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Research Paper

A CRITICAL REVIEW ON KINEMATICS OF HYDRAULIC EXCAVATOR BACKHOE ATTACHMENT

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The Hydraulic excavator machines are heavy duty earth mover consisting of a boom, arm and bucket. It works on principle of hydraulic fluid with hydraulic cylinder and hydraulic motors. The Hydraulic excavator backhoe operation require coordinated movement of boom, arm and bucket to control the bucket tip position by following a desired trajectory and to use the excavator machines effectively in the dark, sever weather, worst working condition, hazardous or unhealthy environment and dirty areas this can be achieved only through the automatic control of the hydraulic excavator machine. Controlling of hydraulic excavator machine is possible if the kinematics and dynamics of the excavator machine are understood. To achieve this goal different reviews related to kinematics of excavator machine are discussed in this paper which is helpful to doing the kinematic modelling of the excavator machine. Kinematic modelling is helpful for understanding behavior and improving the operating performance of the hydraulic excavator machine.

Keywords: Backhoe, Kinematics, Digging, Excavator

INTRODUCTION

The Backhoe excavator can be used for construction of building foundation, construction of highway, gardening work, forestry work, to dig holes, material handling, light duty demolition work, urban works, river dredging, also in hazardous environment. Backhoe excavators are used primarily to excavate below the natural surface of the ground on which the machine rests. According to Forestry, Earthmoving and Excavator Statistics Program (FEE Statistics Committee, 2010), a backhoe excavator is defined as "A ride-on dual purpose self-propelled wheeled machine for on and off road operation". One end with loader arms that can support a full width bucket or attachment and the other end incorporating a boom and arm combination capable of swinging half circle for the purpose of digging or attachment manipulation.

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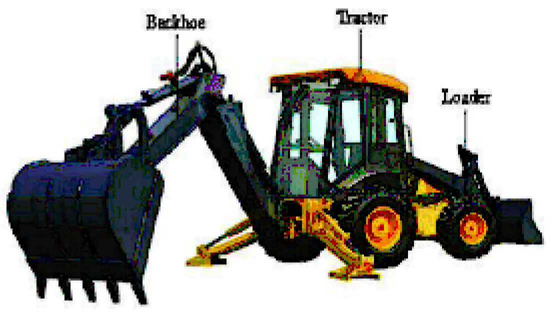
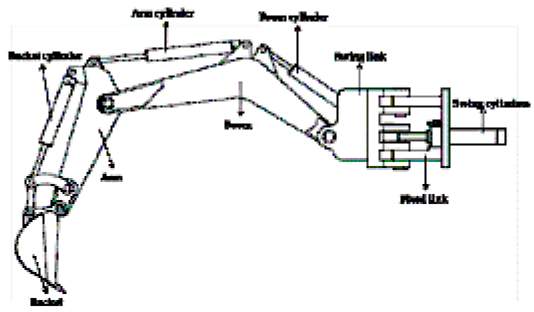
In other words, a backhoe excavator is actually three pieces of construction equipment combined into one unit. These three pieces are a tractor, a loader, and a backhoe as shown in Figure 1. The third piece of the equipment a backhoe also known as a backhoe excavator attachment is the area of research reported in this paper. A backhoe is the main tool of the backhoe excavator. It consists of a digging bucket on the end of a two part articulated arm (Figure 1).

Figure 1: A backhoe Excavator



Backhoe excavator attachment is four degrees of freedom system because each of the four links (swing link, boom link, arm link and bucket link) are allowed to be rotated with their respective joint axes only. Backhoe consist four different mechanisms each of which can be controlled independently (Figure 2). The first mechanism is for the swing motion of the swing link relative to the fixed or base link and can be actuated by swing cylinders. The second mechanism is for the rotation of the boom which is actuated by boom cylinder thus forming an inverted slider-crank mechanism relative to the frame. The third mechanism is for the rotational motion of an arm which is actuated by arm cylinder and is also an inverted slider-crank mechanism. The fourth mechanism is for the rotational motion

Figure 2: A Backhoe Mechanism

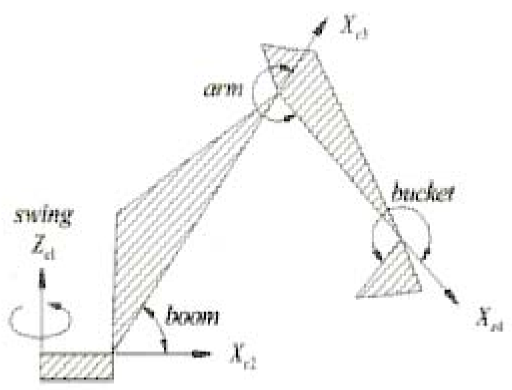


of the bucket which is actuated by bucket cylinder. Since a large bucket oscillation is required, the mechanism used is a series combination of a four bar mechanism, and an inverted slider-crank mechanism, which forms a six link mechanism relative to the arm as shown in Figure 2. Apart from this, the boom assists only in positioning the bucket and the arm for the digging operation, it does not directly contribute in digging operation. On the other hand, the arm and the bucket directly contribute in the digging operation by generating the required digging forces with the help of the hydraulic actuators (Patel, 2013).

