Development of an Adaptive Force/Position Controller for Robot-Automated Composite Tape-Layering

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The quality of parts produced by a composite tape-laying process is sensitive to the contact force exerted and the abutment of adjacent tape courses kept when the tapes are laid. Thus, a prerequisite for a high performance laying process automated by means of industrial manipulators is the ability to regulate laying force and position precisely in the presence of robot motion inaccuracies and laying contour variations.

An on-line adaptive force/position controller for robot-automated laying processes was presented. The contact force error normal to a laying surface is measured by a wrist sensor in real time, while the position error tangent to the surface is measured by sensors found in manipulator joints. Both are modeled as autoregressive (AR) processes, on the basis of which future errors in Cartesian coordinates are forecasted. Via a compliance selection matrix, both predicted errors are fed to joint actuators in a similar manner for taking compensatory actions. In view of the similarity, the force control portion of the scheme was implemented in an experiment using a three degree-of-freedom manipulator and the results indicated a 40 percent average reduction in contact force variations.

1 Introduction

1.1 Problem Statement. The unique quality of composite materials presents advantages over metals in industrial applications. An increasing number of shell-type components in the aerospace industry are designed from composite laminates, e.g., netting the shape of a component by laying unidirectional composite tapes on a surface of the desired contour, layer by layer, with different orientations. Automating the laying process by means of industrial manipulators assures faster production and reduced cost.

The quality of a component produced by the tape-laying technique depends heavily on two factors: (*1*) maintenance of a desired contact force while the composite laminates are laid, and (*2*) maintenance of a tight tolerance abutment of adjacent tape courses. The former guarantees an optimal and uniform adhesion between layers, while the latter reduces the occurrence of large gaps and overlaps between adjacent tapes. Thus, precise force/position control in the face of robot motion inaccuracies and laying contour variations is essential to the quality of tape-laying processes.

1.2 Literature Review. The force/position control approach, which distinguishes one or more degree-of-freedom in Cartesian coordinates as being force-controlled rather than position-controlled, has been proposed by several authors. The method presented in [1] assumed a task with the property that each force or velocity constraint happens to be aligned with a manipulator joint such that the force joint can be servoed on force and the position joint on position independently. The resulting errors limit the usefulness of the system. Paul and Shimano [2] described a system which compensates for the position error due to the force-servoed joints. However, the force control of the system was of the logic branching type. In [3], resolved motion rate control was applied to fine motion; this is essentially a damping control in which a force feedback matrix embodies different control strategies. The provision of damping by velocity feedback favors stability. An alternate approach [4] is first to form a position vector from a measured force using a stiffness matrix, then to form a positional error vector in the Cartesian coordinates, and finally to express it in the joint coordinate system using the inverse Jacobian matrix. Raibert and Craig [5] suggested a system which drives each actuator according to the sum of its contributions along each constraint, whether force or position. This implementation avoids the approximations inherent in a one-to-one matching of actuators to constraints. In the review by Whitney [6], various feedback control methods were compared and their stability problem due to phase lagging were discussed. Whitney and Edsall [7] modeled a time series of force-torque data as an AR model and the goal was to exploit the correlation in the time series for analysis of robot behavior and task progress. A unified approach for robot motion and force control by the means of an operational space formulation was presented in

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[8], which laid a framework for the analysis and control of manipulators with respect to the dynamic behavior of their end-effectors. The implications of the approach for practical controller design, however, are not clear.

1.3 Proposed Approach. This paper presents development of a controller for composite tape-laying industry applications which has the following features:

(*1*) It is assumed that the contract force error, defined as deviation from a nominal value, and position error, defined likewise, are stationary stochastic processes which could be modeled as autoregressive models [9, 10]. The model parameters are updated recursively to account for the time-variant nature of the laying process.

(*2*) On the basis of the AR models which are linear difference equations, position/force errors possibly occurring in the next few moments are predicted. This is equivalent to knowing the rate of change, or the derivative of the errors in the near future for a continuous process. An anticipatory controller structure similar to proportional plus derivative (PD) control is implemented, which is sensitive to the rate of change of the errors.

While the method has been applied with success to a number of areas [11–13], this research marks the first attempt to extend it to controlling the complex tape-laying process. The laying process is first analyzed, the parameter estimation and control scheme is then explained. Finally, experiment results are reported and discussed.

2 Task Analysis

For the tape-laying operation by a robot, certain position (velocity) and force constraints must be imposed. These constraints can be specified in a task configuration space of a manipulator, defined as a collection of all the configurations that the manipulator must take to perform a specific task. The task configuration space is represented by a smooth hypersurface, called a C-surface [14]. The ideal C-surface is assumed to be connected and smooth. Freedom of motion occurs only along the C-surface tangents, while freedom of force occurs along the C-surface normal. Since the ideal end-effector always lies in the ideal C-surface, the end-effector velocity will lie in the vector subspace parallel to the tangent space. Similarly, if tangential forces, such as friction forces, are negligible because only rolling contact normally exists at the laying point, the end effector force is restricted to be orthogonal to the tangent space. Thus, the constraints of the tape-laying process may be decomposed to natural constraints, arising from the geometrical nature of the task; and artificial constraints, derived from certain control strategies based on task requirements.

