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INFLUENCE OF CONTROL PARAMETERS ON THE JOINT TRACKING PERFORMANCE OF A COAXIAL WELD VISION SYSTEM

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16. ABSTRACT

This report describes the first phase of a series of evaluations of a vision-based welding control sensor for the Space Shuttle Main Engine Robotic Welding System. The robotic welding system is presently under development at the Marshall Space Flight Center. This evaluation determines the standard control response parameters necessary for proper trajectory of the welding torch along the joint.

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INFLUENCE OF CONTROL PARAMETERS ON THE JOINT TRACKING PERFORMANCE OF A COAXIAL WELD VISION SYSTEM

INTRODUCTION AND SUMMARY

The present report is the first in a series detailing evaluation of a vision-based welding control system developed by Ohio State University. This evaluation is a part of the program for development and implementation of robotic technology for welding on the Space Shuttle Main Engine. The OSU vision system was developed under contract as a part of the robotic welding system in the Materials and Processes Laboratory's Productivity Enhancement Facility at the George C. Marshall Space Flight Center. The vision system is capable of two basic functions. trajectory control (seam tracking) and weld pool width control. As a first step, this report covers an evaluation of the user programmable parameters which dictate the correcting response to a perceived tracking error. Future work on trajectory control will cover image acquisition and processing (joint and pool detection) and tracking accuracy under non-ideal joint conditions. Irregularities such as mismatch, varying joint gap and tack welds will be considered. Once the trajectory control is thoroughly explored, the weld pool width control will be evaluated.

The evaluation of trajectory control parameters was simplified by eliminating the pool detection capability. The electrode center, defined in a calibration procedure, was used for error calculations in the control routine. A controlled disturbance was provided by welding on straight line square butt joints using a programmed path with a ramp offset and two step offsets. Tracking accuracy was measured at increments along the weld path, and the collected data was statistically reduced to three values for each weld. Two of these values provided a direct indication of accuracy, while the third was indicative of stability. The three gains of the proportional-integral-differential (PID) control algorithm were varied, as well as an averaging factor. Optimal values were chosen from consideration of the three statistical values, using both accuracy and stability as judgement criteria. Steady state error will be quantified in a later report when tracking performance based on weld pool location is compared with the tracking performance examined here.

OBJECTIVE

This report represents the first in a series concerned with evaluating the OSU welding control system's operating performance. Considerable flexibility was provided in the design of the system via over 100 user programmable parameters. A logical first step in the evaluation process was to optimize these parameters for general applications.

The present study concentrated on the trajectory control response, specifically the effects of control parameters on tracking accuracy and stability. Three parameters were identified as requiring further study: the proportional, differential and integral gains and the weighting factor for the exponentially weighted moving average. The overall objective was to evaluate the effects of these parameters on the control response using essentially ideal joint conditions, and recommend values to be used in future tests.

BACKGROUND

When evaluating the performance of a control system, accuracy and stability are the features of principal interest. Stability may be described as the tendency of a system to oscillate after a disturbance, as illustrated in Figure 1. Oscillation arises from delays in the perception of and response to errors, leading to overshoot. In an absolutely unstable system, the amplitude of oscillation increases with time until mechanical failure occurs. In a stable system, the response to an abrupt disturbance still tends to be oscillatory, but the amplitude decreases with time until a steady state value is reached. The amplitude of oscillation in a marginally stable system tends to remain relatively constant.

A system which exhibits absolute stability as described above may still have poor relative stability, as reflected by the number of oscillations before the transient error is damped out. The most desirable condition occurs when the oscillation ceases within a single cycle.

After the transient error is damped out, a steady state error may persist. This will be especially true for a joint tracking system when the joint is skewed from the programmed path. In general, accuracy is improved by increasing sensitivity and speed of response, but stability is thereby imperiled.

The welding control system developed at Ohio State University for MSFC uses illumination from the welding arc for vision-based tracking of square butt joints. The view through the weld torch is depicted in Figure 2. The trajectory control procedure begins with detection of the weld joint. Confidence in the collected image is quantified, and must be greater than a programmed threshold for correction to occur. If the decision is to track the image feature, the present error is calculated as the distance between the joint position and the center of the electrode (defined in a calibration procedure before welding). The system's ability to detect the weld pool center and use it in the error calculation was not employed in the present tests, to simplify the evaluation. Once the present error is calculated, it is averaged with preceding values by a recursive technique. The so called exponentially weighted moving average is expressed by the following equation.

$$A(K) = \frac{(n-1)}{n} \times A(K-1) + \frac{1}{n} \times I(k)$$

where

A(K) = new average value

A(K−1) = present average value

I(k) = input factor

n = weighting factor

The weighting factor, n, defines the influence of the present error on the new average. In the OSU system, n is defined by the user programmable seam data average weight (SDAW), with $n = 2^{(SDAW)}$. Thus n is always a power of 2 (i.e., 0, 2, 4, 8, ...), and a small increment of SDAW will significantly affect the averaging.

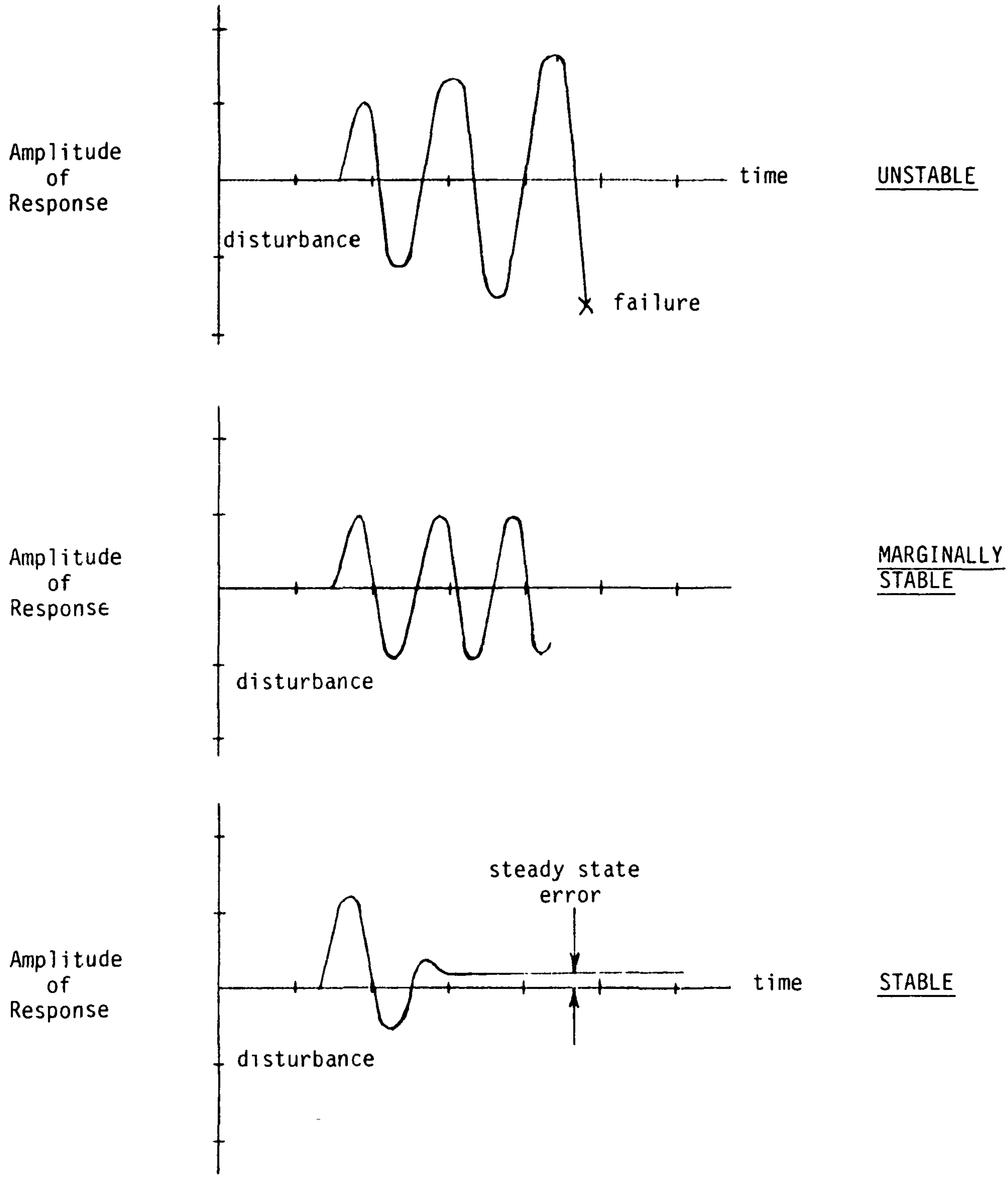


Figure 1. Classes of stability.

