Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

NLR-TP-98417

Efficient harmonisation of simulation competence in a CACE working environment

Its use in the development of a generic vehicle behaviour federate

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Abstract

NLR is developing a generic behaviour model for the simulation of a large class of (space) vehicles, based on multi-body dynamics theory and following object-oriented principles. Special attention is given to the vehicle-terrain interface, which concerns the simulation of the contact and release events and the simulation of the constrained motion during the contact phase. NLR's working environment ISMuS supports the development of the generic vehicle behaviour model by supplying simulation competence such as: application knowledge, model repositories, simulation tools, and model development tools in a user-friendly way. The use of ISMuS allows for more efficient development of the generic vehicle behaviour model, since previously gathered know-how and know-why on modelling, simulation, and control of constrained robotic systems is contained in the working environment for use by the developers of the generic vehicle behaviour federate.

1. Introduction

Simulation of real-world systems for engineering or training purposes usually requires mathematical models of several simulated entities. Within the SIMULTAAN project (Ref. 9) a distributed training simulator is made. SIMULTAAN deals with co-operating federates (i.e., simulators). One such a federate is the vehicle federate. For this vehicle federate NLR develops the Behaviour Model Component. The Behaviour Model Component simulates the behaviour of a large class of wheeled vehicles. The Behaviour Model Component consists of three models: the Behaviour Model, the Control Model, and the Terrain Model (see Figure 1).

One of the important aspects of vehicle simulators is terrain-interaction simulation, i.e. simulation of maintained contact and contact transitions. Examples of important dynamical phenomena related to contact transitions are:

- the occurrence of large vertical accelerations after a transition from non-contact to contact;
- the influence of contact transition on the dynamical behaviour during steering manoeuvres;
- skidding of a vehicle due to a slippery terrain.

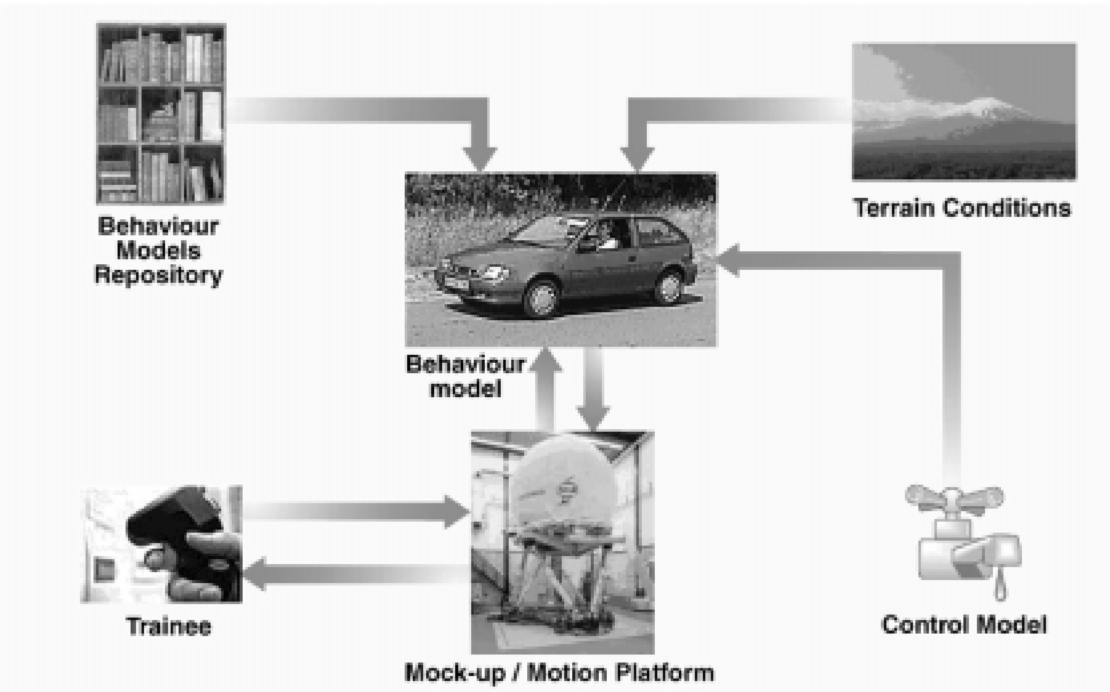

Figure 1: Overview of the Behaviour Model Component in the SIMULTAAN project

The Behaviour Model Component runs in the general-purpose simulation tool EuroSim, which is available in the CACE working environment ISMuS. The Behaviour Model Component can be deployed for various kinds of vehicle simulators, such as planetary rovers, caterpillar tracked vehicles, trucks, and tractors.