PROBLEM DEFINITION

The basic problem in the study of mechanical link mechanism is of finding out the position and orientation of bucket of the backhoe attachment when the joint angles are known, which is referred to as forward kinematics and for any given position and orientation of bucket finding out all possible sets of joint angles which is referred to as inverse kinematics. The problem of link mechanism control requires both the forward and inverse kinematic models of the backhoe attachment of the hydraulic excavator (Mittal and Nagrath, 2008). The kinematic modelling helpful to follow the defined trajectory as well as digging operation can be carried out successfully at required location of the terrain using proper positioning and orientation of the bucket and ultimately digging task can be automated. Here the third section highlights the research work carried out by the researchers in the field of kinematic modelling, which is helpful to understand and improving the operating performance of the backhoe attachment of hydraulic excavator.

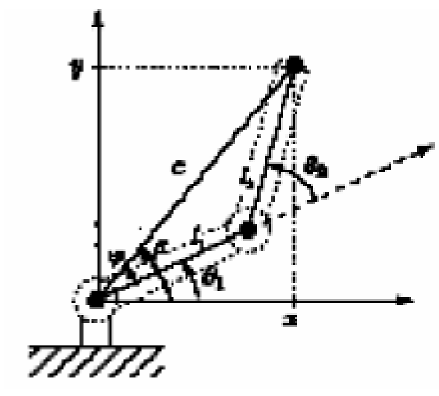
Figure 3: Kinematic Modelling of Excavator



KINEMATIC MODELLING

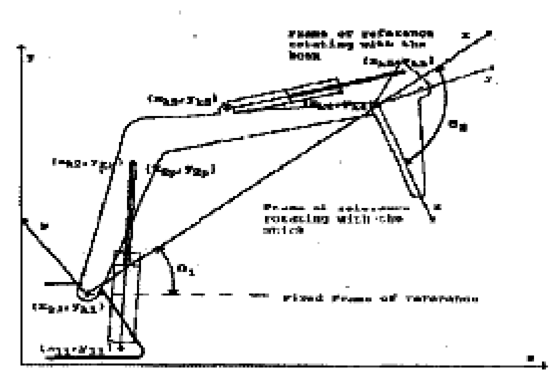
Dongnam Kim *et. al*. (2008) and Le Duc Hanh *et. al.* (2009) have done kinematics of excavator. They have done forward and inverse

Figure 4: Two-DOF Mini Electro-hydraulic Excavator



kinematics. Among this they have done inverse kinematics for two degree of freedom by considering boom and arm link. Figure 4 shows 2-DOF mini electro hydraulic excavator, Medanic *et. al.* (1997) have derived excavator kinematic relation by considering two link only boom link and arm link (Dongnam Kim *et al.,* 2008; Le Duc Hanh *et al.,* 2009; Medanic *et al.,* 1997).

Figure 5: Two Link Excavator



Bodur *et al*. (1994) have control the cognitive force for the automation of the land excavation is developed to include the kinematics of the excavator arm. During digging at a certain point on the excavation trajectory both the crawler and the rotational super-structure bodies are stationary, and thus the kinematic model is reduced to 3 degree of freedom. Kinematic solution of the arm is accomplished in the form of homogeneous transformation matrix by using Denavit-Hartenberg (D-H) notation. The coordinate frame assignment for excavator shown in Figure 6, and Daqing Zhang *et. al*. (2005) have derived the full kinematic model of the excavator arm regarded as a planar manipulator with three degrees of freedom (consider boom, arm and bucket) as shown in

Figure 7. To find a feasible way to control excavator arm and realize autonomous excavation. The exponential product formula based on screw theory is used to develop the kinematic model of manipulator to get the desired trajectory. The experimental result exhibits good tracking performance for boom cylinder under the controller developed. The peak error is less than 4 degrees. However trajectory generation was not demonstrated, and Michael G Lipsett (2009) has described a simple framework for assessing different shovel designs, including kinematic performance of face shovels for surface mining excavation. Key design considerations for an excavating shovel to meet the performance and reliability specifications are based primarily on kinematics. The RH 400 Kinematics shown in Figure 8. The Terex O&K RH 400 is analyzed as a case study reachable workspace, mobility during digging and achievable cutting forces are presented with some simplifying assumptions for the dynamics of the machine. Methods for determining the parameters of the models are discussed,Hongnian Yu *et. al.* (2010), Quang Hoan Le *et. al.* (2012) and Le Quang Hoan *et al.* have described forward and inverse kinematics of excavator by considering three degree of freedom (consider boom, arm and bucket) for controlling purpose, Schematic diagram of an excavator shown in Figure 9 and Projection of the excavator links onto the vertical plane shown in Figure 10, Bundy and Gutkowski have described only forward kinematics of excavator for three degree of freedom system (consider boom, arm and bucket) for trajectory generation,Juma Yousuf Alaydi has described excavator Forward kinematics using Kane method by considering three degree of freedom system. Here all researcher done kinematics of excavator for three degree of freedom system by considering boom, arm and bucket link only