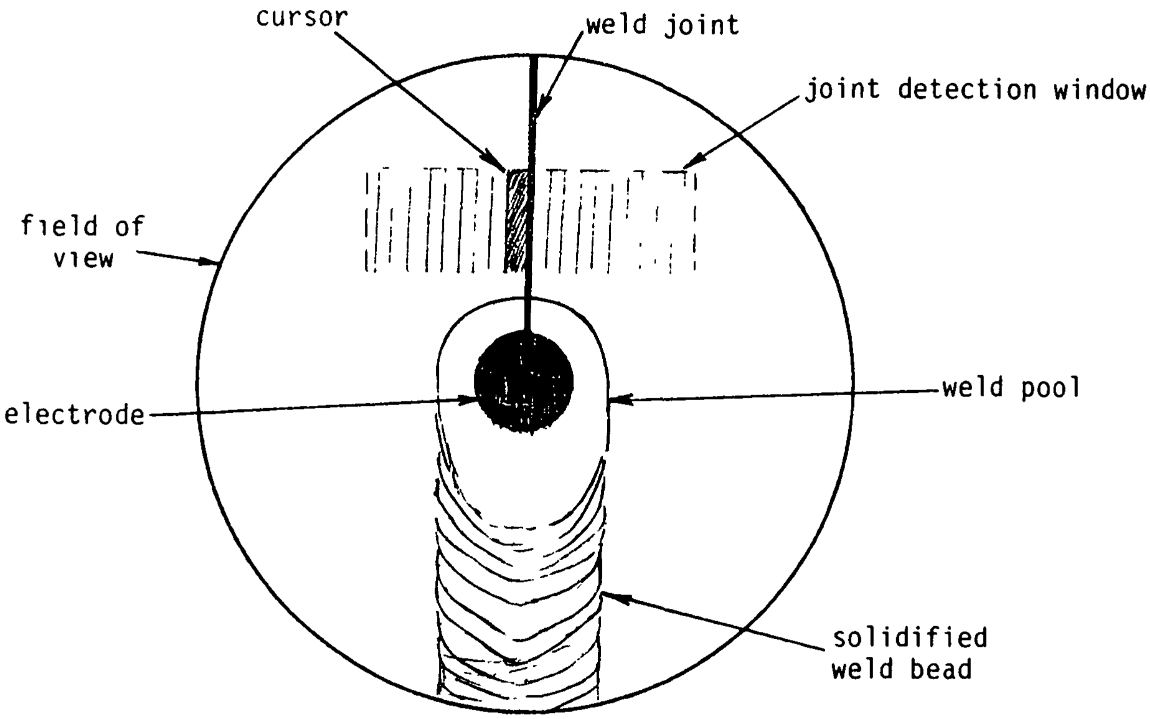


Figure 2. View seen by OSU welding control system.

Using the averaged value, a correcting response is calculated by a proportional-integral-differential (PID) type algorithm. The offset command, M(k), is calculated by the following equation.

$$M(k) = K_p \times [A(k)] + K_i \times \ SUM[A(K)] \ + K_d \times [A(k-1)] - A(k)$$

where

M(k) = control output after sample k

A(k) = averaged error calculated from sample k

A(k-1) = averaged error from previous error (k-1)

SUM A(k) = sum of all averaged errors from o to k

Kp = proportional gain

Ki = integral gain

K_d = differential gain.

User control of the integral gain is limited by the fact that some integration is performed when the control offset command, M(k), is converted from position correction to cross seam speed. This portion of the integral gain is not variable. While a certain amount of integral gain is helpful in removing steady-state errors, too large an increase in this term can effectively decrease stability.

The proportional term produces an offset which varies linearly with error. This is generally the most useful term in dictating the speed of response to a given error. The differential contribution to the offset is related to the difference between the present error and that from the previous sample. This term serves as a damper on the control response, it tends to decrease the rate of change of the offset command.

PROCEDURE

Plan of Investigation

When developing the test to evaluate and optimize the trajectory control parameters for the OSU vision system, care was taken to avoid catering to a particular situation. The test plates were prepared to provide conditions for good joint detection through the entire length of the weld. This essentially "ideal" fitup is considered best for adjusting the control parameters because deviations from the ideal condition are not always known in advance when making production welds. In addition, isolating the tests from the effects of joint detection simplified the analysis considerably.

Observation of tracking performance requires a controlled disturbance of the torch from the joint path. The test developed used a straight joint configuration for simplicity, the robot was programmed to provide a ramp offset and two step offsets from the joint location. A ramp offset is a standard test which primarily indicates the tendency toward steady state error. Step inputs are more severe disturbances which better demonstrate the dynamic response.

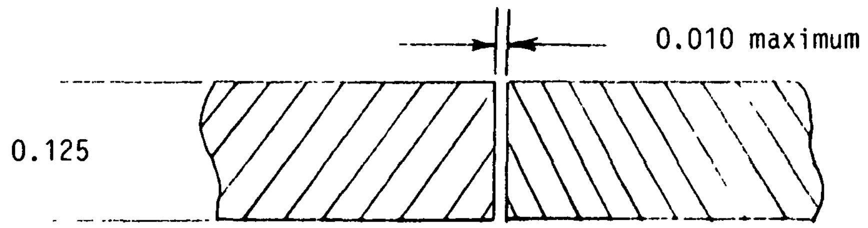
The parameters studied were assumed to be independent of one another for the purposes of these tests. According to Farson of OSU, this assumption is valid as long as the extremes of the usable ranges are not approached. Thus, although extreme values were used in order to define the limits of each parameter, the choice of optimal values was not affected because they occurred well within the usable range.

The proportional gain (K_p) was the most influential of the parameters considered, and was therefore given the most study. When varying K_p, the other three parameters were left at their default values. The optimal value of K_p was then used for the remainder of the tests.

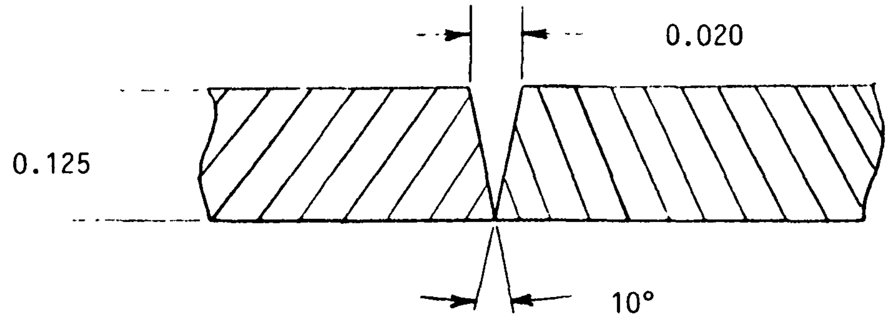
Experimental Procedure

The test welds were run on square butt joints, consisting of two 0.125 in. thick, Inconel 718 plates. For welds 1 through 56, one plate was 7 in. x 2 in. and the other was 7 in. x 1.5 in. The butting surfaces were ground flat to provide fitup with a maximum gap of 0.010 in. The top surface of each plate was sanded in a 1 in. strip adjacent to the joint with 120 grit emery cloth. The plates were wiped with acetone prior to welding.

