CONTROL-CENTRIC SIMULATOR FOR MECHATRONICS DESIGN
Case Study: Gyroscopically Stabilized Single Wheel Robot

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Abstract— A 3-Dimensional simulation platform developed as an aid for designing complex mechatronics system is presented in this paper. It uses ADAMS for simulation with animation of the dynamic behavior of the mechanism whose parts are drawn using a 3-D drawing software e.g., SolidWorks. The overall simulation platform integrates the 3-D simulator ADAMS with control design software MATLAB. This integration allows the designer to adopt a control-centric approach for designing complex mechanical structure to be used in a mechatronics system. Dynamic analysis of single wheel robot is used in this paper as an example to illustrate its uses. The simulating environment can easily be extended to any complex mechanical system simply by altering SolidWorks drawings.

Index Terms—Gyrobot, ADAMS, Single wheel robot, Dynamic simulation

I. INTRODUCTION

THIS article presents a control-centric approach for designing mechatronics systems. In this approach, design of controller is not treated as an isolated problem. Rather design of the mechanism and design of controller are considered intertwined. Two designs should be carried out concurrently. In this paper, we outline the method of concurrent design by placing a virtual prototype of the mechanical system under closed loop control to analyze the dynamic behaviour of the system and thus to fine-tune the mechanical design.

Simulation is important for designing any mechatronics system that involves complex structure and operations. Traditionally, most simulations are computer based and require mathematical modeling. Such model is used for describing system dynamics and for finding its dynamic response. The models are used to predict system behavior for a given set of known parameters and initial conditions.

ADAMS, which was developed for 3-D motion simulation, is integrated with MATLAB/SIMULINK, popular software among control community, to create the control-centric design platform. The motion simulator uses three dimensional mechanical drawings of different sub-systems to be combined into a complex mechatronics system. This eliminates the need for deriving complex, nonlinear mathematical models for the dynamic behaviour of the system. The simulator has been effectively used for the analysis of dynamic behavior of the *gyrobot* in both open loop condition and with closed loop controller.

ADAMS (Automatic Dynamic Analysis of Mechanical Systems) started as a general purpose program that can analyze systems undergoing large non-linear displacements while under the effect of non-linear force and motion input. The methodology was developed by Nicolae Orlandea [1]. It can be categorized as a general purpose numeric code utilizing a non-minimal set of co-ordinates to develop the equations of motion. This motion simulation software analyzes complex behavior of mechanical assemblies and thus enables users to test virtual prototypes and optimize designs without having to build numerous physical prototypes. It uses stiff integrators to solve these equations and sparse matrix algebra to solve the linear algebraic equations in its innermost computation loop [2]. Since its inception, significant development investments resulted in sophisticated virtual prototyping tools for a wide range of industrial applications. Use of virtual prototyping for design and development of a humanoid robot has been reported in a recently published article [3].

ADAMS allows users to import geometry from CAD systems or to build a solid model of the system from scratch. We used the first approach; different parts of the *gyrobot* were created using SolidWorks. These components are then transferred to ADAMS where final model is elaborated.

The *gyrobot* is a wheel shaped autonomous vehicle [4]-[5]. Motivation of this design is rooted in the stability of a running bicycle and its excellent capability to maneuver. A rolling wheel has inherent tendency of remaining upright. If such wheel is tilted, instead of falling on side, it turns towards the side it is tilted to. Special structural design of *gyrobot* incorporates in it these features of rolling wheel.

