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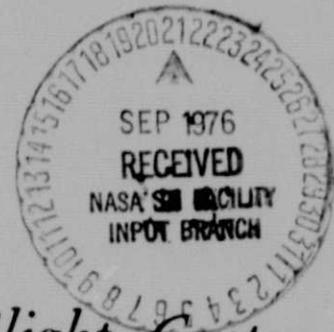
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COMPUTERIZED ADAPTIVE CONTROL WELD SKATE WITH CCTV WELD GUIDANCE PROJECT - STATUS REPORT

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16. ABSTRACT <p>This report summarizes the progress of the automatic computerized weld skate development portion of the Computerized Weld Skate with Closed Circuit Television (CCTV) Arc Guidance Project since work on the project was resumed in 1972 in the former Process Engineering Laboratory during development of Shuttle external tank support. The main goal of the project is to develop an automatic welding skate demonstration model equipped with CCTV weld guidance. The three main goals of the overall project are to:</p> <ol style="list-style-type: none"> 1. Develop a demonstration model computerized weld skate system. 2. Develop a demonstration model automatic CCTV guidance system. 3. Integrate the two systems into a demonstration model of computerized weld skate with CCTV weld guidance for welding contoured parts. <p>It is concluded that the development of parts 1 and 2 above has been successful and that work is almost complete with part 3 to complete the demonstration model equipment.</p>			
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COMPUTERIZED WELD SKATE WITH CLOSED CIRCUIT TELEVISION WELD GUIDANCE PROJECT – PROGRESS REPORT

INTRODUCTION

The problem with automatically welding parts which are neither straight nor uniformly round is that inherent geometric relationships between the welder and the part to be welded can cause large variations in the actual weld speed. Unless countermeasures are taken, these speed variations will result in a nonuniform weld nugget and loss of reliability. Since most automatic commercial welding power supplies and controls are designed to maintain constant current, voltage, and travel speed, welding a straight or a round piece does not present a controls problem because the heat applied in watts per a centimeter of weld length is held constant. However, if the part to be automatically welded with constant speed controls is not straight or uniformly round, the surface speed of the torch tip as it traverses the weld joint usually will not be constant. Hence, the weld nugget will not remain uniform. A better explanation of the reason for these speed variations is included in the Introduction of Reference 1. That document also explains the theory of correcting the torch workpiece. Speaking from the viewpoint of electrical controls only, uniform welds can be made if the voltage and current do not vary more than ± 3 percent. A weld joint which is straight and progresses into a curved section is especially susceptible to weld speed error. The same is true of elliptical bulkheads. Since it is difficult to correctly adjust current and voltage, the most practical solution is to counteract the geometric effects on weld speed with equal and opposite speed corrections of the work table or of the weld skate.

The computerized automatic weld skate with torch angle and weld speed controls has been developed to eliminate the effects of geometrically inherent speed control error sources. It does not have to be reprogrammed for each part and it does not require a numerically positioned table. In fact, as far as the concept is concerned, the method of holding the parts to be welded is of no significance to the weld skate. This development is designed to automatically weld a variety of jobs such as bulkheads, sinusoidal welds, ship hulls, water tanks, automotive parts, boxes, etc. Development of the weld skate was deferred for a few years due to more pressing projects, but since resuming this project in 1972 in the former Process Engineering Laboratory, the Mark II

(second generation) weld guidance equipment has been developed and tested. Results of the guidance equipment tests were published in References 2 and 3. The purpose of this document is to report the successful development of the Mark III, third generation, computer weld skate demonstration model which has the following features:

1. Ability to weld contoured or double contoured parts such as elliptical bulkheads, sine wave contoured parts, unusual aerodynamic shapes, automotive components, ship hulls, etc. Note that the concept is designed for tungsten inert gas (TIG) welding but it is adaptable to other processes such as electron beam, submerged arc, and metal inert gas (MIG) welding and heliarc or acetylene cutting.
2. The contour welder does not control the weld process. Rather, it controls the tip velocity of the torch to keep it constant and keep the torch at the desired attitude with respect to the work.
3. Automatically maintains constant weld speed along the surface of contoured welds at the point of the TIG arc. (A proximity detector would be used with most other weld processes.)
4. Accomplishes this control by the real-time digital computer solution of a set of general equations. The computer continually feeds new information to the servosystems; this automatically regulates weld skate speed and torch angle position.
5. Does not have to be reprogrammed for different parts, as does a numerically controlled machine, and does not depend on a fixed set of X, Y, Z reference coordinates, as does a numerically controlled machine.
6. Control concepts and theory work equally well whether the weld torch moves and the part remains stationary or whether the weld torch remains stationary and the part moves.
7. Concept is usable with standard commercial power supplies and processes such as TIG, MIG, etc.
8. Other mechanical capabilities of the demonstrator model equipment are listed below. Of course, for any specific job these capabilities could be changed or modified as the job requires.

Weld Process	TIG; other processes such as MIG, TIG Pulsed Arc, etc., are optional
Weld Speed Range	0-122 cm/min (0-48 ipm) horizontal or vertical with ± 3 percent accuracy
Torch Angle Rotation Range	± 38 deg at 570 deg/min max
Weld Torch	Linde HW-13, 500 A, or Linde HW-18, 150 A torch
Stroke of Weld Torch Arc Head Manipulator	36 cm (14.25 in.) at 67 cm/min (26.5 ipm) max rate
Wire Feeder	Airco Model HME-A, modified
Operational Track Radius	Straight to 30 cm (12 in.)
Minimum Radius of Workpiece (cm)	2.5 cm (1 in.) at normal TIG welding speeds; or minimum work radius (cm) = k [weld skate speed (cm/min)], $k = 0.1$

Progress since 1972 has been the conversion of an early model analog computer controlled Mark I system to a Mark III digital computer system. The hardware and controls of the new model weld skate, including some signal transducers, etc., changed appreciably from the early model Mark I system. This change was the result of a major redirection in the control theory and operational mathematics to simplify and improve the reliability of control transducers and to minimize some undesirable side effects of the carriage track joints. The overall result was a new configuration called the Mark II computerized weld skate. This working model (Figs. 1 and 2) was completed and tested in June 1974. The next step being taken is equipping the skate with the automatic weld guidance equipment mentioned above.

BACKGROUND

The welding skate with computerized torch angle and welding speed control Mark I control theory was first conceived at MSFC in 1964 and patented in 1969 under U.S. Patents No. 3,443,732 and No. 3,469,068. For a detailed

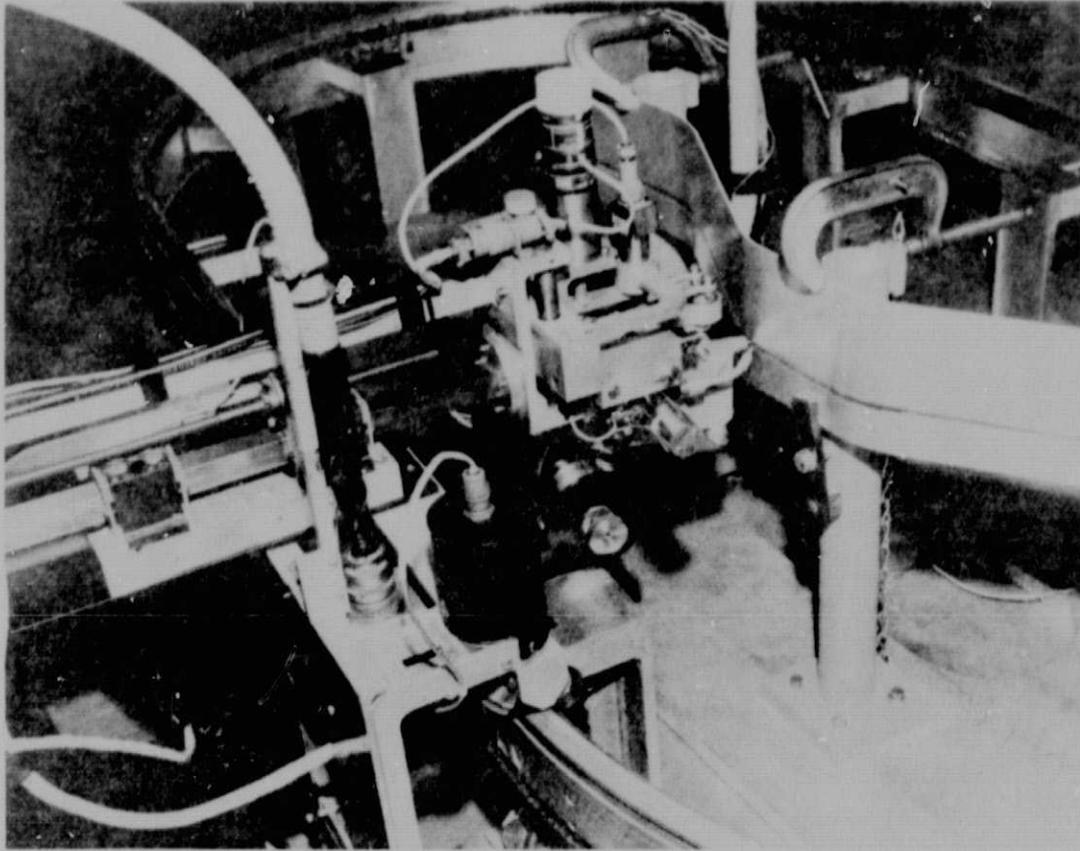


Figure 1. Computer weld skate torch angle manipulation and carriage.

explanation of the Mark I concept, see Reference 1. An analog computer prototype version of this concept was built and tested. However, the early model did not meet all of the objectives in terms of achieving the theoretically attainable accuracy primarily because of the inaccuracy of the analog computer. Because of a higher priority project, effort on this weld skate project was reduced in 1967, but a digital minicomputer was purchased to convert the unit to an on-line, digitally controlled system. Then in 1972, in preparation for possible welding equipment problems on the Space Shuttle Project, this welding skate development was renewed. MSFC Contract NAS8-29215 was established with SCI Systems, Incorporated, of Huntsville, Alabama, to complete the installation, programming, and checkout of the digital computer. This configuration was termed the Mark II weld skate since it differed significantly from the original model in that it was digitally controlled.

