot 10^{-4}$	$4.45 \cdot 10^{-4}$	$4.47 \cdot 10^{-4}$
	DS1006	$0.90 \cdot 10^{-4}$	$1.08 \cdot 10^{-4}$	$0.75 \cdot 10^{-4}$	$0.75 \cdot 10^{-4}$	$0.76 \cdot 10^{-4}$
$\max\limits_i \lVert err_i \rVert_{L^2}$ [m]		$4.22 \cdot 10^{-5}$	$1.80 \cdot 10^{-5}$	$1.65 \cdot 10^{-3}$	$1.65 \cdot 10^{-3}$	$1.65 \cdot 10^{-3}$
$\max\limits_i \lvert g1_i \rvert$ [m]				$6.95 \cdot 10^{-5}$	$1.80 \cdot 10^{-8}$	$1.50 \cdot 10^{-15}$
$\max\limits_i \lvert g2_i \rvert$ [m]				$3.68 \cdot 10^{-5}$	$1.21 \cdot 10^{-8}$	$1.31 \cdot 10^{-15}$

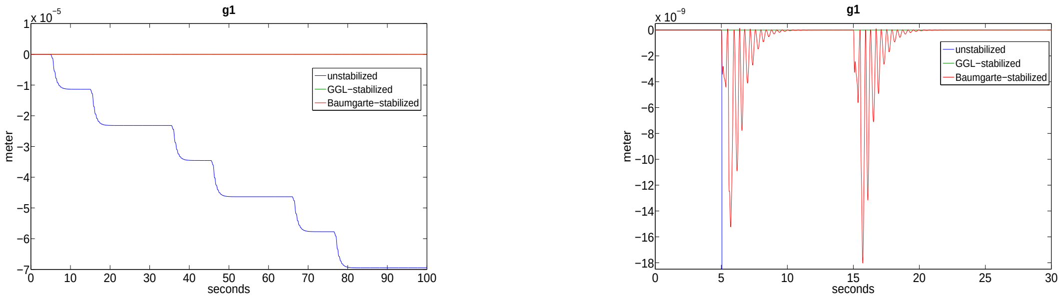
Table 2. Simulation results for truck model and solver techniques given as handcoded numerical C-code

In Tab. 2 also the maximal violations of the constraint terms $g(q)$ of (2) are compared. The unstabilized integration let the violation grow linearly with time (drift-off effect), cf. Fig. 3 (a). The maximal constraint violation for the Gear-Gupta-Leimkuhler stabilized integration is about factor 10^7 smaller than the Baumgarte stabilized simulation. Thus, for systems of this complexity the GGL stabilization is recommended. For more complex systems solving equations (11) might be to time consuming and the Baumgarte-approach is favorable.

4.2.2 SIMPACK Models

The commercial mbs program package SIMPACK generates equations of motion for dynamic systems for the ODE case as well as DAE case. Both forms of equations and adequate numerical integration methods are exportable for simulation outside of SIMPACK.

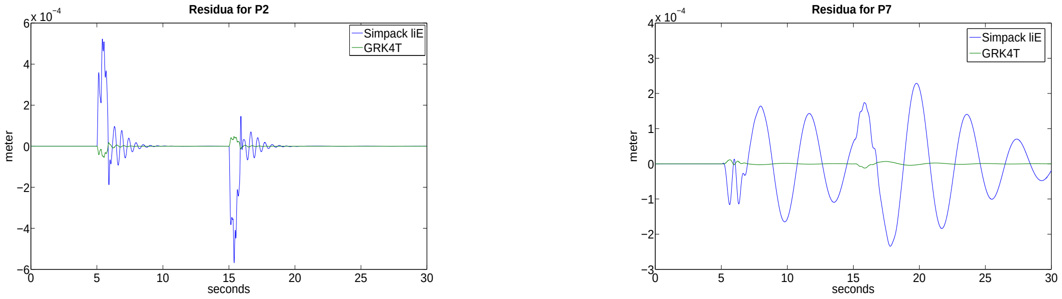
For including the SIMPACK model in MATLAB, the bi-directional interface S-function is used, which calls the right-hand-side of SIMPACK's equation of motion in the MATLAB Simulink environment [14]. For the ODE case one of MATLAB's integration methods can be used as well as the exported SIMPACK solver. After including the mbs model into Simulink, board specific real-time code is generated by the Real-Time Workshop, whereby SIMPACK's element library is linked and loaded onto the processor board.



