Recent Activities Related to Multibody Dynamics at DIAPM

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Abstract: - This paper illustrates recent developments and applications of multibody dynamics at the "Dipartimento di Ingegneria Aerospaziale" of the University "Politecnico di Milano", and highlights the philosophy they are based on.

Keywords: - Multibody Dynamics, Computational Mechanics, Aerospace Engineering, Explicit Integration, Crashworthiness, Open-Source Software, Free Software.

1 Introduction

Multibody dynamics represents a very powerful tool for the analysis of a wide spectrum of problems, ranging from impact dynamics, to fluid-structure interactions, from robotics, to system analysis and design.

This paper illustrates some of the uses of the multibody approach to the analysis of complex, multidisciplinary systems that have been recently performed by different research groups at the "Dipartimento di Ingegneria Aerospaziale" of the University "Politecnico di Milano" (DIAPM).

What appears by considering the different problems illustrated in this work is that in many cases the multibody approach is used as a means to integrate different problems, analyzed by different, specific techniques, in a single analysis framework, rather than a direct means to solve a specific problem.

This is true, for example, for the crashworthiness problems, where in some cases the multibody model provides the boundary conditions for detailed nonlinear FEM analysis of components; or for the fluid-structure interaction problems, where the multibody model essentially takes care of the large-scale displacement and rotation of the structure, while the deformation is alternatively modeled by FEM, as in most of the fixed wing problems, or directly by the multibody solver, as typically occurs in the rotary wing problems.

2 Multibody Philosophy

Even a quick review of the literature and of the applications related to the multibody technology shows that a very broad spectrum of formulations and approaches have been proposed and developed. Common denominators are:

- the capability to directly solve nonlinear problems in differential (ODE, minimal coordinate set) or differential-algebraic (DAE, redundant coordinate set) form
- the generality of the formulation, which typically must not be confined to specific models and problems.

The philosophy of use of the multibody approach that is pursued in the work described herein exploits the above mentioned features in two manners:

1. for the direct analysis of nonlinear, FEM-like models;
2. as an "integrator" of multidisciplinary systems, where dedicated software components

are used to solve specific portions of the problem.

The former case is illustrated, for example by the capability of many multibody software, either commercial or academic, to directly model mechanical rigid and deformable systems, hydraulic and electric subsystems, drive trains and so on. Some FEA software, on the opposite end, allow to exploit some multibody capabilities within the FEM framework; an illustration is provided later in this work with ABAQUS.

There are many examples of the latter case as well; actually, most of the commercial multibody software, as well as many academic software currently available, allow to incorporate, for example, linear deformable components obtained by means of component mode synthesis. Some allow to couple multibody analysis with dedicated solvers for hydraulic and pneumatic subsystems; for example, MSC.Adams with Easy5 and AMESim. Nearly all software allow to couple with control-related modeling tools, like Simulink and Scicos.

The integration of specialized analysis components is actually best implemented by moving some essential tasks to a specific logical block, called "broker" [1], that:

- allows the different software components to communicate;
- synchronizes their scheduling and execution;
- interpolates fields between non-compatible discretizations.

This architecture, illustrated in Figure 1, allows to implement a tight coupling between different software components, where the co-simulation occurs at the nonlinear iteration level in matrix-free form (BiCGStab, GMRES), and frees each software component from the communication burden, which can occur via pipe or socket for distributed co-simulation where access to the software is guaranteed, or via files otherwise, significantly when commercial software is used. Moreover, it frees each component from the need to account for field interpolation, which is done in a robust and reliable manner by means of the unified technique discussed in [2].

In Figure 1 the rounded corner blocks on the left are "driving" components, which, in mechanical terms, compute the kinematics based on the forces they receive from the broker, while the sharp corner blocks on the right represent "driven" components, which, in mechanical terms, compute the forces based on the motion input by the broker.

Explicit multibody analysis can only drive a simulation, while implicit multibody can be used both as a driving or a driven block.

2.1 Multibody Software

Different types of software have been used in the activities illustrated in this work. Basically, they can be divided according to the categories:

- commercial software
- free software
- free software developed at DIAPM
- closed software developed at DIAPM

The interaction of the structure with the dynamics of fluids is an essential topic in the analysis and design of aerospace systems. For this reason, CFD plays an important role in the software systems integration philosophy illustrated in Figure 1, and many CFD-related software developed at DIAPM are discussed in the following.

2.1.1 Explicit Multibody Software

- *VEDYAC*, a multibody closed software developed at DIAPM;
- *ABAQUS*, a nonlinear FEA commercial software with integrated multibody modeling capabilities.