Figure 6: Moving Items of Typical Backhoe and Coordinate Frame Assignment

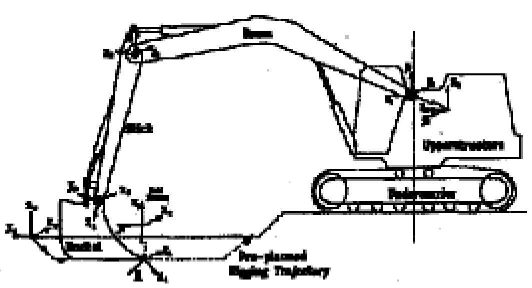


Figure 7: Kinematic Model for Working Mechanism of Hydraulic Excavator

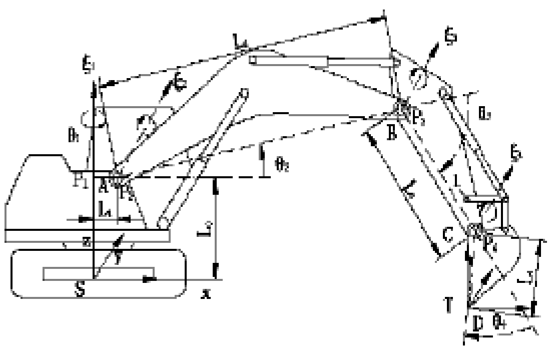
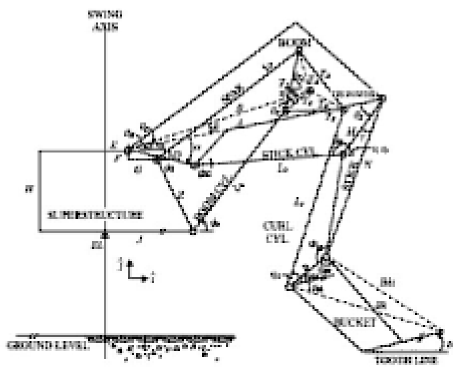


Figure 8: RH 400 Kinematics



still there is scope to develop kinematics of excavator for four degree of freedom system by considering swing, boom, arm and bucket link (Bodur *et al.,* 1994; Daqing Zhang, *et al.,* 2005; Michael G Lipsett, 2009; Hongnian Yu *et al.,* 2010; Quang Hoan Le *et al.,* 2012; Le

Figure 9: Schematic Diagram of an Excavator

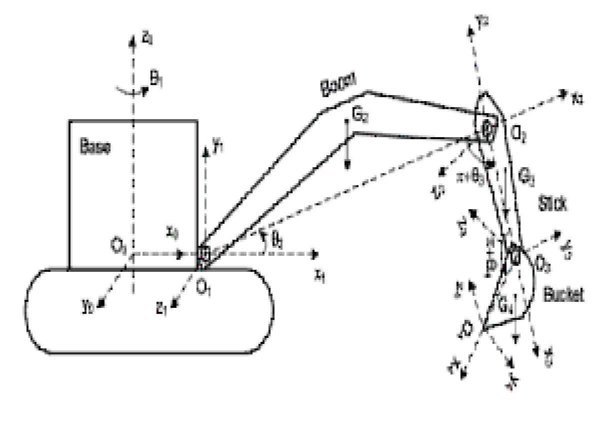
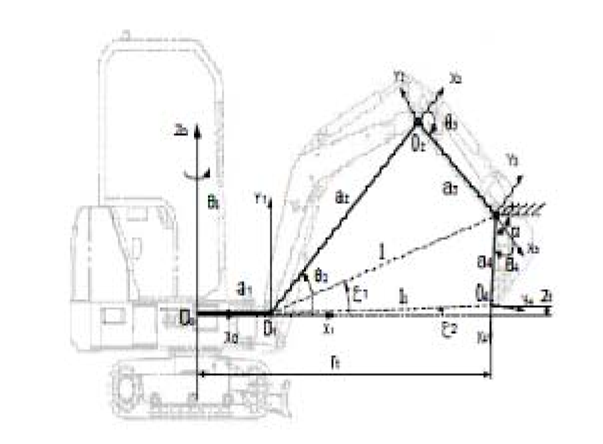


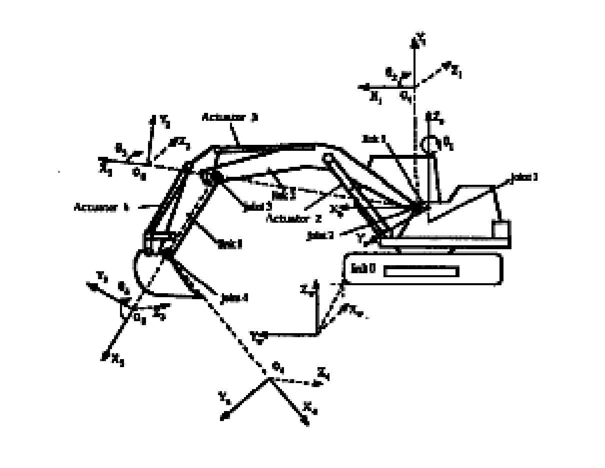
Figure 10: Projection of Excavator Link on to Vertical Plane



Quang Hoan *et al.,* Bundy and Gutkowsk; and Juma Yousuf Alaydi).

Vaha and Skibniewski (1993) have firstly developed kinematics of the excavator by appropriate frame assignments. To describe the position of the points on the mechanism of

Figure 11: Typical Excavator and Its Coordinate Frames



an excavator coordinate systems are first defined as shown in Figure 11.

