Position Accommodation and Compliance Control for Robotic Excavation

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Abstract: A robotic excavator must be able to operate in all three states of manipulator motion: free space, contact, and exertion of a force against an environment. A position accommodation control scheme is ideally suited for this task. The position accommodation method described in this study uses a position controller to track a predefined trajectory in the absence of a force at the excavator bucket. If a force is detected, the measured force is used, through a compliance controller, to modify the commanded trajectory. This allows for better control of the complete excavation cycle. This paper describes a rheological method for modeling the soil–bucket interaction force and how that method must be modified to suit the unique case of excavation. Results for both a fixed and variable spring set-point are shown, illustrating the difference between a purely position controlled robot and one using a position accommodation/compliance controller, when used to dig a level trench.

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Introduction

The focus of this study is the automation of robotic excavation. Large hydraulic excavators have been used in construction and mining applications for years but only recently has there been a desire to automate some of their functions. Backhoes and front-end loaders can be seen at almost every construction site and their use requires a very skilled operator. Although it is still convenient, and relatively cheap, to use human operators for construction there are many situations where it would be of greater benefit to automate some excavation processes.

Smaller excavators have been used in planetary exploration, such as the Viking landers and the failed Mars Polar Lander, but both used simple control systems which required numerous commands to execute tasks. More advanced control systems which could be designed specifically for excavation would be able to perform more complicated excavation tasks with greater accuracy. Autonomous excavation has numerous applications in many different fields. Some of the previous research has centered around applying automation technologies to mining or construction work in hazardous environments; other work has been in the aerospace field.

Specifically, there is a need for excavator control systems which are adaptable to unknown and variable soil conditions, as it can be difficult to predict the soil composition when planning planetary exploration missions. Also, more adaptable control systems can ensure operability over a greater range of soil conditions, allowing for greater flexibility in mission planning. To fill this void, advanced control systems are needed, which can be given high-level commands, such as digging a level trench. With more sophisticated autonomy planetary exploration robots can complete tasks faster, and with greater accuracy. The likelihood of performing an excavation task correctly the first time would increase, reducing the number of commands required from ground controllers to operate the robot.

The challenges of modeling the excavator–environment interaction will be presented along with a proposed solution for use in an excavator computer simulation. This model will then be used to test various robot control schemes. The objectives and form of the controllers will be presented along with a compliance control solution which is used to modify the commanded trajectory. The goal is not a complete model of excavation but the development of a control system which is better suited to deal with the unique type of force response at the tip of an excavator bucket.

Soil–Robot Interaction Model

To accomplish a systematic study of robotic excavation control a model of the soil–tool interaction forces is needed to create a full computer simulation of the dynamic system. Although the literature is replete with methods for calculating the static force required for the excavator blade to shear the soil, there is little information on methods for applying such a force to a dynamic manipulator simulation. Empirical methods by Russian researchers Alekseeva et al. (1985) and Zelenin et al. (1985) can be used to calculate the soil-cutting force on the excavator blade, however, the models say little of the dynamics of digging. Simulating the soil–tool interaction in a quasistatic manner (assuming the soil–tool force is directly applied at the tip of the bucket) will inherently assume that the soil–tool force is an active force, whereas in reality it is a passive resistance to motion. The use of

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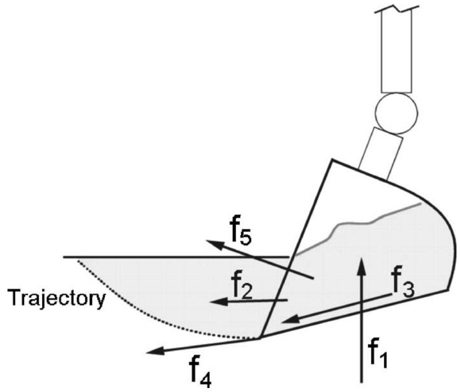

Fig. 1. Bucket–soil interaction forces (adapted from Hemami et al. 1994)

a rheological model, based on a mass–spring–damper second-order system is another option, though, its drawback is the introduction of physically inconsistent ideas such as modeling soil-reaction forces with an elastic spring term.

Soil–Tool Interaction Forces

To study the interaction between an excavator bucket and the soil, the forces involved in the interaction must be first identified. Hemami et al. (1994) have made an extensive theoretical study of excavator bucket–soil interaction and has identified five key forces (see Fig. 1):

- f_1: The weight of the soil accumulated in the bucket. This force varies as the bucket fills with soil.
- f_2: The compacting resistance of the soil in front of the bucket blade. This force is zero if the motion of the bucket is such that no soil is being pushed in front of the blade.
- f_3: The friction force between the soil and the bucket walls.
- f_4: The cutting force required to shear the soil. This force acts at the tip of the bucket blade.
- f_5: The force required to raise the soil inside the bucket and to move the soil above the bucket which is displaced by its motion.

