Controller for Excavator During Digging Operations*

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Abstract

Computer controlled construction machines outperform their manually controlled counterpart in terms of velocity, accuracy and time. A control scheme is here presented to automate the digging operations of an excavator. This controller is designed to follow the desired motion of the bucket during digging operations, and to account for the forces experienced on the bucket during excavation due to interaction of the bucket with the soil. The controller designed guarantees asymptotic stability of the system. Simulation results of a typical digging procedure are presented to illustrate the approach.

Keywords

Robot Control, Construction Automation, Excavation Control.

Introduction

In order to improve productivity and effectiveness in construction related tasks, the automation of machine operations is desirable. Particularly, a computer controlled excavator would outperform its manually controlled counterpart in terms of velocity, efficiency and time.

Some of the advantages of computer controlled excavators versus manually operated excavators include results independent of operator skills, effective management of machine usage and scheduling, effective planning of sequences, repeatability, and capability of operations under hazardous and/or hostile conditions, such as severe weather or unhealthy environments.

The study of excavators as computer controlled machinery has attracted robotics researchers recently. In order to design a controller for excavation procedures, the kinematics and dynamics that describe the behavior of the excavator are necessary. Studies on the kinematic model of excavators and trajectory planning are presented in [2], [3], [4], [7], and [8]. The dynamical modeling of such machinery is described in [6]. Little work has been published in controlling the excavator. The work presented in this article follows the one done in [4] and [6].

A control system is here presented to automate the excavator operations. This control scheme is designed to follow the desired motion of the bucket during digging operations, and to account for the forces experienced on the bucket during excavation due to interaction of the bucket with the soil. Simulation results of a typical digging procedure are presented to illustrate the approach.

Kinematic and Dynamic Models for Excavator

For the automatic motion of the excavator shown in Figure 1, it is desirable to place the bucket at different specific positions and orientations on time. This can be accomplished by regulating the lengths of the piston rods in the hydraulic actuators, and thus the shaft positions of the joints properly. During a digging operation, the rotation angle θ_1 of the first joint remains constant, *i.e.*, the digging operations are performed on the $X_0\, Z_0$ plane. Furthermore, $\dot{\theta}_1 \equiv 0$ and $\ddot{\theta}_1 \equiv 0$.

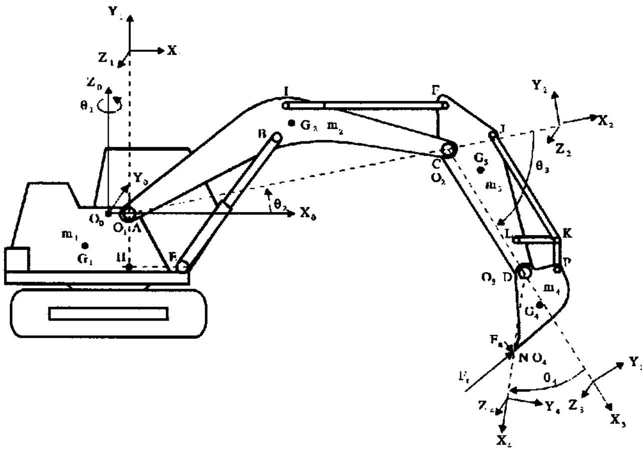

Figure 1. Schematic Side View of Excavator.

The mathematical expressions that relate the position and orientation of the bucket in the Cartesian base coordinate system to the shaft (joint variable) positions and orientations are given by the forward kinematic relation:

$$\mathbf{p}_0^{O_4} = \mathbf{A}_0^4 \mathbf{p}_4^{O_4} = \begin{bmatrix} a_4 c_{234} + a_3 c_{23} + a_2 c_2 + a_1 \\ 0 \\ a_4 s_{234} + a_3 s_{23} + a_2 s_2 \\ 1 \end{bmatrix} \quad (1)$$

where $\mathbf{p}_i^{O_4}$ is the position of the bucket tip expressed in the i-th coordinate frame of the excavator. $\mathbf{A}_0^4$ is the homogeneous transformation matrix that relates a vector in the bucket tip coordinate frame to a vector in the base coordinate system. The coordinate frame assignment for the excavator shown in Figure 1 follows systematically the Denavit and Hartenberg guidelines [5], and is presented in [4].

