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An interactive virtual prototyping platform considering environment effect described by fluid dynamics

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ABSTRACT

Virtual prototyping (VP) technology has been regarded as a cost-effective way of envisaging real circumstances that enhance effective communication of designs and ideas, without manufacturing physical samples. Different from recent interactive VPs that are only based on multi-body systems, our VP platform is based on a multi-body coupled with fluid system, that is, the performance and functions of a VP will not be independent of environment factors or disturbances but interact with each other and constitute a whole system. Using this platform designers can simulate a robot through vacuum, air, water environments, etc., so it can provide a better support to the generality and quality of a VP. As for interactive manipulation, designers can modify the constraints between bodies, apply force/torque to interested bodies and change the parameters of forces/torques. Corresponding to user interaction, the platform automatically updates the dynamic behavior of the VP under current condition in the simulation loop. Furthermore, we implemented a virtual *MiniBaja* vehicle to verify the interactivity and effectiveness of this platform.

1. Introduction

VP (Virtual prototyping) is an advanced computer graphics simulation technology widely used in product development, which permits intuitive visualization of simulation results. Based on this technology, we can give important insights into the real-world behavior of a complex mechanical system, and designers can test, alter and improve controller design in an interactive way without fear of damaging the physical system and/or its environment. For example, by studying the effects of the input force/torque in an operation, permanent damages to a certain type of product can be avoided.

However, most recent VP packages focus on mechanical system models and solutions, and neglect environment effects such as air and water disturbances; using this kind of package we can only simulate some robots in a vacuum space, but not in a real one. This means that this kind of VP will inevitably lose realism and general applicability, especially in cases concerning undersea robots. In this paper we dedicate ourselves to contributing to this issue by constructing a VP platform on which environment effects and mechanical systems will be considered as a whole.

This paper is organized as follows. Section 2 provides an overview of related works. Section 3 describes our VP architecture, and then the multi-body dynamics model and its solution are presented in Section 4. For environment effects, we derive fluid force/torque on a VP from immersed boundaries method in Section 5. Issues concerning the incorporation of dynamic interaction in virtual environment are addressed in Section 6. An example of implementation and an analysis of simulation results are described in Section 7. Finally, in Section 8 the conclusion is given.

2. Related works

Usually, the VP technology uses a graphical model for visualizing and a physical model for producing realistic animation sequences of a scene involving rigid or deformable objects [1]. Similar concepts were also applied to simulate robotic grasping tasks [2,3]. So, translating CAD graphical models to physical ones has to be made. Presently, there is a large amount of commercial and non-commercial applications available on the market offering native conversion between common standard and other well-known CAD data formats. Thus without subsequent restrictions it is assumed that the source data is available in the format that the used CAD system like Pro/E is able to import. For example, under Pro/E environment the freely available Pro/E-to-Matlab plug-in lets us export our given CAD assembly to a single descriptor file called "Physical Modeling XML", which is invented to ease the generation of physical models out of Pro/E data in an automated way [4].

Then regarding the physical modeling of a VP, Bae and Haug [5] apply *D'Alembert*'s principle of virtual work in its dynamics formulation, while Keat [6] uses a velocity transformation, Rosenthal [7] as well as Anderson [8] use Kane's equation and

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Pradhan and Modi [9] employ *Lagrangian* method with velocity and position transformations. Among these formulations, Rosenthal's order-*n* formulation is one of the best known because of its computational efficiency. His formulation is applied by Banerjee [10] to simulate dynamic behavior of an extrusion beam undergoing large deflection, whose DOF (degree of freedom) changes with time. It also has been shown that inter-body constraint forces can be easily computed as a bonus feature of the algorithm without extra computational cost [11]. However, his formalism is limited to systems with open-chain topology. Using specific formalism borrowed from quaternion algebra, Tasora [12] developed and tested a fast solution scheme for the *Lagrangian* multiplier method of *n*-body mechanisms successfully, which handles problems like constraint stabilization, intermitting contacts, redundant joints and impacts, consequently allowing its application to complex problems of interactive dynamics.

While the contact among some objects in a virtual environment, Baraff overviewed the researches on unilateral contact in detail and consistently argued that the methods have to resort to complex model whose solution existence and multiplicity must be dealt with [13]. To overcome the discontinuity of the *Coulomb* friction law, Song et al. [14] introduced a smooth nonlinear friction law, which approximates *Coulomb* friction. Such a friction model can increase the efficiency of both rigid body and compliant contact simulation. Hippmann [15] presented a new contact algorithm for analyzing contacts of complexly shaped bodies in multi-body dynamics, which is based on representation of the body surfaces by polygon meshes and contact force determination by elastic foundation model.