Hemami et al. (1994) concluded from his studies that the f_3 force could be ignored and that the f_5 force was negligible. Also, if the trajectory is properly chosen, the f_2 force can be set to zero. If the f_2 force is zero for an excavation path, Hemami observed, the trajectory requires the minimum energy since no soil is being "pushed" by the bucket blade.

Soil Shear Force Models

Hemami et al. (1994) describes how the excavation forces relate to the bucket blade but other models are necessary to determine the relative values of these forces. Both empirical and analytical models have been developed, but few have been shown to reliably predict the forces encountered during excavation. However, the force models do give an order of magnitude estimate which is suitable for the purposes of this study.

The empirical formulation of Zelenin et al. (1985) for a bucket shaped excavator tool is described in the following. The soil–excavator force can be separated into three components:

$$F = P + R + P_t \tag{1}$$

where P=cutting force; R=combination of the total friction force (between the tool and the soil), the force required to move the wedge of soil in front of the bucket and the resistance of the chip to transverse compression inside the bucket; and P_t=force required due to the filling of the bucket. The model by Zelenin et al. (1985) model for calculating the soil cutting force is based on both the characteristics of the soil and the parameters of the excavator bucket. First the parameter K given by

$$K = 10C(1 + 2.6l)(1 + 0.0075\alpha)(1 + 0.03s)\nu\mu \tag{2}$$

is calculated, where C=compactness or "cohesive factor" (note, this is not the cohesion of the soil but a factor based on a compaction test of the soil). Zelenin et al. (1985) developed nomographs in his text which relate the cohesion and angle of internal friction with the compactness. However, it is still difficult to associate C to standard soil parameters for low values of C. The rest of the terms describe the physical features of the bucket: s=tool plate thickness; α=angle of the tool; l=width; and ν and μ combined are a coefficient which accounts for a reduction in cutting resistance due to teeth at the end of the blade. Then, the depth of the cut is incorporated, to give the force of shearing the soil:

$$P = Kh^{1.35} \tag{3}$$

where h=depth of the tip of the bucket.

Although it is clear from the work of Zelenin et al. (1985) that $P=f_4$, it is more difficult to group the remaining four forces of Hemami et al. (1994) into R and P_t of Zelenin et al. (1985). It is unclear from the formulation of Zelenin et al. (1985) whether or not they include f_3 in the P term. Hemami et al. assumed that $R=f_1+f_2+f_3$ and $P_t=f_5+f_6$, but he cautioned that the equivalence was approximate as much of the data of Zelenin et al. were collected using tools which "push" soil as well as cutting it. Hemami et al. seemed to doubt the claim that Zelenin et al. could isolate the P force from the R force for the purposes of developing the empirical equation. For this study, the shearing force, P, was assumed to be dominant.

Rheological Model

A second-order rheological type of model is standard for simulating contact forces for most types of manipulator–environment scenarios. The drawback is that the values to the coefficients must be determined based on the previously described soil–tool models. Soil poses a further problem in that it is a dynamic environment where the set-point for any "spring" term is constantly moving. Rheological models have two key advantages over a quasistatic model: (1) The dynamic interaction can be made passive and (2) they are easily implemented in a excavator simulation. The passivity requirement is essential as the soil does not physically add energy to the system during a dig.

This type of mass–spring–damper system requires a few key modifications before it can be used to model the bucket–soil interaction. The soil environment deforms, for the most part, plastically, but using a spring term to model the environment introduces an elastic parameter. This physical discrepancy is avoided by only allowing the spring term to act in the direction opposite to the motion of the end effector of the excavator. Also, the set point of the spring model must be reset to reflect the change in the terrain profile, based on the motion of the bucket. See the next subsection for a more detailed description.

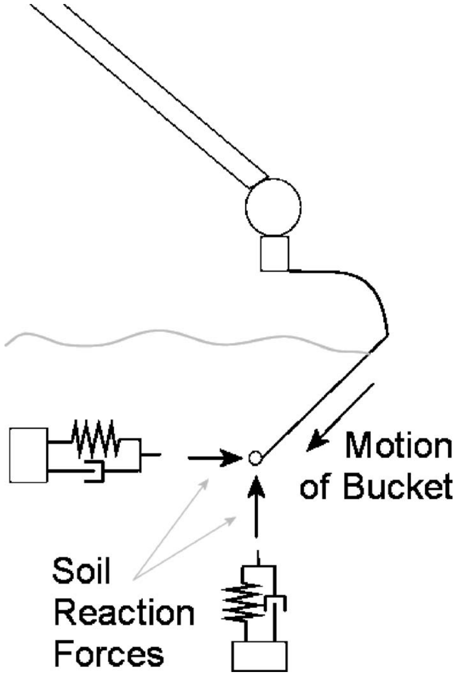

Fig. 2. Rheological environment model downwards bucket motion

Initial modeling can be accomplished with a simpler model such as

$$M_t\ddot{\rho} + B_t\dot{\rho} + K_t(\rho - \rho_{\text{env}}) = F_{\text{soil}} \tag{4}$$

