A HAPTIC EXCAVATOR SYSTEM WITH ACTIVE MASSES UNDER SLIDING MODE PD FORCE/FORCE-POSITION CONTROL

H.I. Torres-Rodríguez, V. Parra-Vega, F.J. Ruiz-Sánchez

Mechatronics Division, CINVESTAV - IPN
AP 14-740, México, D.F., 07300 México

Abstract: We present a haptic interface-based excavator training system. This system is based on the full nonlinear excavator dynamic model which mimics an industrial excavator, and six degrees of freedom haptic interface. The interface is characterized by being conforming by two controlled prismatic joints that compensate the gravitational effects leaving the full power of the actuators to kinesthetic sensations transmission. The control of gravity compensation is based in the gravitational force vector of the dynamic model. On the other hand the excavator control is carried out through a robust, model-free second order sliding mode force-position controller. We present and discuss simulation results of the whole excavator training system.

Copyright © 2005 IFAC

Keywords: Haptic Interface, Robotics, Sliding Modes, Force control

1. INTRODUCTION

Excavators are heavy duty hydraulic machines used in agricultural, mining and construction industry whose main functions are digging, ground leveling and material transport operations. These machines are driven by qualified operators who move joysticks and pedals in an organized manner to reach a desired performance. The sequences of movements are very complex and the fact that these joysticks and pedals are not an intuitive man-machine interface, MMI, expose the human operator to fatigue, reducing the ability to maneuver properly the excavator, provoking mechanical stress in the machine and increasing the risk of an accident. These problems are more evident in the training process. Thus, topics as simplification of the digging task and the reduction of the harm risks during the training period, are interesting for researchers however, until now, their attention has been focused on automating different aspects of the excavator process, as for example (Tafazoli, 1999), (Simon P. DiMaio, 1998), (Stentz, 1998) which focused mainly on simplified modeling and control schemes, while (Koivo A.J, 1996) presented the full nonlinear model (neglecting the inertia of the heavy actuators). Instead of this, we are concerned not only in the control aspect of the excavator but in creating a new MMI, more intuitive and easy to use, based on a Mechatronics approach, that could be able to recreate the real dynamics of the system in a virtual environment furnishing the operator with more sensorial information.

We conjecture that one way to improve the excavation process is through a haptic interface, which makes possible to improve significantly the interaction between the user and a system through kinesthetic coupling in bidirectional way, therefore we focus on the full modeling and advanced control schemes of a novel haptic excavator, composed of a haptic interface as MMI, and an exca-

---

1 Partially supported by CONACYT project 39727-Y. Email: (vicente,htorres,fruis)@cinvestav.mx
vator to achieve kinesthetic coupling under transparency.

In this paper we present the advances in the construction of a haptic interface-based excavator training system. We present the dynamical model of the excavator calculated considering the mechanical effects of the hydraulic actuators. This model will be employed to reproduce with high fidelity the free and constraint motion of the excavator in a virtual environment. To control the virtual digging task we present and modeling a six degree of freedom haptic interface, where two degrees of freedom are used to compensate the gravitational effects. The coupling between the virtual excavator and the haptic interface is accomplished through a non linear PID controllers. We present and discuss simulation results.

2. EXCAVATOR MODEL

2.1 Cinematical Model

We employed the Denavit-Hartemberg procedure to calculate the direct cinematic of the links and to understand the complexity and dependence of the movement of the actuators on the movement of the links. We used the excavator model showed in figure(1). In this particular case, the excavator parameters are showed in the table 1, where the \( \theta_i \) are the rotational joint angles and \( d_i, a_i \) are constant lengths.

<table>
<thead>
<tr>
<th>i</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )</td>
<td>0</td>
<td>( \pi/2 )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( \theta )</td>
<td>( \theta_1 )</td>
<td>( \theta_2 )</td>
<td>( \theta_3 )</td>
<td>( \theta_4 )</td>
</tr>
<tr>
<td>( \phi )</td>
<td>0</td>
<td>( \phi_2 )</td>
<td>( \phi_3 )</td>
<td>( \phi_4 )</td>
</tr>
<tr>
<td>( d_i )</td>
<td>0</td>
<td>( d_2 )</td>
<td>( d_3 )</td>
<td>( d_4 )</td>
</tr>
</tbody>
</table>

Table 1. Link parameters of the excavator.

The cinematical model, also is used to calculate linear an angular velocities of the excavator. These velocities will be used to obtain the dynamical model based in the Euler-Lagrange formulation. (Stai, 1963).