(a)

(b) first 30 seconds, zoom

Figure 3. Horizontal constraint violation, g1



(a) Vertical movement chassis

(b) Tilt angle trailer

Figure 4. Residuals of simulating SIMPACK's ODE truck model with SIMPACK's linearly-implicit Euler method and handcoded GRK4T solver

Additional to using a SIMPACK or MATLAB solver for integrating the mbs model one can solve the equations of motion with an own integration technique. Therefore, the generated C-files of SIMPACK have to be extended and modified with the additional integration routine and recompiled. In table 3 the results of simulating the ODE truck model with SIMPACKs linearly-implicit Euler method and with a handcoded 4-stage GRK4T integration method are compared. As one can see, the required integration step time t_{step} for the simulation on the DS1006 processor board does not differ for these two applications, but again the result for the GRK4T integration is more accurate (cf Fig. 4). The reference solution for these applications is an ODE truck model simulated with SODASRT in SIMPACK.

	(spck) li Euler	GRK4T
t_{step} [s]	$2.63 \cdot 10^{-4}$	$2.99 \cdot 10^{-4}$
$\max_i \|\|err_i\|\|_{L^2}$ [m]	$4.30 \cdot 10^{-5}$	$0.41 \cdot 10^{-5}$

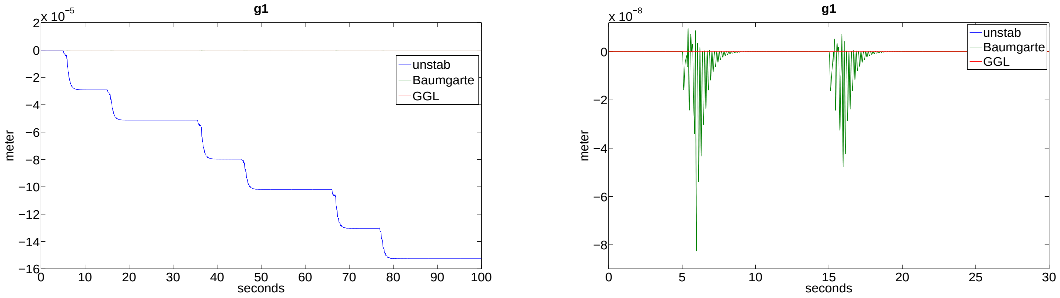
Table 3. Simulation of SIMPACK's ODE truck model on DS1006

Real-Time Simulation of SIMPACK DAE-Equations Since implicit DAE integration schemes, which are implemented in SIMPACK, are numerically very costly and time consuming and integrate with variable step sizes, they are not suitable for real-time applications. Therefore, the SIMPACK generated C-code has been extended with the handcoded routines for the linearly-implicit Euler method with Baumgarte and GGL stabilization techniques (see 3.2).

As it is shown in Tab. 4 this procedure is real-time capable when proposing to simulate with $h = 0.001$s. Again, the best constraint satisfaction is gained with the GGL stabilization technique (cf. also Fig. 6).

	liE		
	unstab	bg	ggl
t_{step} [s]	$7.14 \cdot 10^{-4}$	$7.97 \cdot 10^{-4}$	$8.00 \cdot 10^{-4}$
$\max\limits_i \lvert g1_i \rvert$	$1.5253 \cdot 10^{-4}$	$8.2610 \cdot 10^{-8}$	$3.8855 \cdot 10^{-12}$
$\max\limits_i \lvert g2_i \rvert$	$8.6976 \cdot 10^{-5}$	$3.1297 \cdot 10^{-8}$	$1.6564 \cdot 10^{-11}$

Table 4. Simulation of SIMPACK's DAE model with handcoded linearly-implicit Euler method on DS1006



(a)

