NTERNATIONAL DESIGN CONFERENCE - DESIGN 2002
Dubrovnik, May 14 - 17, 2002.

VIRTUAL PROTOTYPING SIMULATION FOR THE DESIGN OF TWO-WHEELED VEHICLES

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Keywords: CAD, Multi-Body Simulation, Virtual Prototyping, Vehicle Design

1. Introduction

The growing competitiveness in the manufacturing industry forces companies to reduce development costs and time, to increase product innovation, and to react quickly to new customer requirements. Traditionally, product development has been based on iterative design processes making use of costly and time-consuming physical prototypes. During the past decade, advances in Computer Aided Design (CAD) and Computer Aided Engineering (CAE) have enabled development time to be drastically reduced and product quality to be improved. Integration of modelling and simulation tools to create a robust virtual prototyping capability for mechanical system design is a crucial task. Properly integrated, modelling and simulation tools significantly impact the design process of mechanical systems. For example, the combination of Computer Aided Design and mechanism simulation is desirable for various reasons [Daberkow, 1999]: as multibody models become increasingly complex, the amount of engineering knowledge needed by a single designer can increase to an unmanageable level.

In a collaborative engineering design environment, different systems work together in order to achieve design optimisation through the iterative refinement of a virtual prototype. Designers use CAD codes to model geometry of parts and assemblies. Two-dimensional drawings or three-dimensional data in standard formats are then transferred to analysts to predict component reliability and to simulate dynamic behaviours of mechanisms.

Multibody dynamic simulations require mass, moment of inertia and location of centre of gravity of each moving component. Moreover, if the analyst wishes to create an animation, a description based on surface data could be created for visualization. However, a solid model within CAD systems contains information about the geometry of products (points, curves, surfaces and volumes), as well as volumetric data such as mass and inertia properties. The benefits for multibody analysts are obvious: all the properties needed for dynamic analysis and visualization can be directly extracted from solid models and should be accessible to all the analysts, from the earliest stages of the design process. This has suggested the development of alternative procedures to automate exchange of design data between solid modellers and multibody analysis systems [Hardell, 1996].

In this paper, a CAD system and a multi-body kernel have been integrated using a neutral top-down design environment for mechanism definition. The integrated solution, which involves both information management and data transfer, avoids data loss and reduces time to market providing a unified environment for modelling and simulating multibody systems. As examples, virtual prototyping applications are presented in the context of vehicle design, particularly, using two-wheeled vehicles as applications [Aspettati, 2001].

2. Integration of geometric modelling and analysis codes

The rapidly changing and diversified market demands that companies reduce the product development costs and time, and increase product variants and product complexity. In this context, virtual prototyping is a new concept, which enables designers to replace a great part of physical mock-ups with digital mock-ups.

The development of a virtual prototyping process consists of different activities concerning geometry definition, simulation of performance and simulation of manufacturing. Modelling and simulation activities depend on computer-based tools, which operate on, more or less, the same set of data. An important research activity in the current developments of computer aided engineering systems is the integration of different computer-based tools used in virtual prototyping. This has been achieved to some extent in commercial products. However, there is generally no single commercial system that provides solutions to all aspects of the product development process. In general, an integrated computer aided engineering environment consists of software codes from different suppliers. A large part of the profit arising from the use of computer-based systems comes from integration, giving the possibility to transfer data from one tool to another efficiently. It would be important that the integration be achieved by using protocols and tools that conform to standards, so that one program can be replaced by another with the same functionality without affecting the complete environment.

The design of mechanical systems using CAD tools is mainly based on modelling single parts and then assembling them in a subsequent design phase. Mechanical assemblies of components involve sets of relations between mating surfaces and functional characteristics. The information that needs to be represented at the assembly level includes: hierarchical relations, mating conditions, relative position of the components, degrees of freedom. The assembly CAD model can be used to drive the following analyses: interference detection, constraint satisfaction, assembling and disassembling evaluation, and assembly planning. Varying proper dimensions could also simulate, using parametric assembly systems, motion analyses limited to collision detection. However, if dynamics analyses are required, job-specific and sophisticated multibody modules are needed [Daberkow, 1999] on the basis of kinematic constraints. In particular, a kinematic joint is a functional relationship between two components, which allows relative motion, and holds despite changes in the component dimensions.

