Hindawi Publishing Corporation
Journal of Construction Engineering
Volume 2016, Article ID 9409370, 11 pages
http://dx.doi.org/10.1155/2016/9409370

Review Article

A Review on Mechanical and Hydraulic System Modeling of Excavator Manipulator System

Jiaqi Xu and Hwan-Sik Yoon

Department of Mechanical Engineering, University of Alabama, Box 870276, Tuscaloosa, AL 35487-0276, USA

Correspondence should be addressed to Hwan-Sik Yoon; hyoon@eng.ua.edu

Received 26 January 2016; Accepted 29 August 2016

Academic Editor: Eric Lui

A recent trend in the development of off-highway construction equipment, such as excavators, is to use a system model for model-based system design in a virtual environment. Also, control system design for advanced excavation systems, such as automatic excavators and hybrid excavators, requires system models in order to design and simulate the control systems. Therefore, modeling of an excavator is an important first step toward the development of advanced excavators. This paper reviews results of recent studies on the modeling of mechanical and hydraulic subsystems for the simulation, design, and control development of excavator systems. Kinematic and dynamic modeling efforts are reviewed first. Then, various approaches in the hydraulic system modeling are presented.

1. Introduction

The model-based system design approach allows for an efficient way of designing and developing complex engineering systems in a virtual environment [1, 2]. In model-based control system design, four steps are typically employed: (1) modeling a plant; (2) synthesizing a controller for the plant; (3) simulating the plant and controller together; and (4) integrating the overall system. Therefore, system modeling is an important first step in model-based system design. Examples of the systems that can benefit from model-based design include off-highway construction and mining equipment as well as automotive and aerospace systems. By employing the model-based system design approach, product development cost and time can be significantly reduced.

Hydraulic excavators are from the most widely used earthmoving equipment in construction and mining industry, and they will continue to play an important role among off-highway vehicles in years to come [3–5]. Typical operations of hydraulic excavators include grading, digging, and loading, which all require coordinated manipulation of the boom, arm, and bucket cylinders. Due to the high level of skill required for the coordinated operation of the manipulator system, operating an excavator efficiently is not an easy task. An automated excavation system can assist less experienced operators to complete given tasks in a time-efficient manner with acceptable work quality. For example, an autonomous 25-ton hydraulic excavator can fully load a truck in about six passes with a typical loading time of 15–20 seconds per pass. This rate is very close to what an expert operator can perform to manually load a truck using an excavator of the same size [6]. In addition, automatic excavators have the potential to facilitate various excavation and exploration tasks in hazardous environments or remote areas, such as radiation zones [7, 8].

The model-based system design approach can be applied to the design and development of advanced excavators, such as automatic excavators and hybrid excavators. Like any model-based system design, the usual practice in controller development for an advanced excavator system is to derive the system model first and then develop a controller based on the model. Therefore, deriving a system model is a critical component in the development of an excavator. Among many subsystems and components in an excavator, this paper is aimed at providing an overview on the recent development of system models for excavator manipulators.

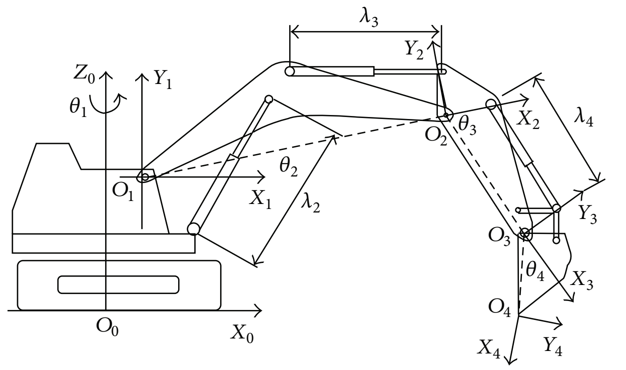


Figure 1: Excavator coordinate systems in Denavit-Hartenberg convention.

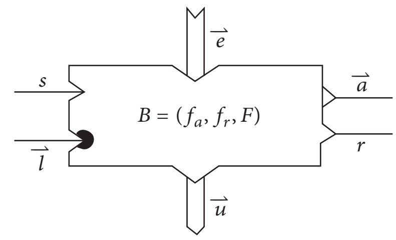


Figure 2: Basic behavior module of integrated behavior-based control framework.

An excavator manipulator is comprised of kinematically operating mechanical links and a hydraulic system. There exist two main approaches in modeling the mechanical and hydraulic systems: mathematical modeling and simulation modeling using commercially available software tools. This paper starts with a review on kinematic and dynamic modeling of the mechanical linkage, and, then, various modeling approaches on hydraulic systems will be presented. In each system modeling review, mathematical models will be presented first and then simulation models will follow.

2. Kinematic and Dynamic Models of Excavator Manipulator

Kinematic and dynamic models are used for simulation and controller development for an excavator manipulator system [9].

2.1. Kinematic Models. Kinematic equations describe the motion of an excavator manipulator without consideration of the driving forces and torques [10]. In the conventional approaches for kinematic analysis, geometrical dimensions of system components are defined first. Although the actual boom, arm, and bucket in a manipulator are irregularly shaped, for the sake of simplicity of the analysis, they are assumed to be straight joint links whose lengths are defined by the distance between two joints. Each link has its own Cartesian coordinate system that moves with the link. In order to handle coordinate transformation between two Cartesian coordinate systems, the Denavit-Hartenberg (D-H) convention is employed in most research. The D-H convention was first adopted by Vähä and Skibniewski [11] to analyze the kinematics of an excavator model and then further developed by Koivo et al. [12, 13]. According to the D-H convention, z-axis of the local coordinate system for each link is chosen to be in the direction of rotation of a revolute joint, and x-axis is set to point the other joint in the same link [10]. Then, the direction of y-axis is defined according to the right-hand rule. Finally, a fixed Cartesian coordinate system is assigned to the excavator cab to be used as the global coordinate system as shown in Figure 1.

Forward kinematic equations were derived to calculate the positions and orientations of the manipulator links when the joint angles and lengths of the links are given [10, 13]. By applying the Denavit-Hartenberg convention, a transformation matrix between two adjacent coordinate systems (from ith to $(i+1)$th) on a link can be written as

$$
{}^{i}T_{i+1} = \begin{bmatrix} \cos\theta_{i+1} & -\cos\alpha_{i+1}\sin\theta_{i+1} & \sin\alpha_{i+1}\sin\theta_{i+1} & a_{i+1}\cos\theta_{i+1} \\ \sin\theta_{i+1} & \cos\alpha_{i+1}\cos\theta_{i+1} & -\sin\alpha_{i+1}\sin\theta_{i+1} & a_{i+1}\sin\theta_{i+1} \\ 0 & \sin\alpha_{i+1} & \cos\alpha_{i+1} & d_{i+1} \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (1)
$$

where θ_{i+1} is the rotation angle about z_i axis, α_{i+1} is the rotation angle of z_i axis about x_{i+1} axis, d_{i+1} is the offset along the z_i axis, and a_{i+1} is the length of the link. Using the coordinate transformation matrix, an arbitrary point in any local coordinate system can be represented in the global coordinate system as

