Multi-body simulation methods for rigid manipulators

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***Abstract*— This paper examines CAD- multi body dynamics approach of modeling and simulation for rigid manipulators. CAD is used for designing mechanical links that can be assembled into linkages and mechanisms. The technique of using CAD designs in multi-body simulation environments has been studied. A summary of procedures is included. Further, the design prototype has been actuated using two input devices popular in the gaming industry, and an overview is presented below.**

I. Introduction

This research is based on material removal after search and rescue (SAR) lifesaving operation scenario. For this purpose, the excavator manipulator mechanism was chosen since they are ubiquitous in SAR sites. In recent years, there have been advances in multibody simulation software. In design methodology, CAD-multi-body dynamic (MBD) simulation in the initial design phase reduces design cycle time. Commercial engineering simulation software have been adapting to changing user requirements by being more user friendly and intuitive. Simulation using combination of CAD-dynamic simulation packages also enables the engineer to access the specific capabilities of different software packages.

Using the appropriate combination of design and analysis packages reduces design cycle times, and permits the analysis of complex mechanical systems. In addition, the design engineer and control engineer can work concurrently thus making the overall design process more efficient. The concept of a simulation environment e.g. game engines, can be advantageous for low cost robot simulation and training[1].

In this paper, the Newton-Euler approach using MBD has been presented. This method helps overcome errors in equations, with accurate and instant calculation of body parameters such as mass and moments of inertia. Joint motion parameters can be easily applied and the respective motion or force parameters can be easily read by using sensors.

Kinematics and dynamics have been considered in both cases. The method can be applied across serial and parallel mechanisms, with the latter offering more robust performance. The different concepts, approaches and procedures have been examined in this paper.

II. Modeling of the System

A. Kinematic modeling

The 3-link excavator kinematic mechanism has been modeled in the 90's [2] following the Denavit-Hartenberg convention of axis assignment, which has 4 degrees of freedom (DoF). The kinematic formulation for the RRR (3DoF) mechanism is considered, since the cab does not slew during digging.

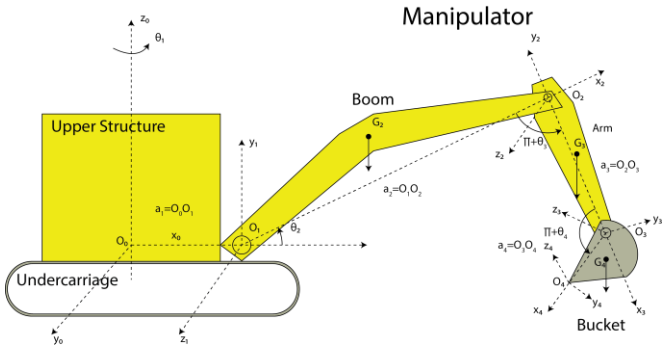

Figure 1 Coordinate assignment and nomenclature of excavator

B. Dynamic modeling

There are 2 approaches to modeling a dynamic system, the classic approach of numerical modeling, and the concept of physical modeling. The advantages and disadvantages of both systems have to be considered while designing the multi-body simulation. Rigid links are assumed.

In traditional numerical modeling, the dynamic model is derived from first principles. Three approaches can be found in literature:

1. Newton - Euler method (force-torque)[3]
2. Euler - Lagrange method (energy)[4]
3. Kane's equation (virtual work)[5]

For 3-link excavator mechanism, having 3R planar configuration the three methods has been presented in literature. Method 1 is seen to be most computationally efficient and is used widely. This is also the method followed in the multi-body dynamic simulation package. The third method allows for the elimination of pseudo-forces forces in the joints.