Vaha developed this kinematic model only as a prerequisite for the dynamic model. He developed the kinematic model for a hydraulic excavator in the general form only, thus giving up to the general transformation matrix relating two consecutive frames (relating frame [i-1] to the frame [i]) as follows:

$$A_{i-2}^{i}\begin{bmatrix} \cos\theta_i & -\cos\alpha_i\sin\theta_i & \sin\alpha_i\sin\theta_i & \alpha_i\cos\theta_i \\ \sin\theta_i & \cos\alpha_i\sin\theta_i & -\sin\alpha_i\sin\theta_i & \alpha_i\cos\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where, a_i is the link length, α_i is the link twist angle, θ_i is the joint angle, and d_i is the joint distance. His kinematic model was not enough, and thus not giving a clear insight in terms of the forward kinematic and inverse kinematic equations. The kinematic model of an excavator presented here provides a useful computation platform for investigating the machine behavior of a typical excavator. Hofstra *et al.* (2000) have described the kinematics of the backhoe of Komatsu H245S with a 12 m boom and 8.5 m stick. This kinematics of backhoe utilized by them for the development of dynamic model. They have determined the relation between the machine orientation and the desired trajectory. In order to do this effectively while describing the position and orientation of the bucket the Denavit-Hartenberg (DH) approach based on homogenous co-ordinates is utilized, however inverse kinematics was not done. Zygmunt Towarek (2003) has developed few kinematic relationships in terms of the transformation matrices between the frames. He only determined those kinematic equations that can be helpful for him to develop a mathematical dynamic model for an excavator. Apart from this, the transformation matrices established by him were only giving the rotational transformation, as it was the only need for his study. Thus he also did not establish any systematic kinematic relationships required encoding the geometrical relationships of the excavator and his kinematic model is not complete. So, there is scope to develop complete kinematic model for four degree of freedom system by considering swing, boom, arm and bucket link (Vaha and Skibniewski, 1993; Hofstra *et al.,* 2000; Zygmunt Towarek, 2003).

Koivo (1994) has presented the kinematics of specific construction machines as excavators. A systematic procedure is presented to assign Cartesian coordinate frames for the links (joints) of an excavator. Coordinate frame assignment for excavator shown in Figure 11. If the lengths of the actuators or the joint variable angles are given, the position and orientation of the bucket are determined by the forward kinematic equations. If the position and orientation of the bucket are specified, the joint variable angles corresponding to this bucket pose and the lengths of the actuators are calculated from the inverse kinematic equations, the corresponding velocity relations are derived for the hydraulically driven excavator. The kinematic equations presented establish the foundation for automatic computer control of this type of construction machine. David A Bradley and Derek W Seward (1995) the LUCIE system has demonstrated a number of novel concepts in its approach to automated and robotic excavation and in particular features such as the use of velocity vector control and software force feedback to control the motion of the bucket through ground. During excavation, the motion of the excavator arm is constrained to the line of the trench in which case referring Figure 12 of excavator kinematics. The equations for angular velocities of each joint were developed. This structure is implemented in real-time using a production rule based AI format. They have control the movement of the excavator or LUCIE through ground by implementation of a real-time artificial intelligence based control system utilizing a novel form of motion control strategy, Rao and Bhatti (2001) have developed a probabilistic model of the manipulator kinematics to account for the random errors in the kinematic parameters. The link and joint parameters of a general robotic arm are shown in Figure 13. Based on the probabilistic model kinematic performance criteria are defined to provide measures of the behavior of the robotic end-effectors. Gaussian distributions are assumed for the various manipulator parameters, and the joint efforts are modelled as Markov stochastic processes. Indices called kinematic reliabilities are proposed as measures to assess the performance of a manipulator. The

Figure 12: Excavator Kinematics

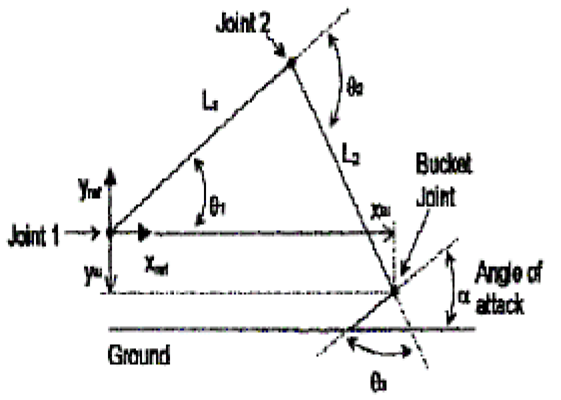
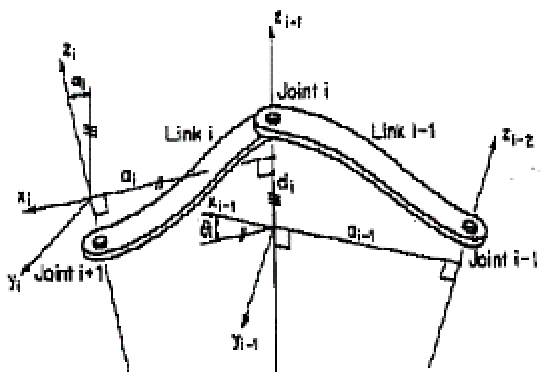


Figure 13: Link and Joint Parameters



analytical approach is computationally more involved and the simulation technique is numerically more convenient to compute the performance measures of a manipulator (Koivo, 1994; David A Bradley, Derek W Seward, 1995; Rao and Bhatti, 2001).