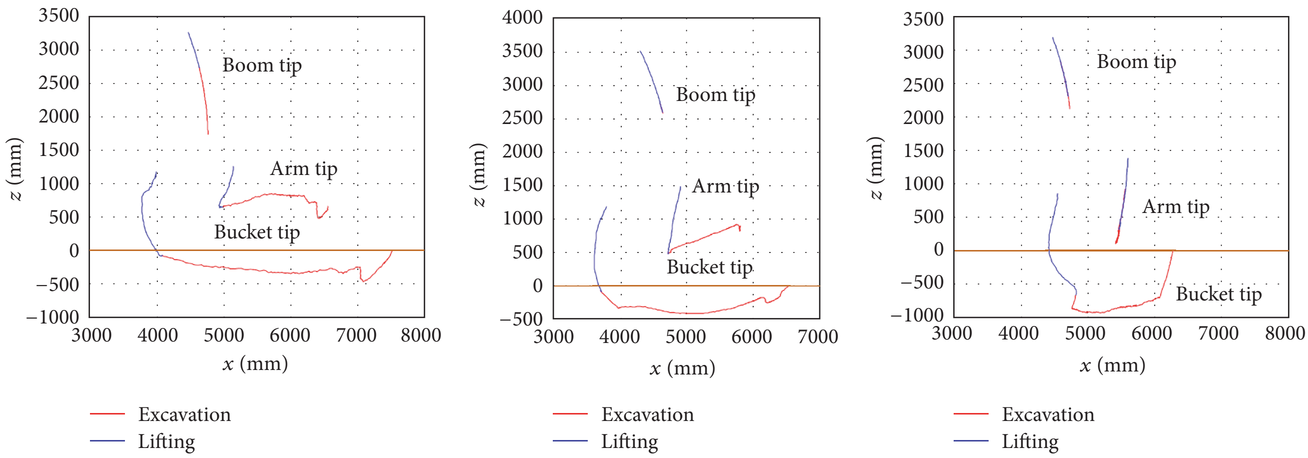
$$
{}^{0}P = {}^{0}T_n {}^{n}P = {}^{0}T_1 {}^{1}T_2 {}^{2}T_3 \cdots {}^{n-1}T_n {}^{n}P, \quad (2)
$$

where ${}^{n}P$ is the position vector in the nth coordinate system, ${}^{0}P$ is the position vector in the global coordinate system, and ${}^{0}T_n$ is the transformation matrix from the nth to the global coordinate systems.

Conversely, inverse kinematic relations can be employed to determine the joint angles and cylinder lengths when the positions and orientations of the links are known [12]. By applying inverse kinematics sequentially, all joint angles and hydraulic cylinder lengths can be obtained. In the research conducted by Pluzhnikov et al., a behavior-based inverse kinematic solver was proposed as shown in Figure 2 [21]. The behavior-based module is characterized by triples such as

$$
B = (f_a, f_r, F), \quad (3)
$$

where f_a represents the activity function, f_r is the target rating function, and F is the transfer function of the joint behavior. In Figure 2, s is the stimulation, $\vec{l}$ is the inhibition, and $\vec{e}$ is the input vector. These functions calculate the output signals: activity $\vec{a}$, target rating r, and the output vector $\vec{u}$. According to the authors, this method does not require high computation power but may not find solutions in some cases even if the desired position is reachable.



(a) Experiment case 1, far operator 2, 5th trial, 1 cycle (b) Experiment case 3, medium operator 2, 3rd trial, 1 cycle (c) Experiment case 2, near operator 2, 5th trial, 1 cycle

Figure 3: Tracks of the tips of the boom, arm, and bucket [14].

In the kinematic design of an automatic excavator, path planning is of primary concern where the desired global coordinates of the bucket tip and the associated motion of the other links need to be determined. As an analytical method, the Cartesian-Space trajectory planning method has been extensively applied in the literature [18, 22–25]. More specifically, 3rd- or 5th-order polynomials have been employed in the path planning of a manipulator occasionally. The most common practice to design the trajectory is to specify a desired starting point and end point corresponding to operation time as well as the working area and apply the 3rd-order polynomial method as shown in the following [24]:

$$q(t) = c_0 + c_1 t + c_2 t^2 + c_3 t^3,$$
$$\dot{q}(t) = c_1 + 2c_2 t + 3c_3 t^2, \quad (4)$$

where c_j's are coefficients of the polynomials, t represents time, q is the displacement, and $\dot{q}$ is the velocity.

Although the 3rd-order method is simple to use, the major disadvantage of this approach is that the acceleration of the manipulator links is not continuous. The discontinuities in the acceleration profile may cause sudden and large force variations, which lead to jerk on the manipulator [18, 24]. For this reason, a jerk-free trajectory planning method was developed using 5th-order polynomials, where the motion trajectories can be described by

$$q(t) = c_0 + c_1 t + c_2 t^2 + c_3 t^3 + c_4 t^4 + c_5 t^5,$$
$$\dot{q}(t) = c_1 + 2c_2 t + 3c_3 t^2 + 4c_4 t^3 + 5c_5 t^4, \quad (5)$$
$$\ddot{q}(t) = 2c_2 + 6c_3 t + 12c_4 t^2 + 20c_5 t^3,$$

where $\ddot{q}$ is the acceleration of a link on the given trajectory [10, 26]. With the position, velocity, and acceleration constraints, the unknown coefficients of the 5th-order polynomials can be obtained. In this manner, the position, velocity, and acceleration of each joint and link can be determined at a given time instance.

Table 1: Example of rule script for truck loading [6].

	Situation	Command
Joint 1: swing	(1) When digging finishes, wait	$\theta_1 = 5^\circ$
	(2) If $\theta_2 > 14^\circ$, swing to truck	$\theta_1 = 101^\circ$
	(3) If $\theta_4 > 10^\circ$, swing to dig	$\theta_1 = 0^\circ$
	(4) If $\theta_1 = 0^\circ$, stop and execute dig	N/A
Joint 2: boom	(1) When digging finishes, raise	$\theta_2 = 18^\circ$
	(2) If $\theta_1 < 60^\circ$, lower to dig	$\theta_2 = 6^\circ$
Joint 3: stick	(1) When digging finishes, wait	$\theta_3 = -100^\circ$
	(2) If $\theta_1 > 31^\circ$, move to spill point	$\theta_3 = -76^\circ$
	(3) If $\theta_4 > -30^\circ$, move to dump point	$\theta_3 = -92^\circ$
	(4) If $\theta_1 < 65^\circ$, move to dig	$\theta_3 = -75^\circ$
Joint 4: bucket	(1) When digging finishes, curl	$\theta_4 = -90^\circ$
	(2) If $\theta_1 > 60^\circ$ and $\theta_3 > -89^\circ$, open	$\theta_4 = 30^\circ$
	(3) If $\theta_1 < 60^\circ$, move to dig	$\theta_4 = 7^\circ$

In addition to the analytical methods, there exist the so-called rule-based path planning methods. Yamamoto et al. and Yoshida et al. conducted a series of experiments to measure trajectories of a manipulator controlled by different operators [14, 27–29]. In their research, trajectories of the links, the corresponding cylinder lengths, and joint angles during excavation and loading processes were measured. In this manner, kinematic features of the motion trajectories could be experimentally extracted for typical excavation operations conducted by skilled operators. Usually, the rule-based paths are designed based on actual manipulator operations and thus are dependent on human operators [6, 14, 29–32]. Laser rangefinders have been applied to scan the target area to recognize the topography to determine the manipulator motion that should be followed. An example set of control rules for a truck loading operation is shown in Table 1.