The end-effector usually contacts the laying surface via a number of rollers, so that a line contact is maintained. A hand frame $\{H\}$ is attached to the end-effector in such a manner that the origin of the frame lies in the center ρ of the contact line, while x and y axes lies within the tangent plane Π of point ρ, with the x axis being coincident with the desired direction of tape forwarding (Fig. 1).

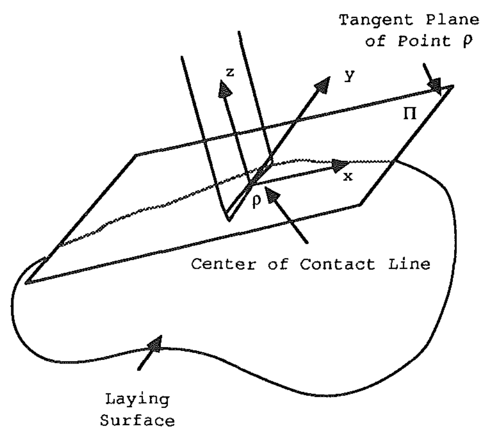

Fig. 1 General tape-laying model

By means of the C-surface formulation, the following natural and artificial constraints are obtained.

For a convex contour:

Natural Constraints:

$$f_x=0 \quad f_y=0 \quad \dot{p}_z=0 \quad \dot{\phi}_x=0 \quad m_y=0 \quad m_z=0$$

Artificial Constraints:

$$\dot{p}_x=v_x^d \quad \dot{p}_y=0 \quad f_z=f_z^d \quad m_x=0 \quad \dot{\phi}_y=0 \quad \dot{\phi}_z=0$$

For a concave contour: (1)

Natural Constraints:

$$f_x=0 \quad f_y=0 \quad \dot{p}_z=0 \quad \dot{\phi}_x=0 \quad m_y=0 \quad \dot{\phi}_z=0$$

Artificial Constraints:

$$\dot{p}_x=v_x^d \quad \dot{p}_y=0 \quad f_z=f_z^d \quad m_x=0 \quad \dot{\phi}_y=0 \quad m_z=0$$

where v_x^d and f_x^d are desired laying speed and contact force, respectively; ${}^H\mathbf{p}=(p_x\ p_y\ p_z\ \phi_x\ \phi_y\ \phi_z)^T$, end-effector position vector in hand coordinate system $\{H\}$; ${}^H\mathbf{f}=(f_x\ f_y\ f_z\ m_x\ m_y\ m_z)^T$, end-effector force vector in $\{H\}$. Note that the zero rate of p_z is regarded as a natural constraint because, as indicated above, a line contact is assumed between the laying head and type.

3 Adaptive Controller

3.1 Autoregressive Modeling. The tape laying task requires that certain forces be exerted by the end-effector of a robot on the laying surface. These forces are often specified in the hand coordinate system $\{H\}$. A measure of actual forces ${}^H\mathbf{f}$ can be obtained with a wrist sensor. The deviation of the

Nomenclature

- $\mathbf{A}$ = force AR model coefficient matrix
- $\mathbf{B}$ = position AR model coefficient matrix
- $\mathbf{e}$ = noise vector
- $\mathbf{f}$ = end-effector force vector
- $\mathbf{I}$ = identity matrix
- $\mathbf{J}$ = Jacobian matrix
- J_M = error criterion
- $\mathbf{K}$ = gain matrix
- M = batch processing size of measurement data
- $\mathbf{m}$ = end-effector moment vector
- N = degree of freedom of a robot
- $\mathbf{p}$ = end-effector position vector
- $\mathbf{q}$ = joint variable vector
- $\mathbf{S}$ = compliance selection matrix
- $\mathbf{T}$ = kinematics of the robot
- $\mathbf{Z}$ = augmented measurement matrix

Greek letters

- Γ = forgetting factor
- Δ = deviation of actual values from the desired values
- θ = parameter vector
- Π = tangent plane
- ρ = contact point
- τ = joint torque vector
- ϕ = end-effector orientation vector

Superscripts and Subscripts

- c = refers to Cartesian coordinate system
- d = refers to desired values
- H = refers to hand coordinate system
- r = refers to rotation