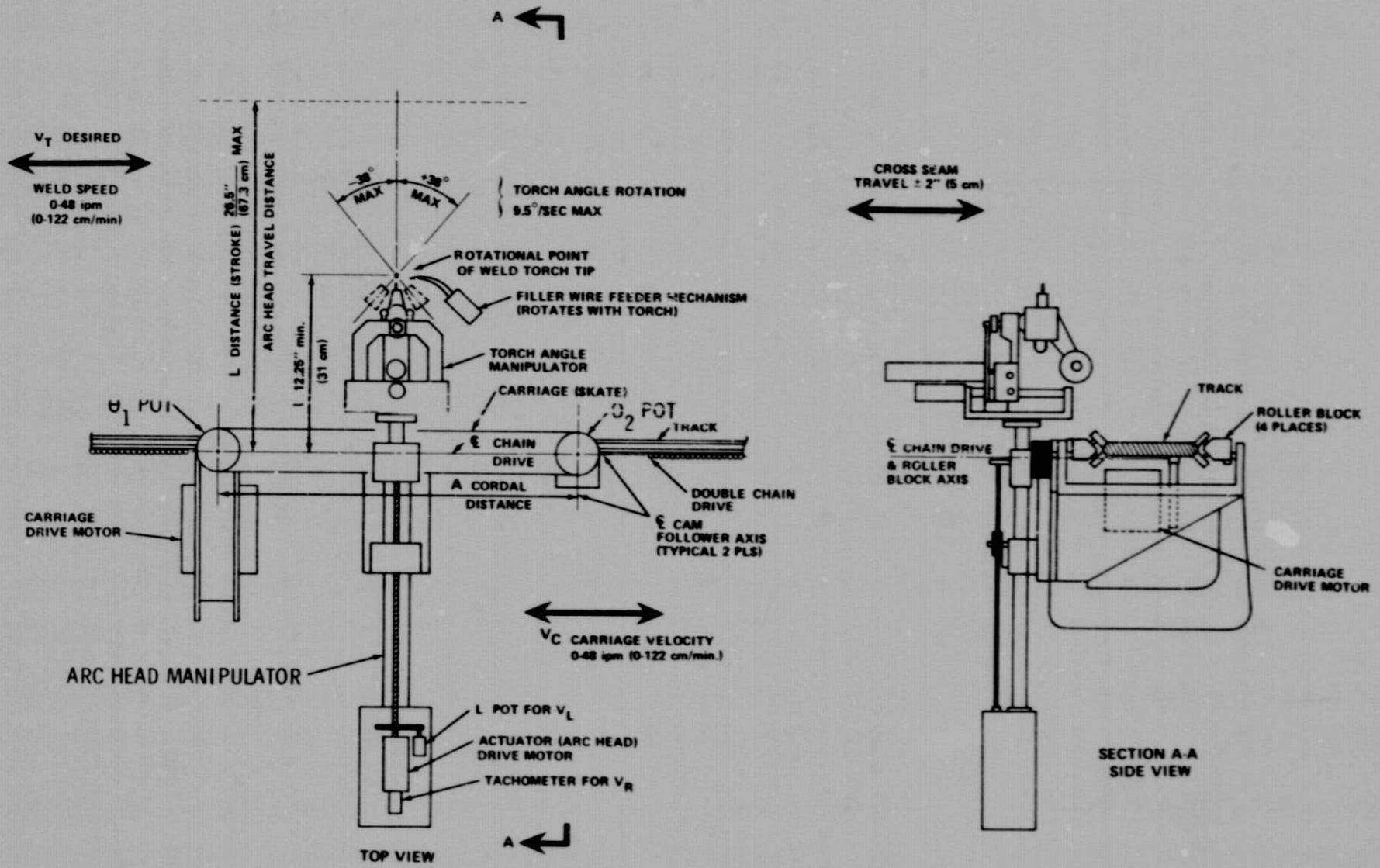


Figure 2. Demonstration model Mark III computer weld skate -- weld carriage layout.

SCI engineers were successful in installing the digital computer, and the ensuing weld skate accuracy was significantly improved. However, during checkout it was apparent that each time the skate crossed a track joint, minor variations in the joint caused noticeable perturbations in the weld (see Appendix A). Also, the Mark I and II control concept required a relatively expensive and error-prone radius transducer to measure the instantaneous track radius. A third inaccuracy occurred when the skate track made a sudden transition — as from a straight track section to a curved track section. In this case, the Mark I theory required the weld skate to make relatively large, instantaneous changes in speed. Since speed changes cannot occur instantly, these track transitions caused momentary inaccuracies in the weld.

To eliminate the three main problems, SCI engineers suggested that the arc-head manipulator, sometimes called in-out arm, be moved from one end of the skate carriage to the center of the carriage. Since the idea had considerable merit, SCI was awarded additional funds to formulate the required theory and mathematics. The theory was successfully worked out and their results published in SCI Final Report No. 3362-M1-001/3, dated July 16, 1973. It must be noted that the new mathematical equations are much more complex than the original Mark I equations. At first, the solution of the new equations seemed too complex for the HP2114A computer to compute the minimum desired output of 14 to 18 control updates per second. However, the benefits to be derived by attempting to implement the new approach made the expenditure of the effort seem worthwhile. One tremendous advantage of the digital control computer is that significant control changes can be made with little or no additional equipment cost. In this instance, the same HP2114A Mark II computer was successfully reprogrammed not only to circumvent the above mechanical problems "mathematically" but also to lower the overall equipment cost at least \$4500 since the expensive radius transducer is no longer needed.

MARK III WELD SKATE OPERATIONAL THEORY

Constant velocity of the weld and torch attitude control with respect to the part being welded is achieved in accordance with Figures 3 and 4. Figure 3 assumes that a weld skate will be built with rollers, or track followers, which guide a carriage along a track of unknown curvature to weld or cut a part of unknown shape. It is further assumed that these rollers will be mounted on a block in such a manner that the block will remain parallel to an instantaneous tangent to the track and will be allowed to rotate with respect to the carriage body (called chordal support) in the plane of the intersection of the chordal

