Laser Tracking Control Implementation for SFF Applications

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Abstract

From a three-dimensional computer graphic model, Solid Freeform Fabrication produces solid objects directly without special tooling and human handling. In order to increas process productivity and accuracy, a time-efficient laser tracking control technique is needed. Based on the minimum time optimal control solution, the desired laser scanning control system is designed and implemented. To obtain uniform solidification during time-efficient tracking which has variable speed, laser power intensity is also controlled in real time by an acousto-optic modulator.

Introduction

A time-efficient tracking control for a laser scanner with on-line laser power adjustment is designed and implemented in order to increase productivity and to improve the geometric accuracy or the isotropic property of parts when one needs to trace the boundary of a part in SFF. It is not appropriate to use conventional raster scanning. Due to repetitive starts and stops, straight-line vector scanning mode can be slow when curves exist in the contour path. Several articles have presented various schemes for this problem. The preview scheme (Tomizuka, Dornfeld, Bian, and Cal, 1984) and the adaptive algorithm (Tsao, and Tomizuka, 1987) need on-line computation effort which is too large for SFF application. The cross coupled compensator (Kulkarni and Srinivasan, 1985) is designed to reduce the tracking error (minimizing the contour error) at a sharp corner, however contouring analysis and optimal speed trajectories are not developed for more general paths. The control trajectory scheme (Doraiswami, and Gulliver, 1984) is directly obtained from a specified path with three simple functions regardless of the capability of the actuator. The trajectory generation scheme (Butler, Haack and Tomizuka, 1988) focuses on constant tracking speed which does not give a minimum time solution. The control technology used in this paper is based upon the results (Wu and Beaman, 1990) of Pontryagin's minimum principle and phase plane techniques (Bobrow, Dubowsky and Gibson, 1985)[6], (Shin and McKay, 1985). The control system implemented in this paper uses the feedback control design model identified by Wu and Beaman, 1991.

The objective is to control a pair of galvanometers to direct the laser beam on the working surface to track a specified path as fast as possible with limited available driving torque and to obtain uniform laser energy exposure by on-line laser power adjustment. As shown in Figure 1, designed trajectories are stored in a computer as driving and reference signals. Through an interfacing board, on-line feedback control for a galvanometer-mirror system is implemented. The laser beam is modulated by an acousto-optic intensity modulator, focused by optics, deflected by a pair of galvanometer-mirror scanners, and directed onto the working surface, to track a prescribed path as shown in figure 2. The following sections include minimum time optimal control, feedback control and simulation, implementation and results, conclusions and references.