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The dynamical model for an excavator describes the equations of motion of the system. These equations can be obtained by considering each link of the excavator (the upperstructure, the boom, the arm, and the bucket) as free bodies, and obtaining their equations of motion in succession on the basis of Newton's and Euler's laws of movement. The equations of motion for an excavator are calculated in this fashion in [6], and will be adapted in this work.

The dynamics of the excavator shown in Figure 1 are described in Lagrange formulation by

$$\mathbf{D}(\theta)\ddot{\theta}+\mathbf{C}(\theta,\dot{\theta})\theta+\mathbf{G}(\theta)+\beta\dot{\theta}=\tau \tag{2}$$

where θ , $\dot{\theta}$, and $\ddot{\theta}$ are four-dimensional vectors specifying the shaft angles, velocities and accelerations, respectively. $\mathbf{D}(\theta)$ is the 4×4 symmetric positive definite pseudo-inertia matrix. $\mathbf{C}(\theta,\dot{\theta})\dot{\theta}$ describes the Coriolis and centripetal generalized forces. $\mathbf{G}(\theta)$ represents the gravitational effects. β is a constant diagonal 4×4 matrix that represents the frictional loading on the joint shafts. $\tau=\Gamma(\theta)\mathbf{F}-\mathbf{F}_{load}(F_t,F_n)$ is the 4×1 torque vector, where the 4×4 matrix $\Gamma(\theta)$ is a function of the moment arms; $\mathbf{F}=[F_b \quad F_{BE} \quad F_{FI} \quad F_{JK}]^T$ specifies the forces of the hydraulic actuators which produce the torques acting on the joint shafts; and $\mathbf{F}_{load}$ is determined by the normal and tangential forces F_n and F_t observed on the bucket due to soil and bucket interaction.

Equation (2) describes the dynamics of the excavator, in which the joint torque vector is expressed as a function of the link masses, the joint positions, velocities, and accelerations. The joint position vector θ determines the configuration of the excavator via the kinematic relations given in Equation (1).

Reaction Force

During the digging operation, the reaction force on the tip of the bucket due to interaction of the bucket with the soil has the form [1]:

$$F_{load}=k_s bh+\mu N+\varepsilon\left(1+\tfrac{V_s}{V_b}\right)bh\sum\Delta x \tag{3}$$

where k_s is the specific resistance to cutting for silty clay, b and h are the width and thickness of the cut slice of soil respectively, μ is the coefficient of friction of the bucket with the soil, N is the pressure force of the bucket with the soil, ε is the coefficient of resistance to filling the bucket and movement of the prism of soil, V_s and V_b are the volumes of the prism of soil and the bucket respectively, and Δx is the increment on the horizontal axis in meters.

This reaction force is defined to be at an angle 0.1 *rad* below the tangent line to the digging direction, in order to achieve a resultant force parallel to the digging direction [8]. Its tangential and normal components are $F_t=F_{load}\cos(0.1)$ and $F_n=-F_{load}\sin(0.1)$ respectively.

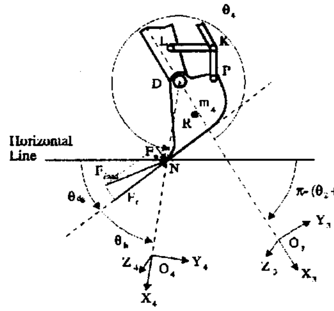

Figure 2. Forces on Bucket Tip Due to Bucket Soil Interaction.