Hsin-Sheng Lee *et al.* (2002) have developed CAD/CAE/CAM and remote control integrated system for a pneumatic excavator mechanism. The Pneumatic excavator prototype shown in Figure 14. The vector loop method and Visual C++ language were used to build the position analysis module. The velocity of the links could be obtained easily by differentiating the position equation with respect to time. Link accelerations were than obtained by differentiating the velocity equation. The position analysis determines the working space of the excavator loader and helps the designer to choose the proper length and link configuration and Rosen Mitrev *et al.* (2011) have described work related to CAD/CAE

Figure 14: Pneumatic Excavator Prototype

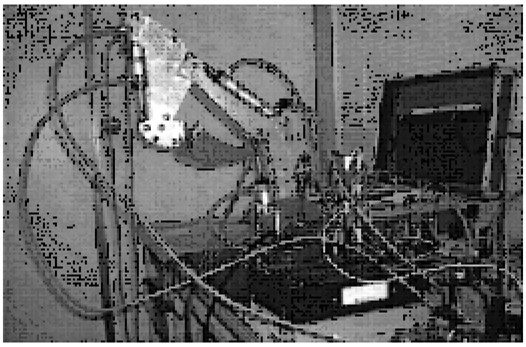
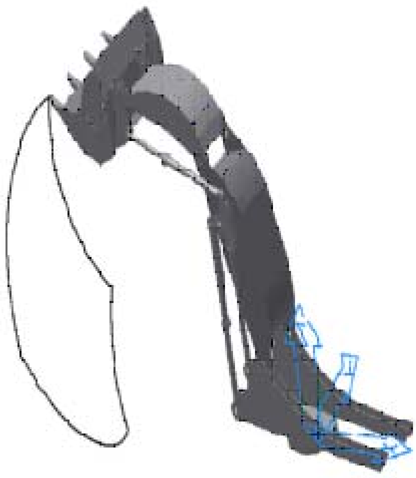


Figure 15: A 3D CAD Model of Excavator Working Equipment



investigation of the mechanical system of large mining excavator with Tri-power system. The investigation is performed in Autodesk Inventor environment. A 3D model of the excavator working equipment is developed as shown in Figure 15, which is helpful for investigation of geometrical forces, Kinematical and dynamical parameters of the mechanical system and it is also useful to finding out the workspace of excavator (Hsin-Sheng Lee *et al.,* 2002; Rosen Mitrev *et al.,* 2011).

Fuad Mrad *et al.* (2002) have developed simulation package using Matlab with several embeded design and analysis tools, Emulation was also carried out on the Rhino educational robot to confirm the simulation results. The constructed simulation package offered an integrated environment for trajectory design and analysis for an excavator while addressing the constraints related to the excavator structure, safety, stability and mode of application. In this simulation package they have carried out kinematic modelling for excavator and the numerical values of specifications are adopted for the JCB-3CX commercial excavator as per brochure of the excavator. The structure of the backhoe excavator model shown in Figure 16, and the structural parameters of the excavator model shown in Figure 17. Vineet R Kamat and Julio C Martinez (2009) have described concept for how can we do forward and inverse kinematics of excavator and showing Configuration of a excavator inverse kinematics Problem shown in Figure 18 (Fuad Mrad *et al.,* 2002; Vineet R. Kamat andJulio C. Martinez, 2004).

Figure 16: Structure of the Excavator Model

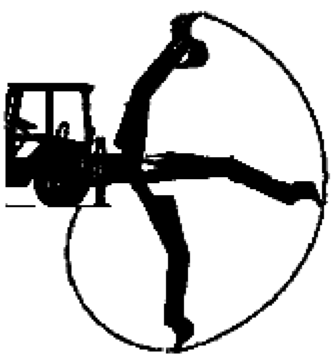


Figure 17: Structural Parameters of Excavator Model

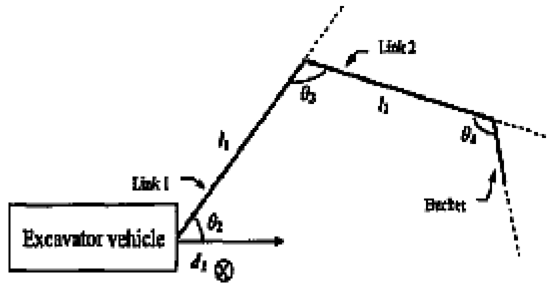
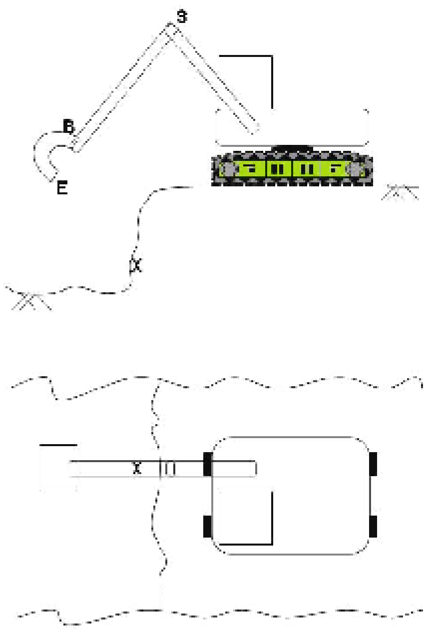


Figure 18: Configuration of Excavator IK Problem



Emil Assenov *et al*. (2003) have carried out study on kinematics of working mechanism of hydraulic excavator. The mechanism of this manipulator is plane multi-linkage, which consists of arms joined and hydraulic cylinders. They have considered the working mechanism as conjunction of jib, arm and bucket, which are joined by the cylindrical joints and hydraulic cylinders. A model of mechanism arm shown in Figure 19. The equation for the length of the cylinder is derived. Simulation of such a mechanism is made by using Lagrange equation of the first type with unknown multipliers. The results can be used for creation of a control system of the working process of the hydraulic excavator. Geu Flores *et. al*. (2007) have described a method based on the concept of kinematical transformers for finding closed-form solutions for the kinematics of Terex face-shovel excavator RH-340 as shown in Figure 20. In this concept, each multi-body loop is regarded as a transmission element, which is coupled by linear equations with the other multi-body loops. The work space of an excavator is carried out for a practical face-shovel excavator using the designed software. The resulting workspace of an excavator in