2.1.2 Implicit Multibody Software

- *MBDyn* (`http://www.mbdyn.org/`), a general-purpose multibody free software developed at DIAPM;
- *ADAMS*, a commercial general-purpose multibody software.

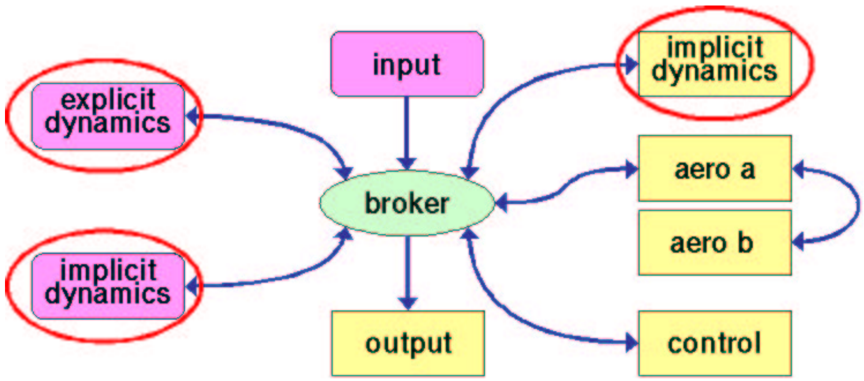

Figure 1: Software systems integration philosophy.

2.1.3 Structural FEM Software

- *NASTRAN*, a commercial FEM software that is the de-facto standard in aerospace;
- *Code Aster*, a free FEM software;
- *ABAQUS*, a commercial FEM software whose peculiar strength is represented by explicit integration and nonlinear constitutive laws.

2.1.4 Computational Fluid Dynamics

- different closed BEM software developed at DIAPM (*NUVOLA*, *ALIS*);
- *FLUENT*, a commercial software;
- *OpenFOAM*, a free software.

2.1.5 Control

- *MATLAB/Simulink*, a commercial scientific environment that is the de-facto standard in control;
- *SCILAB/SCICOS*, a free scientific environment;
- *RTAI/RTAILab* (`http://www.rtai.org/`), a free software real-time application interface developed at DIAPM, and *RT-Net*, for distributed real-time, developed at the University of Hannover.

2.2 Free Software

As already pointed out, many of the software used in this work actually are free software; some of the software developed at DIAPM is free as well. In this context, "free" refers to freedom in using, distributing and modifying the code, according to the philosophy described by the Free Software Foundation, and not simply to the fact that in most cases the software can be obtained free of charge.

The importance and the advantages of freedom in research software has already been discussed in [3, 4]; an essential point is developed in the following.

The knowledge in Engineering Science can be roughly divided in three levels:

1. theory: essentially open (scientific literature);
2. software tools: can either be open or closed;
3. competence: typically requires years to grow.

In the most widely diffused knowledge model, theory is free and software tools are closed. The free software philosophy moves software tools into the domain of open knowledge: they should be viewed at the same level of open literature.

The basic advantage of open software is that users and developers can access it free of charge. Free software adds to this access rights protection; in detail, the right:

- to redistribute the software as is;
- to modify it;
- to redistribute modified versions.

Among the advantages of free software in scientific and engineering applications:

- the experience of each researcher and developer is shared among the community of users;

everyone can access a large deal of functionalities while only investing as much competence as available or desired;

- the likelihood of "reinventing the wheel" is reduced;
- Small-Medium Enterprises (SME) can access rather inexpensive software, which can be further tailored to their needs by resorting to the competence of the research community, either for free or by signing research contracts.

An example of integrated free software system developed at DIAPM is the RT-MBDyn project, where general-purpose real-time multibody simulation capabilities have been obtained by real-time enabling the MBDyn general-purpose multibody simulation software by means of the RTAI application interface, using Scicos for control software generation, RTAILab for process monitoring and user-interface, and RT-Net to distribute Hardware In the Loop (HIL) real-time simulation and control via Ethernet.

It is worth stressing that free and commercial software do not necessarily compete, especially in engineering. In fact, they typically have different targets and capabilities. The goal of academy and research establishment is not to make and sell software; it rather consists in developing (and, occasionally, selling) competence. Free software should be intended as a tool to broaden the capability to provide competence in as many fields as possible, with focus on those that are not covered by commercial software because they represent a niche. In this sense, it is common to see free and commercial software interact; for example, MBDyn can import NASTRAN FEM models; it can talk to Simulink; it can export results in a format that is compatible with ADAMS; development is underway to interact with Altair's pre/post-processing tools, and more.