Usually, geometric data of single components can be transferred from the CAD system to a multibody tool using standard data formats (i.e., IGES or STEP files), whereas assembly data are lost. However, a multibody modelling requires: *i*) model parameters, such as mass, centre of gravity and moment of inertia, which, if properly extracted from the CAD system in use, can be directly used in multibody system definition; *ii*) kinematic properties (joints, springs, dampers and actuators) to constrain the motion of the bodies and to determine the degrees of freedom of a mechanism [Hoeltzel, 1990]. Consequently, the integration problem could be approached by the following methodology:

- comprise the necessary data describing a mechanism model for different multibody programs;
- develop an integrated functional scheme which enables the definition of geometric information about the attachment points of joints and force elements;
- extract the relevant data for multibody systems from CAD models;
- transfer the kinematic and geometric data into a multibody analysis system.

In this paper, solid modelling codes and multibody analysis systems have been integrated on the basis of the previous considerations, in order to create a virtual prototyping environment for dynamic simulation of mechanisms. The individual processes are described in detail in the following sections.

3. A CAD-based multi-body simulation system

In this paper, a CAD-based multibody system has been developed. The system uses CAD models to calculate mass, moment of inertia and gravity centre for mechanism definition, and the description of nominal geometries for visualization. In particular, four modelling steps are identified: i) creation of a schematic multibody system model through definition of rigid body references, kinematic joints and grounds, ii) extraction of part properties from solid models, iii) assembly modelling, iv) multibody mechanism generation. The chart shown in Figure 1 describes the overall methodology. In this work, CAD code Pro\ENGINEER® and multibody tool ADAMS® have been interfaced using a schematic top-down module. The data needed for kinematic and dynamic analysis are determined from the solid models stored in the CAD code.

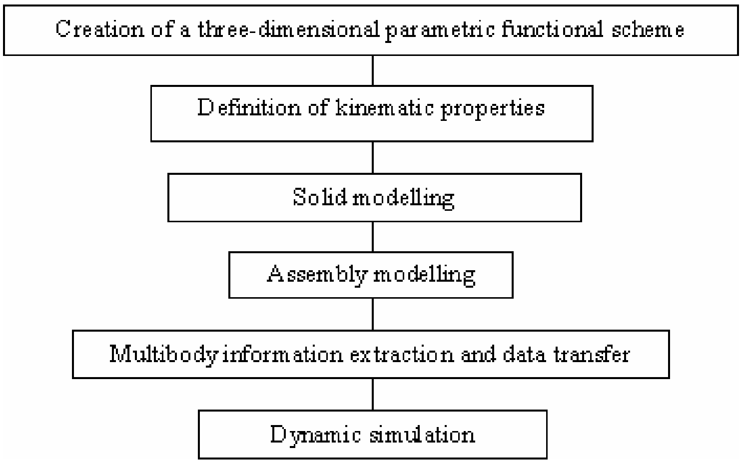


Figure 1. Overall procedure

3.1 A top-down assembly approach

The design activity starts from a conceptual scheme containing the global functional requirements, and proceeds to the design of detailed geometric models [Deng, 2000]. In this paper, a parametric three-dimensional functional scheme, called skeleton, is first introduced as entry-level model to specify mechanism composition and to give starting values to positions and dimensions for all main components [Fauroux, 2000]. This model is built from the kinematic point of view, which is specifying grounds, main components and kinematic joints connecting them. The skeleton defines a mechanism as a collection of rigid bodies that can move relative to each other, with joints that limit relative motion between pairs of bodies. The skeleton can be re-executed with new parameters to obtain new configurations. Figure 2 shows an example of schematic configuration of an engine crank mechanism.

The interfaces between the components are specified by means of datum reference frames on each component. The complete geometry of the components needs not to be defined at this stage. References frames (Figure 3), consisting of an origin and three axes *x*, *y*, and *z*, are used to define locations and orientations of grounds, rigid bodies, joints and forces. A global reference frame (***csys_ground***) is associated to the ground. Rigid body locations are defined by means of body-fixed reference frames (***csys_part***). Physical connections between the parts are determined by specifying the typology of each connection along with the degrees of freedom reduced by it. Locations and orientations of kinematic joints (Figure 4) and forces are defined by using reference frames (***csys_point***) associated to marks attached to rigid bodies. Stiffness and damping between rigid bodies are defined between pairs of reference systems. The loading may be gravity, applied forces, applied motion or initial conditions. The variations of applied forces and applied motions can be described by input functions.