where, $\rho=[x \quad y]^T$ and $\rho_{\text{env}}=[x_{\text{env}} \quad y_{\text{env}}]^T$. For a planar backhoe there will be the draft force in the $-x$-direction, and forces in both $\pm y$-directions. The application of these forces is dependent on the direction of motion as shown in Figs. 2 and 3. Conditions applied are as follows:

- If $\dot{x}>0$ then $F_x=0$;
- If $\dot{y}>0$ and $F_y>0$ then $F_y=0$; and

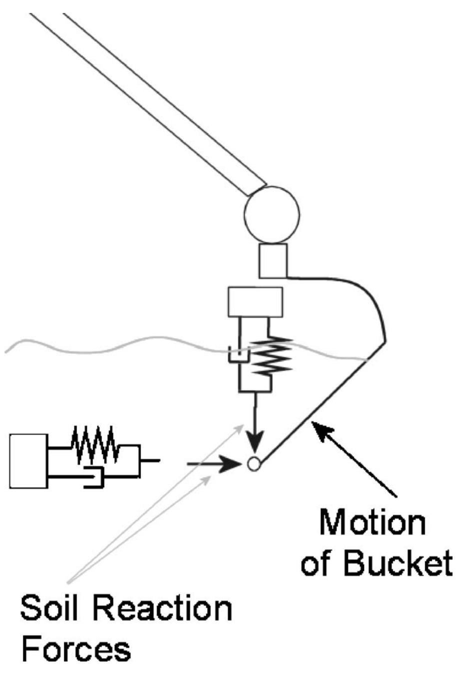

Fig. 3. Rheological environment model upwards bucket motion

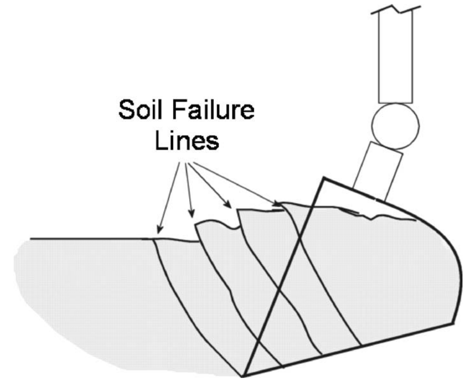

Fig. 4. Soil shear lines

- If $\dot{y}<0$ and $F_y<0$ then $F_y=0$.

The fundamental difficulty with these types of models is relating their coefficients of the rheological terms to the actual soil–tool forces. For this reason Hemami et al. (1994) rejected the use of such models for simulating excavation. An excavation simulation program developed by DiMaio et al. (1998) uses a first-order lumped-parameter model but sets the parameters based on experimental field data.

Stiffness Parameter

This type of soil failure can be analyzed by looking at how the soil progressively fails as the bucket moves forward through the soil (see Fig. 4). Reece (1964) based his study on previous research of shallow foundations and related the foundation bearing pressure to a moving blade in soil. Although the actual failure lines were found to be in the form of logarithmic spirals, they are usually approximated as a straight line. This assumption leads to an analysis which McKyes (1985) calls "The Method of Trial Wedges," shown in Fig. 5.

The plasticity of the soil presents a problem. To model the soil shearing as a spring, the spring set point must be determined at each step of computation. Although assuming that the soil is sheared and moved continuously, perhaps in very low-cohesion sands, in fact the soil shears at larger intervals. Only after enough force has built up at the tip of the blade will the soil shear along a new rupture surface. Malaguti (1994) has determined that the soil fails (shears along the rupture surface) at regular intervals and

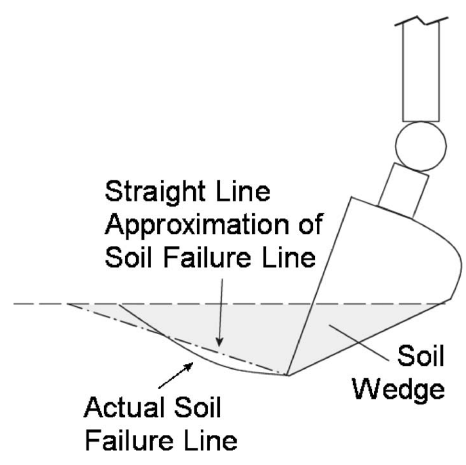

Fig. 5. Wedge theory of passive soil failure

that the length of the interval is dependent on the depth of the blade in the soil. Fig. 4 shows how the soil progressively fails. This stepped shearing of the soil leads to a sawtooth force profile (see the section entitled "Simulation Results," for examples).