In the development of the Behaviour Model Component NLR’s working environment ISMuS plays a central role, which is described in the present paper. In this paper, the emphasis will be on the use of ISMuS by engineers in the development of vehicle models, control model, and terrain. From a management point of view, ISMuS contributes to the harmonisation of simulator competence at NLR. For more details about the management point of view on ISMuS is referred to (Ref. 1).

The remainder of this paper is organised as follows. In Section 2 an overview of the ISMuS working environment from the engineering point of view will be given. Section 3 presents the support that ISMuS can deliver to the engineer during all stages in the development of complex mathematical models. In Section 4 it is described in detail how the development of the generic vehicle behaviour federate profits from the use of ISMuS. Special attention is given to modelling, simulation, and control of contact dynamics. Section 5 contains the conclusions and recommendations. The references are found in Section 6.

2. Overview of the ISMuS Working Environment

The working environment ISMuS is used by simulation and control engineers in the following application domains:

- Robotics,
- Vehicles, and
- FDIR (Fault Detection, Isolation, and Recovery).

In these application domains NLR has broad expertise.

ISMuS provides the engineer's with (Figure 2):

- Shared data, available to all ISMuS users;
- A private working directory ("Local" icon in Figure 2);
- The accessible working directories of other ISMuS users ("Users" icon in Figure 2);
- Other icons.

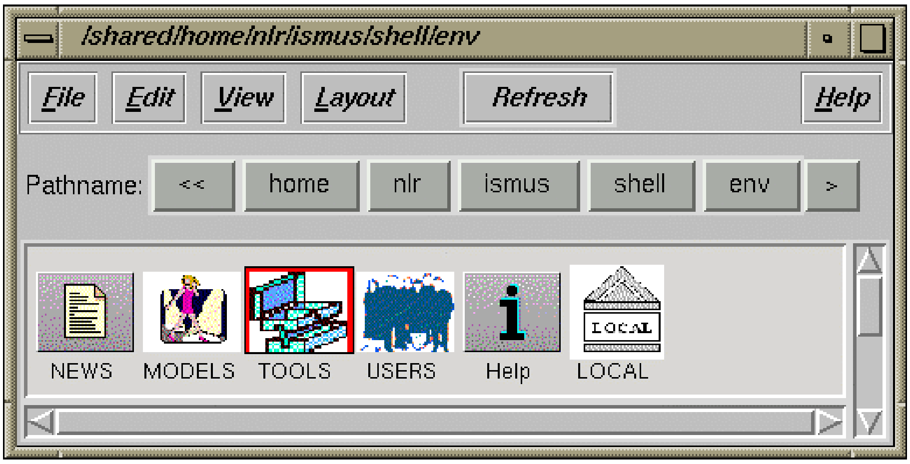

Figure 2: Top level browser window of ISMuS

Here data should be understood in a broad sense. Shared data in ISMuS includes at present:

- Validated models for simulation and control engineering in the ISMuS application domains (Models icon);
- Tools for simulation and control engineering, which are used in the ISMuS application domains (Tools icon);
- Educational models to learn about simulation engineering, control engineering, and the tools that are used;
- Documents about the models and tools, such as software user manuals and programmers guides;
- General utility tools such as text editors;
- Project management tools;
- Any other information that may help the engineer to use the tools and models available. This information is directly accessible from the working environment by opening the Help icon, upon which the appropriate html-pages that reside in NLR's intranet are opened.