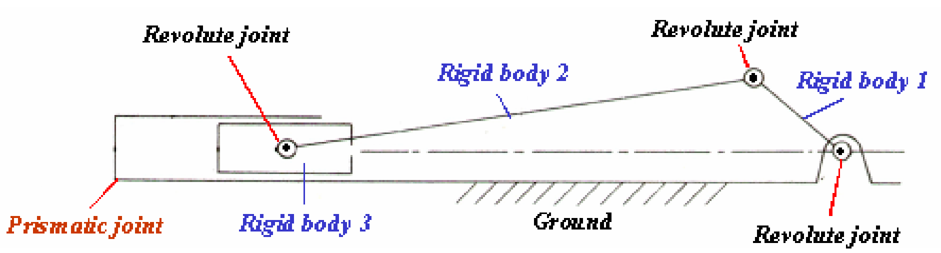


Figure 2. Skeleton scheme of a typical engine crank mechanism

The design scheme synthesizes a mechanism that performs the desired functions, meets the performance standards, and satisfies constraints. The operator has to define components, joints and forces, in terms of typology and location, whereas, all the mathematical relationships and geometric transformations between reference frames are automatically managed by the system. Moreover, a constraint solver is used to satisfy the constraints.

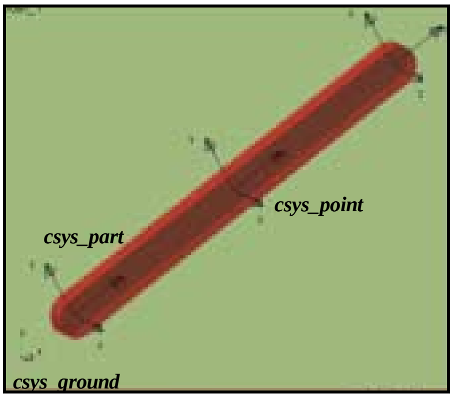


Figure 3. Example of rigid body along with associated reference frames

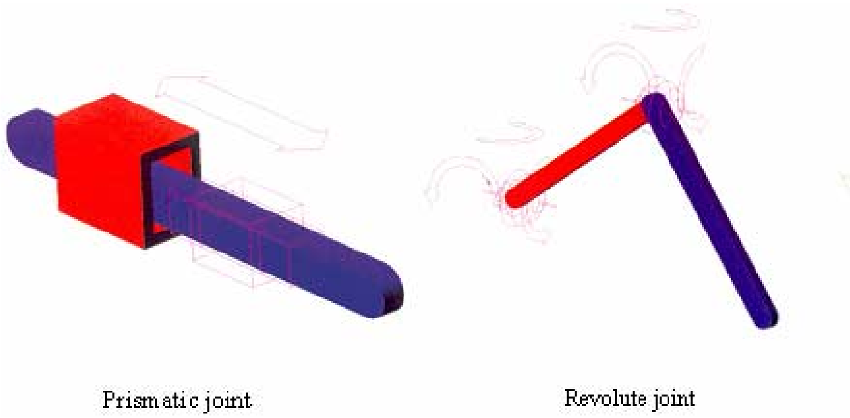


Figure 4. Examples of kinematic pairs

3.2 Solid modelling

In this phase, the geometry of each rigid body is defined using the CAD software. Detailed geometric models are generated and automatically associated to the schematic components of the skeleton. In this paper, feature-based CAD code Pro\ENGINEER® by Parametric Technology, with solid modelling capabilities, has been used in order to define complete and accurate properties of rigid bodies of mechanisms. Form features for single part modelling are used along with features to specify the mating relations between components (Figure 5). The latter features provide additional assembly-specific information based on relationships between geometric entities belonging to different parts/sub-assemblies. Thus, a mechanism is generated by assigning:

- kinematic constraints at the skeleton level, if there is some freedom of motion between two components with a contact relation;
- mating conditions at the assembly level, if there is no longer a freedom of motion between two components or the relative position of two components is specify by some additional relations (*assembly dimensions*).

The program developed in this work includes the utilities to associate each rigid body of the mechanism scheme with a solid model through the reference frame of the part (***csys_part***). Solid models contain all the rigid body data needed for dynamic analysis and all the surface data needed for visualization. In the CAD program, global properties like volume, surface area, moments of inertia and

centre of gravity are computed for later use in analysis. These data are directly related to the input entities needed for the rigid bodies modelling of a multibody system.
In Figure 6, the engine crank mechanism is shown as obtained associating feature-based CAD parts to the skeleton configuration of Figure 2.