According to the energy approach, the dynamics equation can be given as[6]:

$$\boldsymbol{D_a(\theta)\ddot{\theta} + C_a(\theta,\dot{\theta})\dot{\theta} + G_a(\theta) + B_a(\dot{\theta}) = \Gamma\tau_a - F_L}$$

where $\theta = [\theta_1\ \theta_2\ \theta_3\ \theta_4]^T$ is the vector of joint angles $D_a(\theta)$ is a 4x4 matrix which represents inertia, $C_a(\theta,\dot{\theta})$ represents Corioli's and centripetal effects, $G_a(\theta)$ represents gravity forces, $B_a(\dot{\theta})$ represents frictional forces, Γ is the input matrix corresponding to joint torques $\tau_a = [\tau_1\,\tau_2\,\tau_3\,\tau_4]^T$, F_L represents soil-tool or machine-environment interaction forces during digging operation. The first angle, θ_1 represents the rotation of the manipulator about the base of the excavator; the manipulator operation is assumed planar during digging

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since it does not turn about the base during this task, i.e. RRR. The equation reduces to 3x3 form for the planar manipulator.

In the physical modeling, CAD assembly is exported to MBD environment. The data from CAD is exported in 2 formats - .xml for the body properties such as link masses, moments of inertia etc., and .stl (or stereo-lithography) the CAD file visualizations. A common disadvantage of both systems is that no contact modeling occurs and the calculations are based around the centers of gravity of the bodies without accounting for surface contact.

III. Control

The system is fully actuated. Position control was first implemented in early literature. PID control[7], is sufficient if the loading at the end effector tool center point (TCP) is linear and non-time varying. Later models have implemented computed torque control, adaptive and robust control etc. [4]. However in excavators, the tool center point (TCP) is subjected to working with highly non-linear loads when used with bucket attachment.

From the perspective of control, many researches are ongoing regarding full automation of excavators [6][8]. However due to the subjectivity of the task, and non-repeatability of each dig trajectory, a fully automated digger is largely conceptual. With the increasing accident rates in construction equipment[9] , the first step would be to remove the operator from the machine to reduce risk to the life. Towards this end, two game controllers were tested with the software prototype.

A. Input Controllers

Two input control devices were selected 1) Logitech Wingman force 3D and 2) Xbox 360 controller (Figure 2). The first device is a joystick with force feedback and the second is a gamepad. SAE convention for excavator manipulator is followed in mapping input device layout. Both devices are relatively low cost. The second controller is especially robust in construction. The signals were extracted in the Simulink environment using the joystick input block and were linearized to form input for forward kinematics.

Figure 2 Input Controller 2

IV. Simulation

The steps toward simulation are outlined below:

A. CAD Modeling

The first step towards developing a new design in CAD would be to arrive at the approximate dimensions. Here the first design approximation was used a 1:10 scale dimension from the excavator model in literature. The second iteration involved simplifying the design for multi-body analysis. Constraints were applied to the relative link movement e.g. revolute joint for the 3R mechanism, and prismatic joint for the linear actuator. Aluminum alloy was assigned to the first two links, and the third link was assigned hardened steel.

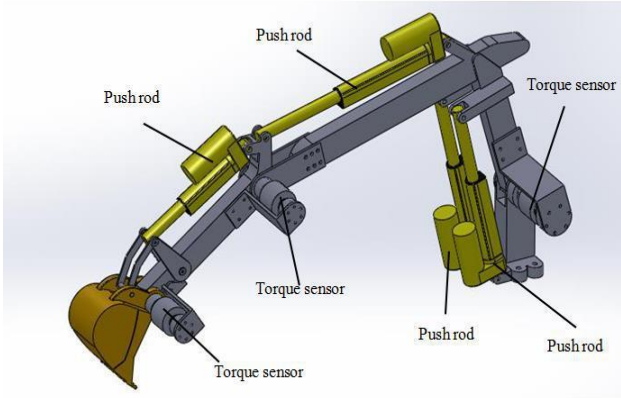

Figure 3 CAD assembly of parallel mechanism

B. Exporting CAD model to multi body dynamics software

SimMechanics software is widely used for MBD simulation. The design data i.e. link parameters, is exported in .xml, and the CAD visualization is exported as .stl.

C. Import into multi body dynamic software

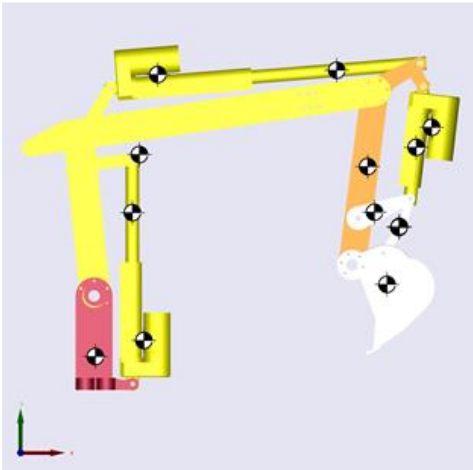

Figure 4 Imported CAD design visualized in SimMechanics 1G

The imported model needs to be checked for appropriate relation between links, i.e. for whether it is prismatic or revolute, and for appropriate units and coordinate systems.