The procedure was revised slightly for welds 57 through 82 to improve joint detection. The plate dimensions for the revised procedure were 9 in. x 2 in. x 0.125 in. Both 9 in. x 0.125 in. surfaces on each plate were ground flat and parallel to within 0.002 in. A bevel was then machined in the butting surfaces to provide a 10 deg included angle, with no land. With the plates butted together at the root on a flat surface, the joint gap at the top surface was approximately 0.020 in. Both weld joint preparations are depicted in Figure 3.



a. Configuration for samples A-DB



b. Configuration for samples EB-SB

Figure 3. Cross-sectional view of sample edges.

Two marks were scribed on one plate from each joint at a spacing of 7 in., corresponding to the start and end points of the weld. The plate width was measured at both locations with Vernier calipers, and recorded. This identified the joint location for the evaluation, and the edge of the plate opposite the joint was used as the reference for weld bead measurements. These features are seen in Figure 4.

The test plate was clamped in a fixture bolted to the two-axis positioner. The weld seam was oriented parallel to the Cyro 750 robot's x-axis, with the weld start point located at the positioner's center of rotation. The robot program rotated the positioner 2.5 deg from the home position and directed the torch manipulator to trace the path shown in Figure 5. The OSU vision system was enabled at the start of the weld. No automatic voltage control (AVC) was used.

The welding conditions were set to provide full penetration, as follows.

- Arc length = 3/32 in.
- Current = 125 Amps
- Travel speed = 5 in./min
- Primary shielding 99.999 percent pure Ar, flow rate 35 cfh
- Back shielding: 99.999 percent pure Ar, flow rate 5 cfh.

The matrix of control parameters studied is shown in Table 1.

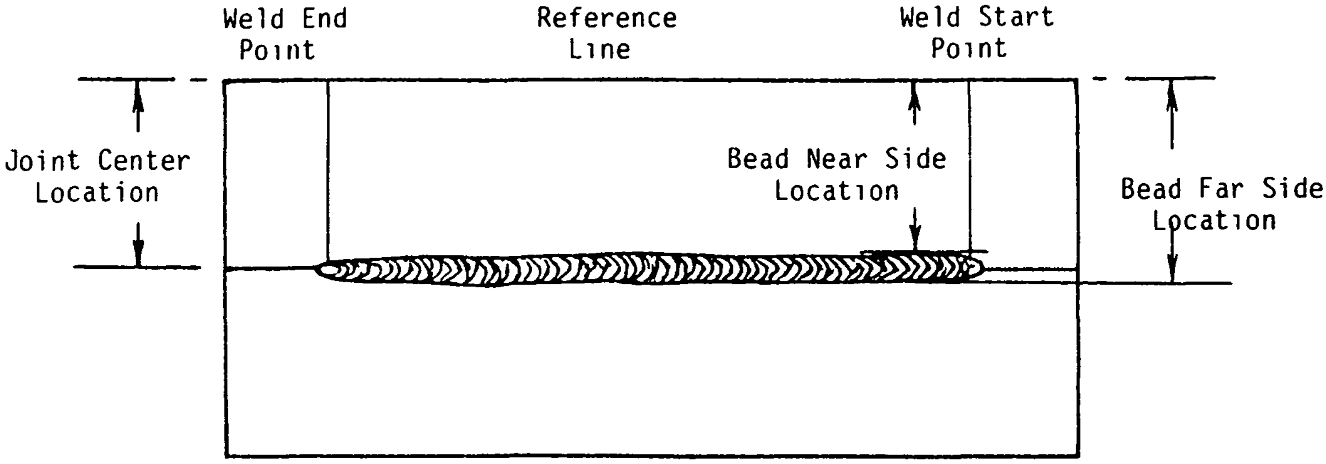


Figure 4. Sample surface showing reference lines.

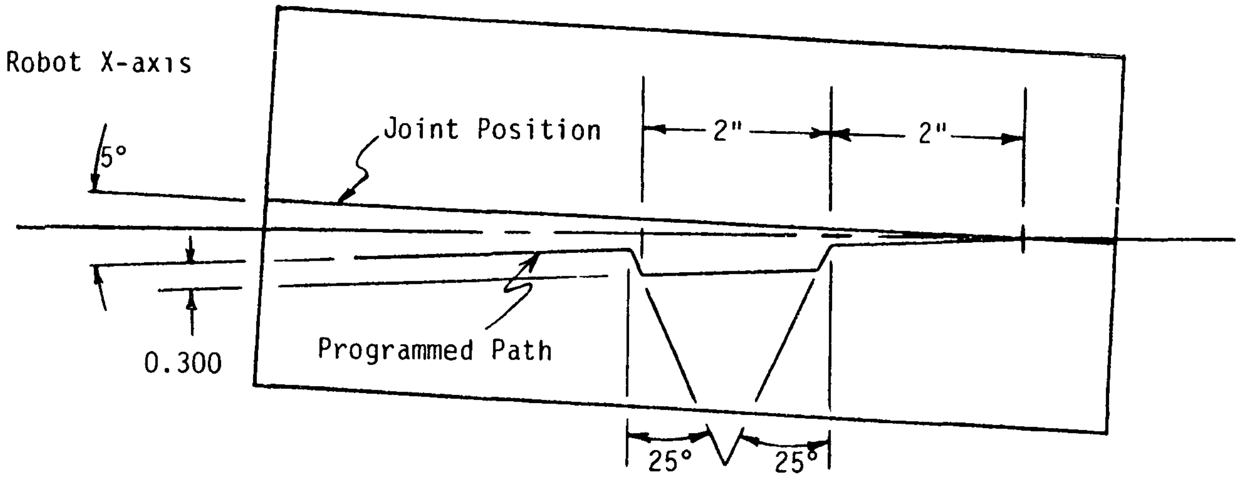


Figure 5. Programmed Test Path.

Evaluation

The plate edge used as a reference for the joint location (plate width) measurements was also used as a reference for measuring the bead position. Vernier calipers were used to locate each edge of the bead at 0.3 in. increments. Segments containing sharp changes were measured at smaller increments. The bead center was defined as the average distance of the two bead edges from the single reference point. The tracking error was calculated as the difference between the bead center location and the joint location.

TABLE 1. MATRIX OF CONTROL PARAMETERS USED IN TESTS

K_p	K_i	K_d	SDAW
16	00	-0A	01
17	00	-0A	01
18	00	-0A	01
19	00	-0A	01
1B	00	-0A	01
1F	00	-0A	01
23	00	-0A	01
2B	00	-0A	01
33	00	-0A	01
3C	00	0A	01
1B	00	0A	01
2B	00	0A	01
2B	01	0A	01
2B	02	0A	01
2B	03	0A	01
2B	00	-19	01
2B	00	-14	01
2B	00	-0F	01
2B	00	-05	01
2B	00	05	01
2B	00	0F	01
2B	00	20	01
2B	00	30	01
2B	00	0A	02
2B	00	0A	03

Allowable Range of Values for:

K_p = 00 to FF

K_d = 00 to FF

K_1 = 00 to FF (normally 00)

SDAW = 00 to FF (normally 01-04)

(n.b. All values of control parameters expressed in hexadecimal notation.)