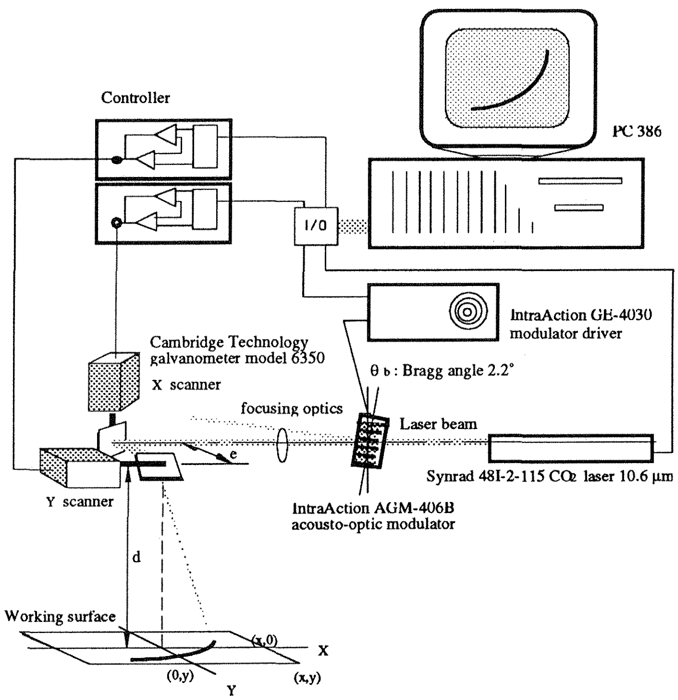


fig.1 The scanner control system

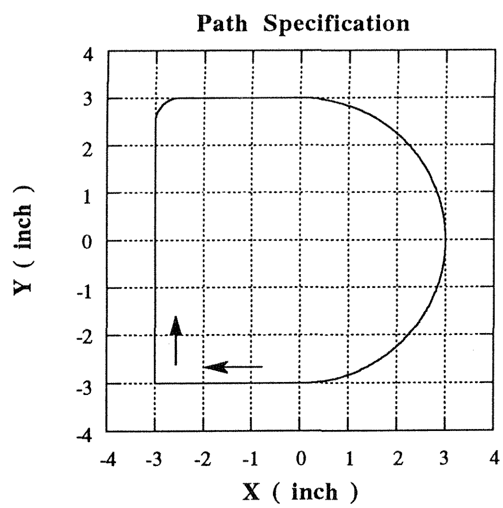


fig.2 The specified path

Minimum time optimal control

According to a trade-off between rapid scanning speed, available scanning torque or force and maximum tracking speed due to available laser power, a minimum time optimal control problem is defined and solved, (Wu and Beaman, 1990 and 1991) From the physical system described in Figure 3, a minimum time optimal control problem formulated in the θx-θy domain is conceptually straightforward. The state variables are chosen as θx, ω_x, θy, ω_y.

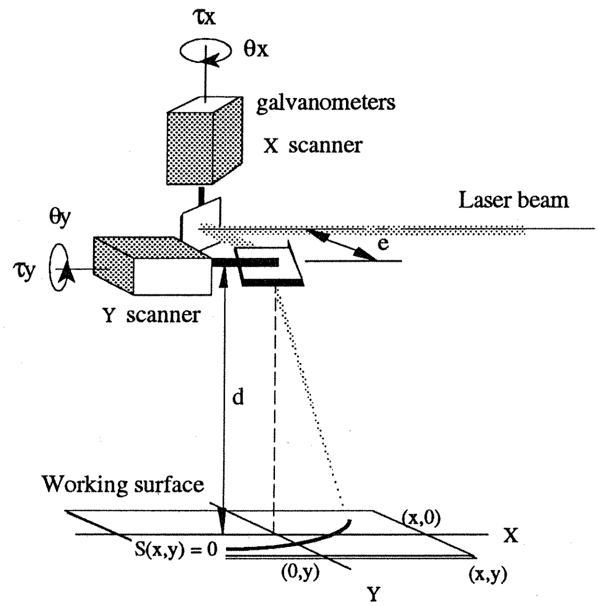


fig.3 The optimal control system

min **J** = min t_f where t_f is final time

subject to : $d\theta x/dt = \omega_x$,

$d\omega_x/dt = -4.9717e{+}03\ \theta x - 1.4102e{+}01\ \omega_x + 576762\ I_x$,

$d\theta y/dt = \omega_y$,

$d\omega_y/dt = -2.5878e{+}03\ \theta y - 1.5261e{+}01\ \omega_y + 359706\ I_y$,

and $-1.1 \le I_x \le 1.1$, $-1.1 \le I_y \le 1.1$,

($I_x = -e_{xin}/3$ and $I_y = -e_{yin}/3$ in the simplified model)

Tracking speed $v \le V_p$ (320 inch/sec.),

where V_p is the allowable speed under the available laser power

$S(x,y) = 0$, shown in Figure 2.

$x(0) = -3$, $x(t_f) = -3$, $v_x(0) = 0$, $v_x(t_f) = 0$,

$y(0) = -3$, $y(t_f) = -3$, $v_y(0) = 0$, $v_y(t_f) = 0$, are given.

with the nonlinear geometric relation between θx-θy space and X-Y space as :

$$\theta x = G_1(x, y) = 0.5 * \mathrm{atan}\left[\frac{x}{\sqrt{12^2+y^2} + 0.75} \right]$$

and
$$\theta y = G_2(x, y) = 0.5 * \mathrm{atan}\left[\frac{y}{12} \right]$$

The solution is shown in figure 4. Note that tracking speed is accelerated from 0 to 320 inch/sec in 31 microseconds.