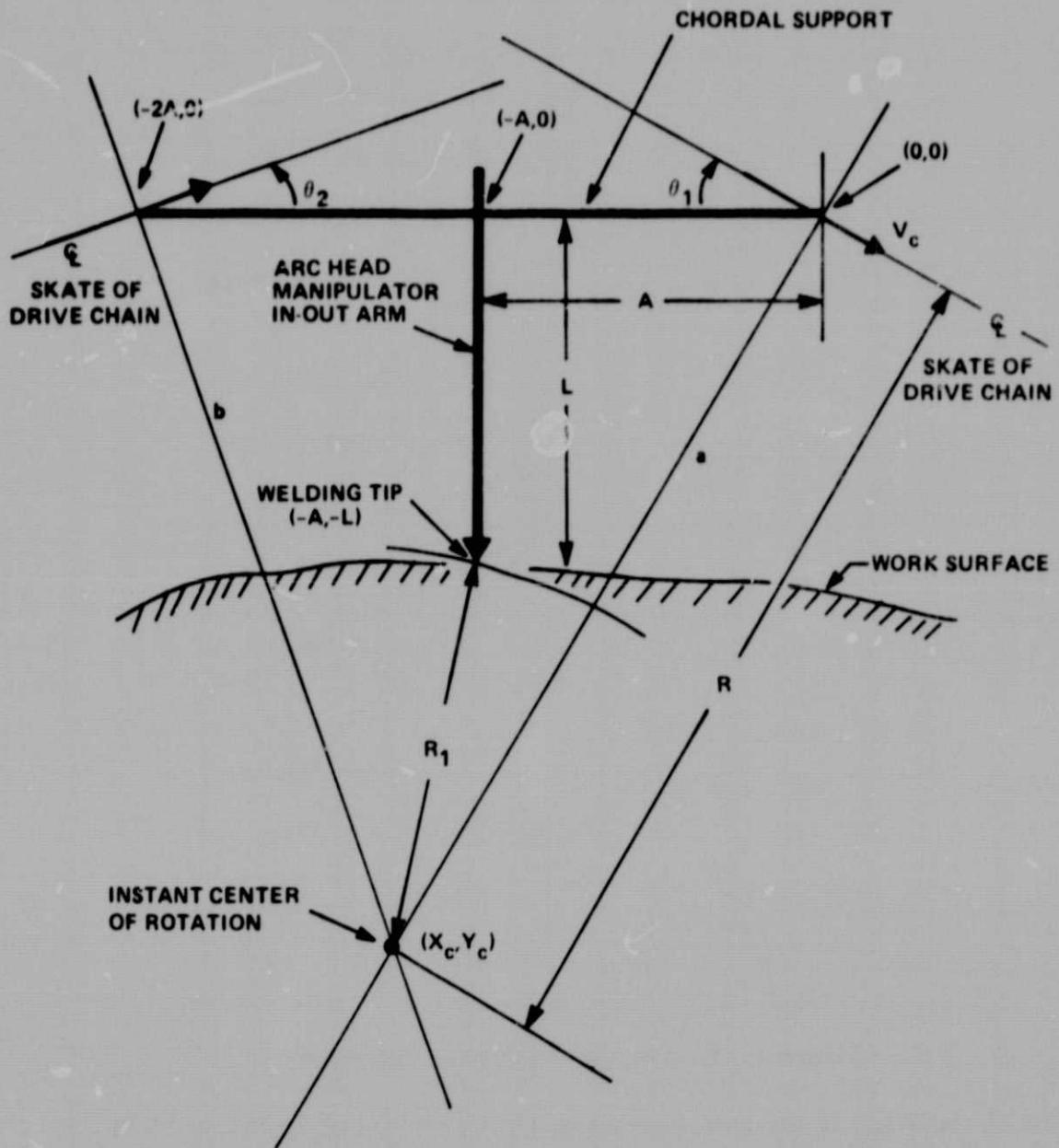


Figure 3. Mark III skate carriage configuration diagram.

support and the carriage drive chain. In this regard, the rollers and their mounting block are identically placed on both ends of the chordal support. These intersect points are designated $(-2A, 0)$ and $(0, 0)$ on Figure 3. The velocity of the intersect point $(0, 0)$ is vector V_c . This vector describes the instantaneous speed of the weld skate drive along the track since it is assumed

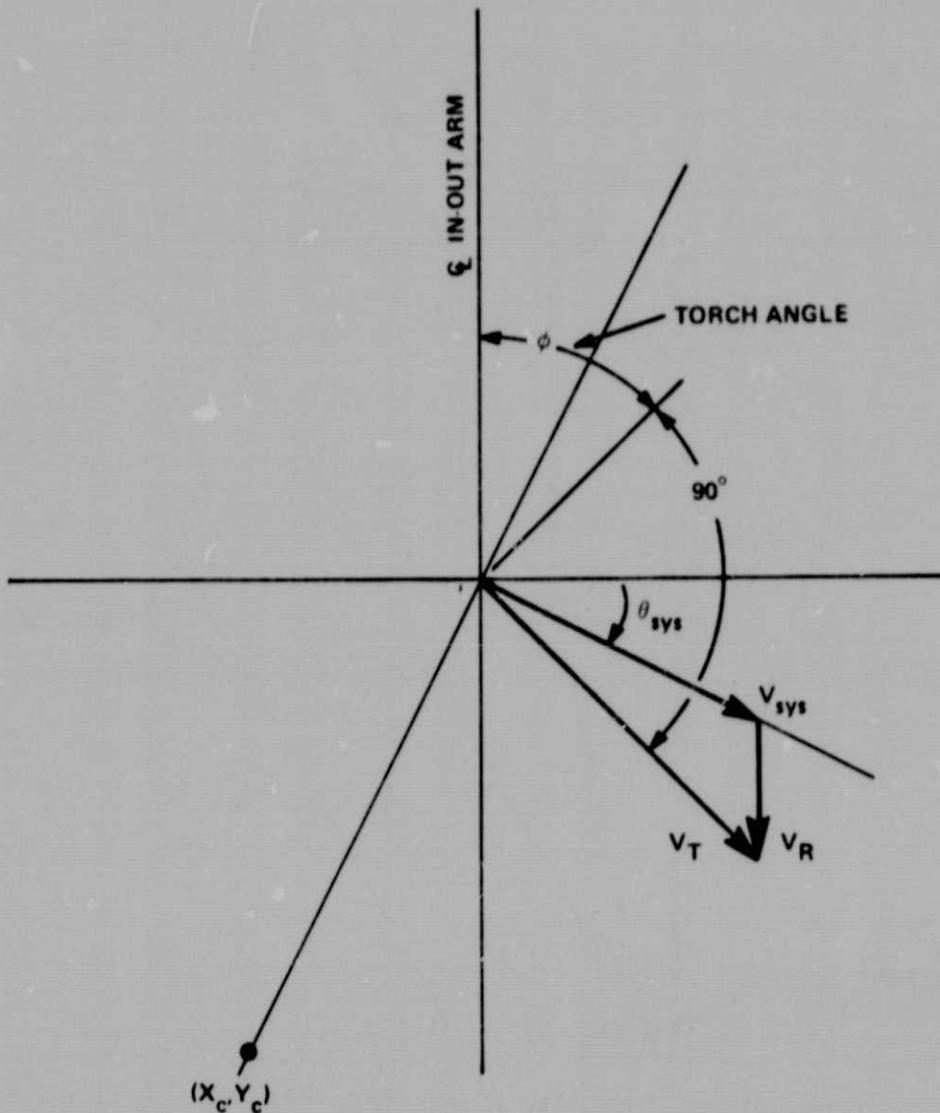


Figure 4. Welding tip velocity vector diagram.

that the carriage is driven at coordinate $(0, 0)$. Note that lines a and b intersect the center of instantaneous radius R at (X_c, Y_c) , and the angular displacements of the roller blocks from the chordal support are called θ_1 and θ_2 . It is important to note that θ_1 is defined to be at the driven end of the carriage. Now assume that a welding or cutting torch tip is at point $(-A, -L)$ mounted on an in-out, servo driven, manipulator arm. This arm, via TIG welding arc voltage control or proximity detection, automatically maintains a constant distance from the torch tip to the work as the carriage traverses the track. L is thereby

defined as the instantaneous distance from the chordal support to the torch tip. To simplify the mathematics, it is convenient to place the manipulator in-out arm on the chordal support at point $(-A, 0)$ which is equidistant from roller points $(-2A, 0)$ and $(0, 0)$. Finally, radius R_1 is defined as the distance from the instantaneous center of rotation (X_c, Y_c) to the torch tip at $(-A, -L)$.

Figures 3 and 4 describe the torch tip velocity vector, V_T , as being the summation of vectors V_{sys} and V_R , where V_R is the instantaneous velocity of the manipulator arm and

$$V_{sys} = \sqrt{V_T^2 - V_R^2 \cos^2 \theta_{sys}} - V_R \sin \theta_{sys} \quad (1)$$

by inspection of Figures 3 and 4.

The desired velocity of the torch tip, V_T , is one of the two parameters which is computer controlled. In fact, V_T is held constant at whatever speed the welding or cutting process requires. Therefore, V_T is an input to the computer and its value is manually selected via a potentiometer on the operator's welding control handbox. Because the desired welding or cutting speed V_T is held constant, the computer must calculate V_c , the required welding skate speed, by utilizing the following inputs which are easily measured by standard electrical devices:

L = instantaneous distance from the chordal to the torch tip
(potentiometer)

V_R = rate of change of L (tachometer)

V_T = desired welding or cutting speed (potentiometer)

θ_1 = angle of carriage chordal support with respect to a tangent to the track at the driven end (potentiometer)

θ_2 = angle of carriage chordal support with respect to a tangent to the track at the end opposite the driven end (potentiometer)

A = one-half the length of the chordal support (entered in computer program)

By inspection of Figures 3 and 4,

$$\left| \bar{V}_{\text{sys}} \right| = \frac{R_1}{R} \left| \bar{V}_c \right| \quad (2)$$

But since the computer must solve for V_c ,

$$\left| \bar{V}_c \right| = \frac{R}{R_1} \left| \bar{V}_{\text{sys}} \right| \quad (3)$$

Therefore,

$$V_c = \frac{R}{R_1} \left(\sqrt{V_T^2 - V_R^2 \cos^2 \theta_{\text{sys}}} - V_R \sin \theta_{\text{sys}} \right) \quad (4)$$

where

$$\frac{R}{R_1} = \frac{2 \cos \theta}{\sqrt{\left[1 + \left(\frac{L}{A} \right)^2 \right] \sin^2 (\theta_1 + \theta_2) + 4 \cos \theta_1 \cos \theta_2 \left[\cos (\theta_1 + \theta_2) - \frac{L}{A} \sin (\theta_1 + \theta_2) \right]}} \quad (5)$$

Thus, the computer accepts easily measured inputs and computes the required increase or decrease in speed of the weld skate to maintain the welding, or cutting, speed constant. Since the equations are general, there are no theoretical restraints on the curvature of either the track or the part to be welded, or cut, except practical considerations such as speed and feed limitations of the equipment.