RESULTS

The tracking errors measured at increments along the length of the weld were reduced to three values for each sample· maximum difference in errors, root mean square (RMS) error, and average difference between local maxima and minima. These values are illustrated for a typical weld in Figure 6. The maximum difference in errors indicates the ability of the system to correct for the step offsets. This quantity is primarily a measure of speed of response, and is not indicative of steady-state error or stability. The RMS error is usually a good measure of overall accuracy, but in the present tests it was dominated by the large deviations at the step offsets. Steady-state error is better evaluated by inspection of the plot of deviation from the seam with respect to position. The third statistical value, average difference between local maxima and minima quantifies the tendency toward oscillation in the control response.

A plot of maximum difference in errors as a function of proportional gain (K_p) is displayed in Figure 7. Clearly, the accuracy of response to sudden disturbances (the step offsets) was improved as K_p was increased. The slope of the curve decreases to essentially zero around \$2B to \$33 (\$ indicates hexadecimal base). A plot of RMS error with respect to K_p is shown in Figure 8. Since this term was dominated by the deviations at the step offsets, the majority of the curve is of the same shape as that in Figure 7. However, at high values of K_p, the RMS error begins to increase as stability begins to break down.

The average difference between local maxima and minima is plotted in Figure 9 as a function of differential gain (K_d). After the first set of tests were conducted, a "bug" in the control algorithm was discovered and corrected at OSU: the differential term had been negative when it should be positive. Inspection of the curve in Figure 9 reveals that varying K_d had little effect over a large range. The stability began to decrease for differential gains below about -\$0A.

Increasing the seam data average weight (SDAW) tended to increase oscillation as shown graphically in Figure 10. With the negative K_d, the effect of increasing SDAW was severely magnified. A photograph of the actual weld sample for K_d = -0A and SDAW = 2 is displayed in Figure 11. The stability was clearly marginal, as no damping of the oscillation was apparent.

A plot of average difference between local maxima and minima with respect to integral gain (K_i) is shown in Figure 12. As with SDAW, the tendency to oscillate with increased values of K_i was magnified when K_d was negative. With K_d positive, the curve in Figure 12 shows only a gradual increase with greater levels of K_i. The steady-state error showed little change with increased K_i over the stable range. This is illustrated by the curves of Figures 13 and 14. With $K_i = 2$ the plot of error with respect to location along the joint actually showed some increase in steady-state error over that for $K_i = 0$.

* The \$ indicates hexadecimal notation, used when entering these values into the computer program.

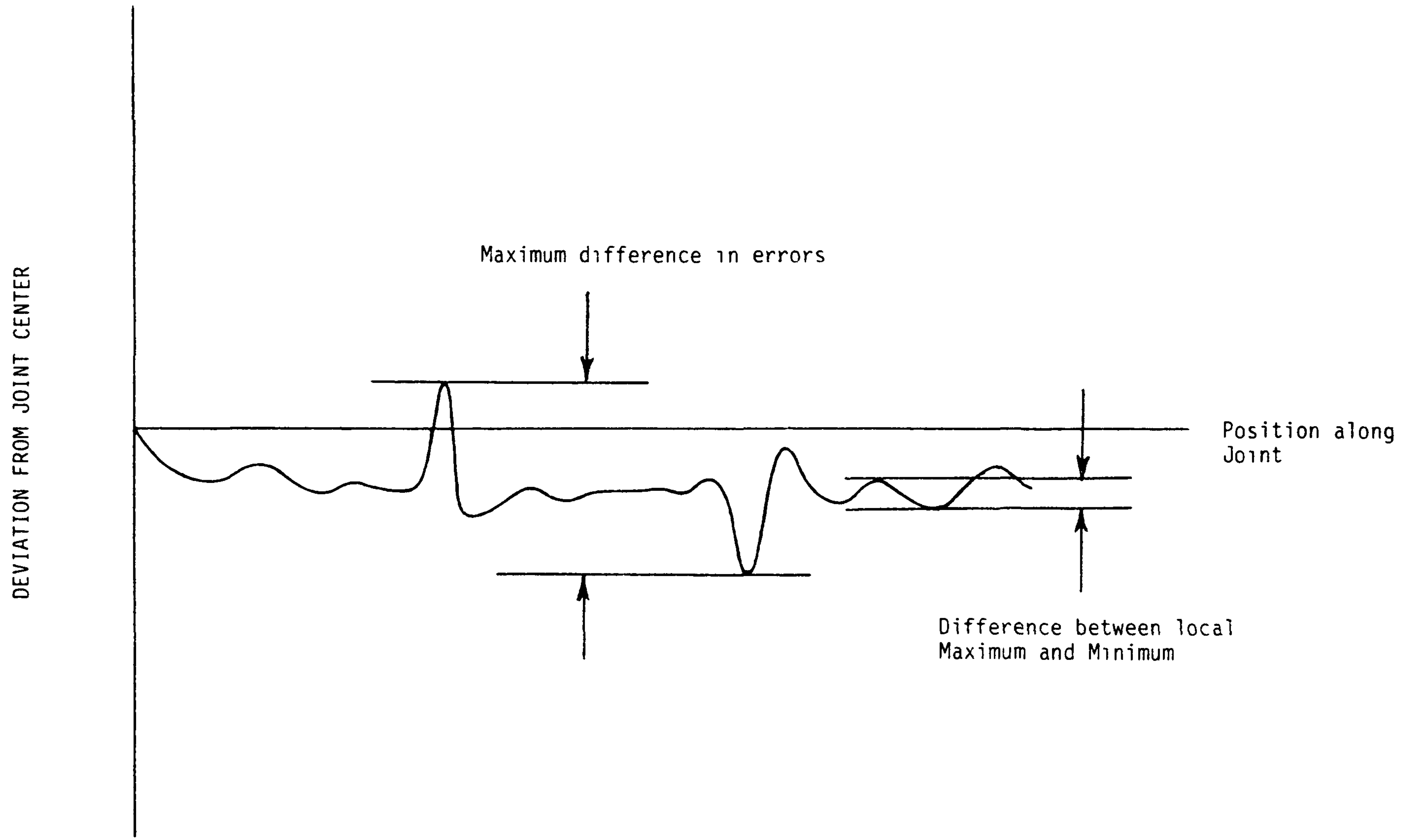


Figure 6. Representative plot showing values used for evaluation.

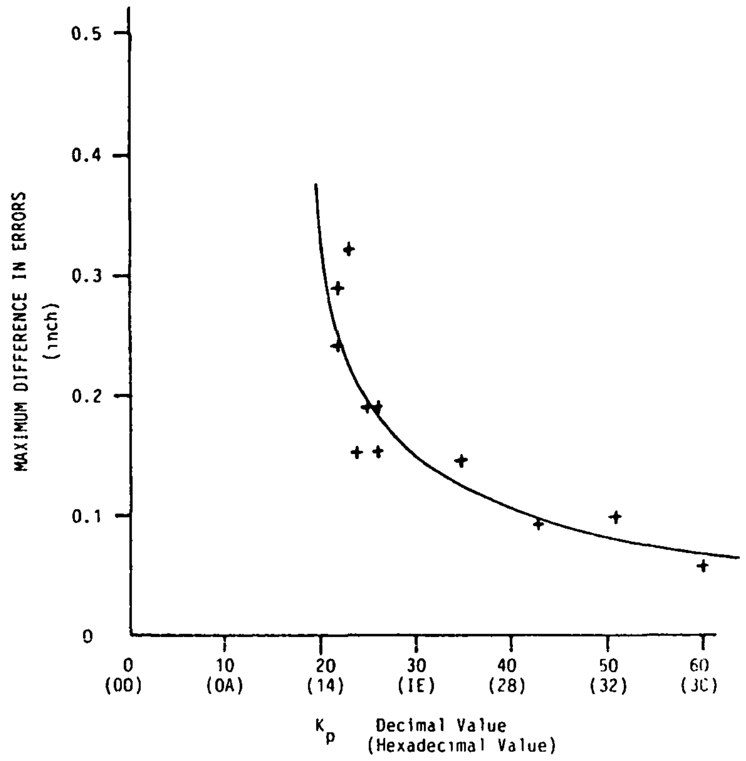


Figure 7. Maximum difference in errors versus proportional gain (K_p).