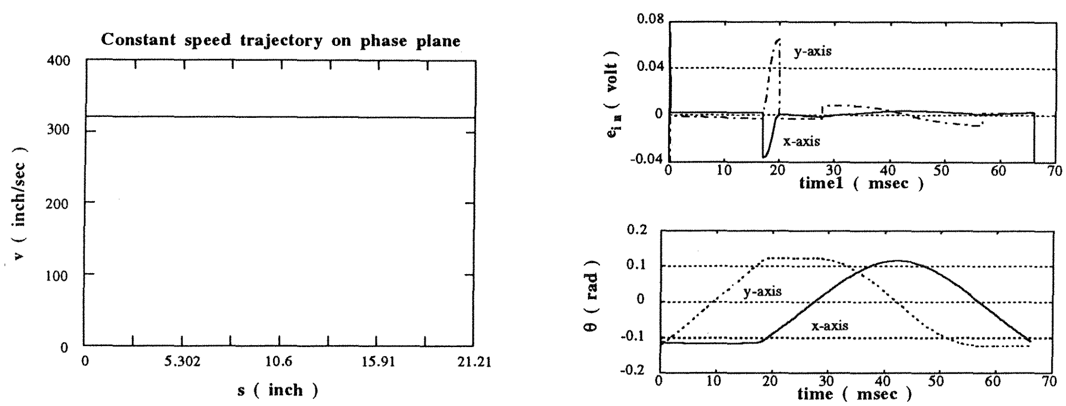


fig.4 The trajectory with 320 inch/sec tracking speed limit

Feedback Control and Simulations

A two-channel PID feedback control design supplies the best advantage in this application and achieves the specifications as simple, low computational load for computer control, fast response, small overshoot in time response and good stability robustness. Performance robustness is an important issue for scanning accuracy also. There is no good technique which may assure it. This will be tested by numerical simulation.

Before implementing a control system with the designed control trajectories and feedback scheme, numerical simulation is necessary. There are two ways to implement the control system with our results of open loop optimal control trajectory planning and the feedback compensator design. One uses a position reference trajectory $\theta_{ref}(t)$ only, and the other uses both position reference trajectory $\theta_{ref}(t)$ and the designed control trajectory $e_{ref}(t)$. Both implementations will be simulated and compared. With the trajectories designed for 320 inch per second of tracking speed, the best performance with 4.7 thousandth inch of maxError could be achieved under various physical limitations. If a better tracking accuracy is required, it is necessary to reduce the tracking speed. The following results are simulations with various desired tracking speeds.

tracking speed v_d (inch/second)	320	200	100	50
maxError (inch)	0.00470	0.00421	0.00275	0.00060

The simulation results also give guide lines on how parameter variations affect tracking performance shown in Figure 5. The worst performance resulted from the inertia variation. However, compared with estimates for the damping factor and the spring constant, it is not difficult to obtain a more accurate estimation of the inertia such that one may expect a little inertia uncertainty exists only with no significant effect on tracking performance. Thus, it is obvious that tracking performance of the implementation with $e_{ref}(t)$ is better under the conditions with both nominal and perturbed system parameters.

Parameter variation : ±50%

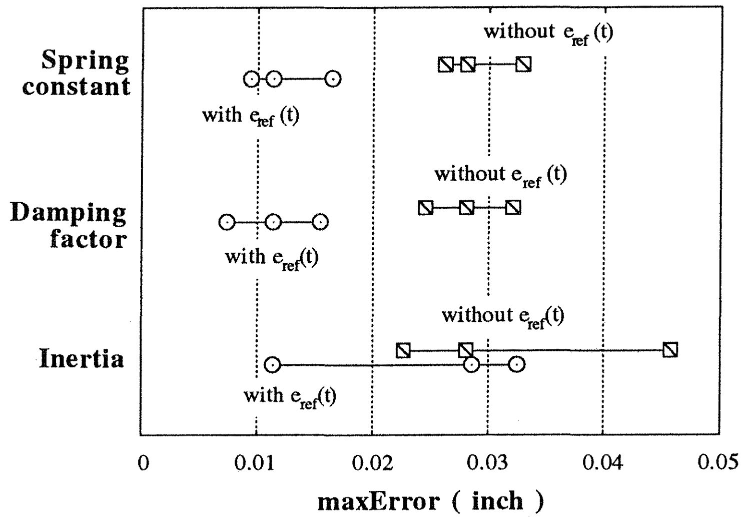


Figure 5 Performance variation due to parameter variation

Implementation and results

For digital control, the feedback control law is implemented by computer software. Besides noise rejection, flexibility is one of the important advantages of digital control. Another advantage is that software can handle a very complicated control algorithm. However, all computations must be finished within the desired sampling interval. Because of the available facilities in the laboratory and an extremely short sampling interval is desired in this application, the digital control scheme does not work and the final results are performed by the analog controller.

A dual channel analog PID controller is designed.(shown in Figure 6) For each channel, a summing amplifier, a gain amplifier, a gain attenuator, a differentiator and an integrator are designed with care for circuit stability, noise attenuation, bias reduction. (Stout, 1976) The signal conditioning unit for the acousto-optic modulator is a unit gain buffering amplifier used for matching impedance.