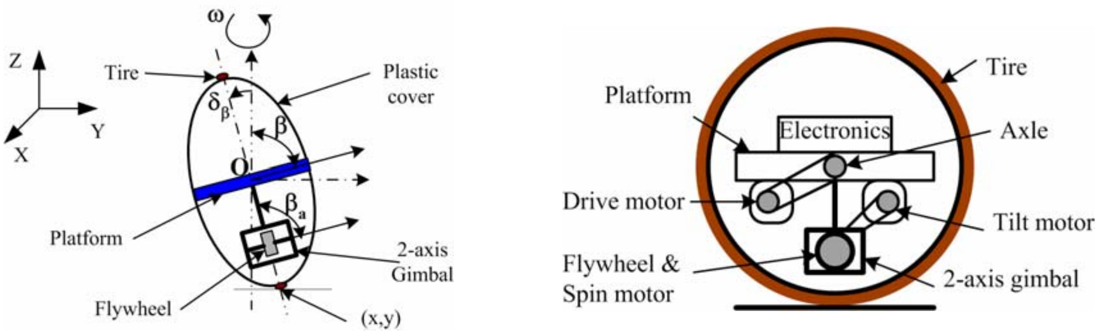
The integrated simulator platform will simplify the phases of design of a mechatronics system. Moreover, it can be used by students and researchers alike to have an in-depth understanding of any complex mechanism. Integration of ADAMS with MATLAB enables control engineers to complete the design cycle without building any prototype. Simulation results can also be used to fine tune mechanical design. Results presented in this paper include (i) open loop simulation of *gyrobot* using ADAMS, and (ii) simulation of the closed loop system. The integrated system can be used for the control-centric design of any mechatronic system simply by replacing the 3D drawings of the mechanical structure of *gyrobot* with that of any complex system.

Structure and principle of *gyrobot* are explained briefly in Section II. Dynamic simulations of the *gyrobot* presented in Section III illustrate basic principles of operation. Results of closed loop simulation are given in Section V. Key features of the developed system and possible areas of improvement are highlighted in the conclusion.

II. GYROBOT: MECHANICAL STRUCTURE AND MODEL

Design of the *gyrobot* is motivated by the excellent steering capability and dynamic stability of a moving bicycle. Stability of this special structure of autonomous vehicle and its ability to steer can be explained using dynamics of rolling wheel as example. The angular momentum of the rolling wheel restrains it from falling on its side. If the wheel is tilted to one side, instead of falling it turns towards that side due the phenomenon called gyroscopic precision. These two mechanisms are exploited in achieving stability and steering of the wheel-shaped *gyrobot*. Actuation required to tilt the *gyrobot* comes from the reaction to the tilting of a heavy flywheel spinning at high speed. The flywheel is placed inside the *gyorbot* shell and is hung from the axle of *gyrobot* using a two-axis gimbal. Large angular momentum of the flywheel adds to the dynamic stability and provides insensitivity to attitude disturbance. As a result, even stationary *gyrobot* can stand upright. This special structure has advantages in many aspects over conventional multi-wheeled autonomous vehicles. Since electronic components are enclosed, the *gyrobot* is especially suitable for deployment in wet areas.

Principle of operation of the *gyrobot* can be explained using the schematic drawing shown in Fig. 1. The flywheel is suspended from the axle of the *gyrobot* using a gimbal assembly that enables tilting of the spinning flywheel. The flywheel is attached to the inner gimbal and is spun by the spin motor. The tilt motor, which is attached to the outer gimbal, can tilt the inner gimbal plus fast spinning flywheel to either side. The gimbal and flywheel structure is suspended from a platform and the axle of *gyrobot* is passed through this platform. The outer shell of *gyrobot* is rigidly joined to the axle. Running the drive motor makes the wheel roll; rolling speed can be controlled by controlling RPM of drive motor. Interested readers may refer to [4]-[6] and many other references cited there for details on the operation of a gyroscopically stabilized single wheel robot.



(a) viewed from back (b) side view

Fig. 1: Internal mechanism of gyrobot

Gyrobot model drawn in SolidWorks and actual hardware are shown in Fig. 2. Size and shape of each part are created as par size and shape of the actual component. To reduce the complexity of model in ADAMS, only the mechanical parts are included in the SolidWorks drawing; these are the outer wheel, the inner gimbal, the outer gimbal, the flywheel with its supporting structure. This structure is sufficient to reflect the physical properties of *gyrobot*, which will be examined later. Mass, density and frictions are defined in ADAMS/View.

(a) Solidworks drawing of gyrobot (b) Hardware of internal mechanism

Fig. 2: External view and internal mechanism of gyrobot

III. DYNAMIC SIMULATION IN ADAMS

In this section, we present simulation results to illustrate the basic operation of the *gyrobot*. These open loop simulations are carried out using ADAMS only.

A. Gyrobot Model in ADAMS

The ADAMS model of *gyrobot* is created by importing the 3D drawings in Solidworks as *parasolids* file. Material, mass, density and friction are then defined. Mass and inertial are automatically calculated. Table I lists main dynamic characteristics of the robot components for the proposed ADAMS model.