Controller Design

The dynamical model of the excavator given in Equation (2) is highly nonlinear and computationally complex. Most general methods for controller design are based on linear time invariant models. For this reason, to design a controller for the gross motion of an excavator, two stages may be considered. First, one may design a primary controller that under ideal conditions makes the bucket tip track the desired position (velocity) and force excavation trajectories. Then, based on a linearized model, to design a controller that compensates for undesirable deviations of the motion from the desired trajectory caused by external and/or internal disturbances, *i.e.*, inaccuracies in the excavator model, small deviations from the desired digging trajectory, or deviations from the expected values of the digging forces experienced during excavation due to interaction of the bucket with the soil.

The purpose of the first controller is to produce the generalized torque values that when applied to the system, result in the desired motion of the bucket under ideal conditions. A primary controller is next designed by means of the computed torque method [5].

The dynamical model for the excavator during digging operations, given by the last three rows of Equation (2) can be rewritten as a set of first order differential equations of the form

$$\begin{bmatrix}\dot{\mathbf{x}}^1(t)\\ \dot{\mathbf{x}}^2(t)\end{bmatrix}=\begin{bmatrix}\mathbf{x}^2(t)\\ \mathbf{f}^2(\mathbf{x})\end{bmatrix}+\begin{bmatrix}0\\ \mathbf{B}^2(\mathbf{x}^1)\end{bmatrix}\mathbf{u}(t) \tag{4}$$

where the six-dimensional state vector $\mathbf{x}(t)=[\theta_2(t) \quad \theta_3(t) \quad \theta_4(t) \quad \dot{\theta}_2(t) \quad \dot{\theta}_3(t) \quad \dot{\theta}_4(t)]^T$ is decomposed in two three-dimensional vectors $\mathbf{x}^1(t)=[\theta_2(t) \quad \theta_3(t) \quad \theta_4(t)]^T$ and $\mathbf{x}^2(t)=[\dot{\theta}_2(t) \quad \dot{\theta}_3(t) \quad \dot{\theta}_4(t)]^T$, and the three dimensional input vector is $\mathbf{u}(t)=[F_{BE}(t) \quad F_{FI}(t) \quad F_{JK}(t)]^T$. The vector valued nonlinear functions $\mathbf{f}^2(\mathbf{x})$ and $\mathbf{B}^2(\mathbf{x}^1)$ are defined next relating the dynamical model of the excavator to Equation (4), and in the sequel, omitting the time notation for convenience.

$$\mathbf{f}^2(\mathbf{x})=-[\mathbf{D}(\mathbf{x}^1)]^{-1}[\mathbf{C}(\mathbf{x})\mathbf{x}^2+\mathbf{G}(\mathbf{x}^1)+\beta\mathbf{x}^2+\mathbf{F}_{load}] \tag{5}$$

$$\mathbf{B}^2(\mathbf{x}^1)=[\mathbf{D}(\mathbf{x}^1)]^{-1}\Gamma(\mathbf{x}^1) \tag{6}$$

where the inertia matrix $\mathbf{D}$, the Coriolis and centripetal terms matrix $\mathbf{C}$, the gravitational effects matrix $\mathbf{G}$, the function of the moment arms matrix Γ , and the external force vector $\mathbf{F}_{load}$ are defined in [6]. The constant diagonal friction matrix β accounts for frictional effects on the motion of the excavator.

The problem at hand is to generate the input vector $\mathbf{u}$ so that $\mathbf{x}$ will track the desired trajectory $\mathbf{x}^d$ and achieve the desired external force $\mathbf{F}^d_{load}(t)$ under ideal conditions. The desired input vector $\mathbf{u}^d$ will be chosen such that $\left(\mathbf{x}^d, \mathbf{u}^d\right)$ satisfy Equation (4), this is:

$$\dot{\mathbf{x}}^{2d} = \mathbf{f}^2\left(\mathbf{x}^d\right) + \mathbf{B}^2\left(\mathbf{x}^{1d}\right)\mathbf{u}^d \tag{7}$$

