A Robotic Soil Excavator for Truck Loading:

Kinematics, Dynamics and Motion control for a 4-DOF Robotic Manipulator prototype

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***Abstract*—This paper presents a developed prototype of an automated robotic soil excavator. This prototype has four degrees of freedom (4 DoF) which consists of a series of four rigid links that are connected by four revolute joints as in Fig. 1. However, developing this prototype aims to reduce time and efforts that are needed by conventional excavator. Therefore, this prototype is developed to achieve predefined motions with various phases: excavation of the soil from a designated point, transportation, as well as deposition the soil in a truck within a specified time duration. For the prototype development, suitable components and mechanical frames must be integrally selected. Moreover the kinematics and dynamics models are derived for the manipulator to analyze and plan motions, determine the necessary driving torques, and form the basis for several model-based motion control algorithms. Using MATLAB and Simulink, model-based motion control algorithms were developed and tested, and a PD controller with a gravity compensator was applied to the physical robot.**

Keywords—Soil excavator, Robot, State-feedback with integral control, PD with gravity compensator.

I. INTRODUCTION

Hydraulic excavators are commonly used in the construction industry for soil removal due to their high power and performance. This study focuses on the development of a robotic soil excavator prototype that uses an anthropomorphic manipulator arm. The four joint actuators have synchronized motions, and these joints mimic the design of the HITACHI model EX 215 LC excavator [1] and the prototype is scaled down from the original size. s1, all of which have been designed using Solidworks program [2] and integrated with other electromechanical components to enable semi- or fully-automated operation.

Figure 1. HITACHI model EX 215 LC.

A proposed development involves mechatronics design, including structural design and the selection of electromechanical components such as electrical actuators, sensors, and a microprocessor [3]. The development also includes programming, robotic modeling, and applying control techniques in order to create a semi-automated robotic excavator (i.e., the excavator be partially controlled by a human operator).

To implement this approach, the MATLAB and SIMULINK software packages [4] are used for the development, analysis, and simulation of the robotic excavator's dynamic model, as well as for implementing nonlinear control methods. The robot operates with the Raspberry Pi 4 (model B) microcomputer that is considered as the main system controller [5], it is used to develop and implement the control algorithms and interface with the hardware components.

The aim of this paper is to develop and apply a control strategy for the manipulator using a nonlinear algorithm [6], [7], that called PD with a gravity compensator. Through this study, we derived the mathematical model that includes both kinematic and dynamic analyses of the manipulator [8]. The robot was simulated using an I-PD controller on MATLAB software. It's worth mentioning that many previous studies considered the effects of the external forces on the bucket while digging [9]. However, these forces were neglected in our real experiments. Finally, the PD with a gravity compensator [10] was applied to the real excavator, and the results of both the simulation and the real experiment are presented accordingly.

II. KINEMATIC AND DYNAMIC ANALYSIS OF THE ROBOTIC MANIPULATOR

The kinematics analysis studies the motion to manipulate an object in space and analyzing its structure without implementing the acting forces. The main objective of kinematics analysis is to determine the position and velocity of the end-effector, as a function of the joint variables and the angular velocities of the manipulator's joints. Furthermore, the dynamic model of the manipulator is derived by examining the relationship between the joint actuator torques and the motion of the structure.

A. Kinematics model

1) Robot forward kinematics

For the 4-DoF excavator manipulator, the forward kinematics is derived. According to Fig. 2 that describes the