Gyrobot model in ADAMS environment takes several aspects into account, such as gravity, contact constraints, friction, inertial properties and reference markers, which enable good approximation of real robot behavior. Each joint of the mechanism is defined with a particular motion. For example, the driving joint is specified as a revolute joint so the rotation associated with this joint specifies the rolling motion of the wheel.

TABLE I: MAIN INERTIAL DATA FOR GYROBOT MODULES

Parts	Mass (kg)	I_{xx} (kg m^2)	I_{yy} (kg m^2)	I_{zz} (kg m^2)
Wheel	0.85	2.78×10^{-2}	1.582×10^{-2}	1.58×10^{-2}
Flywheel	1.02	1.21×10^{-3}	0.65×10^{-3}	0.65×10^{-3}
Shaft	0.15	1.55×10^{-3}	1.55×10^{-3}	0.69×10^{-6}
Inner gimbal	0.75	1.54×10^{-3}	1.38×10^{-3}	3.63×10^{-4}
Outer gimbal	1.44	7.53×10^{-3}	7.43×10^{-3}	2.13×10^{-3}
Total	4.22	39.63×10^{-3}	11.17×10^{-3}	3.30×10^{-3}

B. Simulation Settings

Proper dynamic simulation requires an approximation of the properties of contact between ground and wheel rim. The actual *gyrobot* rim is wrapped in aluminum foil and is tested on a horizontal surface covered by aluminum plate. The friction coefficients chosen are 0.95 for the static condition and 0.8 for the dynamic condition, in agreement with [7].

ADAMS/Solver does all the calculations required to simulate the motion. It allows different types of integrator for a particular problem. Detailed explanation on each integrator can be found in ADAMS/Solver documents.

For integrator setting, GSTIFF is the recommended integrator for most of the mechanical systems. We use default integrator, formulation and corrector. One may use other integrator settings, based on the simulation type (for models other than *gyrobot*) with clear understanding of integrator setting documents on ADAMS/Solver.

One has to specify simulation frequency, internal frequency and step size. Simulation frequency is the frequency of updating the graphic display, whereas internal frequency is closely related to the system under study. It represents the speed at which component states are changed. Internal frequency is very important parameter in simulation setting and other solver settings must be set in accordance with the internal frequency.

The flywheel is the fastest moving object in the whole structure. If flywheel frequency is Y degrees per second (calculated based on its speed) and the desired motion of the flywheel in each step of integration is θ_{Step} degree, then the optimal step size (H_{max}) is obtained using,

$$Y \times H_{\max} = \theta_{Step}\,.$$

For example, when the flywheel speed is set to 7000 rpm or 420000 revolutions per second and the flywheel is expected to rotate by 5° in each integration step then H_{max} should be set to 5/420000.

C. Results of Open Loop Simulation

Law of conservation of momentum and gyroscopic precession govern the operation of the *gyrobot*. Large angular momentum of the fast-spinning, heavy flywheel aids to overcome the external disturbance such as tilting torque caused by gravity. According to conservation of angular momentum, the higher the spin wheel velocity, the longer the robot should be able to stand by itself.

We verify the effect of flywheel speed on the balancing the wheel by simulating the motion with different flywheel speeds while keeping external forces, e.g., gravity unchanged. Simulations are carried out with seven different flywheel speeds between 1000 rpm and 7000 rpm, the highest speed of the flywheel. For each flywheel speed, simulation is done for two conditions – (a) keeping *gyrobot* stationary and (b) making it roll at a speed of 30 rpm. Results are summarized in Table II. It is clearly evident that time elapsed before the fall of *gyrobot* increases with increasing flywheel speed, which conforms to the conservation of angular momentum. When the wheel rolls, its angular momentum adds to the angular momentum of the flywheel aiding the balancing effort. It is observed that for identical flywheel speed, time elapsed before the fall is longer when *gyrobot* rolls.