2.2 Dynamical Model

We obtained the dynamic model of the excavator to create a virtual simulator trying to reproduce with fidelity the behaviour of the excavator. For this reason we consider the dynamic of the links and the contribution of the forces of the mechanic parts of the telescopic actuators. To obtain this model, we employ the Euler-Lagrange formulation considering the angles of the links as the generalized coordinates of the system. Due the energy present the additive property, the lagrangian of the excavator can be separated in two elements

\[
L = Le + Lp.
\]

where \( Le \) is the Lagrangian of the links and \( Lp \) is the Lagrangian of the actuators. Even more, using the linearity property of the derivative operator, the equation (1) can be wrote

\[
\begin{align*}
\frac{d}{dt} \left( \frac{\partial L_e}{\partial \dot{q}} \right) + \frac{\partial L_e}{\partial q} &+ D_p = Q \\
\frac{d}{dt} \left( \frac{\partial L_p}{\partial \dot{q}} \right) + \frac{\partial L_p}{\partial q} &+ D_p = 0
\end{align*}
\]

therefore the dynamic model of the system can be calculated by parts. The first part (the dynamic model of links) was computed using the procedure exposed in (Stai, 1963). On the other hand, to obtain the dynamic model of the actuators, was necessary to obtain the value of the angle \( \beta \) between the axial axis of the piston and the normal vector that links the joint of the link \( i \) and the link \( i + 1 \) figure(2). To obtain \( \beta \) we need to calculate the vector \( ^0V_{pi} \) figure(1), which is function of the lengths \( x_{i+1}, y_{i+1}, x_i, y_i \) figure(2) and the transformation matrices \( ^0A_{i+1}, ^0A_i \)

\[
^0V_{pi} = ^0A_{i+1}^+1V_{2i} - ^0A_i^+1V_{i}.
\]

where the vectors \( ^{i+1}V_{2i}, ^{i+1}V_{2i} \) are defined as

Fig. 1. Model of the proposed excavator.

Fig. 2. Parameters of the links.
The value of $\beta$ is

$$\beta = \text{atan}(\frac{V_{pxi}}{V_{pxi}}).$$

Where $\text{atan}$ is the tangent arc function, and $V_{pxi}$ and $V_{pxj}$ are the position coordinates $(x, y)$ of the distal element of the actuator (the sliding element of the actuator), referenced to frame $i$.

Employing a new reference coordinate frame, located in the proximal extreme of the actuator joint, is possible to establish a similar procedure to Denavit-Hartenberg, in which the transformation matrix $^iA_{pip}$ relates the position of the reference frame of the link $i$ and the reference frame of the actuator $i$, which is defined

$$^iA_{pip} = T(X, x_i)T(Y, y_i)T(Z, \beta).$$

where $T(X, x_i)$ is a displacement matrix along the $X$ axis of the link $i$, $T(Y, y_i)$ is a displacement matrix along the $Y$ axis of the same link, and the matrix $T(Z, \beta)$ represents a rotation in direction of the $Z$ axis a $\beta$ value. Using this transformation matrix the center of mass position $^iP_{cpi}$ of the actuator referenced to inertial frame is

$$^0P_{cpi} = ^0A_{pip}^iA_{pip}^iP_{cpi}.$$  

Once we obtain the equation that describes the movement of the center of mass of the actuator, the actuators jacobians matrices can be calculated using the same methodology used to compute the dynamic model of the links (Stai, 1963).

In this way, the Euler-Lagrange equation of the excavator can be wrote as

$$\sum_{j=1}^{n}(\lambda)\ddot{q}_j + \alpha + \alpha = Q$$

$$\alpha = \sum_{j=1}^{n} \sum_{k=1}^{n} \left[ \frac{\partial(\lambda)}{\partial q_k} - \frac{1}{2} \frac{\partial(\lambda)}{\partial q_k} \right] \dot{q}_k \dot{q}_j$$

$$\beta = \sum_{j=1}^{n} M_{qij} J_{qij}^i + M_{pj} J_{pj}^i$$

where $M_{qij}$, $M_{pj}$ are the inertia matrix of the links and inertia matrix of the actuators respectively, and $Q$ has the form

$$Q = Wf_a + B_a \ddot{q}.$$

and $W$ is the relation matrix between the force of the actuators $f_a$ and the control torques, $B_a$ is a diagonal matrix representing the links viscous damping.

In this paper we consider as first approximation of digging the soil as a rigid surface, under this consideration a constrained model, arises as follows.

$$M_c \ddot{q} + C_c \dot{q} + G_c + B_c \ddot{q} = \tau_a + J^T_c \lambda$$

$$\varphi(q) = 0.$$  

where $\varphi(q)$ define the rigid surface and $J^T_c$ is the orthogonal unit vector to this surface and $\lambda$ is the magnitude of the contact force.