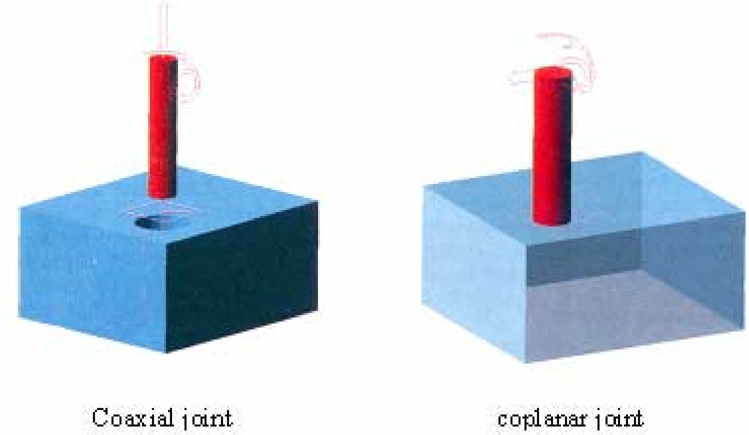


Figure 5. Examples of mating conditions

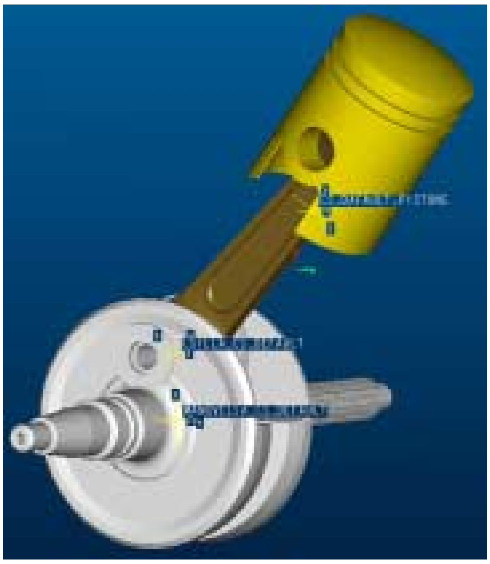


Figure 6. Feature-based solid model of the engine crank mechanism of Figure 2

3.3 Generation of multi-body models

A program that reads multibody system data from the skeleton configuration and from the CAD system, and writes input files for the multibody analysis code ADAMS® has been developed. The program reads the geometric and volumetric data created by the CAD code and writes multibody system data. This program uses specialized subroutines delivered with the CAD software. In particular, the customisation toolkit for Pro/ENGINEER® (Pro/TOOLKIT) has been used to access the solid modelling capabilities by writing C-language codes and integrating the resulting applications into the CAD environment.
The program is completely integrated within the CAD environment and uses the graphical utilities of the CAD code. For this purpose, Pro/TOOLKIT provides a large library of C functions that enables external applications to access the Pro/ENGINEER® database and user interface in a controlled manner. Consequently, the user works within the graphical user interface of Pro/ENGINEER while defining multibody systems. The transfer of data is performed without user interaction and control. This type of integration gives a user-friendly environment because the user interface is not changed

when moving from one application to another.
The data, that are interesting for multibody analyses, are simply extracted from the CAD code and associated to the kinematic structure defined in the top-down environment. Then, the program reads the multibody system data from the product database, manipulates the data and writes an ADAMS input file. In some cases, the transformation from the product database is straightforward and in other cases complicated. In particular, the following data are obtained from solid objects supplied with a physical or a unit density attribute:

- the total surface of the objects;
- the total volume of the objects;
- the total mass of the objects;
- a 3×1 vector describing the centre of gravity of each rigid body with respect to the global CAD internal frame;
- a 3×3 inertia matrix with respect to the centre of gravity and the parallel axes to the global CAD 3D inertia frame.

These output data are directly related to the input entities needed for the multibody modelling. The results of the mass property calculation do not depend on the solid modelling scheme used and they can be directly related to the input entities needed for multibody system modelling independently on the used CAD code.
The ADAMS input file is written in ASCII text file format. This file is used as input information to generate and run a simulation model. The file contains header information specifying geometric source data, simulation model units, run controls and shift information. Geometric models, which do not necessarily have volume properties, can also be considered. In particular, surface models are utilised for high speed 3D visualization and are implemented in graphics standards like IGES format.
Figure 7 shows the multibody representation of the engine crank mechanism of Figure 6 within ADAMS using a functional scheme where only necessary information for multibody analysis are represented (Figure 7-a) and the mechanism with nominal geometry (imported using IGES files) for visualization (Figure 7-b).