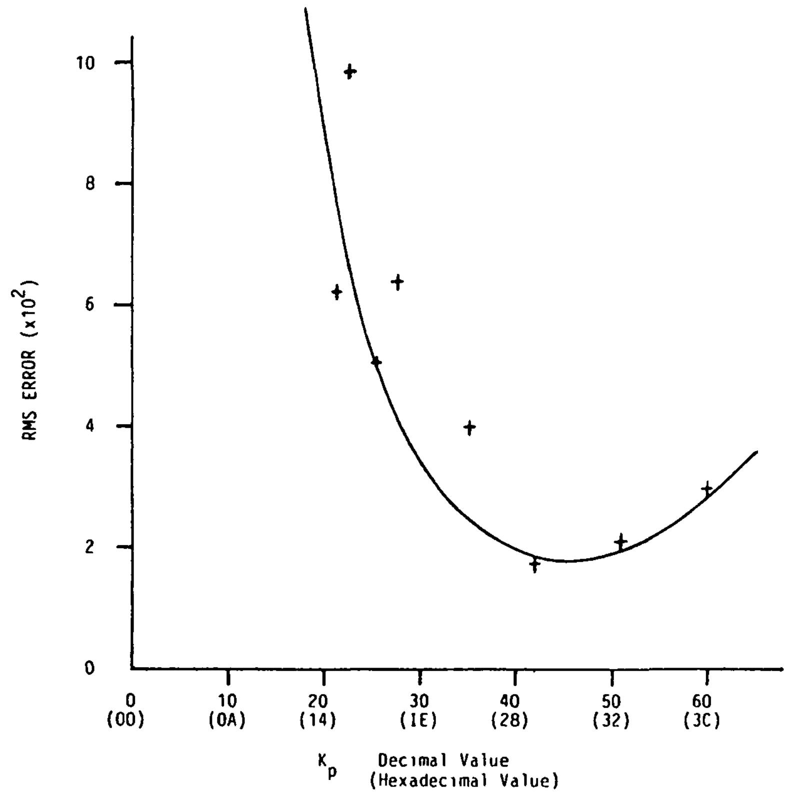


Figure 8. RMS error versus proportional gain (K_p).

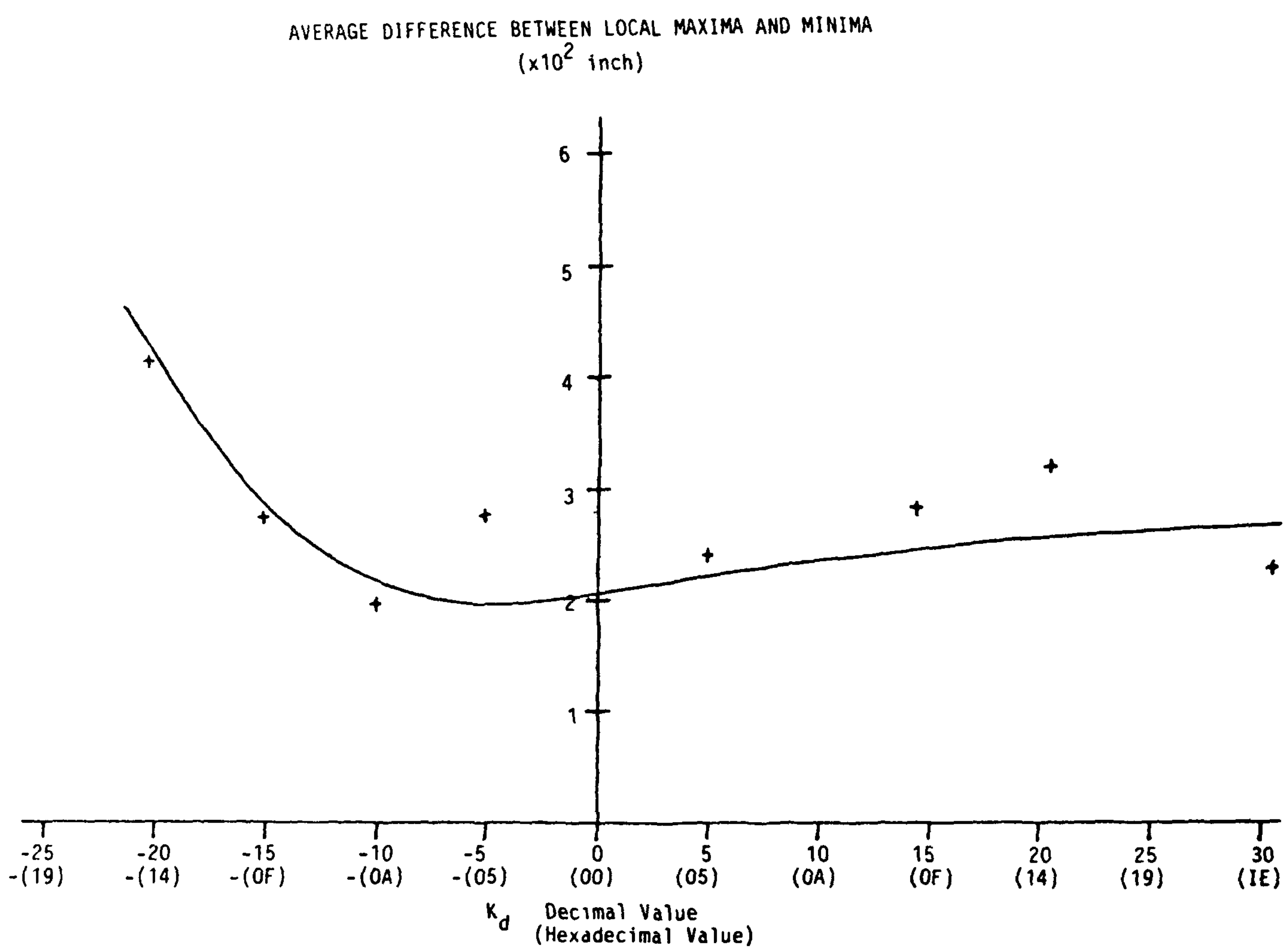


Figure 9. Average difference between local maxima and minima versus differential gain (K_d).