TABLE II: RESULTS OF STABILIZATION TEST

Flywheel speed (rpm)	Time Elapsed before Fall of gyrobot (seconds)	
	Rolling speed = 0	Rolling speed = 30 rpm
1000	2.7	4.5
2000	2.9	13
3000	3.4	20
4000	4.5	26
5000	7.6	35
6000	13	50
7000	13.9	50

Effect of gyroscopic precession is verified using tilt test. When a torque is applied to change the spinning axis of the fast-rotating flywheel, it rotates about the precession axis. This causes the entire system to precess. Change in wheel lean angle (δ_β) is related to the precession rate according to the following [8],

$$\delta_\beta = \frac{\dot{\alpha}\left[\left(2I_{xw} + mR^2\right)\dot{\gamma} + 2I_{xf}\dot{\gamma}_a\right]}{gmR}, \text{ where,}$$

δ_β : change in lean angle of wheel from vertical position

$\dot{\alpha}$: gyrobot precession rate

$\dot{\gamma}$: gyrobot rolling speed

$\dot{\gamma}_a$: flywheel spin speed

g : acceleration due to gravity

m : mass of the gyrobot

I_{xw} : moment of inertia of the gyrobot

I_{xf} : moment of inertia of the flywheel and

R : radius of the gyrobot wheel.

During the tilt test, *gyrobot* is assumed standing on a flat surface with the flywheel spinning at 3000 rpm. At 0.5 second, the flywheel is tilted from 0° to 23° in 0.5 second causing an average tilt velocity of 46°/s. The results of this simulation are shown in Fig. 3. The plots show that while the flywheel is tilted by 23°, the entire *gyrobot* is tilted by -57°. This conforms to the simulation and experimental results published in [8]-[9]. Leaning velocity and precession rate of the *gyrobot* are also plotted in the same figure. The test is repeated by tilting the flywheel from 0° to -7° in 0.5 s. Again the results shown in Fig. 4 are in conformity with the concept of gyroscopic precession.

Fig. 3: Simulation result for changing tilt angle of flywheel from 0° to 23° in 0.5 s.

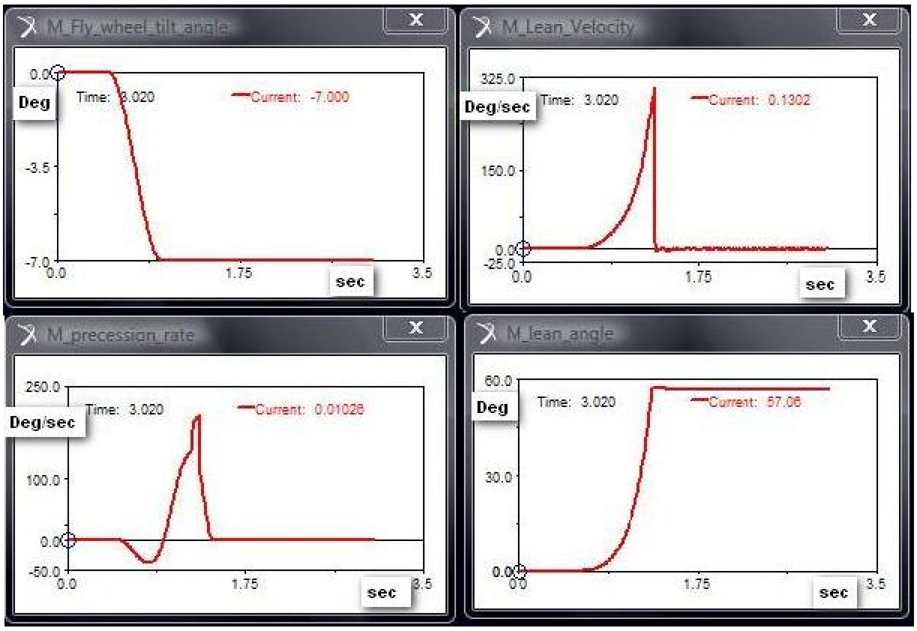


Fig. 4: Simulation result for changing tilt angle of flywheel from 0° to -7° in 0.5 s.

IV. SIMULATION WITH CLOSED LOOP CONTROL

Development of this design environment is motivated by the need for a control-centric approach for mechatronics design. Incorporating the capability of simulating under closed loop control is essential. In this section, we present simulation results for closed loop control.

A. Controller implemented in ADAMS

As a first step, the *gyrobot* is placed under closed loop control with controller realized in ADAMS. Our ultimate goal is an interface between ADAMS and MATLAB. Such interface would ensure that each software is used for the task it is appropriate for – ADAMS for 3D dynamic simulation of mechanical structure and MATLAB for design of controller.