3 Crashworthiness

Typical aerospace crashworthiness problems can significantly benefit from specific features of multibody analysis because they usually require to integrate nonlinear problems subjected to large changes in position and orientation, including finite strain, plasticity, and material and structural components damage. For the latter problems, approaches based on explicit integration algorithms may be better suited, as illustrated by the broad literature available on the subject.

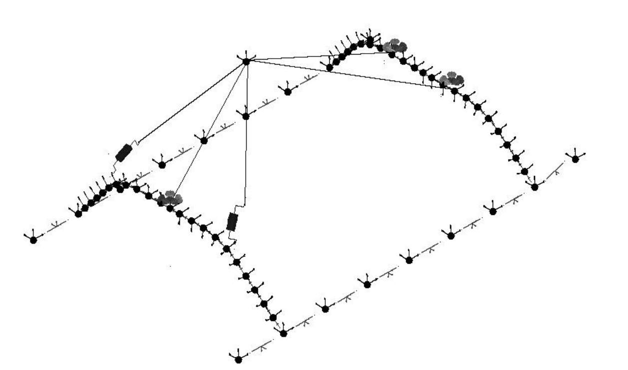

Figure 2: Detail of the helicopter skid landing gear multibody model.

Although capturing the details of structural component buckling, plasticization and other limit conditions may require a modeling detail that is best provided by specialized FEM software, often the need to run a considerable amount of analysis, e.g. for optimization purposes, leaves room for models and analysis software that synthesize the behavior of complex structural components over a wide operational range.

A software called Ve.Dy.ac with the characteristics illustrated above, later evolved into a new version called Musiac, has been developed at DIAPM; it is used for a broad spectrum of fast dynamics analysis. Occasionally, ABAQUS Explicit is used for the same type of problems, significantly when tighter coupling with FEM analysis is required.

3.1 Helicopter Skid Landing Gear

The design of helicopter skid landing gears needs the capability to capture the correct dynamics of the helicopter while the skids and the cross-members are subjected to plasticization in limit landing conditions [5]. Synthetic multibody models, like the one illustrated in Figure 2, help reducing the complexity of the problem while preserving generality (rather different analyses in terms of sizings and boundary conditions can be used), which is key for component design and optimization.

3.2 Shock Absorber for Crashworthy Landing Gear

This activity refers to the development and patenting of an energy absorbing device for shock absorbers [6]. Energy exceeding that of a regular landing is dissipated by crushing a metal component, so that extra stroke is obtained at roughly constant load, resulting in localized plastic damage of a portion of the shock absorber that can be easily repaired, while the performances of the aircraft, in terms of crew accelerations, remains limited. The challenge, from a simulation standpoint, lies in the fact that the component is multidisciplinary, including detailed nonlinearities of the material and fluid-structure interaction. One key feature is that the crushing of the expendable component is triggered by an electro-mechanical device, so the application of the appropriate boundary conditions is essential to determine the behavior of the system, and significantly of the trigger. For this purpose, a multibody model of the rest of the system (Figure 3, left) was added to the detailed FEM model of the shock absorber (Figure 3, right).

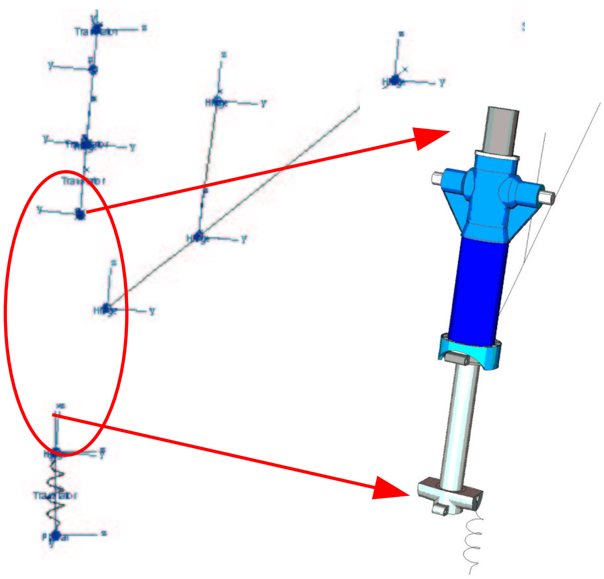

Figure 3: Multibody/FEM model of the controlled collapse shock absorber.