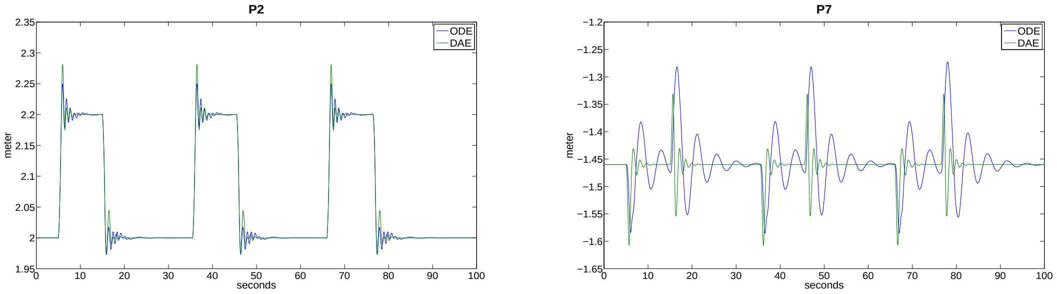
(b) first 30 seconds, zoom

Figure 5. Horizontal constraint violation, cf. Tab. 4

4.2.3 SimMechanics Models

SimMechanics is given as a MATLAB Toolbox and thus is simple to connect to other control or physical modeling elements of MATLAB. Furthermore, C-code can be generated as usual for all MATLAB models with the Real-Time Workshop. However, the mechanical element library is not as elaborate as in other MBS tools like SIMPACK, but can be extended with given MATLAB Simulink functionalities.

DAEs are simulated with the usual Simulink solver methods, which are extended by constraint-solving techniques, thus simulation with fixed step size is possible. The simulation on the DS1006 processor boards of the unconstraint truck model needs $2.13 \cdot 10^{-4}$s for one integrationstep and the constraint model $3.11 \cdot 10^{-4}$s when using the 2-stage Heun integration method.



(a) Vertical movement chassis

(b) Tilt angle trailer

Figure 6. Simulation of ODE and DAE truck model, modelled with SimMechanics, on DS1006

5 CONCLUSION

We have analyzed the possibilities and features of simulating a mbs benchmark model under real-time conditions with respect to three main criteria: modelling approach, onboard platform and integration method.

The considered truck model has been implemented by hand as C-code, in the commercial mbs tools SIMPACK and SimMechanics. The handcoded variant is naturally most flexible, among others concerning license issues. It is also the most elaborate one, but realistic only for systems of moderate size and complexity. Large and complex mbs models can only be handled effectively with an appropriate software package, which offers a navigation, element libraries, etc. A drawback of that approach in turn is, that one needs special (platform dependent) licenses to export and to solve the mbs.

Concerning the used simulation-platforms, the microcontroller is the cheapest and most mobile solution, but it requires a lot of work to implement and simulate the mbs on it and the specific configurations depend strongly on the used board, the programming language etc. In fact, only the C-code version of the mbs could be exported and simulated in a reasonable way on the microcontroller. Additionally, the microcontroller provides the lowest performance properties. Due to these limitations, the microcontroller is a suitable and cheap platform only for small systems, which can be implement by hand. If the system is of moderate or large size and complexity (including the nonlinear truck model) and has to be modelled in a mbs software tool, rapid prototyping boards are more favorable, they provide a much higher performance.

The usage of the integration scheme is a question of the required results. Of course, it is relatively easy to combine handwritten mbs systems with handwritten solver routines. We have seen, that besides the often used linearly-implicit Euler method higher order methods can be applied successfully. In the DAE case, which is very important regarding ’real-life’ mbs models, one has to add a stabilization technique. The GGL-method brings up the best result, but can be costly for larger systems, since additional equations have to be solved. This is avoided by the Baumgarte-approach, which leads to simulation results, which are still very good. As a last important aspect, we emphasize the demonstrated possibility to use own, specific, problem-oriented solver routines in combination with commercial mbs tools and rapid prototyping boards.

To summarize, this paper shows, that with each configuration at most one real-time solution is possible. To choose a specific configuration, one has to strike the balance between model complexity and size, simulation requirements and available hardware.

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