The human dependency of the produced trajectories will introduce variations inevitably. Figure 3 shows recorded

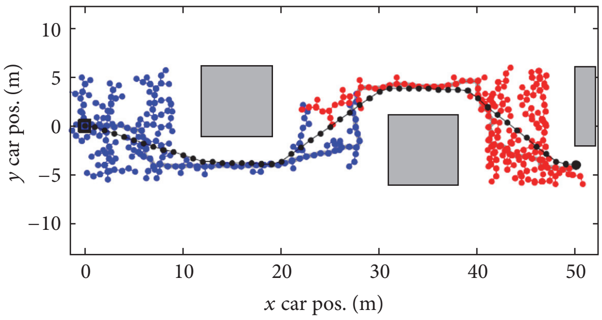


Figure 4: Example trajectory obtained by using random tree method for a path searching problem to avoid obstacles [15].

tracks of tips of the boom, arm, and bucket links during different operations by an expert operator conducting complex maneuvers.

To enhance the tracking capability for a valid path for the manipulator, a rapidly exploring random tree method was developed by Maeda et al. which improved the responses to the environment disturbances [15]. An example trajectory obtained by the random tree method is shown in Figure 4 for a path searching problem to avoid collisions with obstacles (shown as gray rectangles in the figure).

Another method to generate a working path was developed by Makkonen et al. by combining manipulator position data with a working zone terrain CAD model, which employs triangular elements defined by vertices [33, 34]. In the research by Lee and Kim [16], the excavating trajectory of an autonomous excavator was created by using a method called virtual motion camouflage (VMC), which was enlightened by a predator tracking its prey. The researchers conducted two types of simulations and created trajectories accordingly: one is the obstacle avoidance, which is shown in Figure 5(a), and the other is the digging motion, which is shown in Figure 5(b). The red trajectory shown in Figure 5 is the prey path, which is formed without considering obstacles in the path. The green trajectory is the predator trajectory, which is created by considering the physical constraint. The blue points are reference points, which are used to determine the relative position of the points on the prey and predator trajectories.

Recently, artificial neural networks were applied in the trajectory planning. In the research by Atmeh and Subbarao [35], a dynamic neural network consisting of a recurrent neural network and two feedforward neural networks was used to solve the trajectory generation problems adaptively.

Additionally, a trajectory compensation method based on path prediction was developed. Using this method, a trajectory can be predicted and compensated based on real-time simulation of a simplified system model, to improve control accuracy [36]. In order to optimize an energy consumption rate, Kim et al. applied a gradient descent method. Using the method, the minimum torque or minimum working time trajectory was obtained, and the energy consumption rate was reduced as a result. The geometric and dynamic restrictions of the excavator were taken into account as well in this method [37–39].

2.2. Dynamic Models. In a conventional study of manipulator dynamics, mathematical models are derived by applying Newton-Euler's or Euler-Lagrange's method. These two different approaches are equivalent and lead to the same set of dynamic equations [11, 13, 37, 40–43]. In Euler-Lagrange's approach, dynamic equations can be derived from a Lagrange energy function by treating a manipulator system as a whole [10, 26]. Dynamic equations can also be derived by applying Newton-Euler's method successively to each link by considering each link as a free body [11, 13, 23, 41, 42]. In general, the resulting equation takes the following form:

$$\boldsymbol{\tau} = \mathbf{M}(u)\ddot{u} + \mathbf{h}(u,\dot{u}) + \mathbf{g}(u), \tag{6}$$

where $\boldsymbol{\tau}$ is the torque vector at all joints, u represents an angular displacement of the corresponding joint, $\mathbf{M}(u)$ represents the mass matrix, $\mathbf{h}(u,\dot{u})$ is the Coriolis force term, and $\mathbf{g}(u)$ is the gravity term.

In addition to the conventional mathematical modeling, modeling methods based on transfer functions have been developed. In the research by Gu et al. [17], a dynamic response model based on a transfer function was established by using the Simplified Refined Instrumental Variable (SRIV) method. For example, a dynamic equation of a manipulator link can be written as

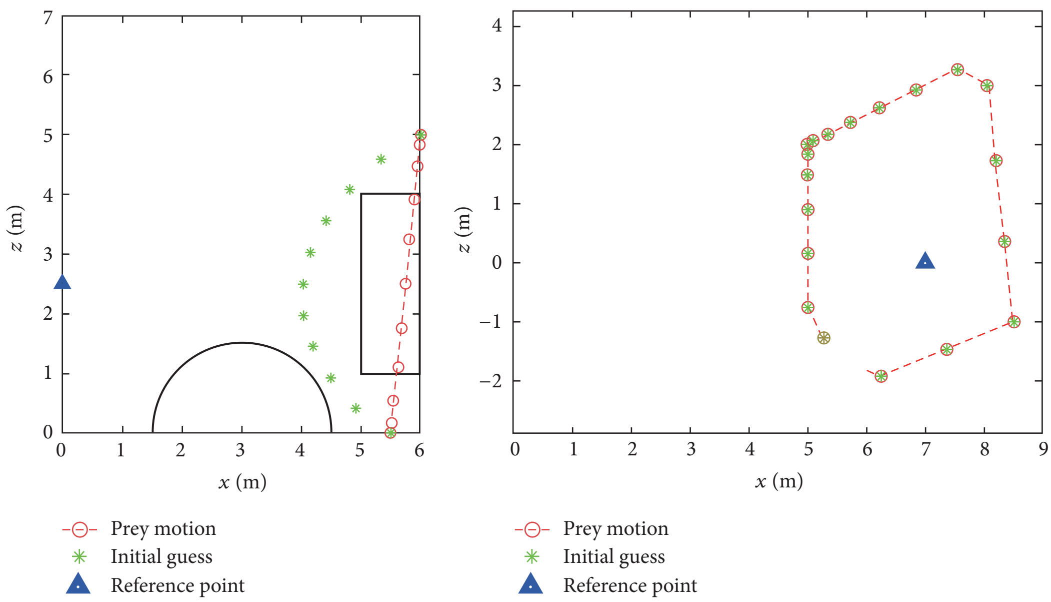
$$y(k) = \frac{b(z^{-1})}{1-(z^{-1})}u(k), \tag{7}$$

where z is a differential operator, $y(k)$ is the output angle of the corresponding link, $u(k)$ is the input voltage, and b is a time-invariant numerator parameter estimated for each manipulator operation. In an experiment for the acquisition of a manipulator input-output relation, input voltage $u(k)$ is specified first. Then, parameter b is estimated by the SRIV algorithm and the system transfer function can be determined as a result [17]. An example plot of an excavator arm displacement for a constant input drive is shown in Figure 6. Also, Filla developed a rule-based dynamic model, where the model is simulated based on human operator's inputs [44].