3.3 Helicopter Subfloor

This activity refers to the structural optimization of helicopter subfloors in composite material for crashworthiness performances [7]. In this case, the need to run a large number of simulations for optimization purposes required to synthesize detailed FEM models of the subfloors, including the bolted joints, the contact and the friction between structural components and other details that are essential to describe the energy dissipation during the impact, suggested to replace the inherently discrete components of the subfloor with equivalent, nonlinear structural components, as illustrated in Figure 4. Further development of this activity will see the addition of a FEM model of the humans sitting on the seats attached on top of the floor.

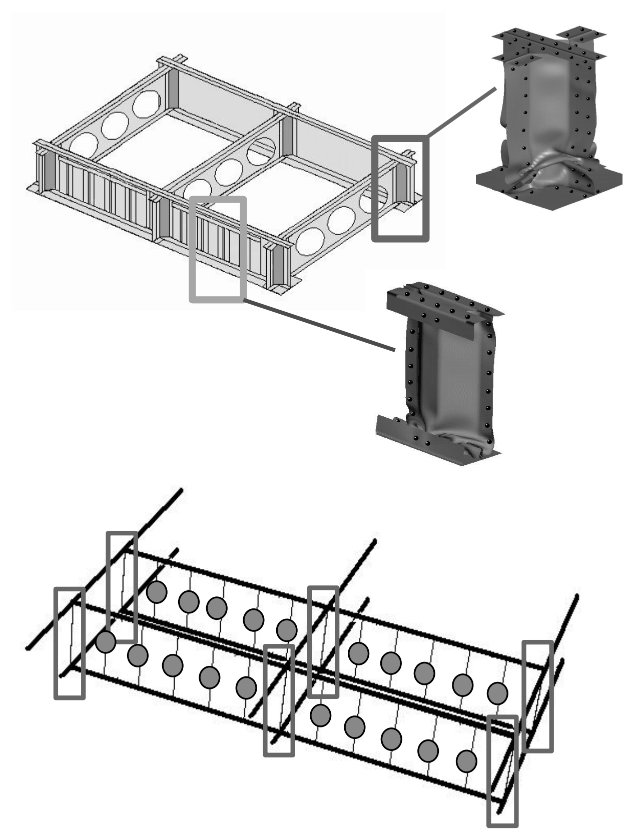

Figure 4: Multibody/FEM model of a helicopter subfloor; the components highlighted in the top figure are replaced by their multibody synthesis.

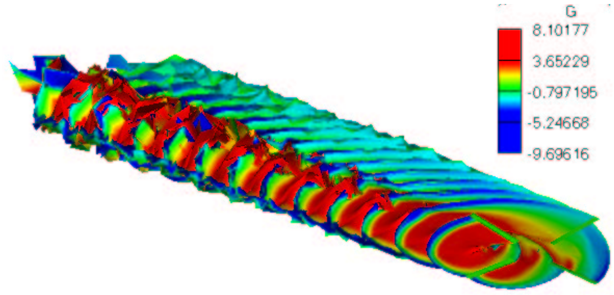

Figure 5: FEM-Multibody/BEM-aerodynamic model of a deformable helicopter rotor in forward flight with the developed wake; the colors show the vorticity intensity.

4 Fluid-Structure Interaction

The FSI activities already performed and currently underway represent perhaps the most challenging activities that see the multibody as the unifying approach for system integration. In fact, those kind of analyses can be assumed as a reference for the set up of a framework for multiphysics analysis tackled with a partitioned approach, based on concurrent simulation using different pieces of software. Among the different numerical aspects which are involved in this kind of analysis, those highlighted in the following require special care:

- data exchange between the participating solvers during the simulation, without the introduction of additional numerical errors; the interfacing scheme must ensure the conservation of the physical quantities exchanged and the possibility to connect independently discretized numerical models possibly with different topological representation [4];
- the definition of flexible time integration schemes, without the introduction of numerical instability during the time marching procedure;

However, to use this kind of simulations not only for system analysis, but also for synthesis and design, techniques for the extraction of Reduced Order Models (ROM) from large multidisciplinary simulations must be developed.

The layout of Figure 1 has been implemented to couple FEM and CFD in selected cases for fixed wing analysis [8], and, in few cases, multibody and BEM for rotary wing [1], in order to represent the complex dynamics of the wake behind the blades. The extraction of ROM models when complex CFD analysis are used for the computation of aerodynamic forces is presented in [8]. Furthermore, the application of ROMs to multibody model has been exploited for the correct representation of unsteady aerodynamic forces in complex machines like tiltrotors [9, 10]. There are ongoing activities to couple the multibody with CFD for the analysis of helicopters.