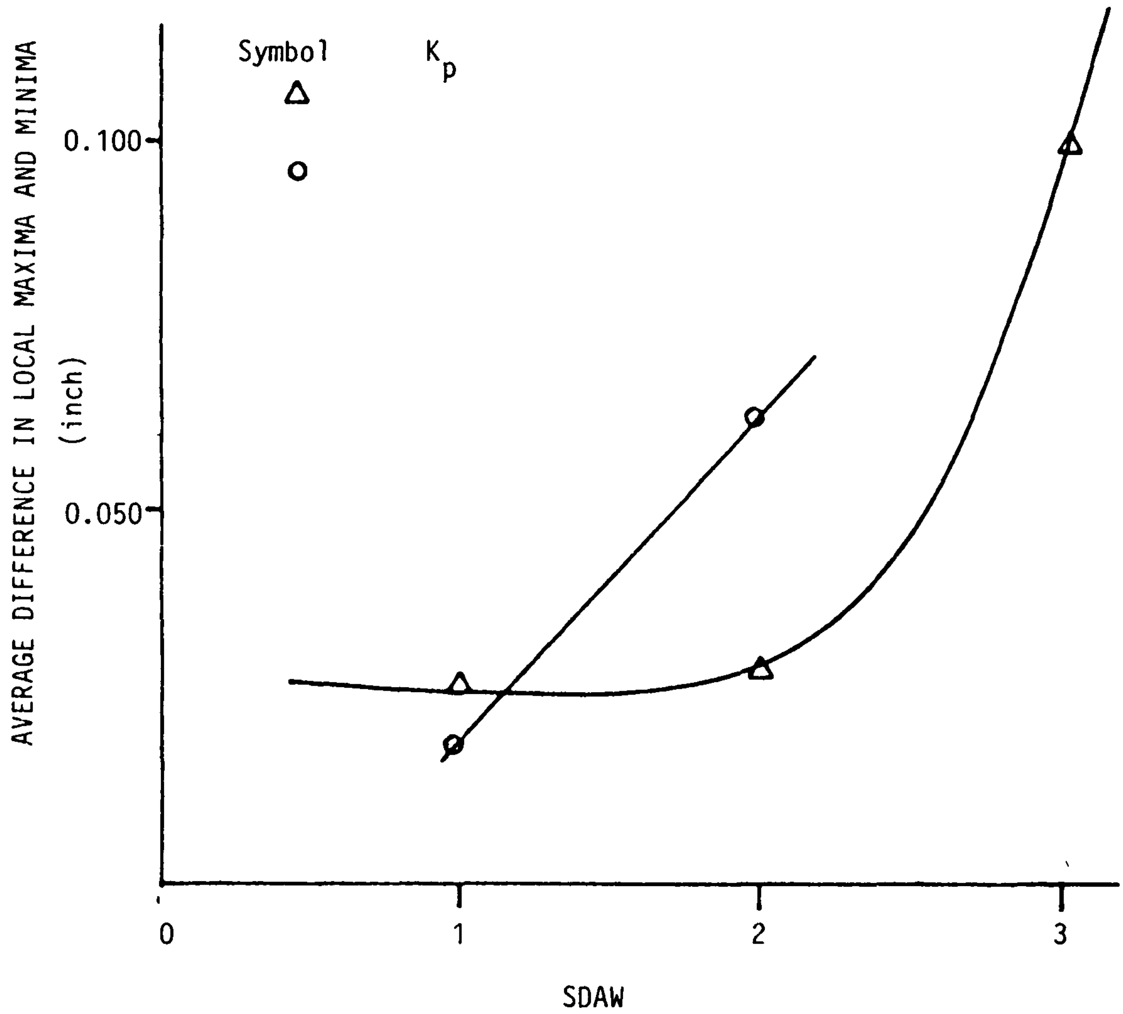


Figure 10. Average difference in local maxima and minima versus seam data average weight (SDAW).

Figure 11. Photograph of test sample exhibiting marginal control stability.

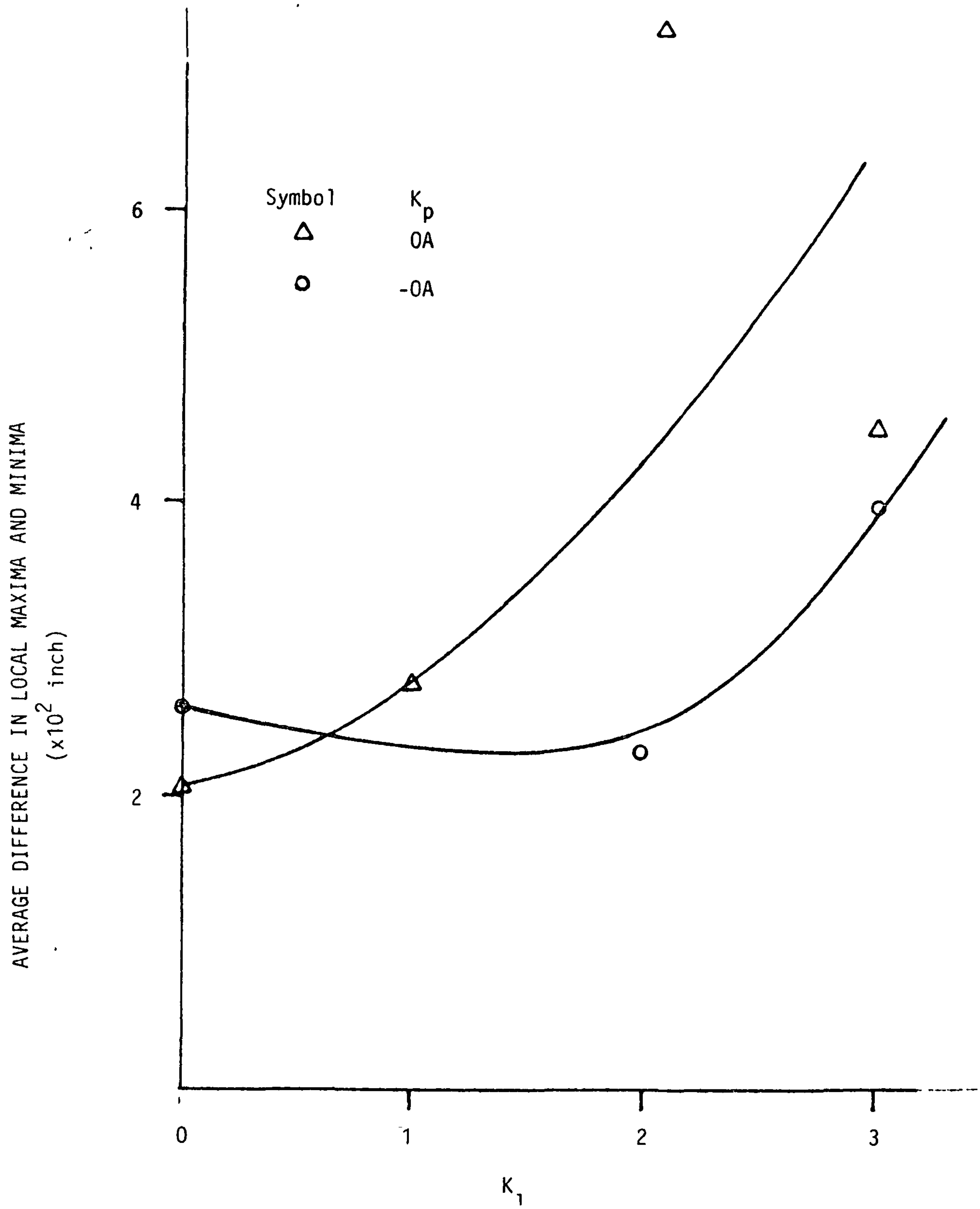


Figure 12. Average difference in local maxima and minima versus integral gain (K_i).