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actual force from the desired force ${}^H\mathbf{f}^d$, both expressed in the hand coordinates, is related to the Cartesian frame $\{C\}$ by

$$ {}^c\Delta\mathbf{f}(k) = {}^c\mathbf{f}(k) - {}^c\mathbf{f}^d(k) = {}^c\mathbf{A}_H(k)\,({}^H\mathbf{f}(k) - {}^H\mathbf{f}^d(k)) \quad (2) $$

where ${}^c\mathbf{A}_H$ is a 6 by 6 transformation from $\{H\}$ to $\{C\}$ and equal to

$$ {}^c\mathbf{A}_H = \begin{bmatrix} {}^c\mathbf{A}_{Hr} & 0 \\ {}^c\mathbf{a}_{Hp}\times{}^c\mathbf{a}_{Hx} \;\; {}^c\mathbf{a}_{Hp}\times{}^c\mathbf{a}_{Hy} \;\; {}^c\mathbf{a}_{Hp}\times{}^c\mathbf{a}_{Hz} & {}^c\mathbf{A}_{Hr} \end{bmatrix} \quad (3) $$

where ${}^c\mathbf{A}_{Hr} = ({}^c\mathbf{a}_{Hz}\;{}^c\mathbf{a}_{Hy}\;{}^c\mathbf{a}_{Hz})^T$ is a 3 by 3 rotation matrix from $\{H\}$ to $\{C\}$, ${}^c\mathbf{a}_{Hp}$ is a 3 by 1 position vector from the origin of $\{C\}$ to that of $\{H\}$, expressed in $\{C\}$ and the sign "$\times$" stands for a cross product.

The desired values of the gripper position are assumed to be given in the Cartesian coordinates as ${}^c\mathbf{p}^d(k)$. Then the position error in $\{C\}$ will be

$$ {}^c\Delta\mathbf{p}(k) = {}^c\mathbf{p}^d(k) - \mathbf{T}(\mathbf{q}(k)) \quad (4) $$

where $\mathbf{q}(k)$ is measured by joint position sensors and $\mathbf{T}$ is kinematics of a robot.

The deviations, Eqs. (2) and (4), appear because of various causes, such as robot motion inaccuracies, laying contour variations, jigging errors, and other disturbances and, therefore, are random in nature. These deviations from the desired trajectory are usually small and stationary. Therefore, it is assumed that they could be modeled as ARMA or equivalent AR processes [9, 10] as:

$$ {}^c\Delta\mathbf{f}(k) = \mathbf{A}(z^{-1})\,{}^c\Delta\mathbf{f}(k) + \mathbf{e}_f(k) \quad (5) $$

$$ {}^c\Delta\mathbf{p}(k) = \mathbf{B}(z^{-1})\,{}^c\Delta\mathbf{p}(k) + \mathbf{e}_p(k) \quad (6) $$

where $\mathbf{e}_f(k)$ and $\mathbf{e}_p(k)$ represent zero-mean independent Gaussian white noise processes with a finite variance and the matrix polynomials $\mathbf{A}(z^{-1})$ and $\mathbf{B}(z^{-1})$ are specified by the following expressions:

$$ \mathbf{A}(z^{-1}) = \mathbf{A}_1 z^{-1} + \mathbf{A}_2 z^{-2} + \cdots\cdots + \mathbf{A}_n z^{-n} \quad (7) $$

$$ \mathbf{B}(z^{-1}) = \mathbf{B}_1 z^{-1} + \mathbf{B}_2 z^{-2} + \cdots\cdots + \mathbf{B}_n z^{-m} \quad (8) $$

The order of models, n or m, could be determined by statistical adequacy tests, such as the conventional F-test and AIC (Akaike's Information Criterion) test [15]. The parameters in $\mathbf{A}(z^{-1})$ and $\mathbf{B}(z^{-1})$ are determined in an off-line phase if the process is time-invariant or they have to be updated recursively in process by real-time measurement data.

3.2 Recursive Parameter Estimation. The parameter matrices $\mathbf{A}(z^{-1})$ and $\mathbf{B}(z^{-1})$ depend on the instantaneous manipulator position and velocity along the desired trajectory and are thus slowly time varying. A recursive parameter identification technique is briefly outlined below to identify the unknown elements in $\mathbf{A}(z^{-1})$. $\mathbf{B}(z^{-1})$ can be estimated in the same manner.

Define parameter matrix $\mathbf{\Theta}$ as follows

$$ \mathbf{\Theta} = [\mathbf{A}_1, \mathbf{A}_2, \cdots \mathbf{A}_n]^T = [\theta_1, \theta_2, \cdots \theta_N] \quad (9) $$

where N is the degree-of-freedom of a robot.

Thus for $i = 1, 2, \ldots, N$,

$$ \theta_i = [a_{i1}^1, \ldots, a_{iN}^1, a_{i1}^2, \ldots, a_{iN}^n]^T \quad (10) $$

where θ_i is a $(N\times n)$ by 1 parameter vector.