5 System Analysis, Design, Optimization

Different activities about integrated system analysis, design and optimization have been performed using multibody technology. Few relevant examples are discussed in the following, to give a flavor of the variety of problems and solution approaches.

5.1 Fiber Problem

This problem has been investigated by the authors in cooperation with Mr. Israël Wander, Apex Technologies, France, using the multibody free software MBDyn to assess the possibility to use multibody analysis to:

- analyze the assembly of systems made of deformable components;
- evaluate the space occupied by complex deformable components when subjected to their full range of displacement;
- evaluate the behavior of the same components when subjected to dynamic excitation;

all within a single analysis tool, with models that share as many modules as possible. In fact, one of the requirements was the use of free software, since that activity is intended for use in a company whose core business is not directly related to modeling of mechanical systems, so the purchase of expensive, dedicated commercial software is not an option, while the accessibility to the source code is essential to allow an easy tailoring of the analysis to the needs of the core business of the user. The need

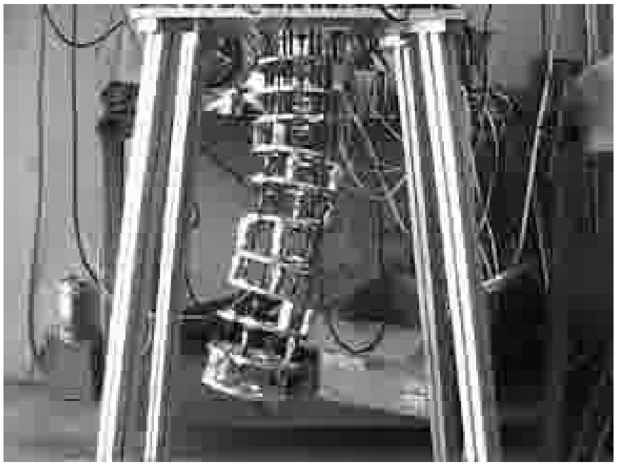

Figure 6: Picture of the robot at VILAS Italia

to perform complex sequences of simulations, with topology changes when changing phase, required to add the capability to modify the model according to the state of the analysis in a rather flexible and versatile manner. This feature, already available in the current release of MBDyn, is called "hints". The research activity is currently under development.

5.2 Trajectory Optimization

This problem consists in the optimization of the trajectory of a two-arm planar robot; it has been developed by Mr. Michele Attolico in partial fulfillment of the requirements for earning a Ph.D. in Aerospace Engineering at the University "Politecnico di Milano". The essential results have been recently presented in [11]. In this case, the role of multibody analysis consists in simulating the dynamics of the robot, to evaluate the cost function and the activation of the constraints.

5.3 Trajectory planning and verification

This problem consists in the planning of the trajectory of the complex robot system illustrated in Figure 6, under development by VILAS Italia, a firm located in Lecco, Italy. The modeling of this robot is being developed by Mr. Marco Mantegazza and Mr. Luca Veroni, in partial fulfillment of the requirements for graduation in Mechanical Engineering, under the supervision of Professors Stefano Bruni and Ferruccio Resta of the "Dipartimento di Meccanica" of the University "Politecnico di Milano", in cooperation with one of the authors of this paper, using the multibody free software MBDyn. A modular model has been developed, consisting in the kinematic description of each disk, represented by a rigid body, and of their reciprocal connection, represented by a revolute hinge. Two families of models result:

- kinematic models: the screw that controls the relative rotation between pairs of disks is replaced by a spring, in order to eliminate the underdetermination of the problem and to introduce a "motion cost" in the kinematic analysis. By imposing the trajectory of the end effector, the motion of the robot is planned.
- dynamic models: the position computed by the kinematic analysis is imposed in a dynamic model, where the inertia, selected deformability and selected nonlinearities of the system can be taken into account. The control forces are computed, and an estimate of the positioning error can be obtained.

The work is under development. The activity so far indicates that trajectory planning can be easily performed in real-time for realistic trajectories and speeds (0.01 s), since the model is made up of ~ 150 equations; uneven and nonlinear springs can be used to tailor the rotation of each hinge. The timing of the dynamic verification depends on the sophistication of the model; when the entire dynamics of the drive system is modeled, the model grows to ~ 1000 equations, making the real-time simulation unrealistic at reasonable sample rates.