The other parameter controlled by the automatic weld skate is the torch angle. By the law of similar triangles, it can be seen from inspection of Figures 3 and 4 that if it is desired to maintain the torch normal to a tangent to the workpiece by some angle ϕ , then the instantaneous angle θ that the torch makes with the in-out arm is

$$\text{Torch Angles } \phi = \text{arc sin } \frac{V_R + V_{\text{sys}} \sin \theta_{\text{sys}}}{V_T} \quad (6)$$

Substituting equation (2) for V_{sys} yields

$$\text{Torch Angle } = \text{arc sin } \phi = \frac{V_R + V_c \left(\frac{R_1}{R} \right) \sin \theta_{\text{sys}}}{V_T} \quad (7)$$

Thus by solving equation (7), the computer constantly outputs new information to correct the torch angle ϕ , and a servo system makes the final instantaneous torch angle corrections per Figure 5. For a more complete derivation of equations (4), (5), (3), and (7), see Appendix A.

MARK III WELD SKATE DEVELOPMENT

The Mark II weld skate system was reconfigured in house at MSFC to the Mark III version by incorporating the following mechanical, electrical, and program changes:

1. The centerline of the track cam follower rotation axis was moved from the centerline of the track to the centerline of the drive chain on the track. This modification was necessary to make the equipment match the theory assumptions.
2. The expensive Mark II radius transducer, part number MR&Tsk-1274E, was eliminated since it was no longer needed.

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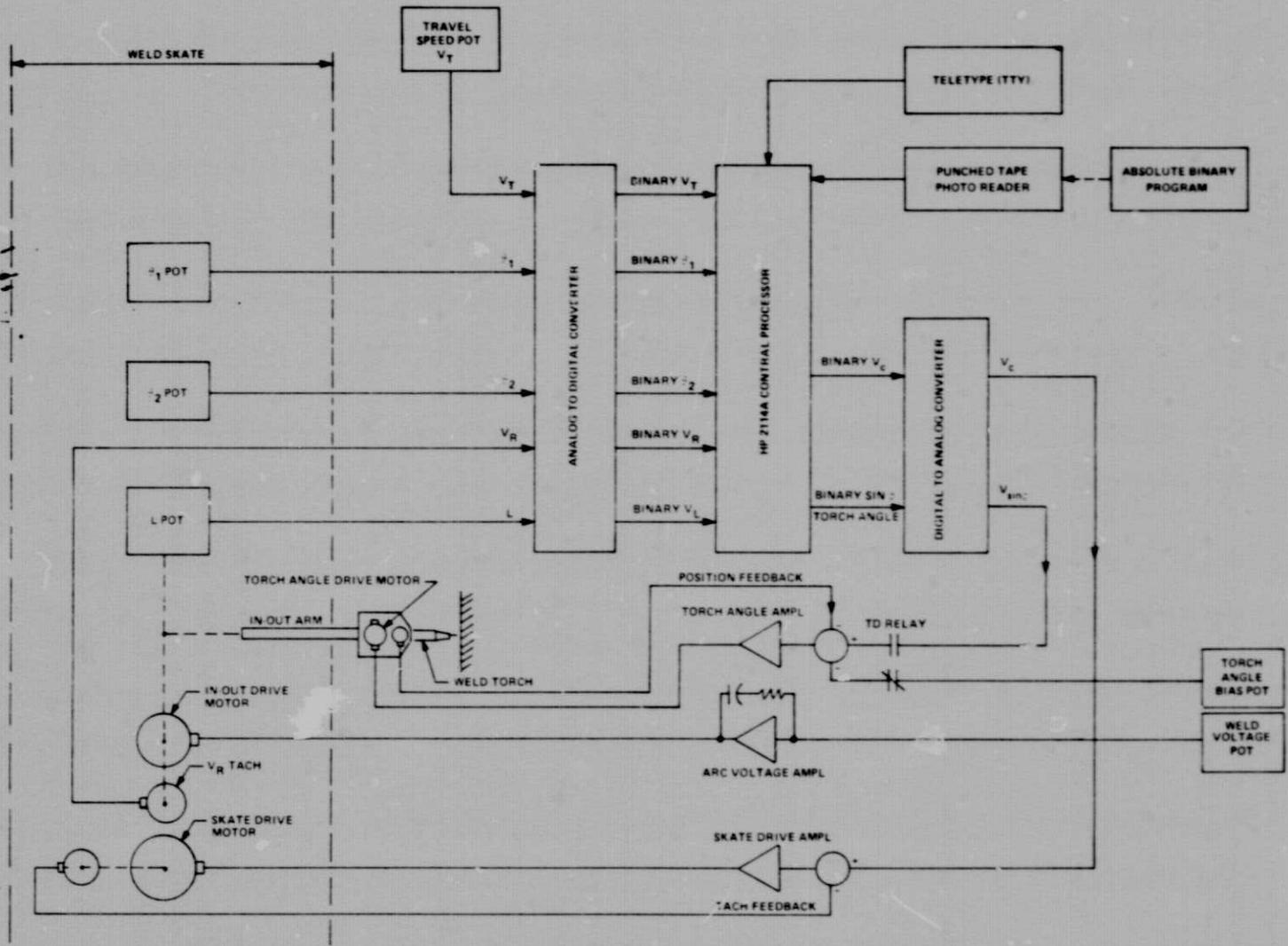


Figure 5. Mark III weld skate system block diagram.

3. Two potentiometers, designated θ_1 and θ_2 , were added in line with the centerline of the cam follower axis to implement the new equations. Actually, these two inexpensive parts in effect replaced the expensive and error-prone radius transducer.

4. The arc-head manipulator was moved from the centerline of the cam follower axis to the centerline of the carriage body.

5. The computer program was rewritten and refined to speed up the computation time, allow certain vital program constants to be quickly changed via the teletype for test and performance refinement, and reject certain out-of-tolerance control signals.

To understand the reasoning behind the above changes, the new mathematical theory, and the error analysis, Sections 4.0 through 4.2 of the SCI final report are included as Appendix A.

MARK III WELD SKATE COMPUTER PROGRAM

The current weld skate computer program, 1002, was configured by MSFC engineers to control the Mark III weld skate welding speed and torch angle. The 1002 program evolved from seven previous programs and has several features which make it desirable from an operational and functional point of view. For the scaling factors and program flow chart for 1002, see Appendix B.

MARK III WELD SKATE OPERATOR'S REQUIREMENTS

It is always desirable to keep the equipment operation as simple as possible. For this reason, the Mark III's controls have been designed to impose a minimum of effort on the operator. The program is maintained in computer memory and will not be lost due to loss of the 120 Vac control power. Therefore, once the program is entered into memory, it will remain there for weeks. Since the program is on punched tape, it can be easily re-entered into computer memory by the weld operator via the procedures of Appendix B. Finally, the program is arranged so that, when 120 Vac control power is turned on, the computer starts running. Therefore, the only action normally required of the operator with regard to the computer is to switch on the 120 Vac control power

and wait 3 or 4 min for the anal -to-digital converter to warm up. Next, he positions the torch within welding distance of the work and electrically positions the torch perpendicular to the work surface by use of a bias pot on the handbox. This initial torch angle adjustment is required to keep the torch at the correct attitude until the automatic torch angle operation takes over immediately after the skate TRAVEL is initiated. When the operator is ready to begin the welding or cutting operation, he simply initiates the arc and performs the process according to the usual procedures. For convenience, there is a MANUAL-AUTOMATIC switch on the handbox which allows the operator to bypass the automatic speed and torch angle controls if they are not needed. One additional feature is that the weld process often requires some degree of lead or lag of the welding torch with respect to a line normal to the work surface. This lead-lag of the torch is, in effect, a bias of the torch angle ϕ by some given number of degrees. To accomplish this bias, the operator loosens a thumbscrew which clamps the torch angle feedback synchro and rotates the synchro until the torch has electrically rotated the desired number of degrees; then the operator reclamps the synchro. Thereafter, this preset angle bias will remain on the torch during automatic welding until it is changed.

MSFC PROGRAM RELATED USES

The demonstration Mark III weld skate was reconfigured per Figures 1 and 2 and some of its more vital capabilities are listed in the Introduction. However, the reader must be aware that any or all of the demonstrator capabilities can be changed or altered significantly to render the concept acceptable for welding a wide variety of parts. For instance, the Mark III weld skate design could be used almost as-is to accomplish Shuttle ET bulkhead gore segment welds and other Shuttle contoured weldments such as some complex Shuttle Main Engine (SSME) components. Whether the weld guidance feature would be required would depend on the precision of the weld fixtures.

CONCLUSIONS

It is concluded that the Mark III demonstration model weld skate has been successfully configured and programmed to meet the accuracy objectives sought. Vital portions of the documentation such as wiring diagrams, mechanical drawings, and the final computer program are on file at the Materials and

Processes Laboratory and are available for review or distribution. The step in progress is outfitting the weld skate torch angle manipulator with automatic cross seam tracking. This addition will enable the concept to be demonstrated to its fullest possibilities.

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1. Wall, W. A.: Welding Skate with Computerized Torch Angle and Welding Speed Control. Recent Advances in Engineering Science, Vol. IV, 1969, pp. 245-262.
2. Mark II CCTV Welding Torch Guidance System, Shuttle External Tank Supporting Development, Evaluation Report. MSFC Memorandum S&E-PE-ME(44-74), Mar. 25, 1974.
3. Hayes International Corporation: Evaluation of the Mark II CCTV Arc Guidance Weld System. Technical Report ED-540, Nov. 29, 1973.