In research by Tafazoli et al. [45], a method for gravitational parameter estimation was proposed. The estimated gravitational parameters were torques produced by gravitational forces. The estimated parameters can be used in gravitational compensation control to obtain improved dynamic performances. For example, for the linkage system shown in Figure 7, joint torque equations can be set up as follows:

$$\begin{aligned}
\tau_4 &= M_{\mathrm{bu}} g r_4 \cdot \cos(\theta_{234} + \alpha_4), \\
\tau_3 &= \tau_4 + M_{\mathrm{bu}} g a_3 \cdot \cos(\theta_{23}) + M_{\mathrm{st}} g r_3 \cdot \cos(\theta_{23} + \alpha_3), \\
\tau_2 &= \tau_3 + (M_{\mathrm{bu}} + M_{\mathrm{st}}) g a_2 \cdot \cos(\theta_2) + M_{\mathrm{bo}} g r_2 \\
&\quad \cdot \cos(\theta_2 + \alpha_2).
\end{aligned} \tag{8}$$

The parameters in the equations above are shown in Figure 7.



(a) Obstacle avoidance motion

(b) Digging motion

FIGURE 5: Example trajectories created by using VMC method [16].

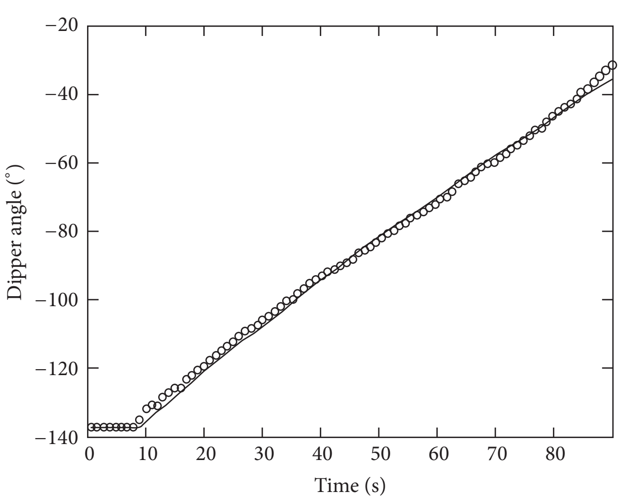


FIGURE 6: Comparison of estimated transfer function model outputs with experimentally measured data [17].

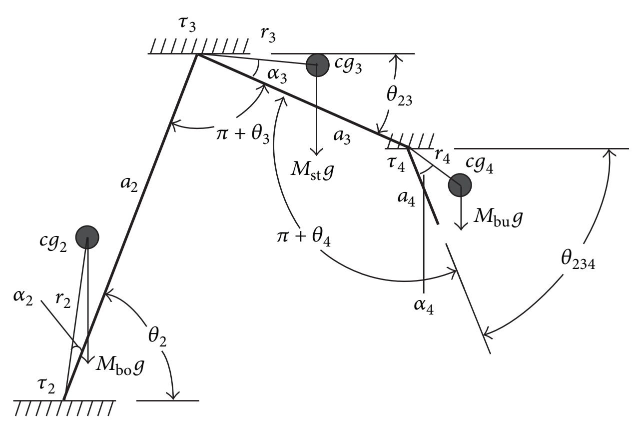


FIGURE 7: Configuration for joint torque equations.

In their research, load pins were used to measure load torques on the links indirectly. Then, a series of static experiments without load on the bucket were carried out. In this manner, the parameters could be estimated with a 5% error [45].

For accurate simulation and visual presentation of excavator manipulators, various commercial software tools have been utilized. Among many choices, three software tools are widely used for excavator simulation: MATLAB/Simulink, Amesim, and Adams [18, 19, 46–48]. For example, an excavator manipulator dynamic model developed in SimMechanics is shown in Figure 8, and an excavator model developed in Adams is shown in Figure 9.

Dynamic system simulation software typically has the functionality to produce dynamic properties of a manipulator when a CAD model for the manipulator is available [18, 46]. This process expedites the dynamic modeling of an excavator system with relatively high accuracies.

3. Hydraulic System Modeling

For excavator manipulators, the drive forces or torques are produced by hydraulic systems including pumps, valves, and cylinders [18, 25, 49]. Therefore, modeling and simulation of hydraulic systems comprise an important component for the design and analysis of an excavator manipulator system. As shown in the general hydraulic system modeling process in

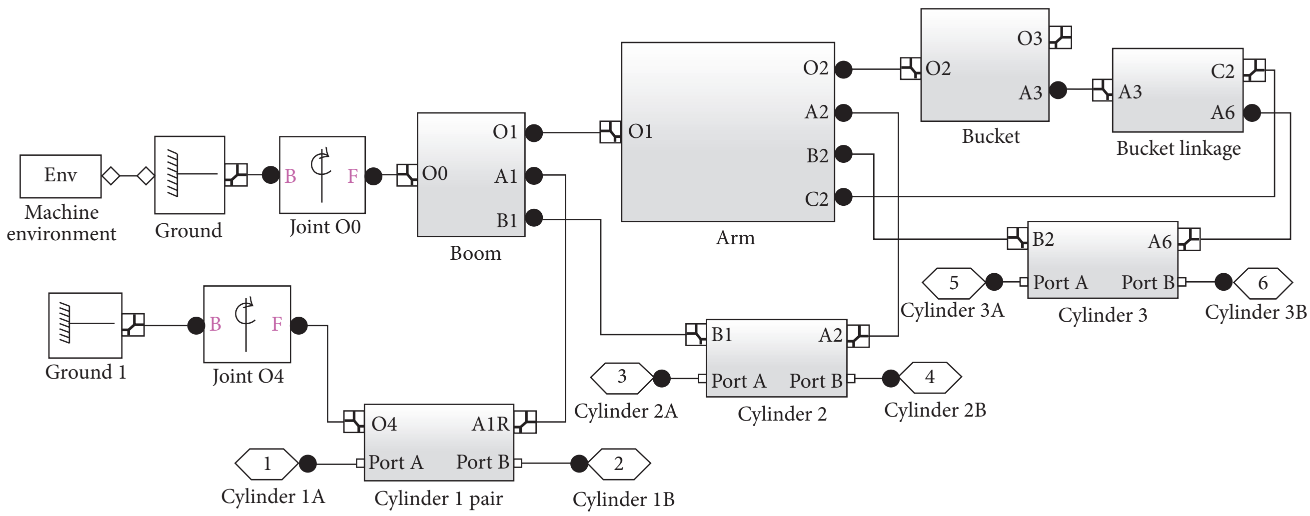


FIGURE 8: Excavator manipulator model developed in SimMechanics [18].