Figure 19: A Model of Mechanism Arm-jib

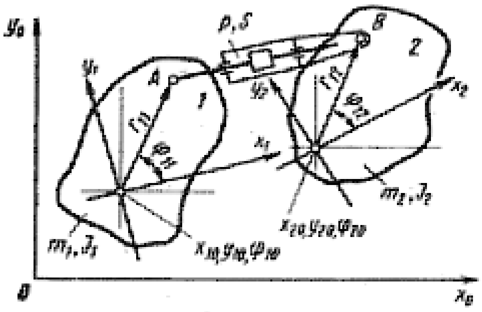


Figure 20: Terex Face-shovel Excavator RH-340

Figure 21: Workspace of an Excavator

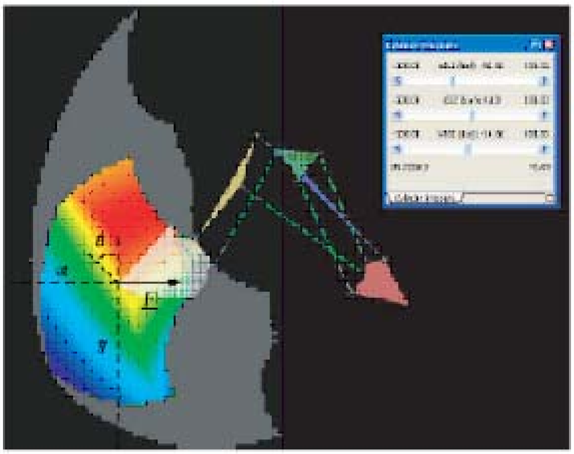
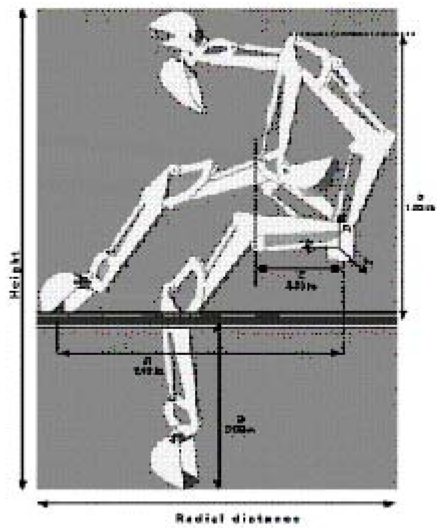


Figure 22: Manipulator Configuration

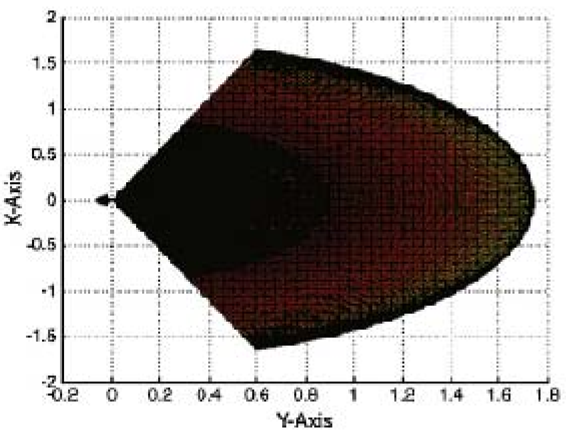


design environment shown in Figure 21 (Emil Assenov *et al.,* 2003; Geu Flores *et al.,* 2007).

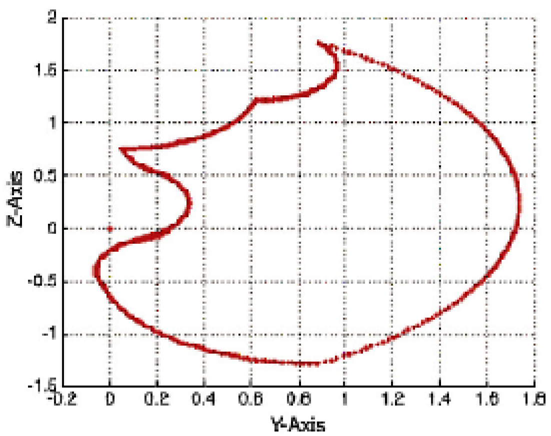
Jungwon Yoon and Auralius Manurung (2010) have developed an intuitive user interface for a hydraulic backhoe excavator.

Figure 22: Workspace of Backhoe Excavator

(a) Workspace Top View

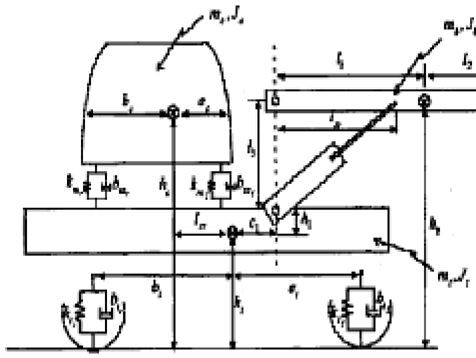


(b) Workspace Side View



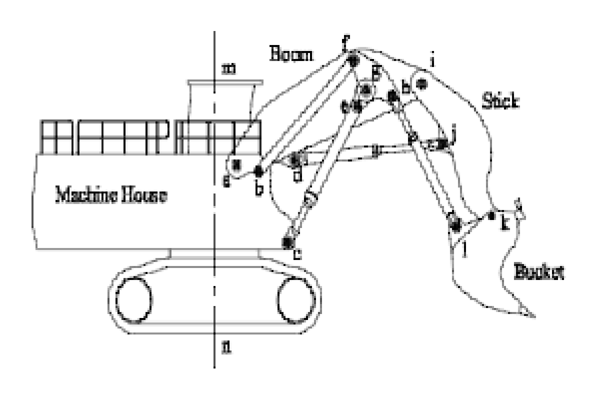
They have developed workspace analysis of the backhoe excavator using three dimensional (3D) modelling tool (Solid works, Dassault system Solid works Corp. Concord, MA, USA) and verified through a numerical analysis of the inverse kinematics and Joint limitation, Workspace of the backhoe excavator shown in Figure 22 (Jungwon Yoon and Auralius Manurung, 2010).