APPENDIX A

**SECTIONS 4.0 - 4.2 OF SCI FINAL REPORT
3362-M1-001/3, MSFC AUTOMATIC WELD
SKATE INTEGRATION**

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4.0 DETAILED DISCUSSION OF PHASE IV SKATE SYSTEM IMPROVEMENTS

4.1 PROPOSED SKATE MODIFICATIONS AND MATHEMATICS

During initial program efforts, it was felt that the original open-loop skate system using analog sensors would have operational problems which could be solved only by eventual conversions to an all digital system using stepping motor drives or closed-loop drive servos. Final weld testing on the corrected original system demonstrated, however, that exceptional accuracy could be achieved with the original concepts except when the skate transverses severe mechanical track perturbations, such as at the joints in the present test track, which are beyond the system electrical controls. It is concluded by SCI that a conversion to an all digital system would be justified primarily for reasons related to production welding system cost reductions, reproducibility, and sensor simplifications and with less emphasis on greater system accuracy.

Because of these considerations, it was decided that the skate sensitivity to the mechanical track perturbations should be reduced to an acceptable level as a primary improvement to the system prior to any changes to the electrical control concepts. After discussions, it was concluded that the simplest mechanical changes to the original system would include relocating the skate arm support mechanism to the centerline of a structure similar to the present skate carriage outrigger. This would provide a longer chordal distance between contacts with the track and, therefore, reduce the mechanical motion at the welding tip resulting from the track joint (or other source) bump. At the same time, it was concluded that the skate arm support mechanism could also be located nearer to the track to allow the welding tip to retract further toward the track which would increase the allowable V_T and provide a larger allowable sample location within the track perimeter. These changes did,

however, change the computer mathematics and also requires the present radius transducer to be replaced with two additional angle transducers; one located at each end of the new chordal support arm.

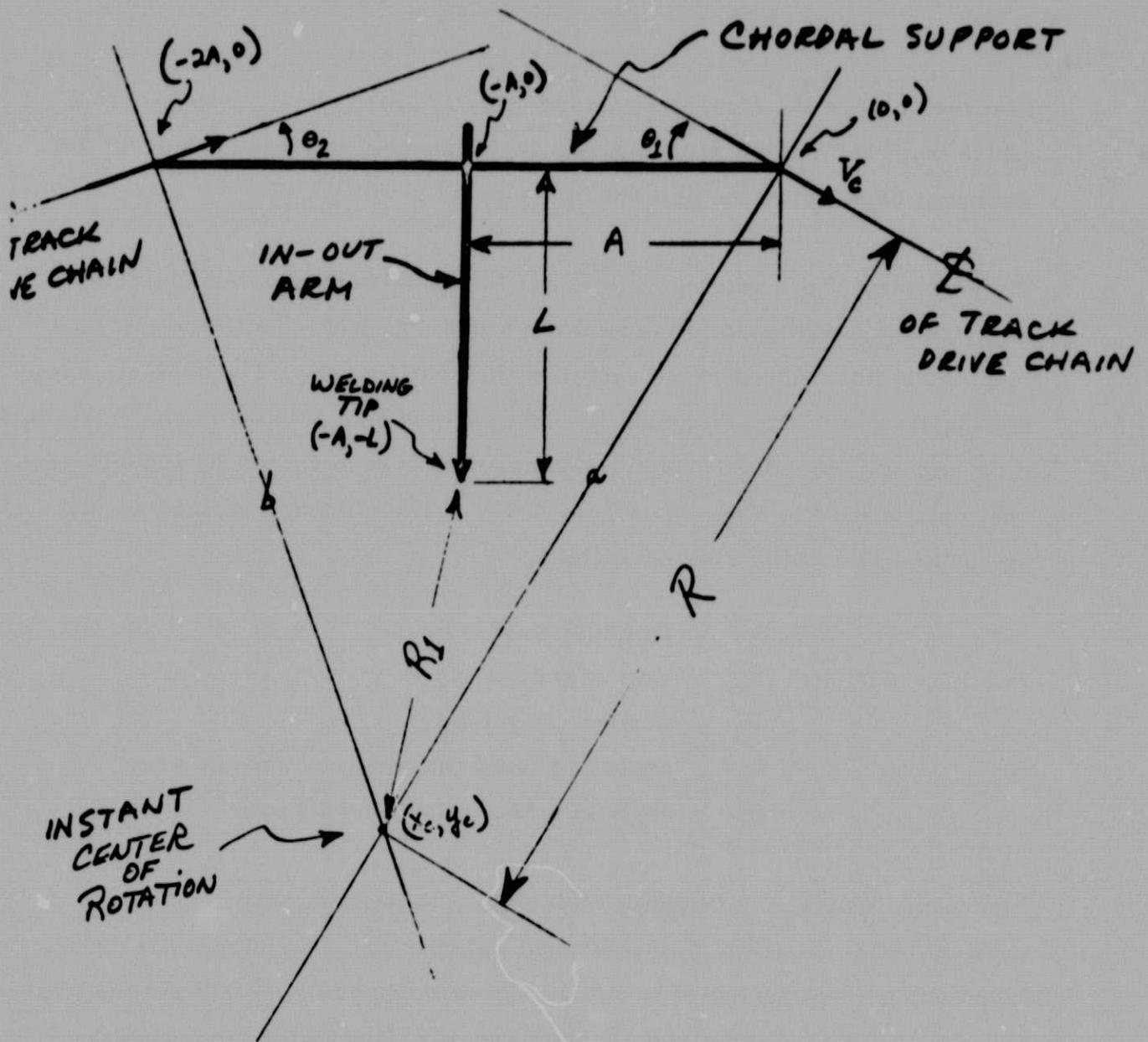
The geometry of the welding system has been analyzed to determine the mathematics required to implement the Automatic Weld Skate with the carriage system moved to the center of the support arm. The analysis shows that the skate velocity, V_C , and the head angle can be calculated and controlled if the angle of the velocity vector is measured at each end of the support arm. The configuration is shown in Figure 4.1-1. The following variables must be supplied as inputs to the computer:

- L = length of weld arm
- V_R = rate of change of L
- V_T = desired tip velocity
- Θ_1 = angle of skate control end of support arm
- Θ_2 = angle at other end of support arm

From these inputs, the computer determines an instantaneous center of rotation for the system. The rotational velocity at the welding tip is determined and vectorially added to V_R (as shown in Figure 4.1-2) to get the total tip velocity. These equations are then solved to determine the necessary skate velocity, V_C , to give the correct tip velocity, V_T . Since the center of rotation is located at infinity for a straight track, the calculations must be in such a manner that infinity does not appear in the numbers which must be handled by the computer.

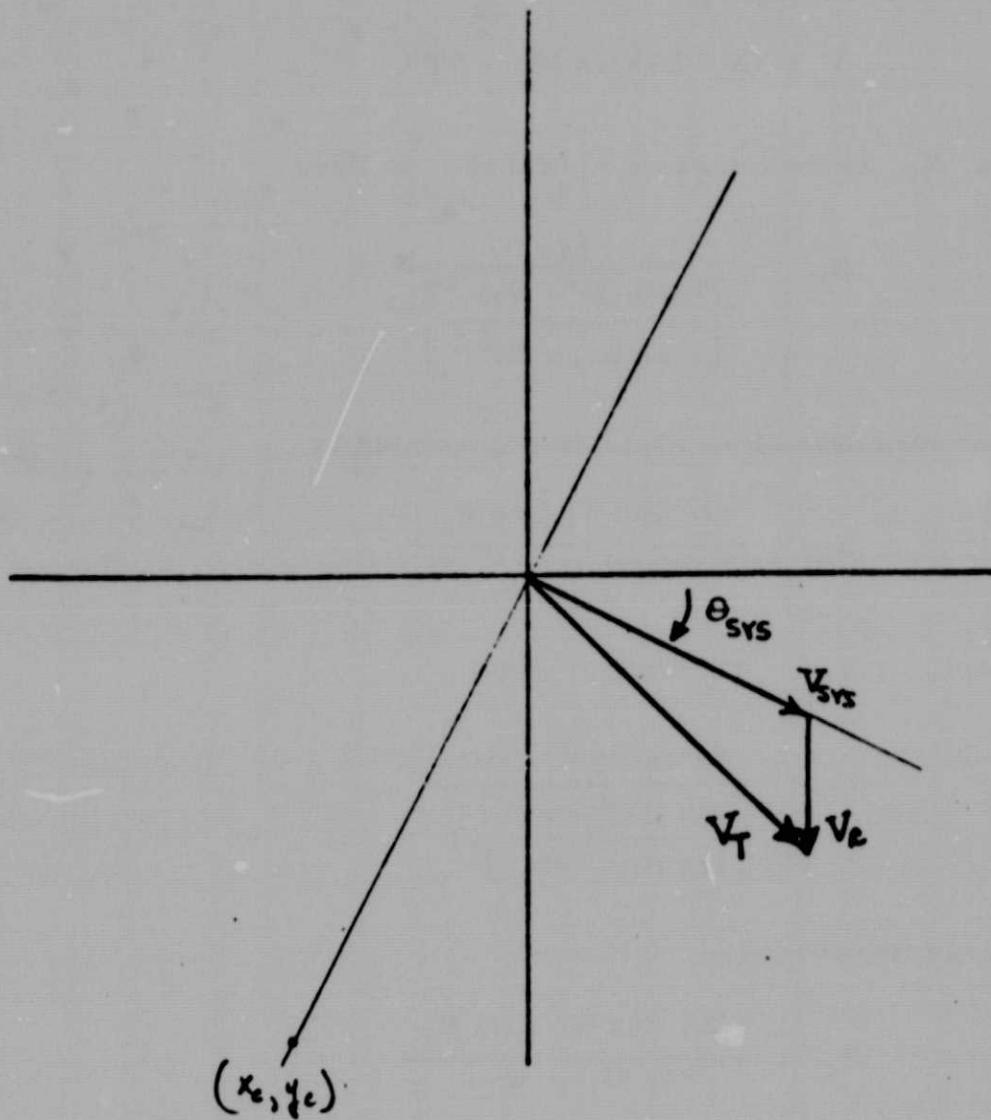
From Figure 4.1-1, it can be seen that the center of rotation is located at the intersection of the perpendicular to each of the velocity vectors. Line (a) can be represented by:

$$Y = X \tan (90^\circ - \Theta_1)$$



NEW SKATE CARRIAGE CONFIGURATION DIAGRAM

FIGURE 4.1-1



WELDING TIP VELOCITY VECTOR DIAGRAM

FIGURE 4.1-2

Line (b) can be represented by

$$Y = (X + 2A) \tan (\Theta_2 - 90^\circ)$$

The abscissa, X_C , is the intersection of these two lines

$$X_C = \frac{2A}{\left[\frac{\tan (90^\circ - \Theta_1)}{\tan (\Theta_2 - 90^\circ)} \right]^{-1}}$$

Trigonometric identities allow X_C to be represented by

$$X_C = \frac{-2A \sin \Theta_1 \cos \Theta_2}{\sin (\Theta_1 + \Theta_2)}$$

Since, $Y_C = X_C \tan (90^\circ - \Theta_1)$

$$= \frac{2A \tan (90^\circ - \Theta_1)}{\left[\frac{\tan (90^\circ - \Theta_1)}{\tan (\Theta_2 - 90^\circ)} \right]^{-1}}$$

This can be rearranged to give

$$Y_C = \frac{-2A \cos \Theta_1 \cos \Theta_2}{\sin (\Theta_1 + \Theta_2)}$$

The distance, R , from the center of rotation to the skate control point is

$$R = \sqrt{X_C^2 + Y_C^2}$$

$$R = \frac{2A \cos \Theta_2}{\sin (\Theta_1 + \Theta_2)}$$

The distance, R_1 , from the center of rotation to the welding tip is

$$R_1 = \sqrt{(X_C + A)^2 + (Y_C + L)^2}$$

Considerable manipulation allows R_1^2 to be expressed as

$$R_1^2 = A^2 + L^2 + \frac{4A \cos \Theta_1 \cos \Theta_2}{\sin^2(\Theta_1 + \Theta_2)} [A \cos(\Theta_1 + \Theta_2) - L \sin(\Theta_1 + \Theta_2)]$$

The system rotational velocity magnitude at the welding tip is a function of the skate velocity, V_C .

$$\left| \overline{V_{sys}} \right| = \frac{R_1}{R} \left| \overline{V_C} \right|$$

Since the computer must solve for V_C ,

$$\left| \overline{V_C} \right| = \frac{R}{R_1} \left| \overline{V_{sys}} \right|$$

The equations for R and R_1 can be combined and manipulated to give:

$$\frac{R}{R_1} = \frac{2 \cos \Theta_2}{\sqrt{\left[1 + \left(\frac{L}{A}\right)^2\right] \sin^2(\Theta_1 + \Theta_2) + 4 \cos \Theta_1 \cos \Theta_2 \left[\cos(\Theta_1 + \Theta_2) - \frac{L}{A} \sin(\Theta_1 + \Theta_2)\right]}}$$

From Figure 4.1-2, the tip velocity can be calculated:

$$V_T^2 = V_{sys}^2 \cos^2 \Theta_{sys} + (V_{sys} \sin \Theta_{sys} + V_R)^2$$

Subtracting V_T^2 from both sides:

$$V_{sys}^2 + V_{sys} (2 V_R \sin \Theta_{sys}) + (V_R^2 - V_T^2) = 0$$

The quadratic equation is used to solve for V_{sys} giving:

$$V_{sys} = \sqrt{V_T^2 - V_R^2 \cos^2 \Theta_{sys}} - V_R \sin \Theta_{sys}$$

Since: $\cos \Theta_{sys} = \frac{Y_C + L}{\sqrt{(X_C + A)^2 + (Y_C + L)^2}}$

$$\cos^2 \Theta_{sys} = \frac{1}{1 + \left[\frac{A \sin(\Theta_1 - \Theta_2)}{2A \cos \Theta_1 \cos \Theta_2 - L \sin(\Theta_1 + \Theta_2)} \right]^2}$$

$$\sin \Theta_{sys} = \sqrt{1 - \cos^2 \Theta_{sys}}$$

Since the head must be perpendicular to the tip velocity, V_T , the sine of the head angle is

$$\begin{aligned} \sin \phi &= \frac{V_R + V_{sys} \sin \Theta_{sys}}{V_T} \\ &= \frac{V_R + V_C \left(\frac{R_1}{R} \right) \sin \Theta_{sys}}{V_T} \end{aligned}$$

The calculations can be summarized as follows:

A : constant stored internally

Input: $L, V_R, V_T, \Theta_1, \Theta_2$

Calculate: $\cos \Theta_1, \cos \Theta_2, \sin(\Theta_1 + \Theta_2), \sin \Theta_1, \cos(\Theta_1 + \Theta_2)$

Output: V_C and $\sin \phi$

$$V_C = \frac{V_T}{R_1} \left[\sqrt{V_T^2 - V_R^2 \cos^2 \Theta_{sys}} - V_R \sin \Theta_{sys} \right]$$

$$\frac{R}{R_1} = \frac{2 \cos \Theta_2}{\sqrt{\left[1 + \left(\frac{L}{A}\right)^2\right] \sin^2 (\Theta_1 + \Theta_2) + 4 \cos \Theta_1 \cos \Theta_2 \left[\cos (\Theta_1 + \Theta_2) - \frac{L}{A} \sin (\Theta_1 + \Theta_2)\right]}}$$

$$\cos^2 \Theta_{sys} = \frac{1}{1 + \left[\frac{A \sin (\Theta_1 + \Theta_2) - 2A \sin \Theta_1 \cos \Theta_2}{L \sin (\Theta_1 + \Theta_2) - 2A \cos \Theta_1 \cos \Theta_2} \right]^2}$$

$$\sin \Theta_{sys} = \sqrt{1 - \cos^2 \Theta_{sys}}$$

$$\sin \phi = \frac{V_R + V_C \left(\frac{R_1}{R}\right) \sin \Theta_{sys}}{V_T}$$

It is assumed that the hardware will be configured to provide Θ_1 and Θ_2 through the analog-to-digital converter and that the angle, Θ_1 , will be measured at the point that the skate is driven. The program reflects these assumptions. Other conditions can be applied, but will require some changes to the program. Due to the trigonometric functions involved, the program will necessarily operate slower than the original program. This problem can be remedied by using look-up tables for the trig functions rather than the general service software.

4.2 NEW SYSTEM ERROR ANALYSIS

Analyses of the skate carriage sensitivity to track joint perturbations were made on both the original skate configuration and the new long chordal support configuration. In order to simplify the analyses, a "standard" track bump

offset step height of .025 inch located on a straight track section was used for the comparisons. While these conditions do not necessarily duplicate the present track condition, it is indicative of a possible condition and allows a sensitivity ratio to be established between the systems at a "standard" condition which will vary depending on the height of the actual bump. A summary of the head angle and V_T errors are included as follows with the actual calculations presented in the following sections 4.2.1 and 4.2.2:

- Original skate head configuration has welding head supported on wheels which are 2.432 inches apart.

The chord length must be five times that to reduce the displacement error by 80 percent on the new system.

New chord length should be 12.16 inches minimum.

- For the new configuration there is no error when one carriage has completely passed the bump and the other carriage has not reached the bump.
- When one carriage is on the bump there is a velocity error and a head angle error due to the fact that the velocity at the ends of the chord are not exactly in the direction of the measured angle.

There is also a velocity and head angle error in the present system in this situation due to the radius sensor.