The same procedure presented to obtain the dynamic model of the excavator in free motion, was employed to obtain the dynamic model of the haptic interface, which also was calculated employing the Euler-Lagrange formulation.

3. HAPTIC INTERFACE MODEL

![Fig. 3. Model of the proposed haptic interface.](image-url)
showed in the table 2, where \( d_i, l_i, x_{m_i} \) are constant lengths.

<table>
<thead>
<tr>
<th>i</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>m1</th>
<th>m2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )</td>
<td>( \pi/2 )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( \theta )</td>
<td>( \theta_1 )</td>
<td>( \theta_2 )</td>
<td>( \theta_3 )</td>
<td>( \theta_4 )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( \omega )</td>
<td>0</td>
<td>( l_2 )</td>
<td>( l_3 )</td>
<td>( l_4 )</td>
<td>( x_{m1} )</td>
<td>( x_{m2} )</td>
</tr>
</tbody>
</table>

Table 2. Link parameters of the haptic interface.

Using the same procedure used to calculate the excavator dynamic model, to calculate the haptic interface dynamic model is necessary solve differential equation

\[
\frac{d}{dt} \left( \frac{\partial L_{ih}}{\partial \dot{q}_{ih}} \right) + \frac{\partial L_{ih}}{\partial q_{ih}} = \tau. \tag{16}
\]

where \( L_{ih} \) is the haptic interface Lagrangian and \( q_{ih} \) is the generalized variables vector, which in this case is formed by the variables \( \theta_i \), and \( \tau \) is the external force vector (Stai, 1963). In this case, the dynamic model the haptic interface model is

\[
\frac{d}{dt} \left( \frac{\partial(\delta)}{\partial \dot{q}_{ih}} \right) + \frac{\partial(\delta)}{\partial q_{ih}} = \tau. \tag{17}
\]

\[
\delta = L_l + L_m + L_{ct} \tag{18}
\]

where \( L_l \) is the links Lagrangian, \( L_m \) is the masses Lagrangian and \( L_{ct} \) is the transmission elements Lagrangian. The general dynamic model is

\[
M_h \ddot{q} + C_h \dot{q} + G_h + B_h \dot{q} = \tau_h + \tau_o \tag{19}
\]

where \( \tau_o \) stands for the operator input torque, since the operator is always grasping the handle of the haptic interface to control the system.

4. THE CONTROL SYSTEM

In this section we present the control algorithms for the excavator and haptic interface, which do not depend of the dynamic of the system, due the complexity of the models. We consider second order sliding mode schemes for free (Parra, 2002), and constrained motion (Parra, 1996), (V. Parra-Vega and Akella, 2003), to guarantee local exponential tracking without using the model (V. Parra-Vega and Akella, 2003).

4.1. Excavator Control System

4.1.1. free motion: In free motion, \( \tau_e = Wf_a \) is a position control, where the desired trajectories of the excavator \( q_{dr} \) are

\[
q_{dr} = \Omega_p q_h \tag{20}
\]

where \( \Omega_p \) is a linear map between the haptic interface coordinates and the excavator coordinates.

Let consider

\[
\tau_e = -K_d \left[ \left( \Delta \dot{q}_e + \sigma \Delta q_c \right) - S_{pd}^c \right] +
\eta_1 \int_{t_0}^{t} \text{sgn} \left( \left( \Delta \dot{q}_e + \sigma \Delta q_c \right) - S_{pd}^c \right) \right] \tag{21}
\]

for \( \sigma > 0, K_d = K_d^T \in \mathbb{R}^{n \times n} \), and \( S_{pd}^c = (\Delta \dot{q}_e + \sigma \Delta q_c) (t_0) e^{\sigma(t-t_0)} \), for \( \Delta q_c = q_e - q_{dc} \). This smooth controller guarantees local exponential tracking, without using the model (V. Parra-Vega and Akella, 2003).

4.1.2. constrained motion: In constrained motion, a force position controlled is necessary where the desired coordinates are

\[
q_{dr} = \Omega_p q_h, \lambda_{dr} = \Omega_f \lambda_h \tag{22}
\]

where \( \Omega_f \) is a linear map between the haptic interface force coordinates and the excavator force coordinates.