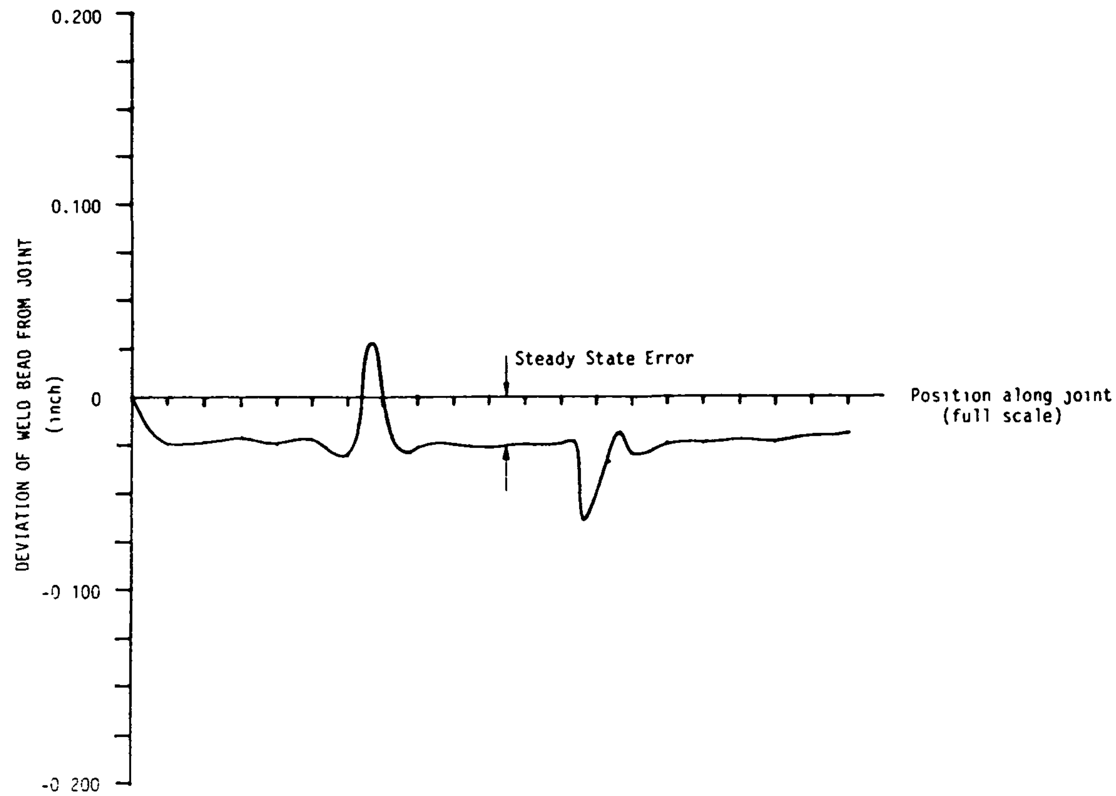


Figure 13. Representative sample showing steady-state error (K_p = 2B, K_i = 00).

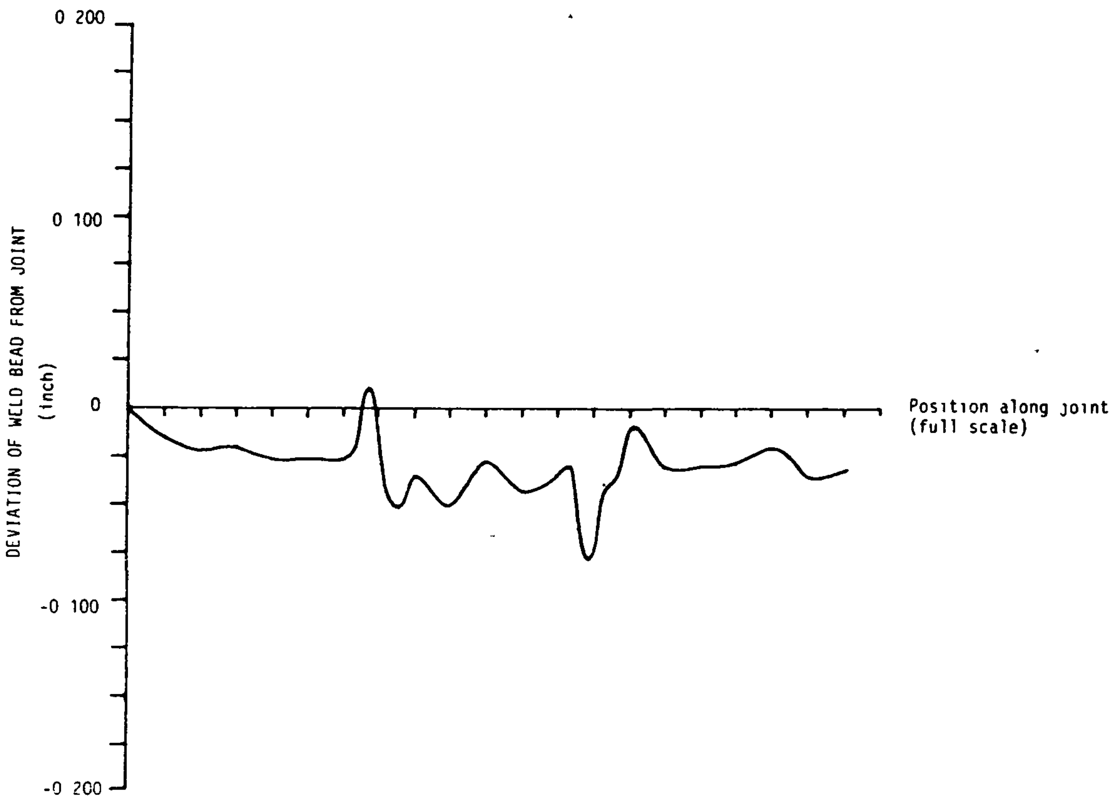


Figure 14. Tracking error with respect to position along the joint for K_p = 2B, K_i = 02.

DISCUSSION

The results of the tests conducted in this study fairly clearly indicate the optimal control parameters for seam tracking with the OSU vision system. A summary of the quantities used for evaluating each parameter is shown in Table 2. Tracking accuracy at the step offsets improved with increased K_p up to about \$2B, where the plotted curve leveled out. Further increases in K_p would decrease stability without improving accuracy, so the value \$2B is considered optimal.

Since varying K_d at positive levels showed very little effect on accuracy or stability, the proper setting may be chosen as the default value, \$0A. Some K_d is desirable to filter out electronic noise, but this term does tend to be sensitive to spurious errors.

Stability, as measured by the average difference between local maxima and minima, showed a gradual but definite tendency to decrease with increased values of both SDAW and K_i. Since there is no apparent advantage in increasing either of these values in terms of accuracy, they should be left at their default values, SDAW = 1 and $K_i = 0$.

Photographs of the weld made using the optimal set of parameters are displayed in Figure 15. Full penetration was achieved for the full length of the weld, and the offsets were almost entirely removed.

TABLE 2. SUMMARY OF CONTROL PARAMETER EVALUATION

Dependent Variable	Independent Variable	Characteristic Evaluated	Figure No.
Maximum difference in errors	K_p	Control accuracy	7
RMS error	K_p	Control accuracy	8
Average difference between local maxima and minima	K_d	Control stability	9
	SDAW	Control stability	10
	K_i	Control stability	12
Steady-state error	K_i	Steady-state error	13, 14