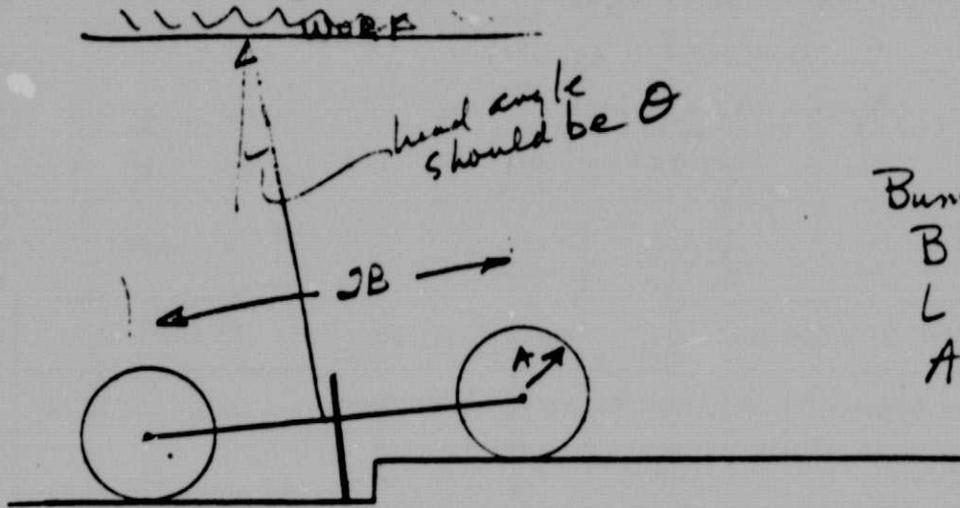
Assumptions:	Length between wheels of present radius transducer	2.432 inches
	New chord length	12.16 inches
	Bump	.025 inch as a step

Arm Velocity, V_R 0
 V_T , Desired Tip Velocity 1.0
 V_C = Skate Velocity
 L = length of welding arm 13 L 26

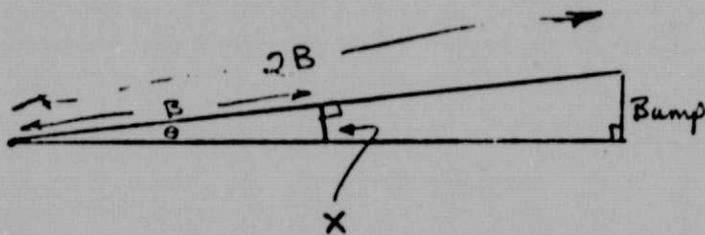
	For L = 26 inches		For L = 13 inches	
	New System	Present Skate	New System	Present Skate
Head Angle Error	.2998°	.58879°	-----	-----
V_T Error	2.2455%	78.138%	1.11%	28%

6-7-73 (1)

2.1 ERROR CALCULATIONS FOR OLD SYSTEM



$$\begin{aligned} \text{Bump} &= .025 \\ B &= 1.216 \\ L &= 26 \\ A &= .25 \end{aligned}$$



$$\sin \theta = \frac{\text{Bump}}{2B} = \frac{.025}{2(1.216)} = .0102796052$$

$$\theta = .5889883681 \text{ degrees}$$

$$\frac{x}{B} = \tan \theta$$

$$x = B \tan \theta$$

$$= 1.216 \tan \theta$$

$$x = .0125006604$$

head angle should be
 $= \theta = .5889883681$
 degrees

head angle is zero

error = .5889883681
 degrees

$$V_{10} = \frac{1}{1 + \frac{L}{R}}$$

R = Negative
X = Negative

$$\frac{1}{R} = \frac{2x}{B^2 + x(x \pm A)}$$

Use Negative sign

$$\frac{1}{R} = \frac{2(-.0125006604)}{(1.216)^2 + (-.0125006604)(-.0125006604 + .25)}$$

1.478116

$$\frac{1}{R} = -.0168706993$$

$$R = \frac{B^2 + x^2 - A^2}{2x}$$

$= -59.14311631$

$$V_{10} = \frac{1}{1 - 26(.0168706993)}$$

$= 1.781382288$

$$R = 59.39936568$$

For L=13 in
Ratio = 1.280933078
Error = 28%

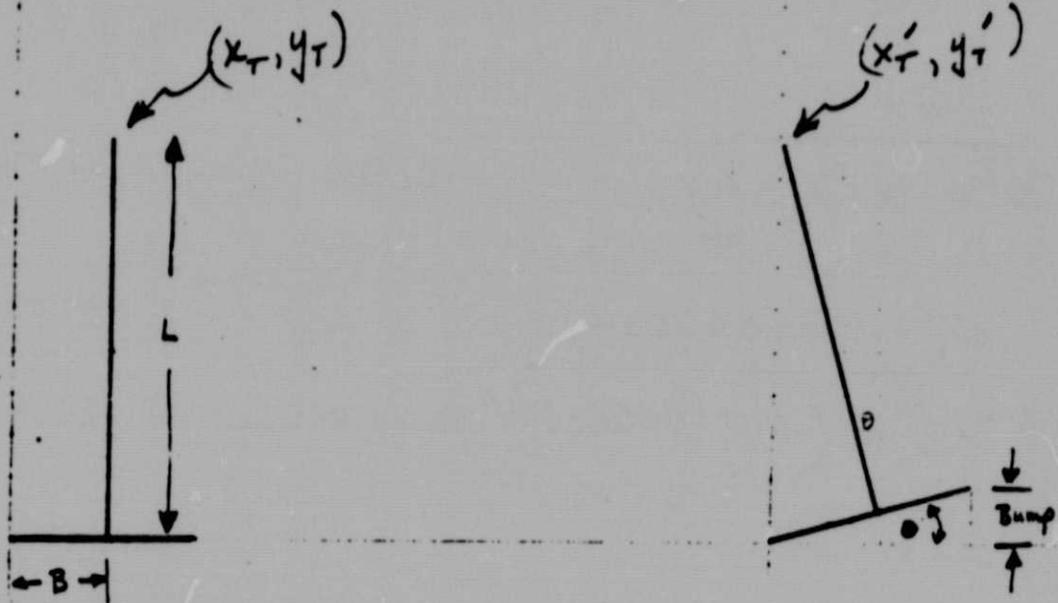
∴ Ratio (V_T) = 1.781382288

should be

$$V_c = V_T = 1$$

error = 78.138%

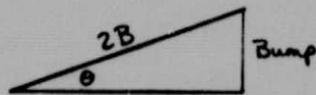
4.2.2 ERROR CALCULATIONS FOR NEW SYSTEM



$$x_T = B$$

$$x'_T = B \cos \theta - L \sin \theta$$

$$e_x = \text{error in } x = B - B \cos \theta + L \sin \theta$$



$$\sin \theta = \frac{Bump}{2B}$$

$$\cos \theta = \sqrt{1 - \frac{Bump^2}{4B^2}}$$

$$e_x = B - B \sqrt{1 - \frac{Bump^2}{4B^2}} + L \frac{Bump}{2B}$$

$$= B - \frac{1}{2} \sqrt{4B^2 - Bump^2} + \frac{L Bump}{2B}$$

lengthen B to b ; keep Bump & L constant

$$\text{new error} = E = .2 e_x$$

$$b - \frac{1}{2} \sqrt{4b^2 - Bump^2} + \frac{L Bump}{2b} = .2 \left[B - \frac{1}{2} \sqrt{4B^2 - Bump^2} + \frac{L Bump}{2B} \right]$$

rd right side = K

$$b - \frac{1}{2} \sqrt{4b^2 - \text{Bump}^2} + \frac{L \text{Bump}}{2b} = K$$

$$\text{where } K = .2 \left[B - \frac{1}{2} \sqrt{4B^2 - \text{Bump}^2} + \frac{L \text{Bump}}{2B} \right]$$

$$\frac{1}{2} \sqrt{4b^2 - \text{Bump}^2} = b + \frac{L \text{Bump}}{2b} - K$$

$$\sqrt{4b^2 - \text{Bump}^2} = \frac{2b^2 + L \text{Bump} - 2bK}{b}$$

$$4b^2 - \text{Bump}^2 = \frac{4b^4 + L^2 \text{Bump}^2 + 4b^2 K^2 + 4b^2 L \text{Bump} - 8b^3 K - 4bLK \text{Bump}}{b^2}$$

$$4b^4 - b^2 \text{Bump}^2 = 4b^4 + L^2 \text{Bump}^2 + 4b^2 K^2 + 4b^2 L \text{Bump} - 8b^3 K - 4bLK \text{Bump}$$

$$8b^3 K - b^2 (\text{Bump}^2 + 4K^2 + 4L \text{Bump}) + 4LK \text{Bump} - L^2 \text{Bump}^2 = 0$$

$$\begin{aligned} \text{Bump} &= .025 \\ L &= 26 \text{ in.} \\ B &= 1.216 \end{aligned}$$

$$\begin{aligned} \text{Bump}^2 &= .000625 \\ L^2 &= 676 \\ B^2 &= 1.478656 \end{aligned}$$

$$K = .2 \left[1.216 - \frac{1}{2} \sqrt{5.913999} + .2672697 \right]$$

$$K = .2 \left[1.216 - 1.2159357 + .2672697 \right]$$

$$K = .0534668$$

$$4K^2 = .0114347$$

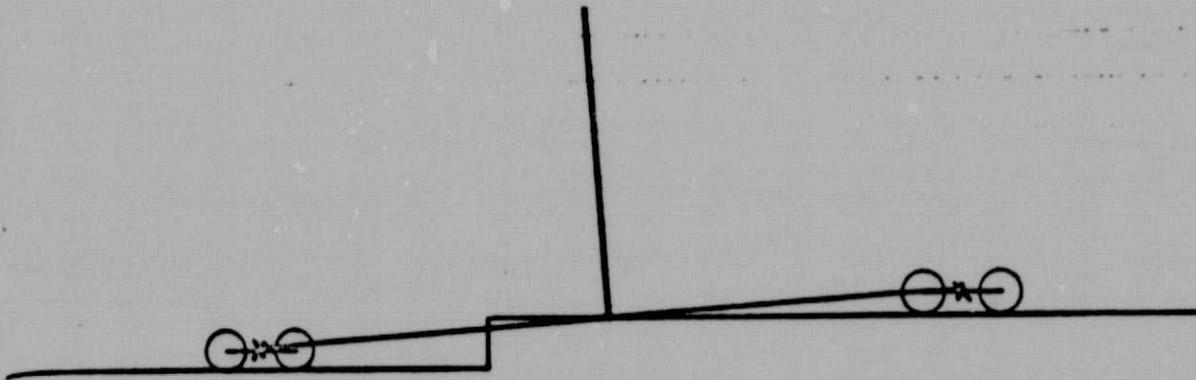
$$.4277344 b^3 - 2.6120597 b^2 + .1390136 b - .4225 = 0$$