Simulation results with a PD (Proportional plus Derivative) controller implemented in ADAMS are shown next. Controller used for these simulations was reported earlier in [6], which was designed using a linear model of the *gyrobot,* obtained by linearizing system dynamics at its vertical position. So the controller may not work well when the lean angle is large. The control law used for this simulation is given next, where $\delta_\beta = (\beta - 90°)$ is the change in lean angle from the vertical position, i.e., $\beta = 90°$,

$$u = k_1(\delta_{\beta,ref} - \delta_\beta) + k_2\dot{\delta}_\beta \,.$$

Gains of the controller are chosen as k_1 = 10 and k_2 = 5. Flywheel speed is kept at 7000 rpm. Simulation is carried out for a step change in $\delta_{\beta,ref}$ from 0° to +10°. Initial conditions for this simulation are set as:

- Change in lean angle (δ_β): 0°
- Angle of flywheel tilt ($\delta_{\beta a}$): 0°
- Wheel lean velocity: 0°/s
- Flywheel tilt velocity: 0°/s

- Wheel velocity: 30 rpm

Simulation results with controller implemented in ADAMS are shown in Fig. 5 and Fig. 6.

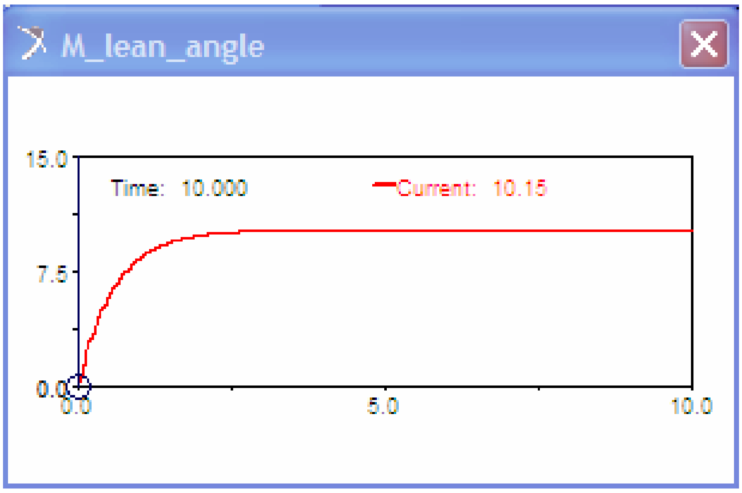


Fig. 5: Lean angle with $\delta_{\beta,ref} = 10°$ (controller in ADAMS)

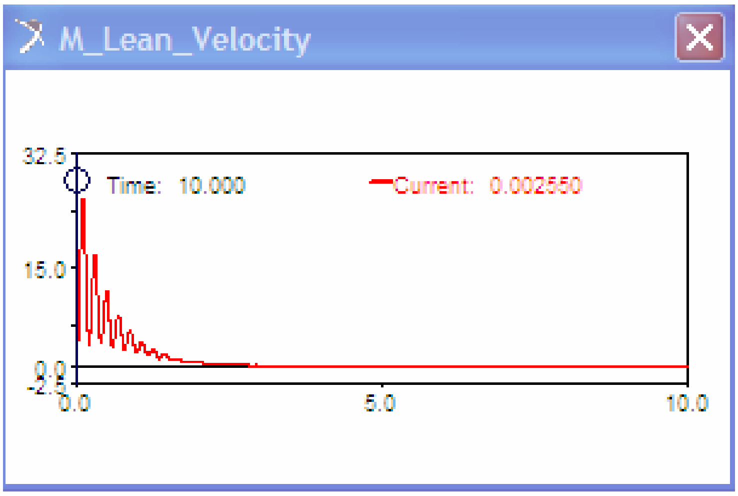


Fig. 6: Lean angle velocity (controller in ADAMS)

B. Controller implemented in MATLAB-SIMULINK

As ADAMS is meant for 3D simulation of dynamics, it has very limited capability for realizing a controller. We created an interface between ADAMS and MATLAB/SIMULINK so that the controller can be implemented using SIMULINK.

Closed loop responses with controller realized in SIMULINK are shown in Fig. 7 and Fig. 8. These results are identical to those obtained with controller realized in ADAMS. Integrating ADAMS with MATLAB let us exploit the better aspects of both. Now we are no longer restricted by the limitations of ADAMS in implementing controllers and we can experiment with more complex controller structures including fuzzy logic control, sliding mode control etc.