The inverse of $\Gamma(\mathbf{x}^1)$ is assumed to exist at all times. Substituting Equations (5) and (6) in Equation (7) and solving for $\mathbf{u}^d$:

$$\mathbf{u}^d = \left[\Gamma\left(\mathbf{x}^{1d}\right)\right]^{-1}\left[\mathbf{D}\left(\mathbf{x}^{1d}\right)\dot{\mathbf{x}}^{2d} + \mathbf{C}\left(\mathbf{x}^d\right)\mathbf{x}^{2d} + \mathbf{G}\left(\mathbf{x}^{1d}\right) + \beta\mathbf{x}^{2d} + \mathbf{F}^d_{load}\right] \tag{8}$$

Equation (8) specifies the primary controller. It also represents the ideal inverse dynamics of the excavator.

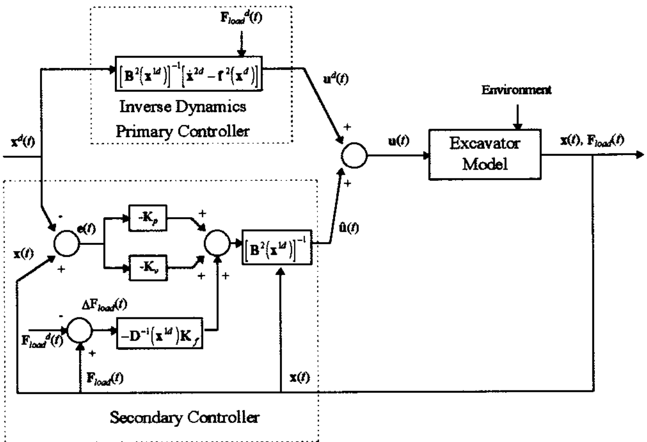

Figure 3. Excavator System Driven by Primary Controller and Secondary PD Position-Force Controller.

A feedback-feedforward linearization method [5] is applied to the nonlinear model of the excavator to determine a linearized model. This method is more suitable than the common linearization method accomplished by determining the variational equations about a nominal trajectory, since the latter requires expressions of the derivatives of the model and, in the case of the excavator, these expressions are quite lengthy.

The excavator model will have now the linear time-invariant form:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\hat{\mathbf{u}} \tag{9}$$

where the constant matrices $\mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ \mathbf{A}_{21} & \mathbf{A}_{22} \end{bmatrix}$, and $\mathbf{B} = \begin{bmatrix} \mathbf{0} \\ \mathbf{B}_2 \end{bmatrix}$ will be chosen in the design of the secondary controller to meet certain given design specifications.

By selecting the control input force $\mathbf{u}$ as:

$$\mathbf{u} = \left[\Gamma\left(\mathbf{x}^1\right)\right]^{-1}\left[\mathbf{D}\left(\mathbf{x}^1\right)\left[\mathbf{B}_2\hat{\mathbf{u}} + \mathbf{A}_{21}\mathbf{x}^1 + \mathbf{A}_{22}\mathbf{x}^2\right] + \mathbf{C}(\mathbf{x})\mathbf{x}^2 + \mathbf{G}\left(\mathbf{x}^1\right) + \beta\mathbf{x}^2 + \mathbf{F}_{load}\right], \tag{10}$$

the nonlinear model given by Equations (4), (5), and (6) assumes the linear form given by Equation (9). This makes the total system appear linear.

To compensate for the effects of internal modeling errors and disturbances, a secondary controller is inserted into the system. It will regulate small deviations of the system response about a nominal trajectory. The purpose of the secondary controller is to drive the tracking error asymptotically to zero. The secondary controller can be designed on the basis of the linearized model shown in Equation (9).