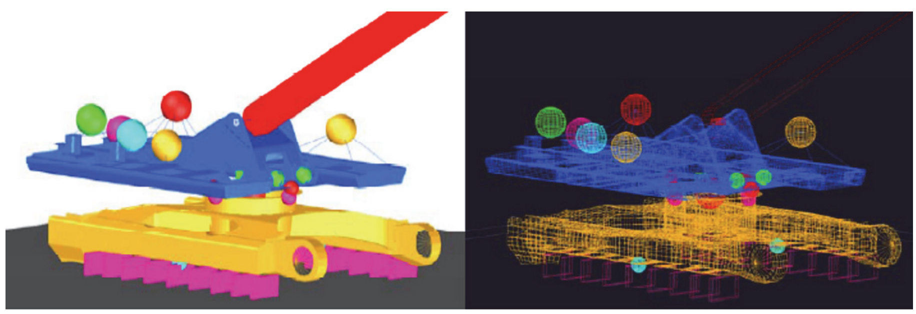


FIGURE 9: Excavator model in Adams [19].

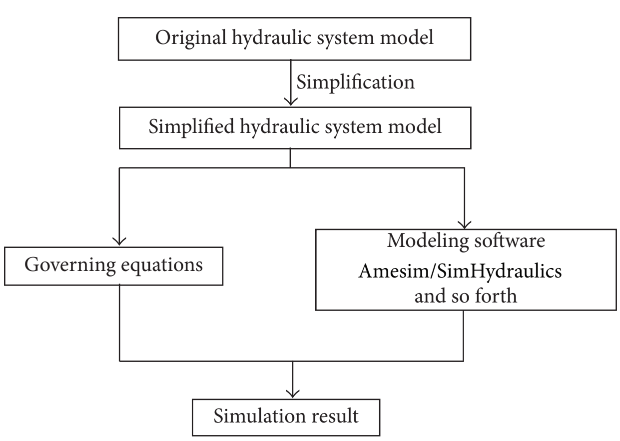


FIGURE 10: Hydraulic system modeling and simulation process.

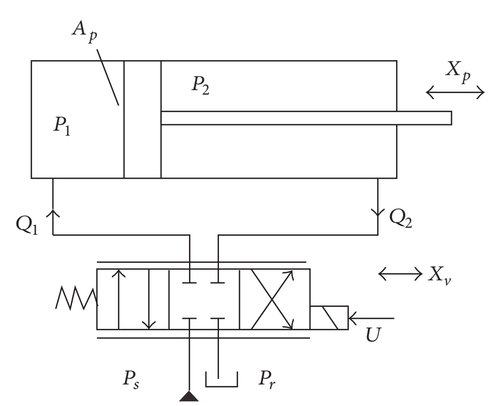


FIGURE 11: Schematic of a hydraulic cylinder and control valve.

Figure 10, a model simplification procedure is important due to the complexity of the system.

The conventional modeling approach for a hydraulic system is to apply Newton's law. For example, the following state variable vector can be defined for a simplified hydraulic system shown in Figure 11:

$$\underline{x} = [x_1 \;\; x_2 \;\; x_3]^T = [x_p \;\; v_p \;\; a_p]^T, \tag{9}$$

where x_p, v_p, and a_p are the displacement, velocity, and acceleration of the piston, respectively. Then, dynamic equations for the hydraulic system can be derived as follows by neglecting the valve dynamics:

$$\begin{aligned}\dot{x}_1 &= x_2 = v_p,\\ \dot{x}_2 &= x_3 = a_p,\\ \dot{x}_3 &= \frac{1}{m_r}\left(A_p \dot{p}_l - \dot{F}_{\mathrm{Re}s}\right) = \dot{a}_p,\end{aligned} \tag{10}$$

where A_p is the cross-sectional area of the hydraulic cylinder, p_l is the cylinder differential pressure, and $\dot{F}_{\mathrm{Re}s}$ is the derivative of the resistance force on the piston [20, 40, 45, 50–55].

Mathematical modeling of hydraulic pipes used in manipulators has been well studied and can be found in textbooks [56]. Thus, it is not included in this review paper. In the research conducted by Casoli and Anthony, a variable displacement hydraulic pump was modeled [55]. As a critical component of the pump, a flow compensator was modeled by governing equations, which described interaction of the fluid dynamics model and mechanical-geometrical model. The fluid dynamics model calculates the internal pressure of the chamber and the flow rate between the adjacent chambers, and the mechanical-geometrical model determines the forces acting on the spool which affects the dynamics and flow area. In the fluid dynamics model, time rate of change of the pressure can be described by the following equation:

$$\frac{dp_i}{dt} = \frac{\beta}{\rho_i} \cdot \frac{1}{V_i(\chi)}\left(\sum \dot{m} - \rho_i \frac{dV_i(\chi)}{dt}\right), \tag{11}$$

where p is the fluid absolute pressure, β is bulk modulus, $\dot{m}$ is mass flow rate, ρ is fluid density, $V(\chi)$ is control volume, and i identifies the control volume considered. The mass flow rate is calculated as

$$\dot{m} = \rho C_d A(\chi) \cdot \sqrt{\frac{2|\Delta p|}{\rho}}, \tag{12}$$

where C_d is the discharge coefficient and $A(\chi)$ is the flow area.

In addition to mathematical modeling, excavator hydraulic systems have been modeled by using software tools, such as SimHydraulics and Amesim. In recent publications, various hydraulic system modeling software tools have been applied to model hydraulic systems [18, 46, 51–53, 57]. These modeling software tools feature graphical modeling capabilities so that a user can easily construct a system model by arranging components in a physically representative manner. For example, an excavator hydraulic system modeled in SimHydraulics in MATLAB/Simulink is shown in Figure 12.

Lee and Chang proposed a bond-graph based hydraulic system modeling approach as shown in Figure 13 [20]. Bond graph, which interprets the relation between components on the basis of energy transmission, is applied to conceptually model a simplified hydraulic system first. Then, a nonlinear mathematical model of the target system can be generated by using modeling software.

It was found that friction in an excavator hydraulic system is significant and cannot be neglected [45]. Due to the difficulties in estimating the loads in the system precisely, however, a gray-box hydraulic system modeling method was developed with an associated machine learning method. In the research conducted by Casoli and Anthony, a variable displacement hydraulic pump was modeled as a gray box as shown in Figure 14 [55]. As shown in the figure, the flow and pressure compensators are modeled as white boxes and flow characteristics as a black box. Together, they are called gray box.

There have also been efforts to develop empirical models. Possible losses in hydraulic systems were also accounted in input-output relations in the gray-box approach [49, 54, 55, 58, 59].

In most hydraulic system modeling approaches, governing equations are derived first. Then, a graphical diagram is formed to construct a system model with hydraulic system modeling software. Additionally, the system uncertainties are estimated and bounded and then added to the system model. In this manner, a relatively accurate hydraulic system model can be developed.

Finally, some of the key features of widely used modeling and simulation software are summarized in Table 2.

4. Conclusion and Outlook

Model-based system design practice can be applied to the design and development of advanced excavators. Since the first important step in the model-based system design is the system model development, significant amount of research has been conducted on the modeling of excavator systems, especially manipulators.