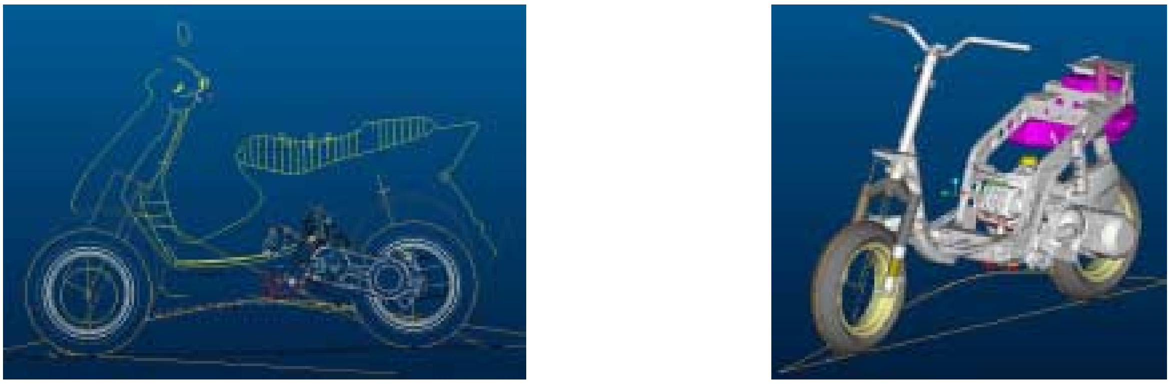
(a) (b)

Figure 7. Multi-body representation of the engine crank mechanism of Figure 6: (a) functional scheme, (b) nominal geometry for visualization

4. Virtual prototyping of two-wheeled vehicles

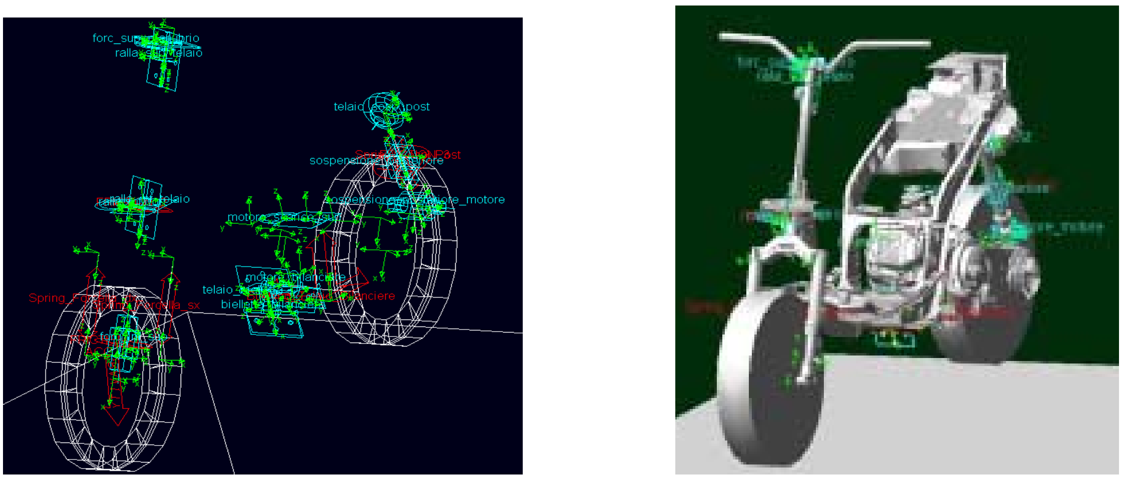
The integrated system for multibody modelling is suitable for simulating the behaviour of all typologies of mechanisms: simple models, which might either represent a simple system or the gross behaviour of a complex system, models consisting of a small number of interconnected bodies, and even models involving more complete assemblies. In this paper, the system has been used for virtual prototyping of two-wheeled vehicles.
In [Aspettati, 2001], a CAD-based framework for automatic configurations of motorcycles was developed using the concepts of functional abstraction and mapping. In this paper, the system has been modified to implement kinematic definition capabilities. The system, which is completely integrated within Pro/ENGINEER®, enables the management of all the kinematic and geometric data used during