It is a leap to model soil-forces using a spring, but in this particular instance the stiffness parameter is more accurately a spring on a ratchet. The spring force will only offer a resisting force in the opposite direction of motion of the excavator bucket. In effect the end of the bucket is not "attached" to the spring, simply pushing against it. This formulation can be used to model the force required to shear the soil along the shear boundary (shown in Fig. 5).

It now remains to determine the magnitude of the spring coefficient and define how the soil will shear. For the test cases the magnitude of spring term coefficient was set so that at the maximum extension of the spring the force would be similar in magnitude to excavation forces found in sandy soils at shallow depths. These values were calculated using the empirical method of Zelenin et al. (1985).

Malaguti (1994) has researched the relationship between bucket position and the distance between successive soil failures. He defines the horizontal distance between instances of soil shearing as a value proportional to the depth of the excavation. So this allows for ρ_{env} to be reset during the excavation simulation. At each step of the simulation the following evaluation is made:

$$\text{if} \quad (\rho_{env} - \rho) > S_{dist} \quad \text{then } \rho_{env} = \rho \tag{5}$$

where

$$S_{dist} = 0.365h + 0.00754 \tag{6}$$

and where h=depth of the tip of the bucket (m) and S_{dist}=distance (m) between successive soil failures (Malaguti 1994).

The magnitude of the force can be calculated from previously described force models. The maximum force at the maximum extension of the spring can be made to coincide with the predicted soil shear values. For the values of the spring term coefficient used, see the section entitled "Simulation Results."

Damping Parameter

The soil–tool friction can be modeled using the damping coefficient, B_t. Again this term is assumed to act in only one direction, so only as the excavator bucket is moving forward will there be a frictional force. Few models approach this term directly but it is assumed that it can be a significant proportion of the soil cutting force. For the purposes of this initial study the friction coefficients were kept very low.

Mass Parameter

The mass, or inertia, parameter of the rheological force can be modeled by the mass of the soil wedge in front of the blade. For this study it was assumed that as the bucket moves through the soil some soil accumulates in the bucket and adds a small additional mass to the bucket.

Excavator Control

A number of different methods for excavation control have been developed over the years. A number have relied on direct force control such as Vähä and Skibniewski (1993) and Koivo et al. (1996). Bernold (1993) suggested impedance control but also investigated using pattern recognition of measured forces during excavation to improve subsequent digs. More current research, by Shi et al. (1995) has been conducted using fuzzy-logic controllers.

Control Objectives

There are numerous problems to solve to fully automate an excavation procedure. Problems such as imaging the dig area, trajectory planning, and combining the excavation with other tasks (such as positioning the collected soil) all need to be addressed. However, this study aims to focus on the ability of the excavator to follow a preassigned path.

During excavation all three of the distinct states of a manipulator are present: Motion in free space, contact and exertion of a force (Bernold 1993). For this reason, any control system must be able to accommodate the conditions of any of these three states. As well, the soil cannot be assumed to be homogeneous and the soil–tool force may vary along the excavation path.

Many of the control systems developed for autonomous excavation use direct force control and, either attempt to estimate soil parameters while digging, or rely on a predetermined soil model to set the required force input data.

The goal here is to develop a control system that has a dynamic response which is independent from the characteristics of the environment allowing for an excavator which could perform consistently in a variable environment.

Manipulator Definition

The manipulator dynamics are governed by the standard equation of motion:

$$M(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} + G(\theta) = \tau - J^T(\theta)F_{soil} \tag{7}$$

where θ=joint position vector; $\dot{\theta}$=joint velocity vector; $M(\theta)$=manipulator inertia matrix; $C(\theta,\dot{\theta})$=manipulator coriolis and centripetal matrix; $G(\theta)$=gravity matrix; τ=joint torque vector; J=manipulator Jacobian; and F_{soil}=external excavation force vector.

Position Controller

The position controller attempts to track a specified commanded trajectory in the manipulator joint space. The form of the proportional-derivative (PD) controller is given by

$$\tau = K_d(\dot{\theta}_d - \dot{\theta}) + K_p(\theta_d - \theta) \tag{8}$$

where τ=commanded joint torque; K_d=derivative gain matrix; and K_p=proportional gain matrix. The simulation assumes no joint motor dynamics.