Similarly, define

$$ \mathbf{Z}(k-1) = [{}^c\Delta\mathbf{f}^T(k-1), \ldots, {}^c\Delta\mathbf{f}^T(k-n)] \quad (11) $$

Equation (5) can be rewritten as follows:

$$ {}^c\Delta\mathbf{f}(k) = \mathbf{\Theta}^T\mathbf{Z}(k-1) + \mathbf{e}(k) \quad (12) $$

The algorithm for the parameter estimation is constructed so that one vector at a time is estimated in $\mathbf{\Theta}$. The error criterion is chosen for each vector θ_i of $\mathbf{\Theta}$ as follows:

$$ J_M = \sum_{j=1}^{M} \Gamma^{M-j} e_i^2(j) \quad (13) $$

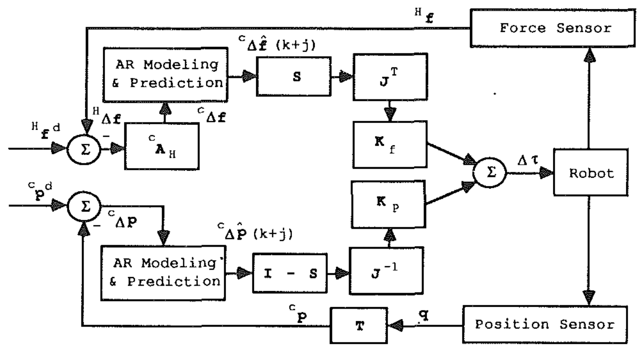

Fig. 2 Schematic of adaptive position/force controller

where Γ is a forgetting factor and M is the batch processing size of the measurement data. The problem is to minimize J_M relative to the parameter vector θ_i. The solution to the least-square problem is summarized below [10]

$$ \hat\theta_i(k+1) = \hat\theta_i(k) + \mathbf{G}(k)\mathbf{P}(k)\mathbf{Z}(k)[{}^c\Delta f_i(k+1) - \mathbf{Z}^T(k)\hat\theta_i(k)] \quad (14) $$

$$ \mathbf{P}(k+1) = \mathbf{P}(k) - \mathbf{G}(k)\mathbf{P}(k)\mathbf{Z}(k)\mathbf{Z}^T(k)\mathbf{P}(k) \quad (15) $$

$$ \mathbf{G}(k) = [\mathbf{Z}^T(k)\mathbf{P}(k)\mathbf{Z}(k) + \Gamma]^{-1} \quad (16) $$

3.3 Adaptive Forecasting Control. With the determination of the parameters in $\mathbf{A}(z^{-1})$ and $\mathbf{B}(z^{-1})$, forecasting with minimum mean squared prediction error is carried out as follows:

$$ {}^c\Delta\hat{\mathbf{f}}(k+j) = \sum_{i=1}^{j-1} \hat{\mathbf{A}}_i\,{}^c\Delta\hat{\mathbf{f}}(k+j-i) + \sum_{i=j}^{n} \hat{\mathbf{A}}_i\,{}^c\Delta\mathbf{f}(k+j-i) \quad (17) $$

$$ {}^c\Delta\hat{\mathbf{P}}(k+j) = \sum_{i=1}^{j-1} \hat{\mathbf{B}}_i\,{}^c\Delta\hat{\mathbf{p}}(k+j-i) + \sum_{i=j}^{m} \hat{\mathbf{B}}_i\,{}^c\Delta\mathbf{p}(k+j-i) \quad (18) $$

where ${}^c\Delta\mathbf{f}(k+j)$ and ${}^c\Delta\mathbf{p}(k+j)$ with hat$\hat{}$ are the j-step ahead forecast of ${}^c\Delta\mathbf{f}(k+j)$ and ${}^c\Delta\mathbf{p}(k+j)$ made at time k.

The covariances of the j-step prediction error are

$$ \sigma_{ef}^2(\mathbf{I} + \mathbf{G}_{f1}\mathbf{G}_{f1}^T + \mathbf{G}_{f2}\mathbf{G}_{f2}^T + \cdots\cdots + \mathbf{G}_{fj-1}\mathbf{G}_{fj-1}^T) $$

$$ \sigma_{ep}^2(\mathbf{I} + \mathbf{G}_{p1}\mathbf{G}_{p1}^T + \mathbf{G}_{p2}\mathbf{G}_{p2}^T + \cdots\cdots + \mathbf{G}_{pj-1}\mathbf{G}_{pj-1}^T) $$

where

$$ \sigma_{ef}^2 = E(\mathbf{e}_f\mathbf{e}_f^T) \quad \text{and} \quad \sigma_{ep}^2 = E(\mathbf{e}_p\mathbf{e}_p^T) $$

and the Green's functions $\mathbf{G}_{fi}$ and $\mathbf{G}_{pi}$ are solutions to

$$ {}^c\Delta\mathbf{f}(k) = \sum_{i=0}^{\infty} G_{fi}\mathbf{e}_{f_{k-i}}, \quad \mathbf{G}_{f0} = \mathbf{I} $$

$$ {}^c\Delta\mathbf{p}(k) = \sum_{i=0}^{\infty} G_{pi}\mathbf{e}_{p_{k-i}}, \quad \mathbf{G}_{p0} = \mathbf{I} $$

A smaller value of prediction lead time j gives a smaller prediction error with the minimum j equal to the delay time of the digital control system.