Specific data in ISMuS can be found easily, since ISMuS has a graphical user interface. Moreover, the data is organised in an engineer-friendly manner: the same data can be accessed from several places in ISMuS. For example, access to the MATLAB simulation model TRaCE for robotics simulation is contained in both a sub-window of the MATLAB-window and a subwindow of the Robots-window. In this way both the MATLAB tool expert and the robotics expert will find TRaCE easily.

In his working directory ("Local") the engineer can carry out his work in the way he likes, while having easy access to the shared data in ISMuS at the same time. For example, the engineer can store simulation results obtained using a simulation model from the shared data part of ISMuS. Moreover, the engineer can copy a validated model from the shared models in ISMuS to his private working directory, and the engineer can use a model development tool from the shared tools in ISMuS. The use of ISMuS for model development is further detailed in Section 3.

Access to the working directories of other ISMuS users allows an engineer to co-operate with the colleague that is working in the same or other project projects.

The ISMuS graphical user interface provides easy operation, such drag-and-drop of icons to start shared tools, copy files, etc.

The ISMuS working environment has been constructed by use of the SPINEware middleware package (Ref. 10). SPINEware has been developed to support construction and operational use of functionally-integrated working environments. SPINEware is developed by NLR for NEC. SPINEware supports the following functions (Ref. 4):

- Access to computer facilities and know-how as if everything is located on a PC (the virtual computer approach);
- Graphical user interface based operation of tools to execute standard or routine chains of activities;
- Environment management, enabling customisation of personal environments;
- Know-how management, such as software version management on distributed computers.

Moreover, SPINEware provides specific tool sets, such as tools for software development on the NEC/SX-4 parallel vector computer of NLR, which acts as the central computing facility for large, demanding (both with respect to through-put time and memory use) application jobs.

Various working environments have been created at NLR with SPINEware. The working environment ISNaS for Computational Fluid Dynamics is described in (Ref. 2). SPINEware has also been used to create project specific working environments. The ISMO project environment for Multidisciplinary Design Optimisation is presented in (Ref. 3).

3. ISMuS Support in the Development of Models

3.1 Model development approach

To develop application software, e.g., to develop a space vehicle simulation model in EuroSim, typically the following development approach is taken. Firstly, an object-oriented design of the application software is made, see Figure 3. Next it is identified which submodels of the application software need to be made and which submodels are available in ISMuS. The submodels that are not present in ISMuS are developed using CACE tools that are available in ISMuS. Finally, the submodels are connected through dedicated interfaces. This model development approach is supported by ISMuS. It contains both tools for the development of new models and a model repository.

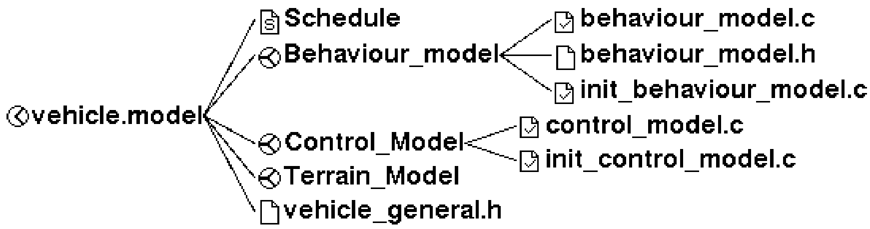

Figure 3: Tree-like structure representing a part of the object-oriented design of the application software.

In Section 3.2 the support of ISMuS to the development of new models is explained. Section 3.3 concerns the re-use of models.

3.2 Tools for the development of new models

ISMuS supports the development of new models with an appropriate model development tool. For this purpose ISMuS provides several generic model development tools, like MATLAB/SIMULINK, see Figure 4. The model is exported from the model development tool. Ideally, a model can be imported directly into a simulation tool. ISMuS contains several simulation tools, like EuroSim, see Figure 4. This approach is not always feasible: in many cases the exported model is not compatible with the simulation tool. In these cases ISMuS provides the engineer with information, procedures, and/or tools that will help him to extend and/or to modify the exported model such that it becomes compatible with the simulation tool.