the design process of two-wheeled vehicles. The top-down module enables the synthesis of a motorcycle scheme (Figure 8-a) that performs the desired functions, meets the performance standards, and satisfies the constraints. The skeleton consists of the schemes of frame, front and rear suspensions, surface model of the engine, wheels, ergonomic references, standard bump; space claims for vehicle rolling. The skeleton is adaptable to different dimensions and various mechanical solutions.
When the skeletal representation of the vehicle has been defined, individual component, such as frame, suspensions, battery, engine suspension, brakes, handlebar, silencer, radiator are assembled and associated to the skeletal elements (Figure 8-b). At this stage, individual parts can be related to each other also using other functionality such as mating relations to further capture design intentions.
The final vehicle model consists of a list of components and their hierarchy within the assembly design associated to the kinematic structure. The designer can add or remove assembly constraints using standard Pro/ENGINEER® commands.
After having assembled all the components, the geometric and kinematic data are processed to define the functional multibody model suitable for ADAMS code (Figure 9-a). Surface models, implemented in graphics standards, can also be included for 3D visualization (Figure 9-b). Dynamic simulation can now be performed. In this paper, a drop-test simulation has been successfully conducted. Figure 10 shows the multibody model with the forces acting on the vehicle and the plot of the forces acting on front and rear wheel axes obtained by a drop-test simulation



(a) **(b)**

Figure 8. CAD model a two-wheeled vehicle: (a) skeleton model, (b) feature-based assembly



(a) **(b)**

Figure 9. Multi-body representation of the two-wheeled vehicle of Figure 8: (a) functional scheme, (b) nominal geometry for visualization

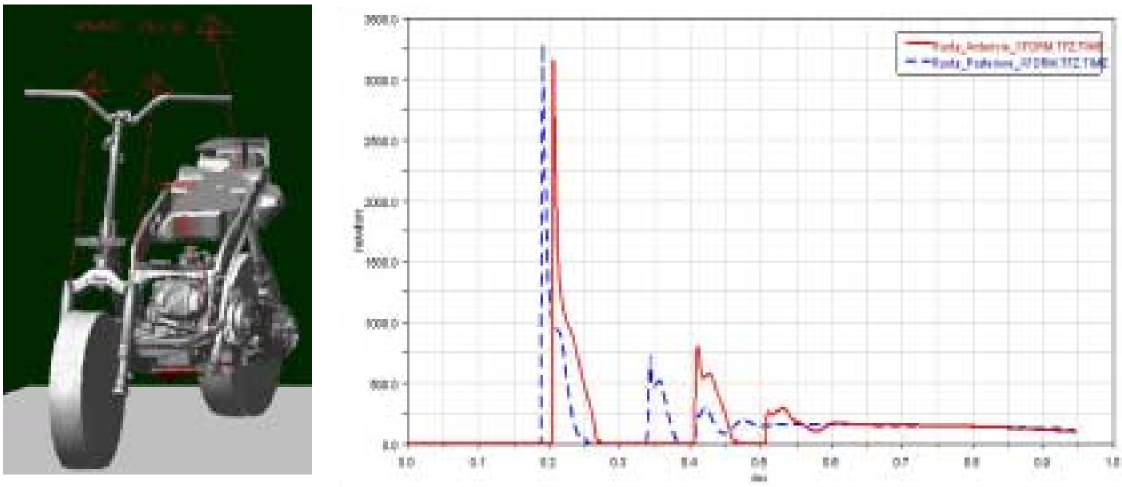


Figure 10. Forces acting on front (-) and rear (- -) wheel axes obtained by a drop-test simulation

5. Conclusions

In this paper, an integrated system for design and analysis of multibody system has been described. The system consists of commercial CAD and multibody codes integrated using an independent module to define mechanisms on the basis of a top-down approach. The main advantages of the integrated system are the possibilities of using calculated component data such as mass and moment of inertia from CAD code in the simulation models, the automatic formulation of input files for the multibody analysis code, and finally the visualization of simulation results using surface data of solid models.

The integrated system is suitable for design and analysis of even complex multibody systems, especially when parameter studies and optimisation are to be performed.

Acknowledgement

The authors gratefully acknowledge Piaggio S.p.A. for the technical support provided during the development of the work presented in this paper.

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