Compliance Controller

One promising solution is a compliance control system developed by Seraji (1998) at the Jet Propulsion Laboratory. Seraji developed two types of controllers, a force controller and a compliance controller. Both use the idea of "position accommodation" which modifies the desired trajectory data to implement the control. One advantage is that the manipulator can use a position controller (in this case the joint PD controller was used for position control) when no tip force is measured, and will only use the compliance controller if a force is detected at the end effector (see Fig. 6). If there is no force at the end effector there will be no change to the

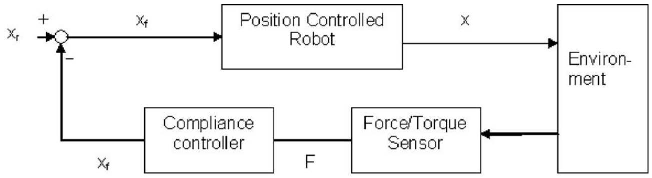

Fig. 6. Compliance controller using position accommodation (adapted from Seraji 1998)

desired path. When contact is detected and a force is measured by a wrist-mounted force–torque sensor, the control system will generate the appropriate changes to the prescribed trajectory. The nonlinear controller allows the manipulator to deal with a wider range of environmental stiffness than a fixed linear controller.

The next step is a controller which can adapt to the environment as it digs. Seraji (1998) developed an adaptive controller which is an extension of the nonlinear controller. In the adaptive controller the gain parameters of the controller are variable and set based on the contact force at the tip. Seraji maintains that the unique difference between his proposed compliance control scheme and impedance control is that the relationship between the Δx_r and F is dependent on the stiffness, damping, and inertia of the environment. Under impedance control the robot will exhibit different contact characteristics when contacting different surfaces. The proposed adaptive compliance control "attempts to maintain a user-defined invariant target dynamics between Δx_r and $\hat{F}$ irrespective of the surface stiffness" (Seraji 1998). This sort of situation is ideal for excavation as the composition of the soil is often unknown and variable. This type of control system would preclude the need for soil models to predict contact forces. The difficulty then becomes assigning the target contact force, or the target contact stiffness.

Form of the Compliance Controller

Seraji (1998) used a first-order lag controller $K(s)$ for the compliance controller

$$K(s) = \frac{x_f(s)}{F(s)} = \frac{1}{k_d s + k_s} \tag{9}$$

The performance characteristics of such a compliance controller are well known (Lawrence and Stoughton 1987). Instability may arise when a high stiffness force is encountered at the end effector so Seraji added a force feed-forward gain k_{ff} which resulted in a filtered-PD compliance controller

$$K(s) = \frac{x_f(s)}{F(s)} = k_{\mathrm{ff}} + \frac{1}{k_d s + k_s} = \frac{\alpha s + \beta}{\tau s + 1} \tag{10}$$

where $\alpha = k_{\mathrm{ff}} k_d / k_s$; $\beta = (k_{\mathrm{ff}} k_s + 1)/k_s$; $\tau = k_d / k_s$; and $k_s \neq 0$.

Seraji (1998) rejected the use of fixed PD gains for the compliance controller because the reaction of the controller is highly dependent on the expected stiffness of the environment. He showed that if a softer-than-expected surface was encountered, the apparent stiffness (as seen by the requested position increment) would decrease and if a harder-than-expected surface was encountered, the apparent stiffness would increase. The nonlinear controller aims to reduce the effect of the environment stiffness on the response of the controller.

The position accommodation term, x_f (or, equivalently, y_f if the compliance is in the y Cartesian direction), is generated by a nonlinear PD-control law

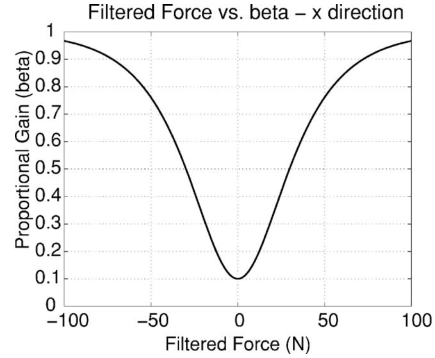

Fig. 7. Filtered force in the x-direction

$$x_f(t) = \alpha \frac{d}{dt}\hat{F}(t) + \beta(\hat{F})\hat{F}(t) = \frac{\alpha}{\tau}F(t) + \left[\beta(\hat{F}) - \frac{\alpha}{\tau}\right]\hat{F}(t) \tag{11}$$