Based on the artificial constraints discussed in section 2, a diagonal compliance selection matrix $\mathbf{S}$ may be determined [5] as:

$$ \mathrm{Diag}\,(\mathbf{S}) = (0, 0, 1, 1, 0, 1) \quad (19) $$

Equation (19) is based on the assumption that the laying contours are concave.

The predicted force error, Eq. (17), and position error, Eq. (18), all expressed in $\{C\}$, are then transformed to a compensatory torque $\Delta\tau(k)$ at the joint coordinates via the matrix $\mathbf{S}$ and the inverse and transform of the Jacobian matrix $\mathbf{J}$ as follows:

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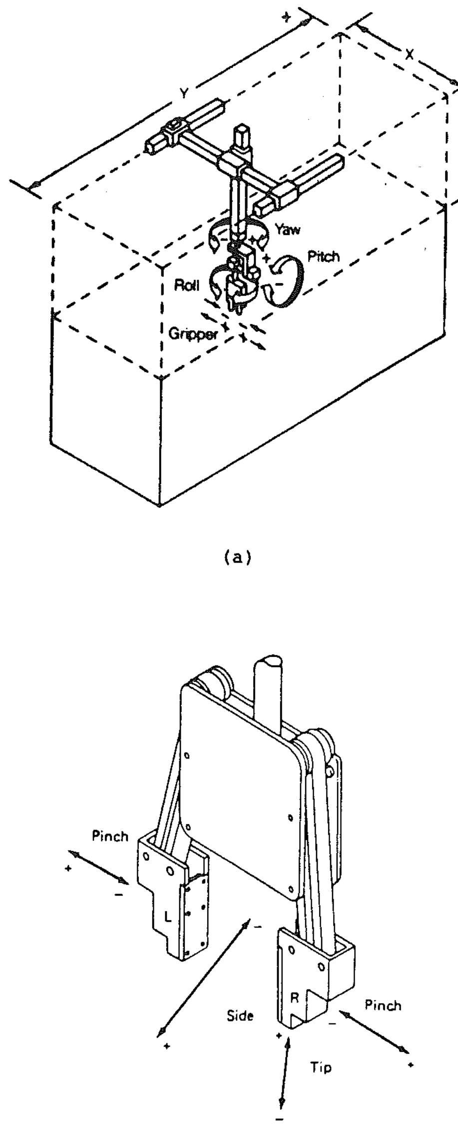

Fig. 3 Schematic of experiment manipulator (*a*) IBM 7565 robot (*b*) gripper force sensors

$$\Delta\tau(k) = \mathbf{K}_f \mathbf{J}^T(k) \mathbf{S}\, {}^c\Delta\hat{\mathbf{f}}(k+j) + \mathbf{K}_p \mathbf{J}^{-1}(k)(\mathbf{I}-\mathbf{S})\, {}^c\Delta\hat{\mathbf{p}}(k+j) \quad (20)$$

where $\mathbf{I}$ is an identity matrix and force gain matrix $\mathbf{K}_f$ and position gain matrix $\mathbf{K}_p$ are determined based on stability considerations [5].

The controller represented by Eq. (20) is essentially anticipatory. The large overshoot is predicted ahead of time and an appropriate counteraction is produced before too large overshoot occurs. This is similar to a PD controller in the continuous case, except that a PD controller measures the present error derivative, while this method based on AR difference equations also predicts the rate of change in the near future. The value j is chosen such that jT equals the delay time of the digital control system where T is the control interval. Further control actions between time k and time $k+j$, that is, $\Delta\tau(k+1)$, $\Delta\tau(k+2)$, ... , $\Delta t(k+j)$, will not affect the output until after time $k+j$ because of the delay time.

4 Experiment

Tape-laying experiments were carried out to examine the feasibility of the proposed approach and to compare it with control without prediction.

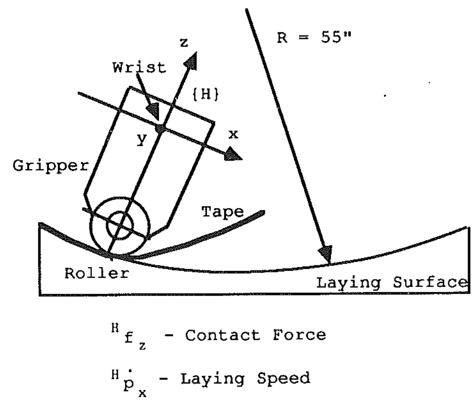

Fig. 4 A simplified three DOF planar laying model

4.1 Manipulator. The manipulator chosen for the experiment was an IBM 7565 industrial manipulator. The IBM 7565 consists of seven axes: joints x (JX), y (JY), z (JZ), *yaw* (JW), pitch (JP), roll (JR), and gripper (JG). The first three are prismatic joints, while the next three are revolute intersecting at the robot wrist. The manipulator wrist is the intersection of the rotational axes of the pitch and yaw motors, Fig. 3(*a*).