The Denavit-Hartenberg process has been extensively applied in the kinematic analyses of excavator manipulators, and both experimental and analytical trajectory planning methods have been used to generate desired trajectories of excavator manipulators. Dynamic system models have been derived by applying Newton-Euler's method or by using software tools such as SimScape, Amesim, and Adams. Hydraulic system models are usually simplified greatly due to the complexity of the real hydraulic systems. For hydraulic systems, modeling of the hydraulic loss is essential for simulation accuracy. Since it is difficult to accurately model hydraulic systems especially when the system is complex, however, designers rely mostly on commercial software tools for that purpose.

Advancement in excavator systems design can occur in many different ways. Two notable directions include electrification and hybridization for energy efficiency and automation of excavator operations. Due to the increasing complexity in the system architecture, development of these advanced excavator systems inevitably requires model-based system design approach. Therefore, accurate model development will be increasingly important and high-fidelity multiphysics software tools will be required to design and simulate both mechanical and hydraulic subsystems simultaneously.

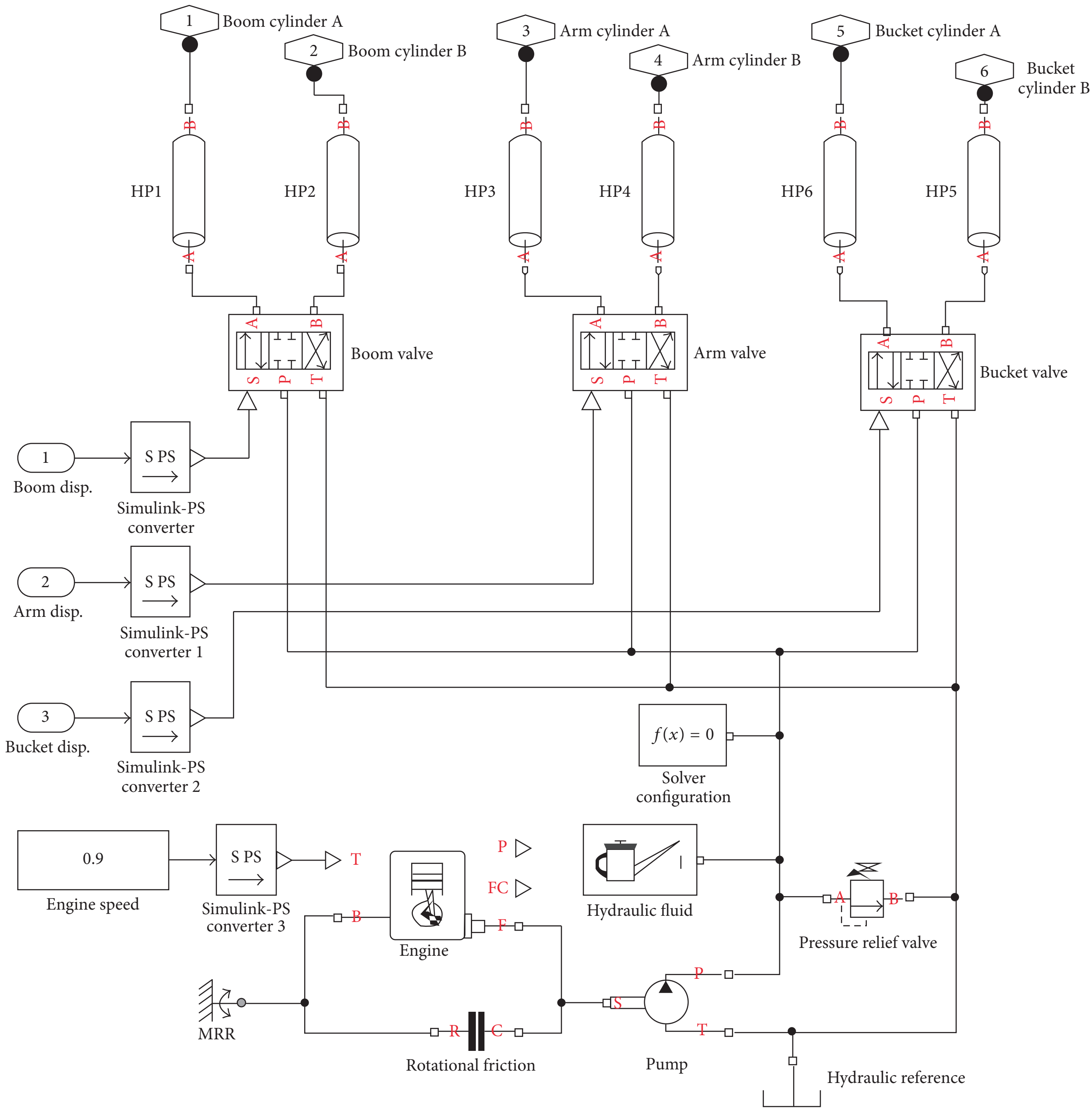


Figure 12: Hydraulic system model developed in SimHydraulics [18].

The current state-of-the-art simulation software allows high-fidelity simulation of hydraulic systems in connection with mechanical multibody dynamics. They allow formation of complex hydraulic systems using numerous built-in component models including pipes, valves, and pumps. Using thus-formed system models, various dynamic and hydraulic performances can be simulated and studied. The simulation results are accurate enough to replace numerous physical prototyping and testing required for new system development.

While the current simulation models and software are focused mainly on the mechanical and hydraulic performances, the future research needs to be directed toward development of more energy-efficient systems by incorporating power sources and transmission. Thus, a high-fidelity internal combustion engine or hybrid electric system model needs to be employed and drive-cycle simulations need to be conducted to improve the system design for better energy efficiency.

Table 2: Key features of the different modeling software.

Software	Key features
Amesim by Simens PLM	(i) Open libraries available based on physics and applications (ii) Graphical user interface (iii) The solver can automatically select an appropriate one among various different algorithms based on the dynamics of the system (iv) Provides a multidomain simulation including linear analysis
Adams by MSC Software	(i) Creation or import of component geometry in wireframe or 3D solids (ii) Definition of internal and external forces on the assembly to define the product's operating environment (iii) Model refinement with part flexibility, automatic control systems, joint friction and slip, hydraulic and pneumatic actuators, and parametric design relationships (iv) Automatic generation of linear models and complex loads for export to structural analyses
Simscape by MathWorks	(i) Single environment for simulating multidomain physical systems with control algorithms in Simulink (ii) Physical modeling blocks cover more than 10 physical domains, such as mechanical, electrical, hydraulic, and two-phase fluid (iii) Ability to conduct real-time simulation and hardware-in-the-loop (HIL) testing (iv) Support for C-code generation (with Simulink Coder)

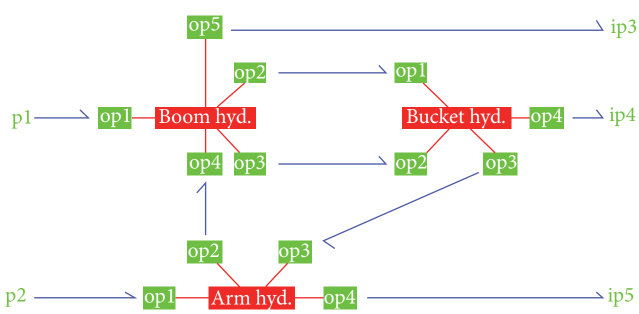


Figure 13: Bond-graph model for hydraulic circuit in excavator manipulator [20].