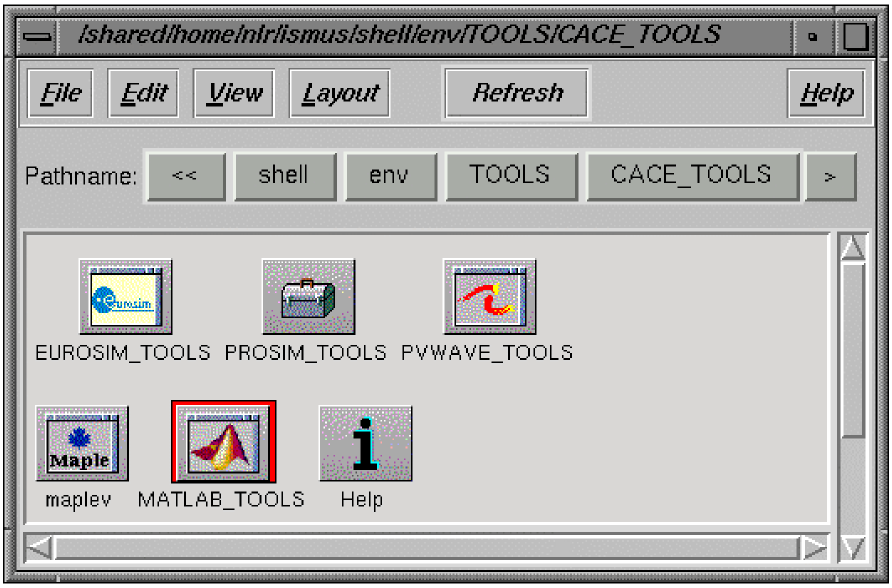

Figure 4: CACE-tools window in ISMuS

At present, expertise is available with respect to the use of DYMOLA in the development of a multi-body model. The model has been extended so that is compatible with EuroSim. In the near future other model development tools like DCAP will be considered for inclusion in ISMuS.

3.3. Re-use of models and model repositories

Model repositories are useful to provide access to departmental, workgroup or enterprise models. Know-how and know-why is stored in software, data and documents, which are placed in computer-based engineering infrastructures (i.e. repository). Tools must be available to access know-how and know-why in a coherent manner and to support a way of working that is directed towards accumulation and re-use of knowledge.

At present the model repository is of limited complexity and mainly provides systems and control engineers with available models. The SPINEware tool sr is used for configuration management in ISMuS. The model repository that is envisaged also provides means to store and retrieve information concerning models. This information will include at least:

- Model code;
- Design Documentation;
- User manuals, and related information;
- Relevant session results;
- Any other information (for example proprietary information).

In addition, information on the coupling of components to a simulation tool, for instance the coupling of a hardware component to EuroSim may be stored in a similar fashion (with the obvious replacement of the actual hardware by the interface software, such as DIS, HLA or any other interface description).

The availability of a model repository within ISMuS also facilitates fast and early prototyping of systems by providing simulation models as objects to an engineer, thus stimulating the re-use of existing models.

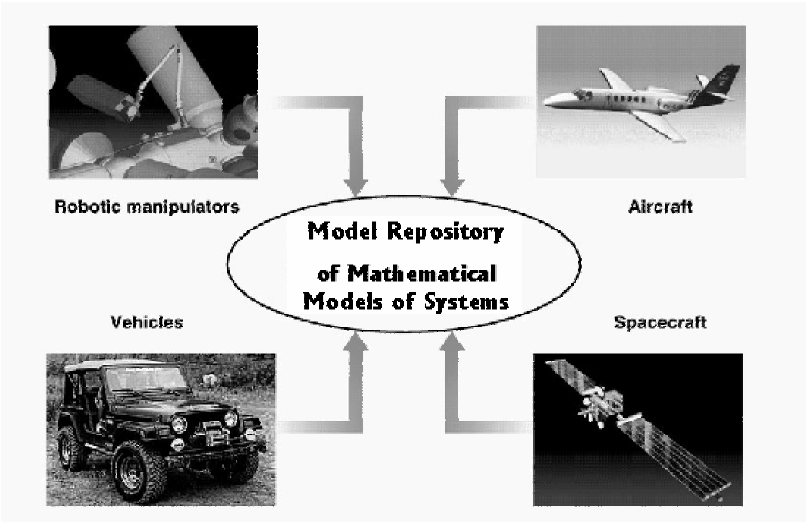

Figure 5: Model repository in ISMuS

The envisaged model repository will consist of two parts:

- a shell, i.e. the IT part of the model repository;
- aerospace models, i.e. the application dependent part of the model repository.