5.4 Landing Gear Simulation

The simulation of aircraft and helicopter landing gears for landing, taxiing and ground maneuvers in general was initially conducted by means of dedicated software. As soon as the multibody technology gained momentum, the experience gained with those specialized software, mainly related to the modeling of shock absorbers and tire and ground interaction models, was diverted into commercial and free software, mainly ADAMS and MBDyn. The analysis activity has mainly been performed

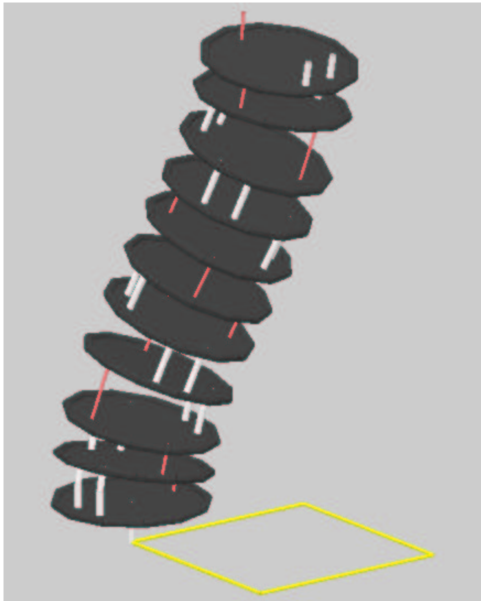

Figure 7: Multibody model of the robot in Figure 6

in support to experiments, both for research purposes and for validation and certification of industrial hardware [12, 13, 14].

Recent activities focused on the investigation of gear-walk instability of executive aircraft [15]. Gear-walk is a dynamic instability related to the interaction of deformable landing gear legs with the ABS system. The analysis has been performed with the free software MBDyn, using a modal component synthesis model of the airframe, a multibody FEM model of the landing gear system, wheel brakes based on the LuGre friction model and simple ABS logics, directly built into MBDyn using generic scalar model components; the model is shown in Figure 8. Good correlation with experimental evidence of the phenomenon onset have been obtained.

5.5 Hydraulic Systems Modeling

In recent times, the need to model the dynamics of the hydraulic system that actuates the controls of rotorcraft by controlling the position and orientation of the swashplate led to the introduction of hydraulic systems modeling capabilities in MBDyn, in cooperation with AgustaWestland [16, 17].

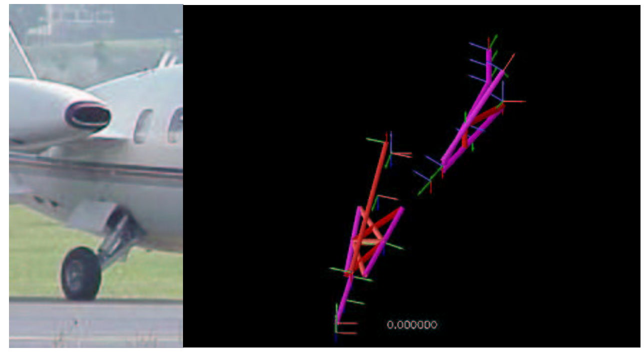

Figure 8: Executive aircraft multibody model for gear-walk instability investigation.

6 Real-Time Simulation

The RT-MBDyn project, already mentioned earlier in this paper, consists in giving the general-purpose free multibody software real-time simulation capabilities [18, 19, 20]. Typical real-time simulation software is dedicated, because the real-time simulation requirements constrain the CPU usage; as a consequence, fixed worst-case execution time and very efficient formulations are essential. However, this approach suffers from few potential drawbacks:

- dedicated software may lack some modeling capabilities, either because they have not been implemented, or because they are incompatible with the formulation dictated by the real-time constraints
- dedicated software implies code duplications;
- dedicated software implies model duplications.

The RT-MBDyn approach is somewhat different: provide general-purpose software with real-time capabilities. This wipes out all the above mentioned drawbacks, since the very same code is used for batch and real-time simulation. Although performance constraints may prevent the most sophisticated and complex models from running in real-time, code and model commonality is guaranteed, and modular modeling allows to build models that share essential modules, while increasing levels of detail are reserved to batch simulation.