To design a secondary PD position-force controller to drive the tracking error $\mathbf{e} = \mathbf{x}^1 - \mathbf{x}^{1d}$ and the external force error $\Delta\mathbf{F}_{load} = \mathbf{F}_{load} - \mathbf{F}^d_{load}$ asymptotically to zero, one can select $\mathbf{A}_{21} = \mathbf{A}_{22} = 0$ and $\mathbf{B}_2\hat{\mathbf{u}} = -\mathbf{K}_p\mathbf{e} - \mathbf{K}_v\dot{\mathbf{e}} - \mathbf{D}^{-1}\left(\mathbf{x}^1\right)\mathbf{K}_f\Delta\mathbf{F}_{load}$ in Equation (10), where matrices $\mathbf{K}_p$, $\mathbf{K}_v$, and $\mathbf{K}_f$ are the constant controller gains. If such a selection is chosen, the secondary controller $\hat{\mathbf{u}}$ will be proportional to the position and force errors.

$$\hat{\mathbf{u}} = \left[\Gamma\left(\mathbf{x}^1\right)\right]^{-1}\left[\mathbf{D}\left(\mathbf{x}^1\right)\left[-\mathbf{K}_p\mathbf{e} - \mathbf{K}_v\dot{\mathbf{e}}\right] - \mathbf{K}_f\Delta\mathbf{F}_{load}\right] \tag{11}$$

The total input $\mathbf{u}$ to the excavator system is determined by the combination of the primary and secondary controllers:

$$\mathbf{u} = \mathbf{u}^d + \hat{\mathbf{u}} \tag{12}$$

Under the assumption that $\mathbf{B}^2\left(\mathbf{x}^1\right) = \mathbf{B}^2\left(\mathbf{x}^{1d}\right)$ and $\mathbf{f}^2(\mathbf{x}) = \mathbf{f}^2\left(\mathbf{x}^d\right)$, this input can be expressed as follows:

$$\mathbf{u} = \left[\Gamma\left(\mathbf{x}^{1d}\right)\right]^{-1}\left[\mathbf{D}\dot{\mathbf{x}}^{2d} + \mathbf{C}\left(\mathbf{x}^d\right)\mathbf{x}^{2d} + \mathbf{G}\left(\mathbf{x}^{1d}\right) + \beta\mathbf{x}^{2d} + \mathbf{F}_{load} + \mathbf{D}\left(\mathbf{x}^{1d}\right)\left[-\mathbf{K}_p\mathbf{e} - \mathbf{K}_v\dot{\mathbf{e}}\right] - \mathbf{K}_f\Delta\mathbf{F}_{load}\right] \tag{13}$$

When the composite controller in Equation (13) is substituted into the excavator Equation (4), and assuming that the nonlinear terms cancel exactly, the dynamical model for the error equation becomes:

$$\ddot{\mathbf{e}} + \mathbf{K}_v\dot{\mathbf{e}} + \mathbf{K}_p\mathbf{e} + \mathbf{D}^{-1}\left(\mathbf{x}^{1d}\right)\mathbf{K}_f\Delta\mathbf{F}_{load} = \mathbf{0} \tag{14}$$

The 3×3 matrices $\mathbf{K}_p$, $\mathbf{K}_v$, and $\mathbf{K}_f$ are chosen diagonally in order to achieve independent joint control, *i.e.*, the error of each joint will evolve in time independently of the errors of the other joints. The values of K_{pi} and K_{vi}, $i = 2, 3, 4$, are chosen so as to guarantee the eigenvalue assignment corresponding to the design specifications. Simulations are presented to demonstrate the performance of the proposed controller.

Simulations

Simulation studies were performed with the use of a hypothetical excavator model on a 486DX computer using MatLab 4.2c for Windows (MathWorks, Inc. ©1994). On a digging operation, the soil is to be removed by a ploughing action. The depth of the bucket edge, *i.e.*, the cut depth is determined by two factors: the need to have the bucket full at the end of the stroke, and the requirement that the excavating forces stay at sufficiently low values so as not to unduly impede the progress of the bucket.

A desired trajectory is first designed in the Cartesian plane (see Figure 4). The direction of the digging operation must be tangent to the trajectory of the bucket. This is achieved by properly selecting the digging angle as a function of the Cartesian position of the fourth coordinate frame. Using the inverse kinematic equations of the excavator [4], the desired joint positions are calculated. First-order forward approximations of the joint positions are used to generate the desired joint velocities and accelerations.