The Cartesian coordinate frame $\{C\}$ is defined by a set of stationary coordinate axes centered at the manipulator's wrist when the manipulator is positioned so that values of the JX, JY, JZ, JP, ans JW are all 0.0 and the value of the JR joint is -45.0 deg. The force sensor is composed of strain gauges embedded in the gripper as shown in Fig. 3(*b*). There are three sensing units in both fingers of the gripper. A calibration procedure [16] was used before an experimental session.

4.2 A Simplified Tape-Laying Model. A laying operation was carried out by three joints, JY, JZ, and JP only, while the rest were kept stationary. This reduced the problem to a three degree-of-freedom planar control, in the hope that such simplicity would provide better insight into the approach. The hand coordinate system $\{H\}$ was attached to the manipulator in such a manner that its origin was located at the wrist; its z axis represented the direction of the contact force to be exerted when the laminates are laid and its x axis coincided with the desired laying direction (Fig. 4).

For this simplified model, the constraints imposed in the hand coordinate frame $\{H\}$, Eq. (1), are reduced to

$$\begin{array}{ll} \text{Natural Constraints: } f_x=0 \;\; \dot{p}_z=0 \;\; m_y=0 \\ \text{Artificial Constraints: } \dot{p}_x=v_x^d \;\; f_z=f_z^d \;\; \dot{\phi}_y=0 \end{array} \quad (21)$$

under the assumption that tangential forces are neglected. The compliance selection matrix $\mathbf{S}$ is then reduced to

$$\mathrm{Diag}\,(\mathbf{S}) = (0,\ 1,\ 0) \quad (22)$$

and the force vector ${}^H\Delta\mathbf{f}$ is reduced to a scalar ${}^H\Delta f_z$. As noted in section 3, the adaptive position control portion is similar to the adaptive force control portion. For simplicity without the loss of generality, only the adaptive force control portion was implemented, while leaving the position portion still under the feedback control existing in the internal controller of IBM 7565 as shown in Fig. 5.

To simulate the line contact in a practical tape laying operation, a pair of attachments incorporating a roll bearing and sliding fixture was designed, which also minimizes the sliding friction. For simplicity without the loss of generality, a laying surface with an arc of radius of 55 inches was chosen.

4.3 Experimental Results and Discussion. The experi-

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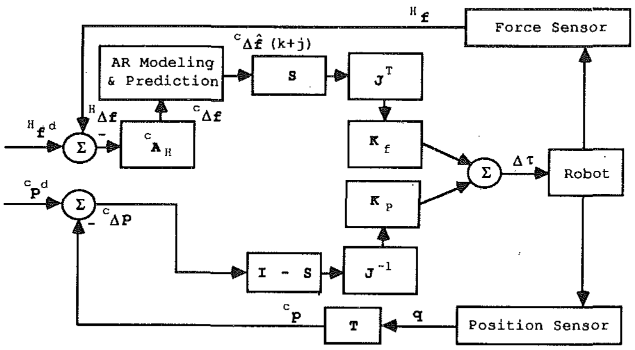
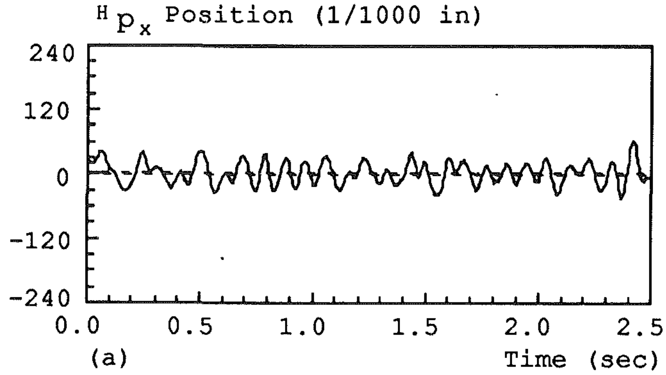