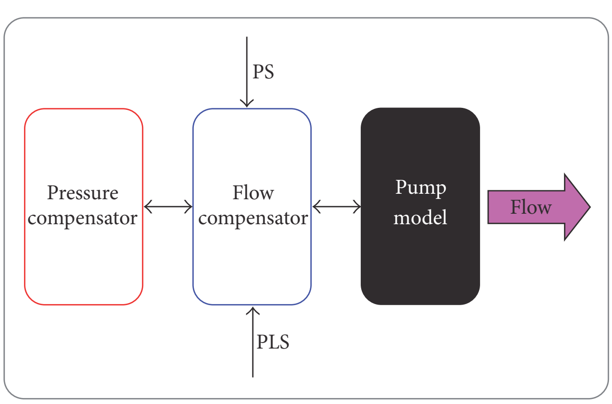


Figure 14: Gray-box model of an integrated hydraulic pump system.

Competing Interests

The authors declare that they have no competing interests.

References

[1] J. Reedy and S. Lunzman, "Model based design accelerates the development of mechanical locomotive controls," SAE Technical Paper 2010-01-1999, SAE International, Warrendale, Pa, USA, 2010.

[2] G. Barbieri, C. Fantuzzi, and R. Borsari, "A model-based design methodology for the development of mechatronic systems," *Mechatronics*, vol. 24, no. 7, pp. 833–843, 2014.

[3] W. E. N. Hao, "Analysis report of 2010 excavator market in China," *Construction Machinery Technology & Management*, vol. 2, article 23, 2011.

[4] T. Ni, H. Zhang, C. Yu, D. Zhao, and S. Liu, "Design of highly realistic virtual environment for excavator simulator," *Computers and Electrical Engineering*, vol. 39, no. 7, pp. 2112–2123, 2013.

[5] "Global excavator market report: 2014 edition," 2014.

[6] A. Stentz, J. Bares, S. Singh, and P. Rowe, "A robotic excavator for autonomous truck loading," *Autonomous Robots*, vol. 7, no. 2, pp. 175–186, 1999.

[7] S. Singh, "State of the art in automation of earthmoving," *Journal of Aerospace Engineering*, vol. 10, no. 4, pp. 179–188, 1997.

[8] H. Yu, Y. Liu, and M. S. Hasan, "Review of modelling and remote control for excavators," *International Journal of Advanced Mechatronic Systems*, vol. 2, no. 1-2, pp. 68–80, 2010.

[9] B. P. Patel and J. M. Prajapati, "A review on kinematics of hydraulic excavator's backhoe attachment," *International Journal of Engineering Science and Technology*, vol. 3, no. 3, pp. 1990–1997, 2011.

[10] M. W. Spong, S. Hutchinson, and M. Vidyasagar, *Robot Modeling and Control*, vol. 3, Wiley, New York, NY, USA, 2006.

[11] P. K. Vähä and M. J. Skibniewski, "Dynamic model of excavator," *Journal of Aerospace Engineering*, vol. 6, no. 2, pp. 148–158, 1993.

[12] A. J. Koivo, "Kinematics of excavators (backhoes) for transferring surface material," *Journal of Aerospace Engineering*, vol. 7, no. 1, pp. 17–32, 1994.

[13] A. J. Koivo, M. Thoma, E. Kocaoglan, and J. Andrade-Cetto, "Modeling and control of excavator dynamics during digging operation," *Journal of Aerospace Engineering*, vol. 9, no. 1, pp. 10–18, 1996.

[14] T. Yamaguchi and H. Yamamoto, "Motion analysis of hydraulic excavator in excavating and loading work for autonomous control," in *Proceedings of the 23rd International Symposium on Robotics and Automation in Construction (ISARC '06)*, pp. 602–607, Tokyo, Japan, October 2006.

[15] G. J. Maeda, S. P. N. Singh, and H. Durrant-Whyte, "A tuned approach to feedback motion planning with RRTs under model uncertainty," in *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA '11)*, pp. 2288–2294, May 2011.

[16] B. Lee and H. J. Kim, "Trajectory generation for an automated excavator," in *Proceedings of the 2014 14th International Conference on Control, Automation and Systems (ICCAS '14)*, pp. 716–719, Seoul, Republic of Korea, October 2014.

[17] J. Gu, J. Taylor, and D. Seward, "Modelling of an hydraulic excavator using simplified refined instrumental variable (SRIV) algorithm," *Journal of Control Theory and Applications*, vol. 5, no. 4, pp. 391–396, 2007.

[18] J. Xu, B. Thompson, and H.-S. Yoon, "Automated grading operation for hydraulic excavators," SAE Technical Paper, 2014.

[19] C.-G. Park and K. Lim, *A Simulation Environment for Excavator Dynamics*, 2004.

[20] S.-J. Lee and P.-H. Chang, "Modeling of a hydraulic excavator based on bond graph method and its parameter estimation," *Journal of Mechanical Science and Technology*, vol. 26, no. 1, pp. 195–204, 2012.

[21] S. Pluzhnikov, D. Schmidt, J. Hirth, and K. Berns, "Behavior-based arm control for an autonomous bucket excavator," *Commercial Vehicle Technology*, pp. 251–261, 2012.

[22] J. Gu, X. Ma, J. Ni, and L. Sun, "Linear and nonlinear control of a robotic excavator," *Journal of Central South University*, vol. 19, no. 7, pp. 1823–1831, 2012.

[23] Q. Ha, M. Santos, Q. Nguyen, D. Rye, and H. Durrant-Whyte, "Robotic excavation in construction automation," *IEEE Robotics and Automation Magazine*, vol. 9, no. 1, pp. 20–28, 2002.

[24] G. Jun and D. Seward, "Improved control of intelligent excavator using proportional-integral-plus gain scheduling," *Journal of Central South University of Technology*, vol. 19, no. 2, pp. 384–392, 2012.

[25] Q. He, D. Zhang, Z. Huang, and X. Zhang, "Adaptive control of hydraulic excavator manipulator," *Journal of Tongji University*, vol. 35, no. 9, pp. 1259–1288, 2007.

[26] S. Niku, *Introduction to Robotics*, John Wiley & Sons, 2010.

[27] T. Yoshida, T. Koizumi, N. Tsujiuchi, K. Chen, and Y. Nakamoto, "Establishment of optimized digging trajectory for hydraulic excavator," in *Topics in Dynamics of Civil Structures, Volume 4*, F. N. Catbas, S. Pakzad, V. Racic, A. Pavic, and P. Reynolds, Eds., Conference Proceedings of the Society for Experimental Mechanics Series, chapter 58, pp. 543–554, Springer, Berlin, Germany, 2013.