D. Joint Actuation

Input for joint actuation is provided from a custom forward kinematics module created by us. Joint input requires angular motion including angle, angular velocity and acceleration.

E. Sensors

The advantage of using MBD software is that joint motion parameters and force parameters can be read directly using joint sensors. Joint motion and force parameters including computed torque, reaction force, and reaction torque.

F. Simulation modes

The MBD environment has 4 modes: Kinematics, Forward Dynamics, Inverse Dynamics and trimming mode. The first three modes are straightforward and require no explanation. Trimming mode is a steady state analysis mode, which calculates the solutions for the mechanism satisfying specified conditions beforehand.

V. Visualization

Design engineers rely on visualization for verification, and checking physical performance of mechanism. Interference checks in CAD and MBD ensures the designed linkage meets physical performance requirements, and does not interfere with itself or with other components. To achieve this, the visualization capability of MBD package can be used. Alternatively, for high fidelity visual approach, Simulink3D animation.

A. SimMechanics

Animation mode can be toggled from the control window. First generation allows the designer to play animation along with dynamic simulation while second generation decouples animation from dynamic simulation, making it independently replay-able.

B. Simulink 3D Animation

Alternatively, for high fidelity visual approach, Simulink3D animation with VRealm editor can be used, driven by the signals from dynamic simulations. Simulink3D animation is a very powerful visualization tool, albeit tedious owing to the underlying VRML modeling language.

C. Visualization in game engine

An alternative technique for 3D simulation environment is using game engines, which has its advantages and disadvantages. Among the advantages are surface contacts, kinematic and dynamic simulation, destructible and deformable surfaces, POV cameras and most importantly the ability to freely model the robot. The disadvantages include approximations in dynamic interactions, and grey or black-boxed components.

Perhaps what is most interesting is that this modeling environment has customizable gravity, designable levels (scenes), and destructible objects, which can be used to train a SAR operator based on the required application, at a minimal cost [1].

A convergence in engineering simulation and game simulation, across the current 'chasm' that divides the two, is expected in the future.

VI. Results

The results from simulation of 3 link serial actuator have been presented below. The simulation has been run for 10 seconds with specified input. Figure 5 shows the motion parameters - angular input, and its derivatives for the first