The model repository shell will provide the means to store and retrieve in a coherent manner all information that is relevant with respect to models. The shell will also provide users with standardised interfaces with commercial tools such as DYMOLA and DCAP for multi-body modelling, and MatrixX and MATLAB for control engineering. Furthermore, the model repository will provide interfaces to a 'simulator composition' tool that will provide a user with real-time dynamics and control simulation software ready for use in EuroSim. The model repository tools shall support a distributed architecture, i.e. the underlying databases may be installed on distributed computer systems yet offering the end-user a single comprehensive structure of storing and retrieving the desired model information. The aerospace application models in ISMuS will be a further extension of the models that are already present.

4. Support by ISMuS on Simulation of Contact

4.1 Some issues in contact dynamics

From a mathematical point of view, interactions of mechanical systems with their environment fall into the class of hybrid systems, or non-smooth dynamical systems. Mathematical descriptions of non-smooth dynamical systems usually involve inequalities. At NLR there are many applications that deal with non-smooth dynamical systems. Examples are:

- Robotic manipulators: simulation and control of constrained motions of the European Robotic Arm ERA, and of the manipulator in NLR's robotics laboratory;
- Wind tunnel experiments: contact between an aerospace model with the walls of the test section in a wind tunnel must be avoided at all times to prevent damage;
- Wheeled vehicles: simulation and control of a wheeled road-vehicle or rover under several terrain conditions.

Simulation of contact dynamics is by no means a trivial task, and the list below - taken from (Ref. 5) - gives an idea of the difficulties that have been encountered and for which solutions have been derived at NLR

- Study of wellposedness of impact dynamical systems, i.e. properties of solutions. This is important to obtain a unified treatment of contact problems across boundaries of application domains, and for enabling real-time simulation of constrained multi-body mechanical systems. Part of NLR's expertise is presented in (Ref. 7).
- Study on impact between two rigid bodies via macroscopic laws that relate the motion after and before the shocks. A particular solution is described in (Ref. 6).
- Develop new models of contact-impact laws for specific applications using engineering competence available in an organisation, see also Section 4.3.
- Investigate the complex dynamics of vibro-impact systems that may model systems with clearances. An example of such a system is ERA on the International Space Station.
- Study of numerical algorithms to integrate systems subject to unilateral constraints. Simulation of non-smooth mechanical systems is known to be liable to numerical instabilities. A procedure for real-time simulation has been developed at NLR (Ref. 8).
- Design control strategies to improve the behaviour of mechanical systems subject to repeated impacts with the environment. Control of constrained robotic manipulators is part of ongoing research at NLR. Knowledge is accumulated in TRaCE, see Section 4.2.

In the remainder of this section knowledge transfer with the aid of ISMuS is illustrated by two simulation projects: TRaCE and SIMULTAAN.

4.2 Simulation of contact in robotics: TRaCE

TRaCE is a CACE research simulator that has been developed at NLR for the study of simulation and of control of unilaterally constrained robotic systems. TRaCE contains several dynamics models for robotic manipulators, a number of numerical methods for the simulation of contact, and various control methodologies. TRaCE is used for extensive evaluation of control laws, including robustness with respect to sensor noise, parameter uncertainties, and model uncertainties. TRaCE is written in MATLAB 5.2.

In TraCE, simulation studies can be executed with a 2D robotic manipulator (as shown on the opening window of TRaCE in Figure 6) that can make contact with a surface through the following four motion phases:

- Pre-impact phase, also called the free motion phase,
- Impact phase, the phase in which the effect of making contact are notable in the manipulator and/or surface,
- Post-impact phase, the phase in which the robot remains in contact with the surface,
- Release phase, the phase in which a controlled release is made.