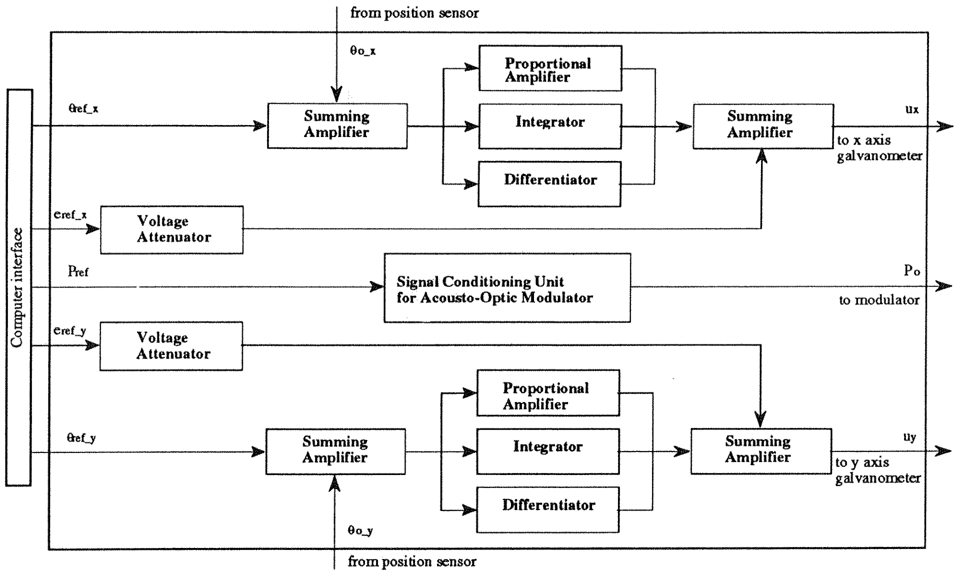
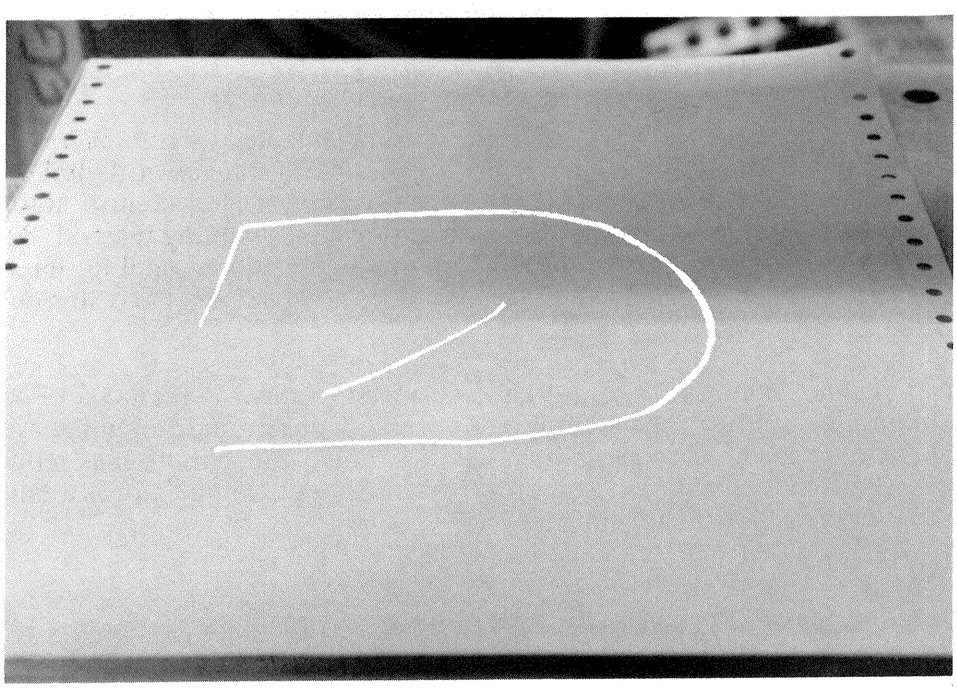