Figure 23: Schematic and Various Dimensions of the Backhoe Model



Donald Margolis and Taehyun Shim (2003) have developed a complete pitch/plane model of a backhoe that includes the hydraulic dynamics and kinematics of the control linkage. Schematic and various dimensions of backhoe model shown in Figure 23. Equations were derived directly from the bond graph and programmed for simulation using a digital computer. Simulations were run for an initial condition response from near equilibrium. The model predicts the instability observed on the actual backhoe, and is now ready to be used as a design tool for future backhoe development. Hall and McAree (2005) have studied on the excavation arm of a large hydraulic mining shovel having a multi-loop kinematic form. They have described an iterative algorithm that allows the position of the bucket to be tracked from measurements of the linear actuator extensions. The important characteristic of this algorithm is that it is numerically well-behaved when the linkage is close to singular configuration. They have also carried out forward kinematic tracking using a multi-dimensional Newton–Raphson solver

Figure 24: Kinematic Layout of the Excavation Arm



which is helpful to determining the time-varying trajectory from measurements of the cylinder lengths. The kinematic layout of the excavation arm shown in Figure 24 (Donald Margolis and Taehyun Shim, 2003; Hall and McAree, 2005).

Hyongju Park *et. al*. (2008) the recurrent neural network was implemented for better kinematics control of the excavator with obstacle avoidance capability. A recurrent neural network algorithm and joint constraints was conducted to effectively accomplish the goals of excavation task execution, joint limit control, and obstacle avoidance at the same time. The forward kinematics model of the excavator was established. For convenience and generality Denavit-Hartenburg (DH) notation was used to build homogenous transformation matrices. With additional bound constraints, excavator model can perform its job without any problem, such as malfunctioning, sudden stop, etc. Simulation results show that the position error was reasonably small, on the assumption that excavator model has only one available redundancy. Dongnam Kim *et al.* (2009) have review a novel concept of applying tele-operated device was developed for the remote control of excavator-like dismantling equipment. As a tele-operated system, this controller is designed to improve the operability of the excavator. They have developed all the necessary kinematic analysis to design the tele-operated system and basic motion control simulations to the real excavator working at construction site are conducted with designed tele-operated system. This device is designed based on the kinematics of the excavator, which can cover 3-dimensional workspace. Kinematic model of excavator shown in Figure 25, Yan Jun *et al.* (2013) have described reviews on modelling, identification, and low level control

Figure 25: Kinematic Model of Excavator

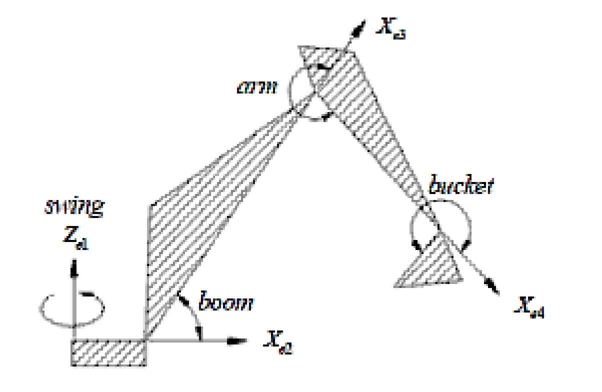
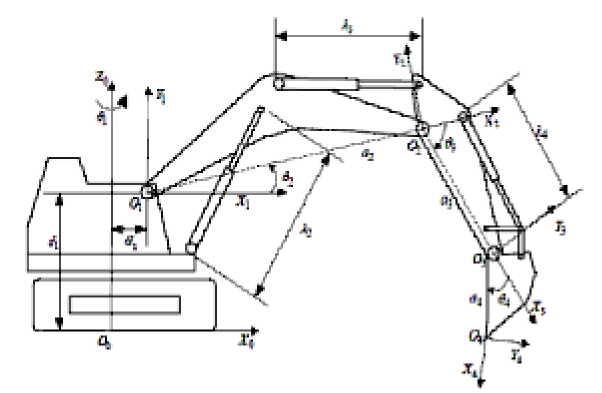


Figure 26: Typical Excavator and Its Coordinate Frames

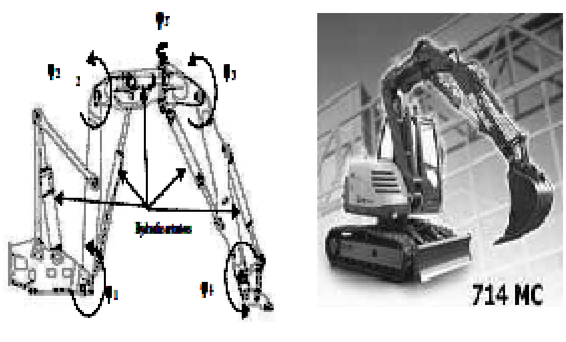


of the robotic excavator. Typical Excavator and Its coordinate Frames as shown in Figure 26. First modelling of the nonlinear hydraulic dynamics, coupling manipulator dynamics and soil-tool interaction dynamics are reviewed. Then, methods for identification of the established models are discussed. Finally, robust position control and compliance control of the robotic excavator are investigated (Hyongju Park *et al.,* 2008; Dongnam Kim *et al.,* 2009; Yan Jun *et al.,* 2013).