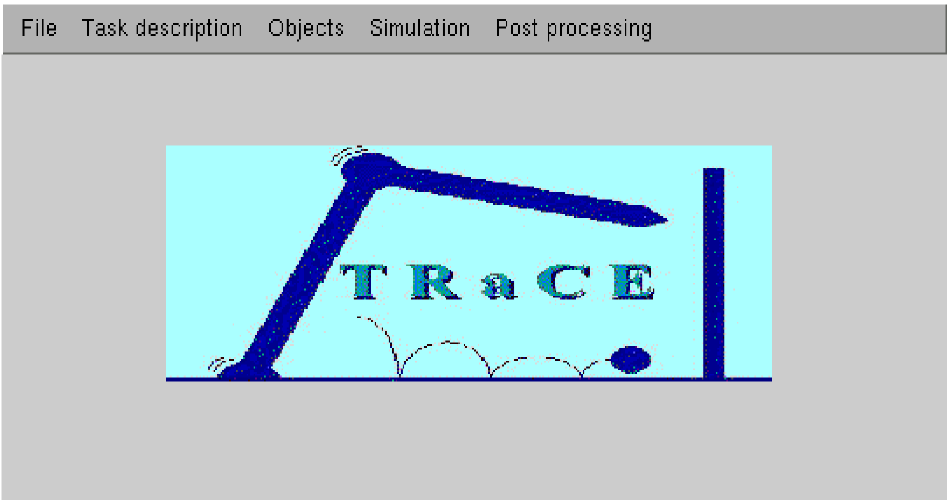

Figure 6: Opening window of TRaCE

TRaCE is included ISMuS. The graphical user interface of TRaCE and the software user manual of TRaCE assists new TRaCE users and non-MATLAB experts in using TRaCE. The programmers' guide, which is also available in ISMuS, helps the engineer to find the code of interest.

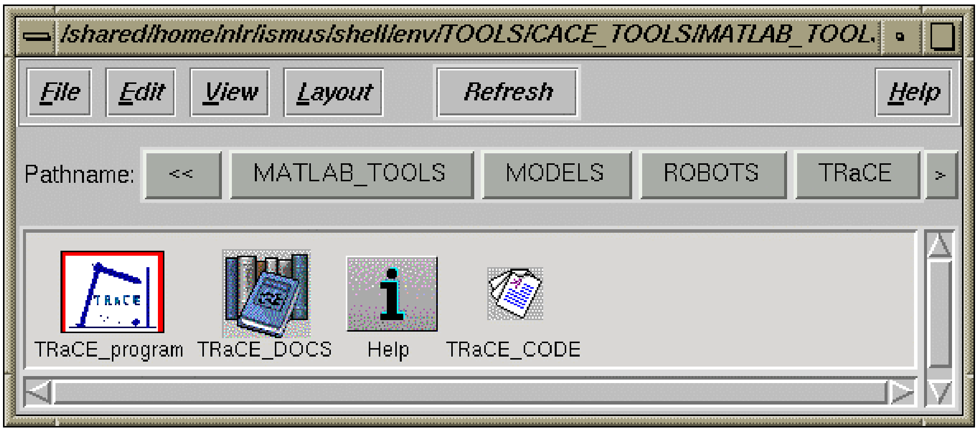

Figure 7: TRaCE window in ISMuS

Students working in TRaCE have profited from several relatively simple models that are available in ISMuS. These programs are stored in the Educational directory, see Figure 8.