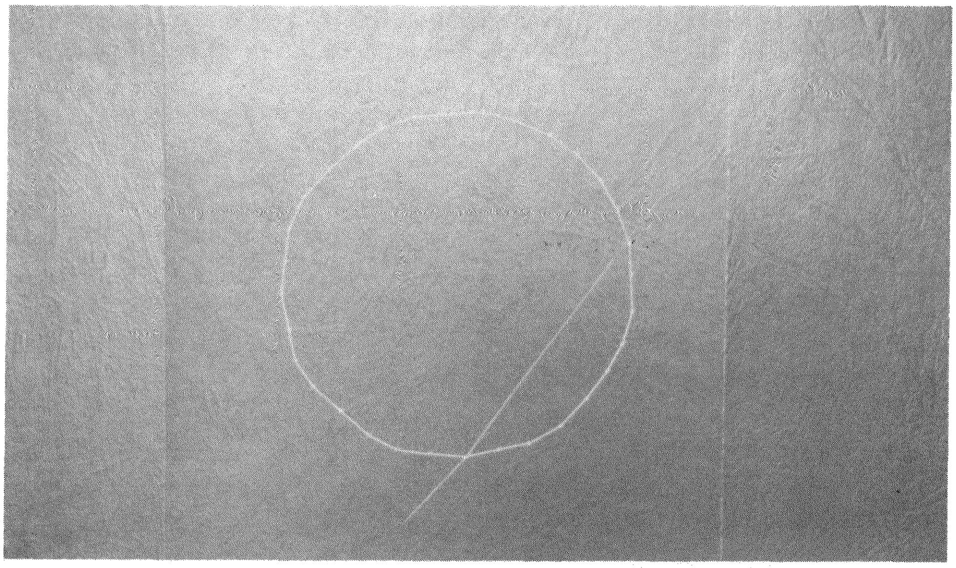
Figure 6 Block diagram of dual channel analog controller

A traveling laser spot (red HeNe laser) is shown in Picture 1 with 320 inches per second tracking speed. The control design in this paper shows fast and smooth performance when high speed tracking is desired.

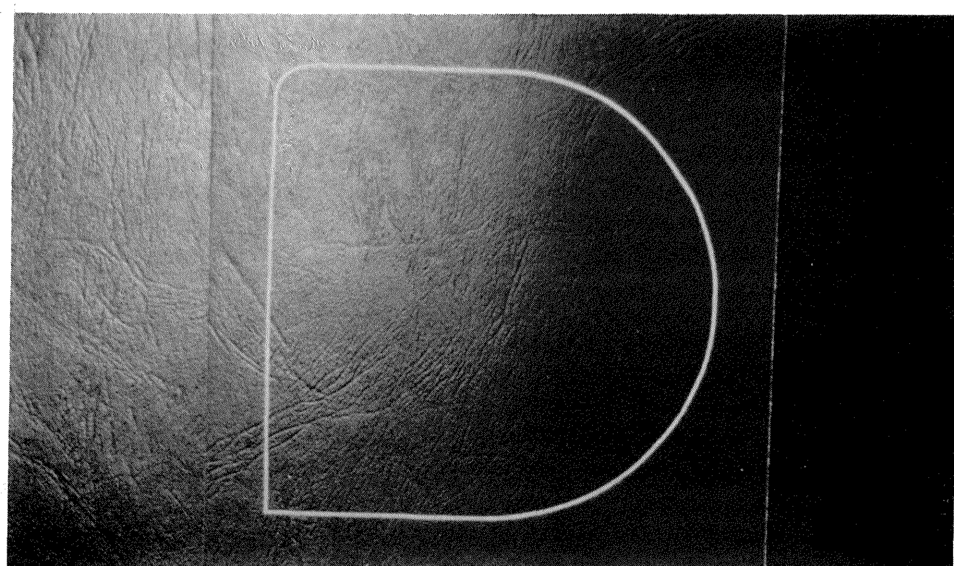


Picture 1 Traveling of Red HeNe Laser Spot

Uniform laser exposure is achieved by smooth tracking speed trajectory design and the acousto-optic power modulator, where the laser power level is determined by the designed tracking speed trajectory. Compared with the vector scanning shown in Picture 2, the control design in this paper has no repetitive starts and stops such that fast and smooth tracking results (shown in Picture 3) when curves exist in the contour path. Notice that there exists an overheated spot at every end-point of the scanning vector in Picture 2.



Picture 2 The Result of Vector Scanning



Picture 3 The Result of Control Design in This Paper

Conclusions

While part boundaries need continuous scanning, conventional raster scanning does not work. Compared with a straight-line vector scanning mode, the advantages in this study are fast, smooth curve tracking without repetitive starts and stops. It is a minimum time optimal solution with constraints of available driving torque, specified tracking path and available laser power. Since the feedback measurement for the closed loop control system is from the galvanometer shaft position instead of the location of the laser spot on the working surface, accurate calibration for the nonlinear geometry between the galvanometer axis and the working surface is necessary to obtain a better geometric tracking accuracy. Sophisticated optical accessories are also needed to obtain better alignment for the optical path.

For industrial applications, two main issues must be researched in the future. One is a convenient algorithm to convert CAD geometric data into parametric curve representation with uniform point distribution. The other is a convenient software to automatically generate optimal trajectories in the phase plane. The initial idea is to setup a computer library with some common paths, for example, circle path, line segment, splines etc.

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