where $\hat{F}(s) = (\tau s + 1)^{-1} F(s) =$ filtered force. The output of the compliance controller, x_f, is then subtracted from the desired position input (x_d) to give x_c, the commanded position. It is the actual input to the PD position controller. The commanded position value is written as

$$x_c = x_d - x_f \tag{12}$$

The hyperbolic secant function can be used for the nonlinear controller gain $\beta(\hat{F})$

$$\beta = \beta_0 - \beta_1 \,\mathrm{sech}(\beta_2 \hat{F}) \tag{13}$$

Using the hyperbolic secant formula suggested by Seraji (1998), the following plots (Figs. 7 and 8) shows the variation of β with respect to the filtered force. The gains of the compliance controller are given in Table 1. Although increasing the gains could lead to better tracking of the input path, some instability was seen when higher forces built up at the bucket tip.

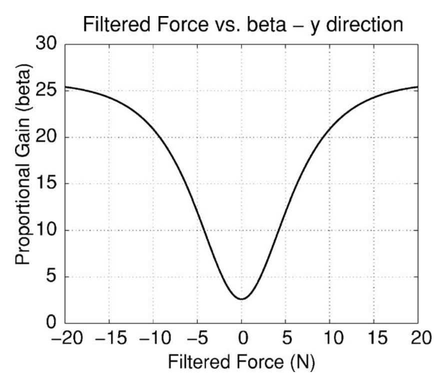

Fig. 8. Filtered force in the y-direction

Table 1. Compliance Controller Gains

	Direction	
Gain	x	y
α (m s/N)	0.005	0.01
β_0 (m/N)	1	26
β_1 (m/N)	0.9	23.4
β_2 (N^{-1})	0.04	0.22

J. Aerosp. Eng. 2008.21:27-34.

Table 2. Manipulator Configuration

Manipulator component	Mass (kg)	Length (m)
Joint 1 (shoulder)	0.75	—
Link 1	2.0	1.0
Joint 2 (elbow)	0.75	—
Link 2	2.0	1.0
Joint 3 (wrist)	0.5	—
Link 3 (bucket)	0.5	0.2

Simulation Results

The excavator model used in the simulation is a 3 degrees-of-freedom planar manipulator. The simulation runs using a predetermined desired trajectory which takes the form of a set of joint positions and velocities in the simulator. The robotics equations are implemented in a C++ program using ROBOOP (Gourdeau 2004) (an Object Oriented Robotics Library created by researchers at Montreal's Ecole Polytechnique). The manipulator is configured to resemble a small scale exploration manipulator, similar in size to the Mars Polar Lander robotic arm (see Table 2).

Environmental Parameters

The proposed control schemes were tested using a rheological model (with coefficients shown in Table 3).

Fixed Set-Point Results

In the first set of simulations the environment "set point" is fixed at the initial point of the manipulator end effector [in this case: $(x,y)=(1\text{ m},-0.15\text{ m})$]. The motion of the manipulator is from right to left tracking a level trench at a depth of 15 cm. Fig. 9 shows that the PD position control cannot maintain a level depth nor can it reach the desired final x position.

Table 3. Environment Parameters

	Simulation type			
	Fixed set point direction		Moving set point direction	
Parameter	x	y	x	y
K_{env} (shear) (N/m^2)	8,000	7,000	1,200	9,700
B_{env} (friction) $(N\,s/m^2)$	3,000	3,500	3,500	4,000
M_{env} (inertia) $(N\,s^2/m^2)$	300	0	200	0

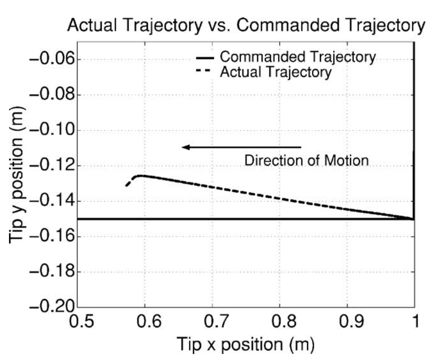

Fig. 9. Path of bucket using PD control

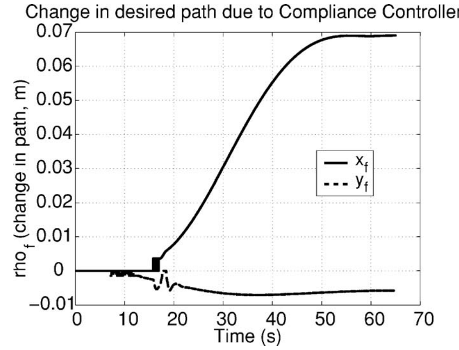

Fig. 10. Change in path of bucket due to nonlinear compliance control

Figs. 10–12 show the results from the compliance controller. The first plot (Fig. 10) is the change in the input position data generated by the compliance controller. Fig. 11 shows here that the compliance controller can follow the desired depth better than a simple position controlled robot without requiring prior knowledge of the soil conditions. Fig. 12 shows the variation in β over the course of the simulation. The larger tip forces in the x-direction produce a larger change in the commanded force.