Coming to dynamic simulation of mechanical products, many companies have been developing tools to improve their design process. A successful case [16] is the design of the Boeing 777 airplane. Haug et al. [17] developed a new class of implicit SDIRK (singly diagonal Runge–Kutta) methods for solving stiff ODE, which has been implemented in the commercial DADS software for vehicle engineering. Stribersky et al. [18] outline their techniques for numerically simulating motion of a virtual metro train. Various components of a virtual train were modularized into a database that allowed the authors to examine various configurations. Some of their calculated results are compared with measurements made on an actual prototype rail vehicle. In DigitalSpace Damer et al. [19] created a virtual model of Bucket Wheel Excavator, which is a common mining vehicle adapted for lunar size and power. This virtual vehicle in a lunar base/ISRU processor setting proves that a physics-based, force feedback joystick driven simulation could be delivered to consumer personal computers via internet.

In order to improve model and simulation accuracy, some researchers are paying much more attention to environment effects on VP [20–22]. The environment effects are often modeled as a result of various hydrodynamic forces. While these forces result from incompressible fluid flow determined by the Navier–Stokes (distributed fluid-flow) equations [23], "lumped" approximations to these forces are always used. Yuh [24] and Ioi and Itoh [25] have identified four separate effects that need to be included in a dynamic simulation of submerged rigid bodies. Under limiting assumptions that the net hydrodynamic force on an object can be represented as a sum of separately identified components modeling the effects of added mass, drag, fluid acceleration and buoyancy forces. However, the added-mass effect of an accelerating rigid body in a viscous flow is still in controversy [26].

3. Architecture

Fig. 1 illustrates the architecture of our VP platform, which contains several modules. The CAD-VE data translation interface handles the mechanism model data, which can be imported from CAD systems. The external force/torque module enables users to control the simulation in the virtual environment by 2D or 3D interaction. Employing DAEs description for each object and fluid, the solver module calculates and returns simulated results to users. After the DAEs solution, updated dynamic information such as joint angles, velocity, acceleration, generalized forces, etc. will be sent to the postprocessor module to update the display of the simulated result visually. It also exports the model and result data to files stored in disk, which can be exchanged among other software.

In process of data translation from a CAD model to our VP platform, the design information of a mechanical product created in CAD system is dealt and exported in a neutral file format by Pro/Toolkit APIs. Such information includes geometry features (vertexes, edges, faces, etc.), topology of all parts and the assembly

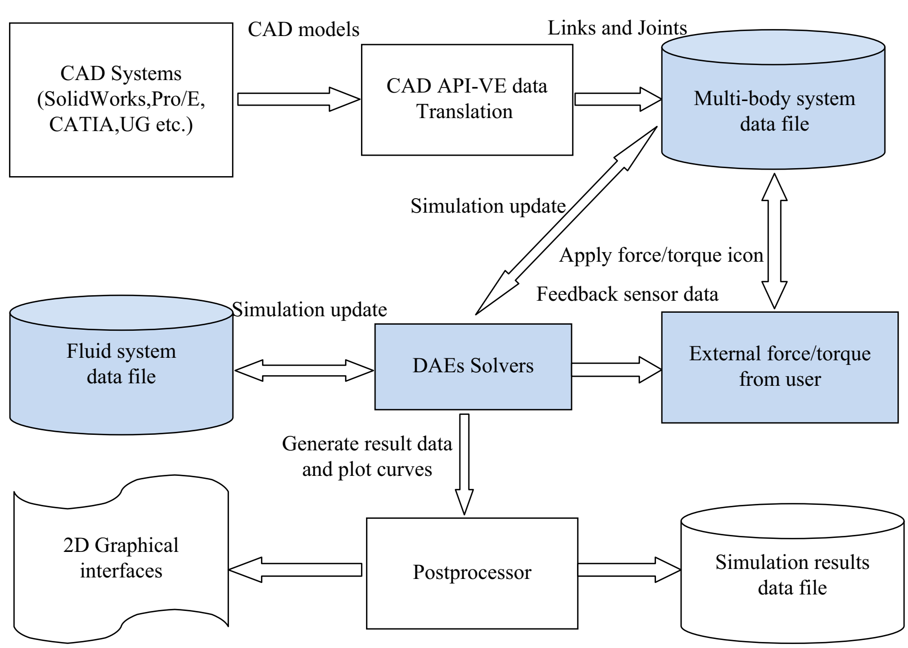

Fig. 1. Architecture of our VP platform.