Fig. 5 Schematic of simplified controller



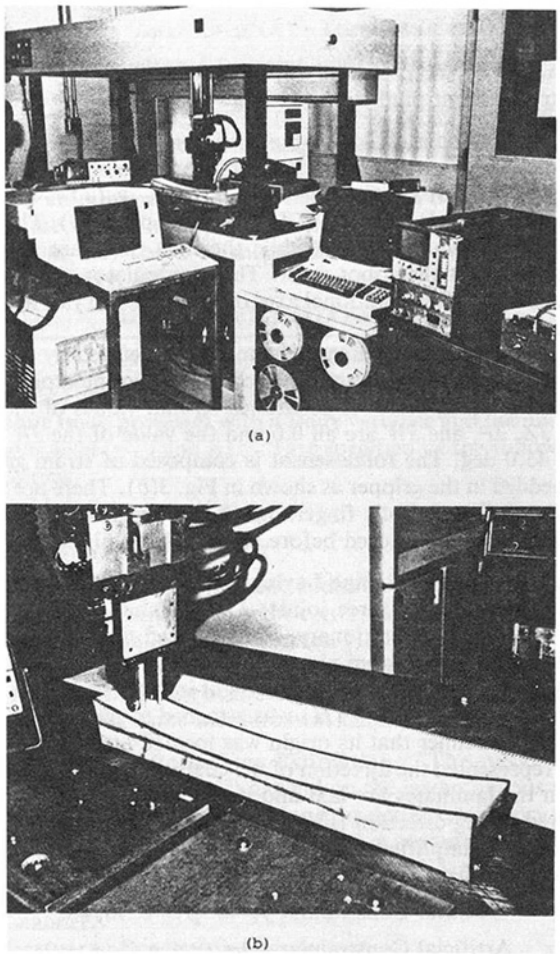


Fig. 6 Experiment (*a*) experiment set-up (*b*) tape laying operation

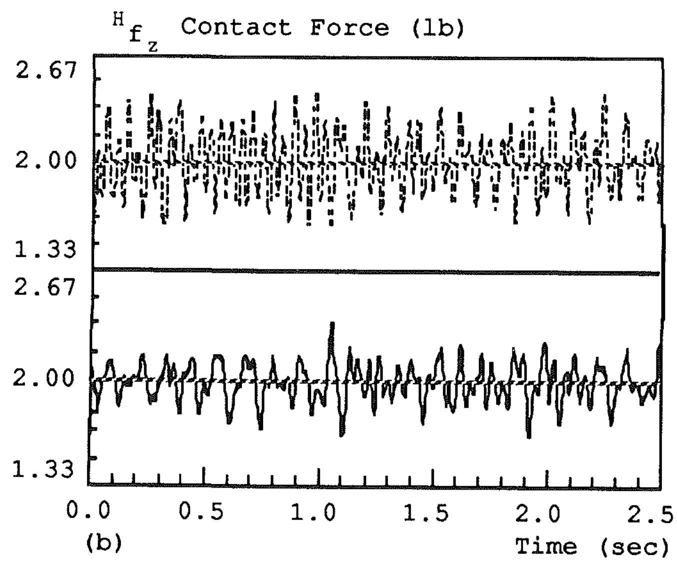


Fig. 7 Contact force (while ${}^H p_x$ kept constant) (*a*) ${}^H p_x$ position held constant (*b*) dotted line—control without prediction and solid line—control with prediction

ment set-up and the tape-laying experiment are shown in Fig. 6. The internal controller of the IBM 7565 was primarily used to implement motion commands by its built-in servo control and coordinate transformation capability, while the IBM AT-based external controller was used mainly for on-line data acquisition, error prediction, and compensatory command generation. The external controller also performed the in-process parameter updating, using new measurements. During experimental movements, strain gage signals were sampled at regular intervals and transformed into measurements of force given in the hand coordinate system $\{H\}$. The AR model of Eq. (5) was used to pattern the measurement data of contact force. The order n of the model was found to be 8 by the AIC test based on measurements under typical laying conditions and was assumed to be valid throughout the experiment. The model parameters were updated at a rate of 10 Hz due to computer limitation, while data sampling and servo were carried out at a rate of 25 ms (40 Hz) through interrupt. The gain matrices $\mathbf{K}_f$ and $\mathbf{K}_p$ were chosen as diag $(\mathbf{K}_f) = [50, 50, 50]$ and diag $(\mathbf{K}_p) = [10, 10, 10]$, respectively, based on stability considerations [5]. The off-diagonal elements in $\mathbf{K}_f$ and $\mathbf{K}_p$ were assumed to be zero. For this particular case, the quick convergence of parameter estimation was obtained by tuning the forgetting factor Γ, Eq. (13). More detailed analysis is needed for a general case.

Since the relative low laying speed of 1.2 in/sec, the robot dynamics was not considered.

The first session of the experiment tested the ability of the method to hold a 2-lb constant contact force when no motion was in progress (${}^H p_x = 0$). The results are shown in Fig. 7. Figure 7(*a*) is the actual ${}^H p_x$ in thousanths of an inch and the fluctuation is considered normal. Shown in Fig. 7(*b*) are comparative plots of contact force along the z axis ${}^H f_z$. For the control without prediction case, represented by the dotted line, peak-to-peak value of 0.908 lb, while for the control with prediction proposed in this paper, represented by the solid line, it was 0.626 lb. About a 35 percent reduction in the peak-to-peak value of the contact force was observed. The control without prediction is similar to that presented in [5].