Moving Environmental Set-Point Results

Using Eq. (5) to adjust the environment set-point, the simulations were performed again. The environment stiffness parameter coef-

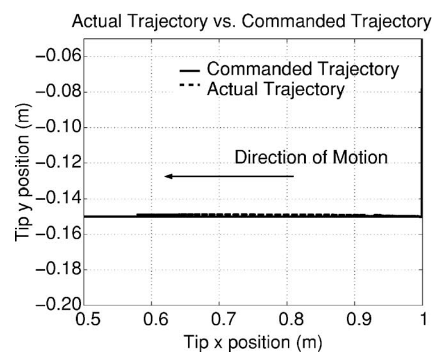

Fig. 11. Path of bucket using nonlinear compliance control

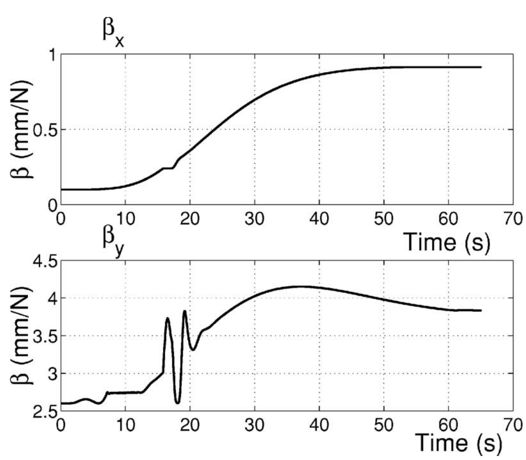

Fig. 12. Change in proportional compliance gain, β

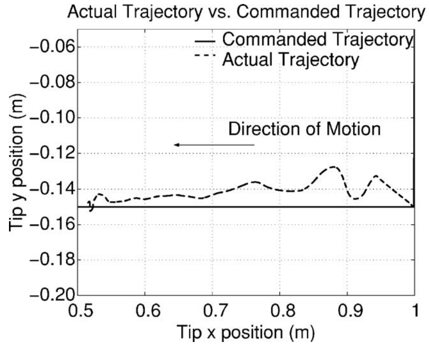

Fig. 13. Path of bucket using PD control

ficient has been increased as the spring term will now act over a shorter distance. This simulation is meant to more closely resemble the manner of force interaction that might exist at the excavator bucket tip. The controllers originally tested for a fixed set-point are now applied to the case where the set point is readjusted to model the periodic shearing of the soil.

The rheological parameters are shown in Table 3. The PD-controlled manipulator is highly affected by the periodic nature of the environment-bucket force as seen in Fig. 13. The plot of the path shows that the motion of the tip diverts from the prescribed path at the start of the dig and never fully recovers. This is to be expected since there is large torque build up required to shear the soil, followed by a large decrease in the force at the bucket tip. The force profile is shown in Fig. 14. The position-controlled manipulator exhibits errors in the y-direction of around 2.5 cm but more importantly the controller is unable to adequately deal with the large spikes in the bucket-tip force.

The position accommodation scheme using the compliance controller is better at tracking a level path (shown in Fig. 15). Maximum error in depth is less than 1 cm but over the course of the path the bucket tip remains closer to the prescribed trajectory. As the bucket tip moves along the prescribed path the compliance controller, using the forces measured at the tip generate modifications to the commanded trajectory (see Figs. 16 and 17). In the case of the moving environment set-point, the compliance controller outputs, x_f and y_f, are constantly changing, attempting to compensate for the periodic nature of the soil-tool force. The proportional nonlinear gain, β, also goes through spikes as seen in Fig. 18.