Patel and Prajapati (2011) have described review of a work carried out by researchers in the field of kinematic modelling of the excavatorbackhoe attachment to understand relations between the position and orientation of the bucket and spatial positions of joint-links.Yang Cheng *et. al.* (2012) have described development of hydraulic excavator attachment. This paper focuses on the research work of excavator backhoe attachment, which is mainly includes those aspects, such as the kinematic analysis, dynamic analysis, structural analysis, trajectory planning and control, fatigue life analysis and structural optimization design and the development trends of excavator backhoe attachment in near future are forecasted (Patel and Prajapati, 2011; Yang *et al.,* 2012).

Jolly Shah *et al.* (2013) have described the kinematic analysis of a Pravak Robot arm which is used for doing successful robotic manipulation task in its workspace. The Pravak Robot Arm is a 5-DOF robot having all the joints revolute. The kinematics problem is defined as the transformation from the Cartesian space to the joint space and vice versa. In this study the Denavit-Hartenberg (D-H) parameter is used to model robot links and joints. Pravak Robot arm is a simple and safe robotic system designed for laboratory training and research applications. This robot allows to gain theoretical and practical experience in robotics, automation and control systems. Matlab software is used to analyze end effectors position for a set of joint parameter. Anil Jadhav *et al.* (2014) have described the kinematic analysis of whole assembly of excavator backhoe attachment for understanding the behavior of the various joints which are used for connecting the parts of excavator machine. Sardana *et al*. (2013) have described a simple geometric approach to solve the problem of multiple inverse kinematic solutions of redundant manipulators, to find a single optimum solution and to easily switch from one solution to another depending upon the path and the environment. Boris Vidolov and Svetoslav Genchev (2005) have developed two heuristic approaches for inverse kinematics of a real 12 MXT MECALAC redundant excavator. They have presented a priority approach and alternating approach in simulation, the method gives a very smooth overall motion. They have developed a simulator in order to test and validate their

Figure 27: MECALAC Arm Scheme



developments. This is generic tool that allow us to simulate different kinematics and dynamic models to evaluate various control algorithms, to observe the behavior of the different body, actuators, tools of the studied arms, to quantify the capacities of developed approaches to follow specified trajectories. MECALAC arm scheme shown in Figure 27 (Jolly Shah *et al.,* 2013; Anil Jadhav *et al.,* 2014; Sardana *et al.,* 2013; Boris Vidolov and Svetoslav Genchev, 2005).

Figure 28: A Backhoe Excavator

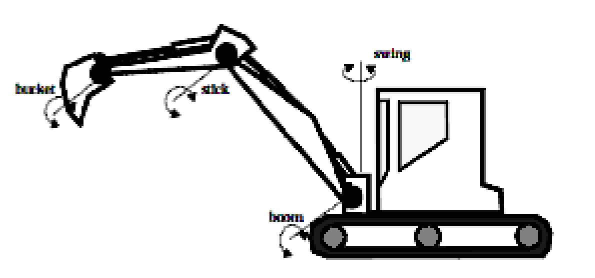
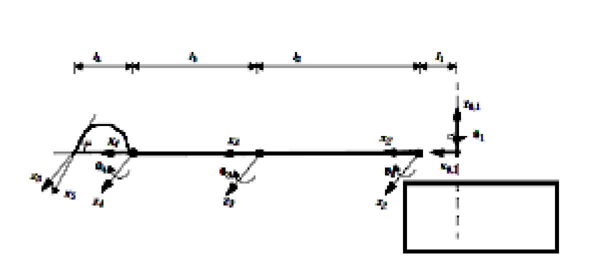


Figure 29: Kinematic Model of Backhoe Excavator



Sanjiv Singh (1995) has showing kinematic model of backhoe excavator as shown in Figure 29 and described Forward and Inverse kinematics of backhoe excavator. Arvind Kumar Sharma (2005), Joe Frankel (2003), Matthew E Kontz (2007) and Nguyen Hong Quang (2000) have described kinematics of excavator backhoe attachment, and showing backhoe Relationship between Cylinder Space to Joint Space and Joint Space to Cylinder Space (Sanjiv Singh, 1995; Arvind Kumar Sharma, 2005; Joe Frankel, 2003; Matthew E Kontz, 2007; Nguyen Hong Quang, 2000).

CONCLUSION

A Critical Reviews carried out on kinematics of excavator backhoe attachment and conclude that no. of researcher work on kinematics of excavator backhoe attachment by considering boom and arm link only (2-DOF system) and no. of researcher work on kinematics of excavator backhoe attachment by considering boom, arm and bucket link (3-DOF system) for planner case using this kinematic model only digging operation can be controlled but no one can explain deeply kinematics of excavator by considering swing, boom, arm and bucket link (4-DOF system) for three-dimensional space still there is scope to develop kinematic model of excavator by considering 4-DOF system by using this kinematic model both digging and dumping operation can be controlled which is helpful to develop autonomous excavator machine.

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