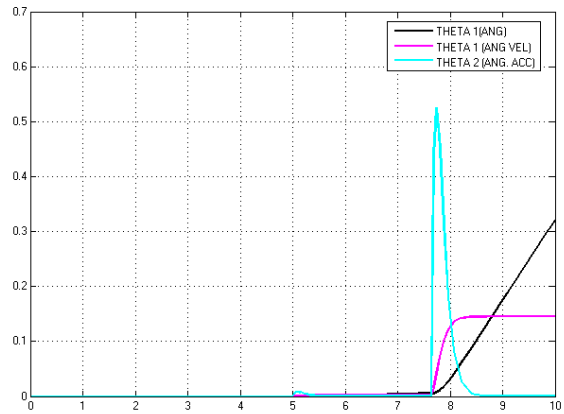

Figure 5 Input parameters for joint 1

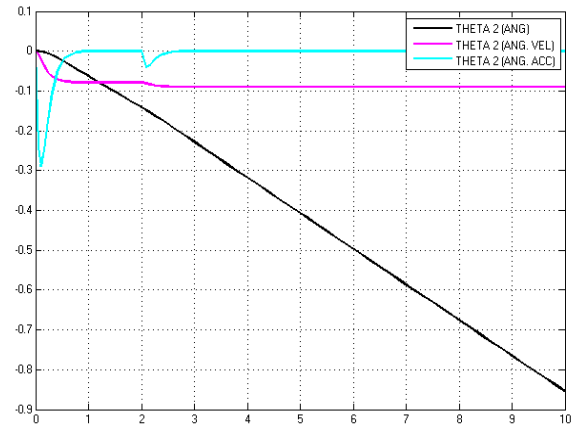

Figure 6 Input parameters for joint 2

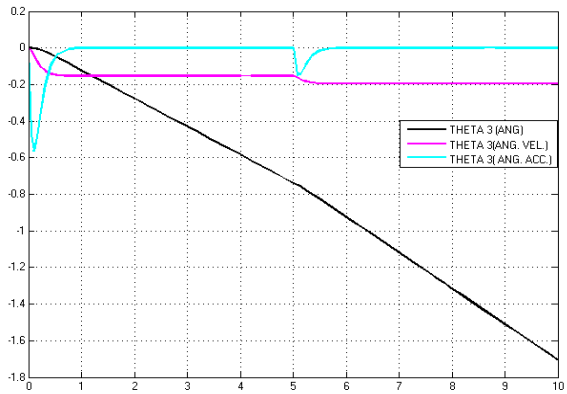

Figure 7 Input parameters for joint 3

revolute joint. Similarly Figure 6 and Figure 7 represent the second and third joints of the three link manipulator.

Figure 9 shows the computed torques for the three joints. Figure 8 represents the motion of the tool center point (TCP) in the vertical plane.

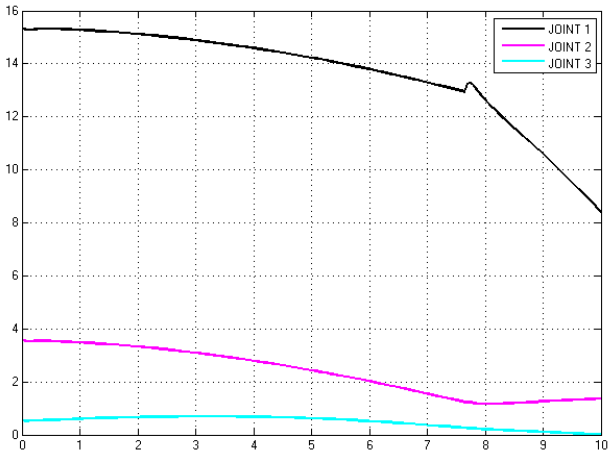

Figure 9 Computed torques (Nm) for joints 1, 2, and 3

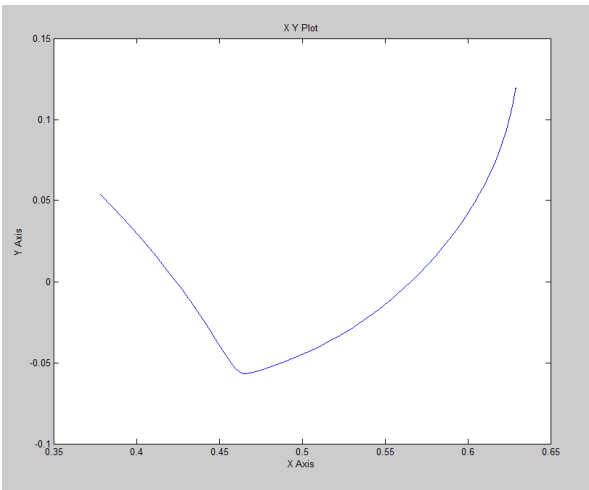

Figure 8 End effector motion in vertical plane

VII. Conclusion

Alternative modelling strategy using CAD and physical modeling concept in multi-body simulation software has been presented. Two novel input controllers have been tested on the software prototype. Body and joint input and output parameters have been recorded.

VIII. Future Work

Simulation of dynamic model on a real-time target computer is envisaged. This would help overcome the problem of non-real-time simulations on a workstation. The output can also be used to simulate hardware in loop simulation and used for validation of the dynamic model.
Parallel link manipulator design and dynamic simulation is also being conducted. Loading has been applied Euler-Lagrange model previously, and this would be extended to this dynamic model.

To overcome the issue of operator perception without cognitive overloading, a specialized input device is envisaged which will provide feedback from end effector sensors on a physical prototype, enhancing operator awareness of environment.

Acknowledgment

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