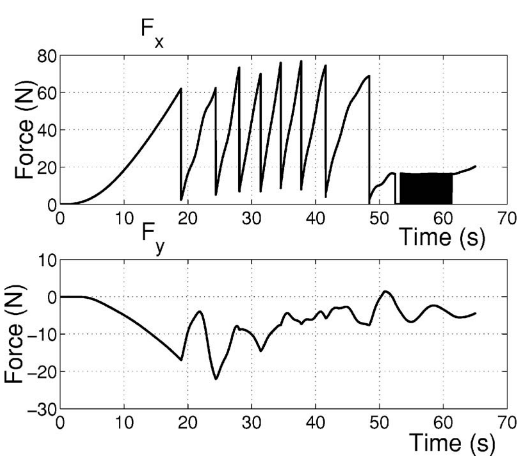

Fig. 14. External force at the excavator bucket tip, PD controlled

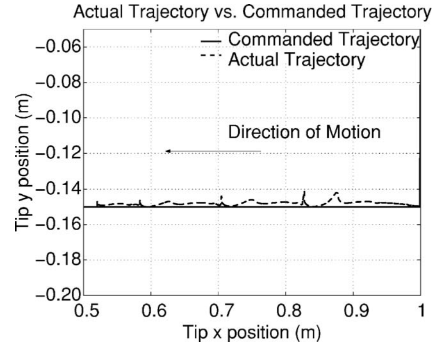

Fig. 15. Path of excavator bucket tip under compliance control

Conclusions

The compliance control system, in conjunction with the position accommodation scheme, works well to reduce the error in depth of the excavation. The modeling, although not a perfect representation of the bucket–soil force interaction, still roughly represents the force profile of the excavation that must be controlled. If the control system can be made to work under the conditions of this rheological model it would likely be well suited to be used for

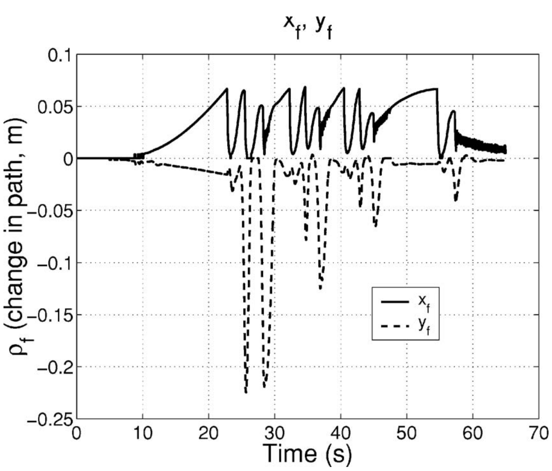

Fig. 16. Change in desired trajectory due to compliance controller

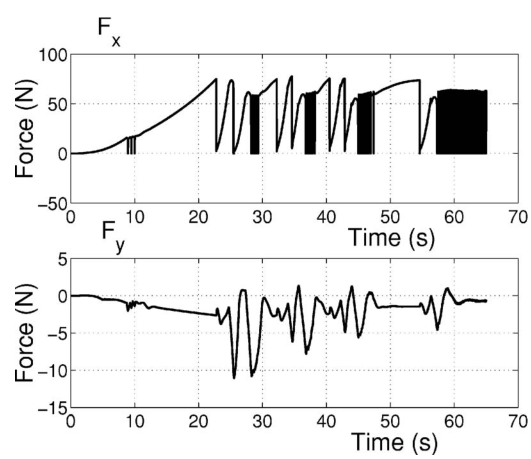

Fig. 17. External force at the excavator bucket tip, compliance controlled

J. Aerosp. Eng. 2008.21:27-34.

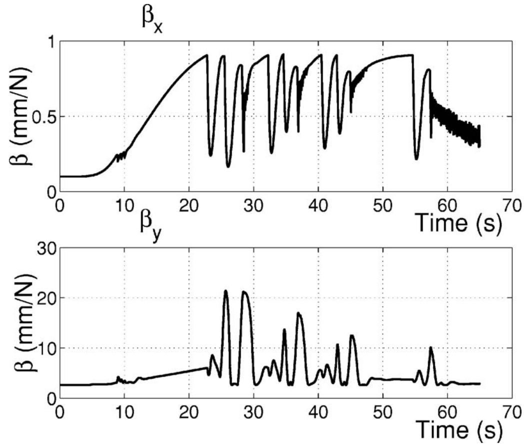

Fig. 18. Change in the proportional compliance control gain, β

actual excavation. The nature of excavation is such that experimental results in actual digs will still be needed to validate excavator control systems.

Smooth operation of such a robotic excavator is essential for delicate work where failure of the control system to follow the prescribed path can lead to unacceptable delays in missions with very short time frames (such as planetary exploration).

Future Work

Although the position accommodation scheme reduces the overall error when attempting a level dig, there are still some oscillations in the path of the end effector and the end effector does not reach the desired end point of the trajectory. Along with the nonlinear compliance controller Seraji (1998) also developed an adaptive compliance controller. The use of an adaptive controller may yet prove to be an even better candidate for robotic excavation. However, such an adaptive controller would require a force to track at the end effector (along with the commanded position and velocity required by the position controller). This would eliminate the versatility of position accommodation by requiring the manipulator to know its state of motion (free space, contact or exerting a force).

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