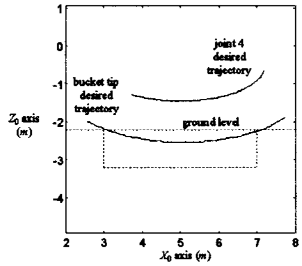

Figure 4. Desired Cartesian Trajectory.

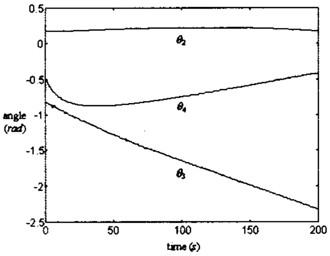

Figure 5. Joint Position.

On the design of computer controlled excavation special attention has to be focused on the transient response of the system. No oscillation shall be permitted such that the actuators are required to generate torques that surpass their limits. The designer compromises in this case the settling time of the system for the undesirable overshoot. Simulation results of the model are presented here, where the underdamped response of the joint position was designed for a 10% overshoot of the steady state value, and the settling time was selected at $0.1s$.The sampling period was $0.01s$, and the sampling subinterval $0.001s$. Figure 5 shows the desired and simulated joint positions, and Figures 6 and 7 show the Cartesian position error.

The torques required on the joint shafts are presented in Figure 8, and they are related to the actuator torques by the Γ matrix. A common measure of the overall performance of the system is the Euclidean norm of the error of the joint positions. For this simulation $\|e_2\|_2/N = 1.0825\times10^{-4}\,rad$, $\|e_3\|_2/N = 6.2551\times10^{-4}\,rad$, and $\|e_4\|_2/N = 7.5729\times10^{-5}\,rad$, where N=200 is the number of samples. The simulation demonstrates that the controller performs properly during the excavation procedure.

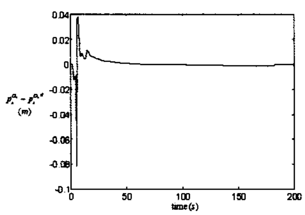

Figure 6. Bucket Tip Cartesian Position Error Parallel to the X_0 axis.

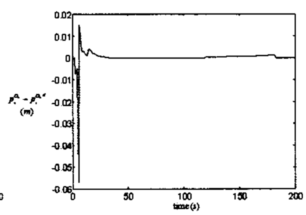

Figure 7. Bucket Tip Cartesian Position Error Parallel to the Z_0 axis.

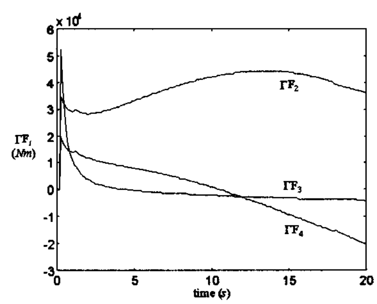

Figure 8. Joint Shaft Torques.

Conclusions

A control system is described to automate the operations of an excavator. The control scheme presented is designed to follow the desired motion of the bucket during digging operations, and to account for the forces experimented on the bucket during excavation due to interaction of the bucket with the soil.

The kinematics, dynamics and reaction forces on the bucket tip for a typical excavator are taken into account in the design of the controller. One drawback of this approach is that the control scheme depends on a sufficiently accurate dynamical model for the excavator, and on an accurate estimation of the expected reaction forces in the bucket of the excavator due to soil-bucket interaction.

Simulation results of a typical digging procedure illustrate that the controller performs properly during free motion as well as during soil constrained motion.

One intermediate step previous to complete automatic excavation would be to perform manually a digging task recording the positions and forces exerted by the excavator at all times, and then, take advantage of the repeatability of an autonomous system to perform the same task without the help of the operator. Teleoperation should also be considered for the cases when an operator cannot perform the teaching experience, such as at hazardous or contaminated sites.

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