Let consider

\[
\tau_e = -K_d Q \left[ \left( \Delta \dot{q}_e + \sigma \Delta q_c \right) - S_{pd}^c \right] +
\eta_1 \int_{t_0}^{t} \text{sgn} \left( \left( \Delta \dot{q}_e + \sigma \Delta q_c \right) - S_{pd}^c \right) \right] -
\beta K_d J_{+}^T \left[ -\lambda_{ih} + \eta_h \Delta F_c \right] - \gamma_{2h} K_d J_{+}^T \left[ \tanh(\mu S^c) + \eta_h \int \text{sgn}(S^c) \right] \tag{23}
\]

where \( \Delta F_c = \int_{0}^{t} \Delta \dot{q}_c \) (\( \lambda_e - \lambda_{dc} \), \( \mu_e > 0, \eta_e > 0, \gamma_{2e} > 0 \)), and \( S^c = \Delta F_c - \Delta F_c (t_0) e^{-\eta_e(t-t_0)} \). Notice that \( J_{+}^T \) is the normalized gradient of \( \varphi_c(q_c) \), and \( Q \) its orthogonal complement.

4.2 Haptic Interface Control System

4.2.1. free motion: In free motion input signal is the torque of the operator \( \tau_o \) and the control of the sliding masses. This control compensates the gravitational effects varying the positions of the sliding masses computing the gradient of the haptic interface potential energy which is function of these positions \( (x_2 \) and \( x_3) \)

\[
\nabla U(q) = \left[ \frac{\partial U(q)}{\partial q_2}, \frac{\partial U(q)}{\partial q_3} \right] \tag{24}
\]

then, the partial derivative with respect to links 2 and 3 must be zero to null the gravitational torques

\[
\left[ \frac{\partial U(q)}{\partial q_2}, \frac{\partial U(q)}{\partial q_3} \right] = [0, 0] \tag{24}
\]
Finally, solving for $x_2$ and $x_3$, we can obtain the desired position of the mass 2 and 3 for a position PID controller that nullifies the gravitational torques $g(q) = 0$. Notice that this controller is always turned on and produces a floating free haptic interface.

4.2.2. constrained motion: In constrained motion, $\tau_h$ is formed by the sliding masses control and a new control that must be designed to reproduce a virtual constraint

$$\varphi_h = \Omega f_h q_h = 0$$ (25)

where $\Omega f_h$ is a linear map between the haptic interface force coordinates and the excavator force coordinates. This control must generate force to operator

$$\tau_h = J_{\varphi h}^T \lambda_o$$ (26)

to therefore the dynamic equation is as follows

$$M_h(q) \ddot{q} + C_h \dot{q} + G_h + B_h \dot{q} = J_{\varphi h}^T \lambda_o + \tau_o$$ (27)

$$\varphi(q_h) = 0.$$ (28)

Let consider

$$\tau_e = -K_d Q \dot{q} - \beta K_d J_{\varphi h}^T [-\lambda_{dh} + \eta_h \Delta F_h] - \gamma_{2h} K_d J_{\varphi h}^T \left[ \tanh(\mu S_{qF}^h) + \eta_h \int \text{sgn}(S_{qF}^h) \right]$$ (29)

where $\Delta F_h = \int_{t_0}^{t} (\lambda_o - \lambda_{dh}) dt, \mu_h > 0, \eta_h > 0, \gamma_{2h} > 0$, and $S_{qF}^h = \Delta F_h - \Delta F_h(t_0) e^{-(t-t_0)}$. Notice that under this control, the servosystem exerts a force $J_{\varphi h}^T \lambda_o$ to the hand of the human operator, and there is not any control over the position.

Some simulation results of the excavator and haptic interface performance under some of the control algorithms exposed in this section will be presented and discussed in the next section.

5. SIMULATIONS RESULTS

In this section we present simulation results which describe the behavior of the excavator and the haptic interface separately; in fact we are considering employ a dynamic model to simulate the response of the human.

The results of simulation of the haptic interface are presented in the figure(4) and figure(5). We present two simulation results implementing a tracking control in free motion. In the first simulation figure(4) we present a result employing a PD control to maintain a predefined position of the masses. It can be observed the constant value of the torque when the haptic interface reach the final position. In the second simulation figure (5) we used the balance control with the sliding masses. Employing this control the value of the control torques are reduced due the system is balanced and when the system reach the final position, the control torques of links 2 and 3 are reduced to zero.

In the simulation of the excavator figures(6,7,8, 9,10) was considered the transition of movement from free motion to constrained motion. In this simulation results it can be observed the increment of magnitude of contact force and its subsequent stabilization and tracking of a sine function. In the other hand the tracking position errors are different to zero before the excavator touch the soil due the holonomic constraint imposed by the rigid surface.

6. CONCLUSIONS

A new haptic interface, a complex dynamical model of an excavator which considers the dynamic of the telescopic actuators and an advanced force-position and force controllers have been proposed. Simulation data suggest that the controlled motion of sliding masses are critical to achieve haptic transparency. On the other hand the control system of the excavator produce a satisfactory
position tracking in free movement and a satisfactory force tracking in a constraint movement.

REFERENCES