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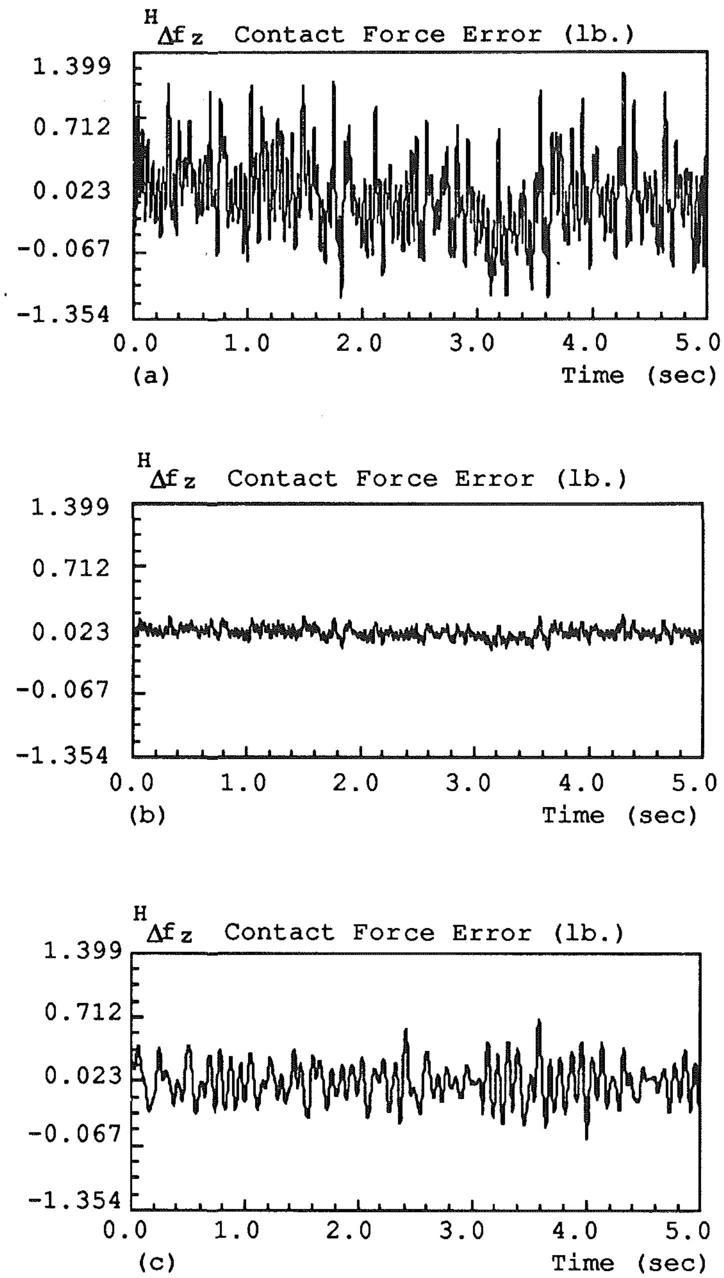

Fig. 8 Contact force (while proceeding with a speed of 1.2 in/sec) (*a*) without control (*b*) simulation result (*c*) experimental result

In the next session of the experiment, the ability of the method to maintain the same 2-lb contact force was tested while the laying was in progress with a constant speed of 1.2 in/sec. Figure 8 plots the contact force error, which was defined as ${}^{H}\Delta f_z = {}^{H}f_z - {}^{H}f_z^d$, where ${}^{H}f_z$ was measured by a wrist sensor on-line and ${}^{H}f_z^d$ was desired to be 2-lb. Shown in Fig. 8(*a*) is the error of the contact force error without control. Figure 8(*b*) shows simulation results of the proposed adaptive controller while Fig. 8(*c*) illustrates experimental results of the proposed adaptive controller. The RMS values for (*a*), (*b*), and (*c*) were 0.412, 0.061, and 0.241 lb, and the peak-to-peak values were 2.352, 0.363, and 1.302 lb, respectively. A 45 percent reduction in contact force variation was observed experimentally.

5 Conclusion

(*1*) An on-line adaptive force/position controller for robot-automated composite tape-laying processes has been presented. Its effectiveness was validated in simulation and experiment.

(*2*) The implementation of the force control portion of the scheme in an experiment using a three degree-of-freedom manipulator has been achieved and the results showed a 40 percent average reduction in contact force variation.

(*3*) While the method meets the urgent needs of the growing composite industry, it is readily extendable to other industrial contour processes, such as robot deburring [17].

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