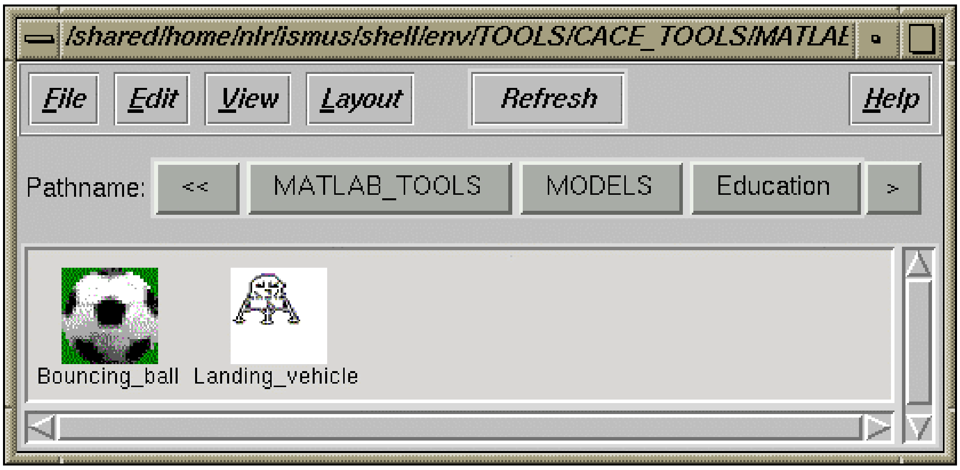

Figure 8: Educational models window of ISMuS

4.3 Simulation of contact in SIMULTAAN

Within the SIMULTAAN project (Ref. 9) NLR is responsible for the vehicle Behaviour Model Component of a training simulator. The Behaviour Model Component simulates the behaviour of a large class of wheeled vehicles (with at least four wheels). The Behaviour Model Component consists of three models (Figure 1):

- a Behaviour Model,
- a Control Model, and
- a Terrain Model.

Special attention is given to the interaction between the vehicle and the terrain to ensure proper motion cues to a driver during training sessions.

The know-how and know-why that is stored in TRaCE is re-used in the development of the Behaviour Model and the Control Model in SIMULTAAN. The four motion phases mentioned in Section 4.2 also apply to the vehicle behaviour with respect to vehicle-terrain interaction. Also numerical methods for the simulation of contact are re-used. Moreover, the know-how in TRaCE with respect to the development and the evaluation of control laws is used within the development of the Control Model in SIMULTAAN.

The development of the vehicle behaviour models has been divided into six sub-projects. These sub-projects target at a series of vehicle behaviour models of growing complexity. Each model is stored in the model repository in ISMuS. In this way, vehicle models can be re-used easily within SIMULTAAN. The model repository makes it possible that models that have been made in SIMULTAAN can be re-used in follow-on projects, possibly in different application domains such as planetary rovers.

The starting model, referred to as Model 1, is shown in Figure 9. The model has been implemented in MATLAB/ SIMULINK as well as in DYMOLA. A wrapper has been developed such that the model as implemented in DYMOLA can also be run in EuroSim. The development of two instantiations of the mathematical model of Model 1 is done for test and evaluation purposes.

Model 1 consists of a vehicle with five main bodies. One rigid body represents the chassis. Each single wheel, including axle and tyre, is also represented by one rigid body. The lower spring-damper combination in the wheel model represents the elasticity and damping of the tyre, and the spring-damper combination represents the wheel suspension, which is connected to the chassis. The model is meant for basic analysis of the motion in the vertical (z) direction and the rotational motion around the axis perpendicular to the x- and z-axis. This motion depends on the vertical displacements of the ground contact points of the wheels, which are governed by the road or terrain conditions. The wheels are assumed to be always in contact with the ground.

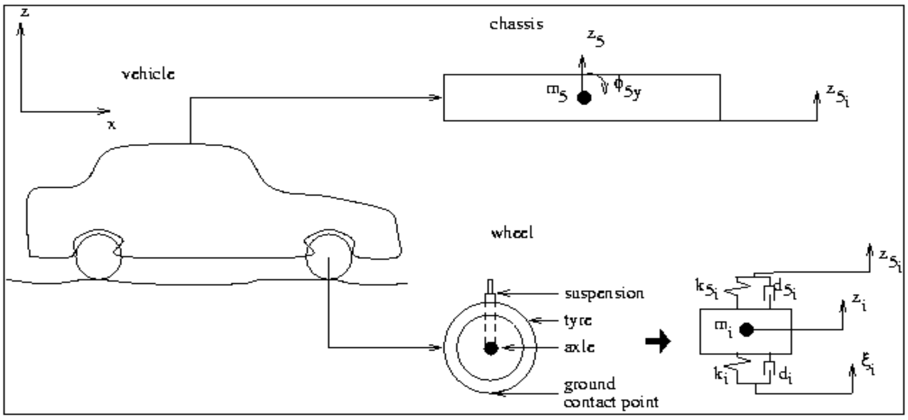

Figure 9: Illustration of the vehicle behaviour model taken from the Model 1 Help window.