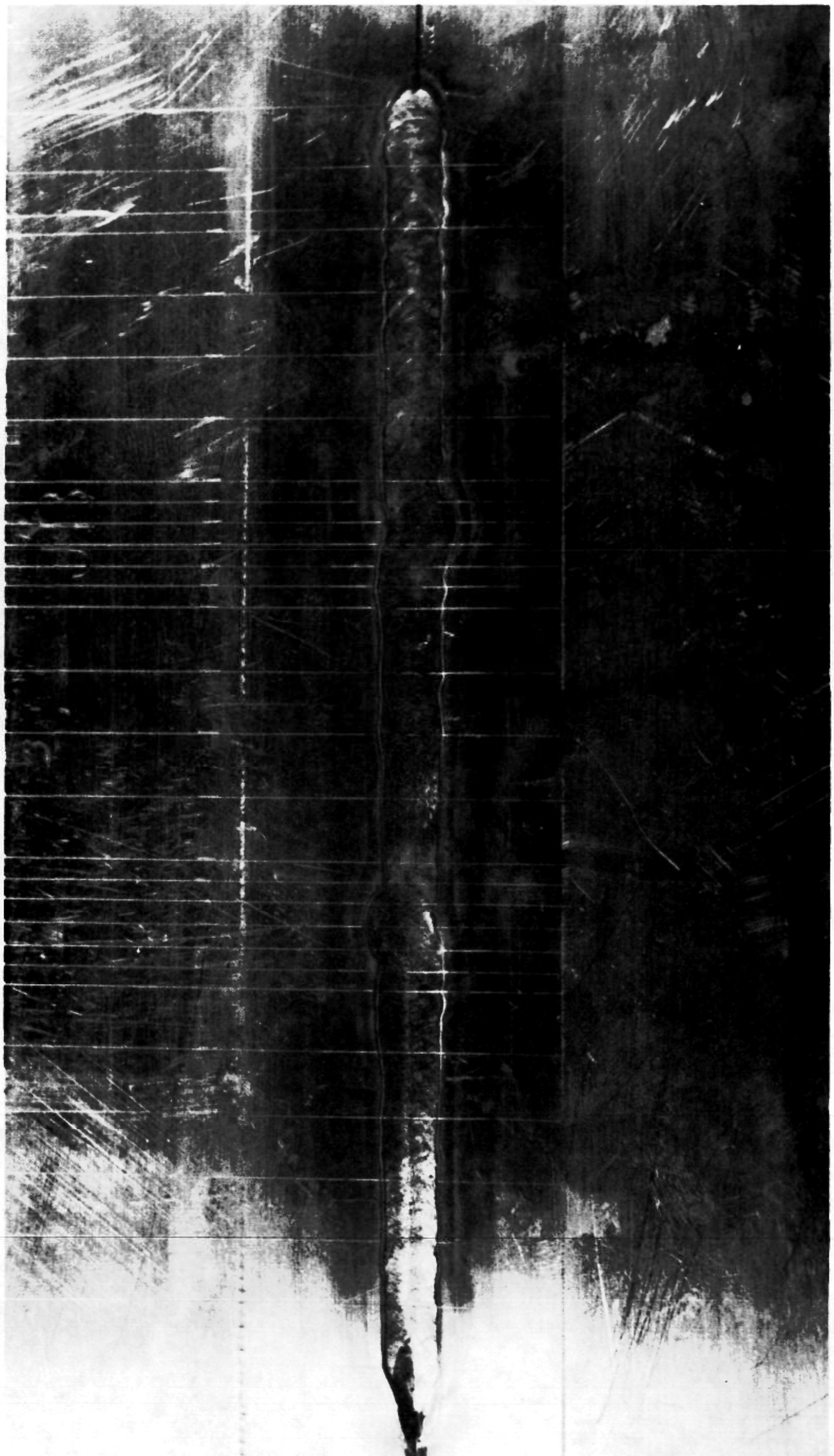


Figure 15a. Front view photograph of test sample welded with optimal control parameters.

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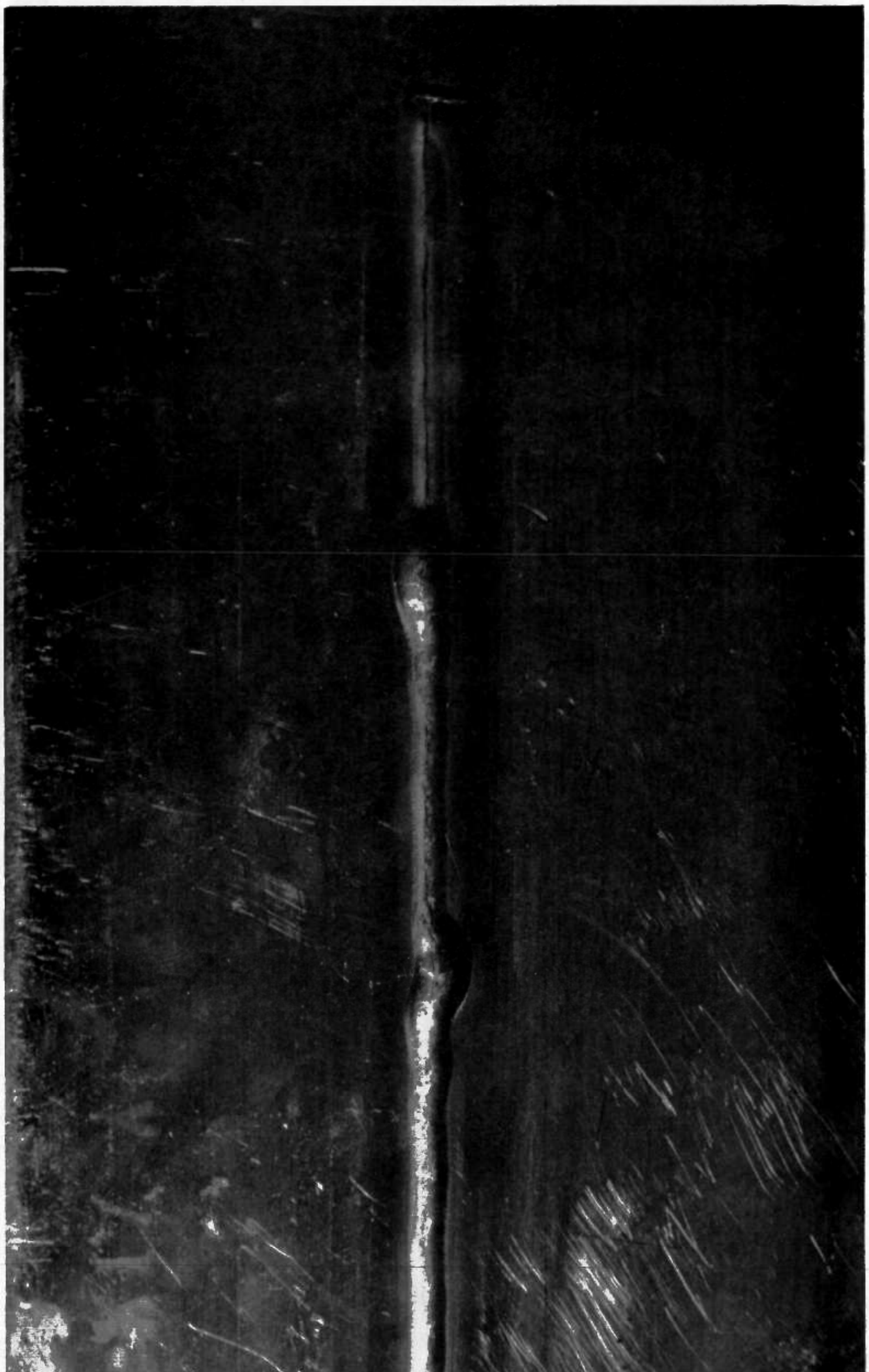

Figure 15b. Back view photograph of test sample welded with optimal control parameters.

CONCLUSIONS

On the basis of the tests conducted in the present study to evaluate the effects of the OSU vision system's control parameters, the following conclusions may be drawn:

1) Increasing the proportional gain (K_p) improved the system's ability to correct for abrupt offsets. However, the overall accuracy (as expressed by the RMS error) tended to decrease with levels of K_p greater than $2B. Therefore, $2B is the optimal value for K_p.

2) Varying the differential gain (K_d) caused little change in the control response over a wide range. Therefore, the default value, $0A, is considered optimal.

3) Increasing the integral gain (K_i) tended to reduce the stability of the control. Since no advantage was apparent in using higher levels, the default value for K_i ($00) is optimal.

4) Increasing seam data average weight (SDAW) also led to reduced stability. The default value of $01 will be used for this parameter in future tests.

5) The optimal control parameters chosen in the present study were developed on the Advanced Robotics Cyro 750 robot and controller, and may be unique to this system. When setting the control parameters for other systems, these tests should be repeated.

CONCURRENCE

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APPROVAL

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The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

R. J. Schwinghamer

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Director, Materials and Processes Laboratory

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