Of course, the RT-MBDyn approach may suffer from other limitations, especially in performances; however, careful tuning of many key algorithms led

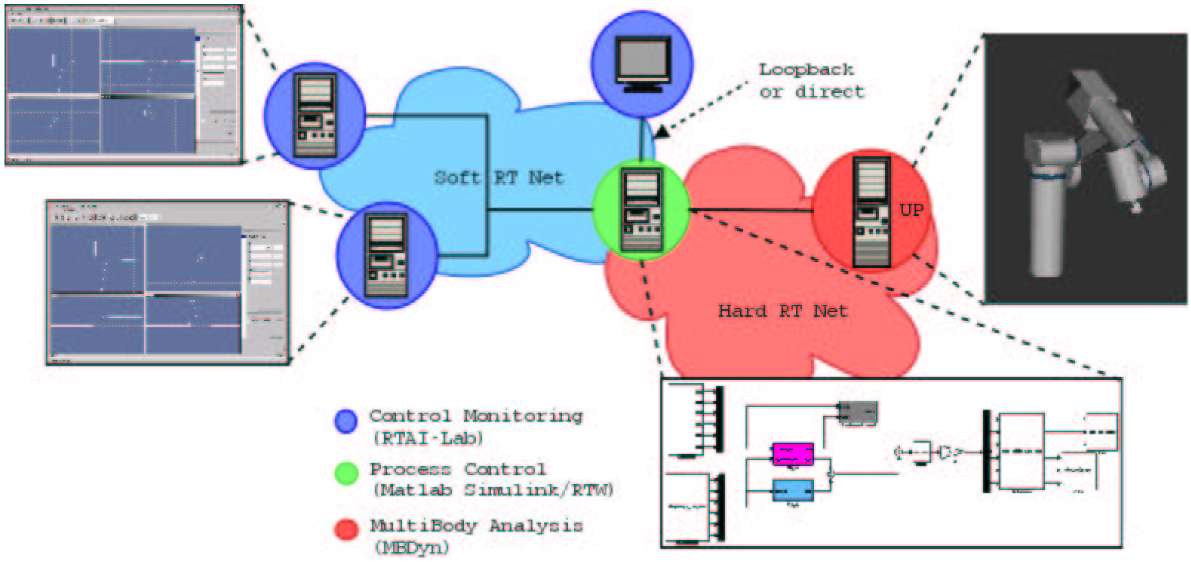

Figure 9: RT-MBDyn real-time simulation layout.

to very interesting simulation capabilities. For example, the multibody model of the 6 degree of freedom industrial robot shown in Figure 9 on the right, which is described by means of about 120 equations, can be run in real-time with a 2 KHz sample rate, including friction in the joints based on the LuGre dynamic model, on a normal PC (an AMD Athlon XP 2400+ GHz single CPU, with a 256 KB L2 cache). A tiltrotor wind-tunnel model, with rigid blades but full control system modeling, which accounts for about 200 equations, runs in real-time with a 900 Hz sample rate, which is sufficient for rotor aeromechanics accuracy, on an Opteron 3000+ 2 GHz single CPU, 64 bit architecture, with a 512 KB L2 cache.

A typical setup consists in a real-time simulator connected to a controller in a hard real-time network. A real-time monitoring and user-interaction facility is connected to the simulation and the controller by means of a soft real-time network. The controller can be designed either in Simulink or in Scicos, and turned into C code by means of Real-Time Workshop or by the equivalent Scicos feature. The monitoring is performed by means of RTAILab. The whole system is illustrated in Figure 9.

Conclusions

The multibody technology is a fundamental tool for research at DIAPM; it is used in a wide variety of applications, either directly or as a framework to integrate different analysis tools from different disciplines. Specialized and general-purpose software tools, often based on original formulations, are developed; in many cases, they are distributed in form of free software, to encourage their use outside DIAPM as well.

Acknowledges

Credits for many of the works illustrated in this presentation go to their respective Authors. The most appropriate citations are reported where available, or the names of the Authors are directly cited where no reference exists because the work is in progress.

References

[1] G. Quaranta, G. Bindolino, P. Masarati, and P. Mantegazza, "Toward a computational framework for rotorcraft multi-physics analysis: Adding computational aerodynamics to multibody rotor models," in 30th *European Rotorcraft Forum*, (Marseille, France), pp. 18.1–14, 14–16 September 2004.

[2] G. Quaranta, P. Masarati, and P. Mantegazza, "A conservative mesh-free approach for fluid structure

interface problems," in *Coupled Problems 2005*, (Santorini, Greece), May 24–27 2005.

[3] P. Masarati, M. Morandini, G. Quaranta, and P. Mantegazza, "Open-source multibody analysis software," in *Multibody Dynamics 2003, International Conference on Advances in Computational Multibody Dynamics*, (Lisboa, Portugal), July 1–4 2003.