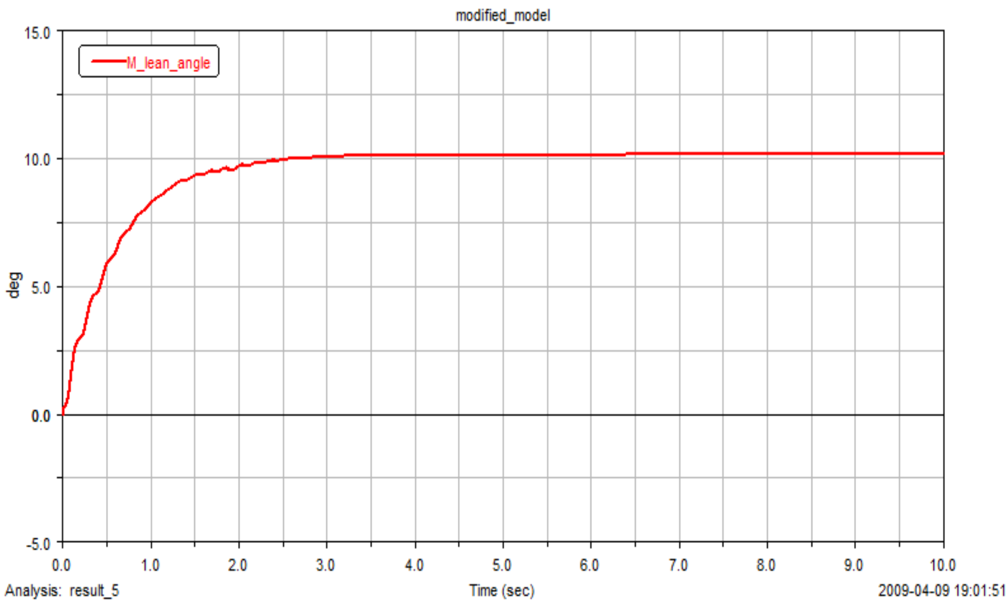


Fig. 7: Lean angle with $\delta_{\beta,ref} = 10°$ (controller in MATLAB)

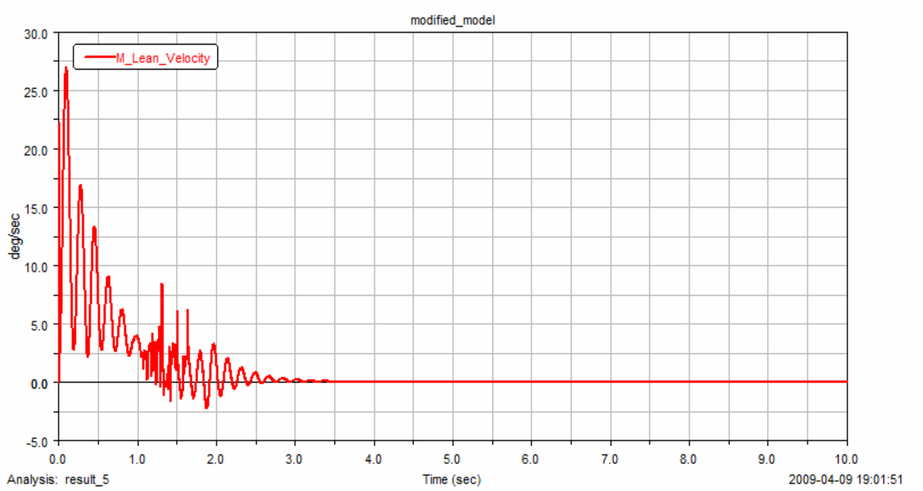


Fig. 8: Lean angle velocity (controller in MATLAB)

V. Conclusion

Dynamic simulation of *gyrobot* in ADAMS environment has been successfully developed. Several tests have been carried out to verify principle of operation of the *gyrobot*, namely the law of conservation of angular momentum and gyroscopic procession. Test results show that the virtual prototype's behavior is in accordance with the two principles and, therefore, the virtual *gyrobot* created in ADAMS represents the actual mechanical system.

A controller is also implemented to strengthen the justification of building such virtual robot. The virtual prototype can now be used for various investigations which are otherwise time-consuming or costly.

Using the internal control template provided by ADAMS to design and implement closed loop operation limits the flexibility of this virtual system as an effective tool. So we integrated ADAMS with MATLAB /SIMULINK to exploit its strength.

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