Model 1 is extended to five models of growing complexity: Models 2 to 6.

Model 2 is obtained by extending the Model 1 with the necessary submodels to simulate contact transition. Model 2 can simulate the vertical and pitching movements. Contact transitions are provoked by suitable terrain conditions (e.g. a bump in the road). Besides the Model 1, ISMuS provides knowledge of the contact problem for the development of Model 2.

Model 3 also allows for the simulation of the forward movement (compared to Model 2). The forward velocity is regulated by acceleration signals and braking signals. The Control Model generates these signals. The Control Model is developed using the know-how and know-why available in TRaCE on the development and evaluation of control laws for the control of contact.

Model 4 is a 3D-model, which simulates, in addition to Model 3, the lateral, the yawing, and the rolling motions of the vehicle. In Model 4 the suspension submodel also takes into account the geometrical connection between the wheels and the chassis. Model 4 will not contain submodels for the simulation of contact nor a connection to a control model for velocity regulation. In case of terrain conditions that are constant in the lateral direction, the simulation results of Model 3 can be compared with the simulation results of the Model 1, as available from the model repository of ISMuS.

Model 5 is an extension of Model 4, and is obtained by further addition of submodels for simulation of contact. These submodels are based on the submodels that are used in Model 3. The submodels from Model 3 are available from the model repository of ISMuS. In case of terrain conditions that are constant in the lateral direction, the simulation results of Model 5 are compared with the simulation results of Model 3.

In addition to Model 5, Model 6 allows velocity regulation and steering regulation. The control model of Model 3, which is found in ISMuS, is extended with a model for the control of steering.

With Model 6 extensive evaluations on the impact of contact on the dynamical behaviour during steering manoeuvres will be made.

The way of working in SIMULTAAN provides ISMuS with a well-defined series of generic vehicle behaviour models of increasing complexity.

With the generic vehicle behaviour models a specific vehicle can be simulated by appropriate choice of the parameters, such as the gravitation constant, mass properties and wheel characteristics. With appropriate modifications, these generic models can be made suitable to simulate other vehicles. For example, a planetary rover simulation can be obtained by relatively simple modifications to the SIMULTAAN multi-body dynamics model by adding, amongst others, more wheels, and by using a more complex, hinged-frame multi-body chassis model.

5. Concluding remarks

At NLR, engineers who work in the field of CACE do their job more efficiently by employing the computer based engineering working environment ISMuS. Apart from technological problems an engineer is facing in his daily work, he is required to ensure timely delivery of his products within the allocated budget. ISMuS supports engineers in the development process by supplying models, tools, documentation, etc. through a user-friendly graphical user interface.

The benefits of ISMuS are experienced daily at NLR in the development of the generic vehicle behaviour federate in the SIMULTAAN project. In this project, CACE competence in the area of real-time simulation and control of constrained robotic systems is re-used. The various models and methodologies, and the accompanying documentation that has been made are all stored in ISMuS for future use, both in SIMULTAAN itself and in envisaged projects in other application domains. One of the envisaged projects deals with planetary rovers, in which case a simulation model can be obtained by relatively simple modifications to the SIMULTAAN multi-body dynamics model.

Accumulation of competence in ISMuS is of course an on-going activity. Knowledge obtained in projects that are executed today will be made available tomorrow via ISMuS. To support and encourage reuse, the model repository of ISMuS will be extended so that the growing CACE competence is presented to engineers in a transparent and coherent manner.

Experience at NLR shows that ISMuS harmonises simulator competence at NLR. Know-how and know-why is neither hidden nor lost. On the contrary, fruitful co-operation between engineers from different application domains is encouraged and guided. This leads to more efficient system development in terms of identification of critical items in the design, keeping within budget, and timely delivery of products that satisfy customer requirements.

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