[28] H. Yamamoto, M. Moteki, H. Shao et al., "Development of the autonomous hydraulic excavator prototype using 3-D information for motion planning and control," in *Proceedings of the IEEE/SICE International Symposium on System Integration (SII '10)*, pp. 49–54, IEEE, Sendai, Japan, December 2010.

[29] Y. Sakaida, D. Chugo, H. Yamamoto, and H. Asama, "The analysis of excavator operation by skillful operator—extraction of common skills," in *Proceedings of the SICE Annual International Conference on Instrumentation, Control and Information Technology*, pp. 538–542, August 2008.

[30] D. Schmidt, M. Proetzsch, and K. Berns, "Simulation and control of an autonomous bucket excavator for landscaping tasks," in *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA '10)*, pp. 5108–5113, Anchorage, Alaska, USA, May 2010.

[31] H. N. Cannon, *Extended Earthmoving with an Autonomous Excavator*, Carnegie Mellon University, Pittsburgh, Pa, USA, 1999.

[32] J. Seo, S. Lee, J. Kim, and S.-K. Kim, "Task planner design for an automated excavation system," *Automation in Construction*, vol. 20, no. 7, pp. 954–966, 2011.

[33] T. Makkonen, K. Nevala, and R. Heikkilä, "A 3D model based control of an excavator," *Automation in Construction*, vol. 15, no. 5, pp. 571–577, 2006.

[34] T. Makkonen, K. Nevala, and R. Heikkilä, "Automation of an excavator based on a 3D CAD model and GPS measurement," in *Proceedings of the 21st International Symposium on Automation and Robotics in Construction (ISARC '04)*, 2004.

[35] G. Atmeh and K. Subbarao, "A dynamic neural network with feedback for trajectory generation," *IFAC-Pap*, vol. 49, no. 1, pp. 367–372, 2016.

[36] G. J. Maeda, S. P. N. Singh, and D. C. Rye, "Improving operational space control of heavy manipulators via open-loop compensation," in *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems: Celebrating 50 Years of Robotics (IROS '11)*, pp. 725–731, September 2011.

[37] Y. B. Kim, J. Ha, H. Kang, P. Y. Kim, J. Park, and F. C. Park, "Dynamically optimal trajectories for earthmoving excavators," *Automation in Construction*, vol. 35, pp. 568–578, 2013.

[38] S.-H. Lee, J. Kim, F. C. Park, M. Kim, and J. E. Bobrow, "Newton-type algorithms for dynamics-based robot movement optimization," *IEEE Transactions on Robotics*, vol. 21, no. 4, pp. 657–667, 2005.

[39] F. C. Park, J. E. Bobrow, and S. R. Ploen, "A Lie group formulation of robot dynamics," *The International Journal of Robotics Research*, vol. 14, no. 6, pp. 609–618, 1995.

[40] D. Zhang, *A Research on the Motion Control of the Hydraulic Excavator Manipulator*, Central South University, 2006.

[41] T. Yoshida, T. Koizumi, N. Tsujiuchi, Z. Jiang, and Y. Nakamoto, "Dynamic analysis of an excavator during digging operation," SAE Technical Paper, 2013.

[42] Y. H. Zweiri, L. D. Seneviratne, and K. Althoefer, "Model-based automation for heavy duty mobile excavator," in *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, vol. 3, pp. 2967–2972, October 2002.

[43] S. Tafazoli, P. D. Lawrence, and S. E. Salcudean, "Identification of inertial and friction parameters for excavator arms," *IEEE Transactions on Robotics and Automation*, vol. 15, no. 5, pp. 966–971, 1999.

[44] R. Filla, "Operator and machine models for dynamic simulation of construction machinery," 2005.

[45] S. Tafazoli, P. D. Lawrence, S. E. Salcudean, D. Chan, S. Bachmann, and C. W. De Silva, "Parameter estimation and actuator friction analysis for a mini excavator," in *Proceedings of the IEEE International Conference on Robotics and Automation*, vol. 1, pp. 329–334, 1996.

[46] Q. H. Le, Y. M. Jeong, C. T. Nguyen, and S. Y. Yang, "Development of a virtual excavator using simmechanics and SimHydraulic," *Journal of The Korean Society for Fluid Power & Construction Equipments*, vol. 10, no. 1, pp. 29–36, 2013.

[47] E. Assenov, E. Bosilkov, R. Dimitrov, and T. Damianov, "Kinematics and dynamics of working mechanism of hydraulic excavator," *University of Mining and Geology "St. Ivan Rilski" Annual*, vol. 46, pp. 47–49, 2003.

[48] S. M. Prabhu, "Model-based design for off-highway machine systems development," SAE Technical Paper, 2007.

[49] M. Krishna and J. E. Bares, "Hydraulic system modeling through memory-based learning," in *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, vol. 3, pp. 1733–1738, October 1998.

[50] M. Cobo, R. Ingram, and S. Cetinkunt, "Modeling, identification, and real-time control of bucket hydraulic system for a wheel type loader earth moving equipment," *Mechatronics*, vol. 8, no. 8, pp. 863–885, 1998.

[51] Q. He, D. Zhang, P. Hao, and X. Zhang, "Study on motion simulation of hydraulic excavator's manipulator," *Journal of System Simulation*, vol. 3, article 51, 2006.

[52] S. Věchet and J. Krejsa, "Hydraulic arm modeling via Matlab simhydraulics," *Engineering MECHANICS*, vol. 16, no. 4, pp. 287–296, 2009.

[53] S. Johnny Fu, M. Liffring, and I. S. Mehdi, "Integrated electro-hydraulic system modeling and analysis," *IEEE Aerospace and Electronic Systems Magazine*, vol. 17, no. 7, pp. 4–8, 2002.

[54] M. Krishna and J. Bares, "Constructing hydraulic robot models using memory-based learning," *Journal of Aerospace Engineering*, vol. 12, no. 2, pp. 34–42, 1999.

[55] P. Casoli and A. Anthony, "Gray box modeling of an excavator's variable displacement hydraulic pump for fast simulation of excavation cycles," *Control Engineering Practice*, vol. 21, no. 4, pp. 483–494, 2013.

[56] E. Doebelin, *System Dynamics: Modeling, Analysis, Simulation, Design*, CRC Press, 1998.

[57] S. H. Park, K. Alam, Y. M. Jeong, C. D. Lee, and S. Y. Yang, "Modeling and simulation of hydraulic system for a wheel loader using AMESim," in *Proceedings of the ICROS-SICE International Joint Conference (ICCAS-SICE '09)*, pp. 2991–2996, August 2009.

[58] P. Casoli, A. Anthony, and M. Rigosi, "Modeling of an excavator system—semi empirical hydraulic pump model," *SAE International Journal of Commercial Vehicles*, vol. 4, no. 1, pp. 242–255, 2011.

[59] M. Krishna and J. Bares, *Constructing Fast Hydraulic Robot Models for Optimal Motion Planning*, The Robotics Institute, 1999.