[4] G. Quaranta, P. Masarati, and M. Morandini, "Multibody free software for teaching purposes," in *Multibody Dynamics 2005, ECCOMAS Thematic Conference*, (Madrid, Spain), June 21–24 2005.

[5] A. Airoldi and L. Lanzi, "Design of skid landing gear by means of multi-body optimisation," *Journal of Aircraft*, 2005. Accepted for publication 17 May 2005.

[6] A. Airoldi, A. Guardone, P. Astori, and L. Parazzoli, "Development of a shock absorber for a crashworthy landing gear," in *18º Congresso Nazionale AIDAA*, (Volterra, Italy), pp. 1–12, September 19–22 2005.

[7] L. Lanzi, A. Airoldi, and E. C. Chirwa, "Numerical techniques for the design of crashworthy subfloors," in *ICrash 2004*, (San Fancisco, USA), pp. 1–12, July 14–16 2004.

[8] L. Cavagna, G. Quaranta, G. L. Ghiringhelli, and P. Mantegazza, "Efficient application of CFD aeroelastic methods using commercial software," in *International Forum on Aeroelasticity and Structural Dynamics IFASD-2005*, (Munich, Germany), June 28 – July 1 2005.

[9] P. Masarati, D. J. Piatak, G. Quaranta, and J. D. Singleton, "Further results of soft-inplane tiltrotor aeromechanics investigation using two multibody analyses," in *American Helicopter Society* 60th *Annual Forum*, (Baltimore, MD), June 7–10 2004.

[10] P. Masarati, D. J. Piatak, G. Quaranta, J. D. Singleton, and J. Shen, "Soft-inplane tiltrotor aeromechanics investigation using two multibody analyses," in 31st *European Rotorcraft Forum*, (Firenze, Italy), 13–15 September 2005.

[11] M. Attolico, P. Masarati, and P. Mantegazza, "Trajectory optimization and real-time simulation for robotics applications," in *Multibody Dynamics 2005, ECCOMAS Thematic Conference*, (Madrid, Spain), June 21–24 2005.

[12] M. Boschetto, R. B. Mengotti, G. Ghiringhelli, and S. Gualdi, "Analysis of landing gear behaviour for trainer aircraft," in 15th *European ADAMS Users' Conference*, (Rome, Italy), November 15–17 2000.

[13] R. Bianco-Mengotti, M. Boschetto, G. L. Ghiringhelli, and S. Gualdi, "Multibody analysis of the dynamic behaviour of a trainer aircraft landing gear," in *XVI Congresso Nazionale AIDAA*, (Palermo), pp. 77.1–10, 24–28 Settembre 2001.

[14] S. Gualdi, P. Masarati, M. Morandini, and G. L. Ghiringhelli, "A multibody approach to the analysis of helicopter-terrain interaction," in 28th *European Rotorcraft Forum*, (Bristol, UK), pp. 72.1–12, 17–20 September 2002.

[15] S. Gualdi, M. Morandini, P. Masarati, and G. L. Ghiringhelli, "Numerical simulation of gear walk instability in an aircraft landing gear," in *CEAS Intl. Forum on Aeroelasticity and Structural Dynamics 2005*, (Muenchen, Germany), June 28–July 1 2005.

[16] P. Masarati, G. L. Ghiringhelli, M. Lanz, and P. Mantegazza, "Integration of hydraulic components in a multibody framework for rotorcraft analysis," in 26th *European Rotorcraft Forum*, (The Hague, The Netherlands), pp. 57.1–10, 26–29 September 2000.

[17] P. Masarati, P. Mantegazza, P. A. Nour, C. Monteggia, and R. Raval, "Helicopter control system synthesis by multibody multidisciplinary analysis," in 28th *European Rotorcraft Forum*, (Bristol, UK), pp. 18.1–12, 17–20 September 2002.

[18] M. Attolico and P. Masarati, "A multibody user-space hard real-time environment for the simulation of space robots," in *Fifth Real-Time Linux Workshop*, (Valencia, Spain), November 9–11 2003.

[19] P. Masarati, M. Attolico, M. W. Nixon, and P. Mantegazza, "Real-time multibody analysis of wind-tunnel rotorcraft models for virtual experiment purposes," in *AHS* 4th *Decennial Specialists' Conference on Aeromechanics*, (Fisherman's Wharf, San Francisco, CA), January 21–23 2004.

[20] M. Morandini, P. Masarati, and P. Mantegazza, "Performance improvements in real-time general-purpose multibody virtual experimenting of rotorcraft systems," in 31st *European Rotorcraft Forum*, (Firenze, Italy), 13–15 September 2005.