left side

$$\begin{aligned} &-1.231937 \\ &-11.56212 \\ &.4282632 \\ &.1586422 \\ &-.575908 \end{aligned}$$

b	left side
6.08	.0000067

$$\frac{6.08}{1.216} = 5$$



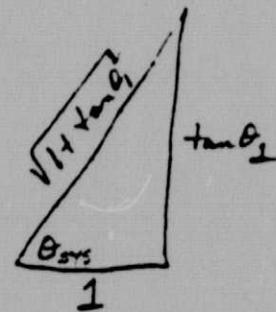
In this situation, everything seems to be OK since the velocity of each end is in the same direction as the wheels. The center of rotation is still at infinity
 \therefore $V/R_1 = 1$ and $V_{SYS} = V_C$

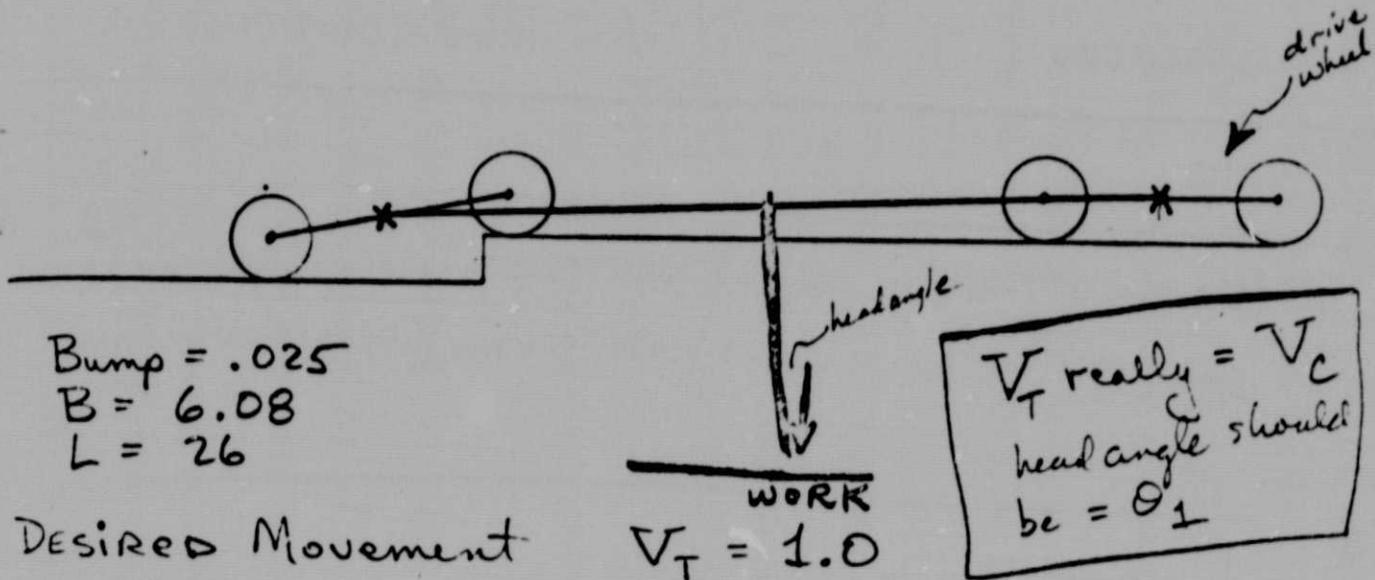
$$\theta_1 = -\theta_2$$

$$\cos^2 \theta_{SYS} = \frac{1}{1 + \left[\frac{-2A \sin \theta_1}{-2A \cos \theta_1} \right]^2}$$

$$= \frac{1}{1 + (\tan \theta_1)^2}$$

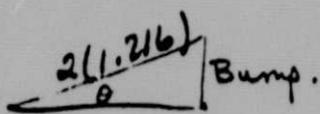
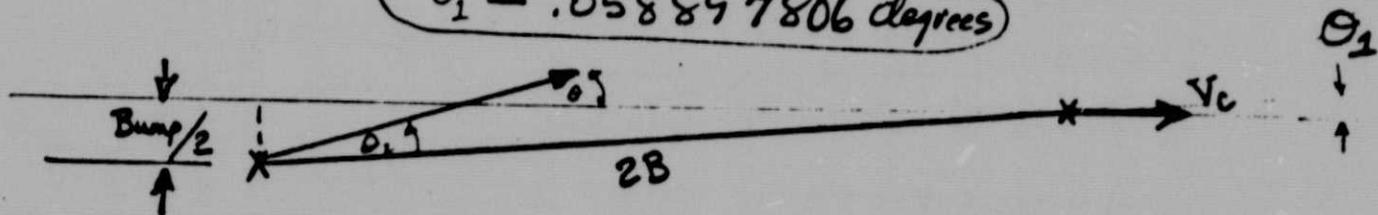
$$\therefore \theta_{SYS} = \theta_1$$





$$\sin \theta_1 = \frac{\text{Bump}/2}{2B} = \frac{\text{Bump}}{4B} = .001027960526$$

$$\theta_1 = .058897806 \text{ degrees}$$



$$\sin \theta = \frac{\text{Bump}}{2(1.216)} = .0102796$$

$$\theta = .5889883681 \text{ degrees}$$

$$\theta_2 = \theta - \theta_1 = .5889883681 - .058897806$$

$$\theta_2 = .5300905621 \text{ degrees}$$

$$\theta = \theta_2 + \theta_1$$

$$\theta_1 = .058897806 \text{ degrees}$$

$$\theta_2 = .9999994716$$

$$\theta_3 = .001027960526$$

$$\theta_2 = .530090562 \text{ degrees}$$

$$\cos \theta_2 = .9999572026$$

$$\theta = \theta_1 + \theta_2 = .588988368 \text{ degrees}$$

$$\cos \theta = .9999471634$$

$$\sin \theta = .0102796052$$

1

$$\theta_{SYS} = \frac{1}{1 + \frac{\left[(6.08)(.0102796052) - 2(6.08)(.001027960526)(.9999572026) \right]^2}{(26)(.0102796052) - 2(6.08)(.9999994716)(.9999572026)}}}$$

1

$$= \frac{1}{1 + \left[\frac{.0634999996 - .0124994647}{.2672677352 - 12.15947316} \right]^2}$$

1

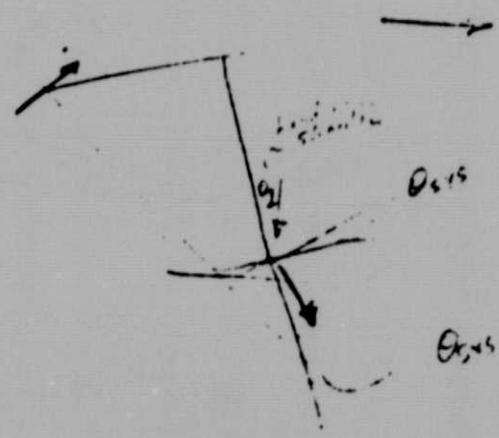
$$1 + \left[\frac{.0500005348}{-11.89220342} \right]^2$$

$$\cos \theta_{SYS} = .9999823223$$

$$\sin \theta_{SYS} = .9999911611$$

$$\theta_{SYS} = .240899994 \text{ degrees}$$

$$\sin \theta_{SYS} = .0042044857$$



head angle error
is $\theta_{SYS} + \theta_1$

$$\text{head angle error} = \theta_{SYS} + \theta_1 = .2997978 \text{ degrees}$$

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$$\frac{R}{R_1} = \frac{2(.9999572026)}{\sqrt{\left[1 + \left(\frac{26}{6.08}\right)^2\right] (.0102796052)^2 + 4(.9999994716)(.9999572026)\left[.9999471634 - \left(\frac{26}{6.08}\right)(.0102796052)\right]}}$$

$$= \frac{2(.9999572026)}{\sqrt{2.038049724 \times 10^{-3} + 3.823787626}}$$

$$= \frac{2(.9999572026)}{\sqrt{3.825835676}}$$

$$= 1.022465869$$

for $V_R = 0$

$$V_c = 1.022465869 \quad V_T = 1.022465869$$

or $L = 13 \text{ in}$

$$\frac{2(.9999572026)}{3.887651435 \times 10^4 + 3.911701493}$$

$$= 1.011104108$$

$$\text{error} = 1.11\%$$

should be

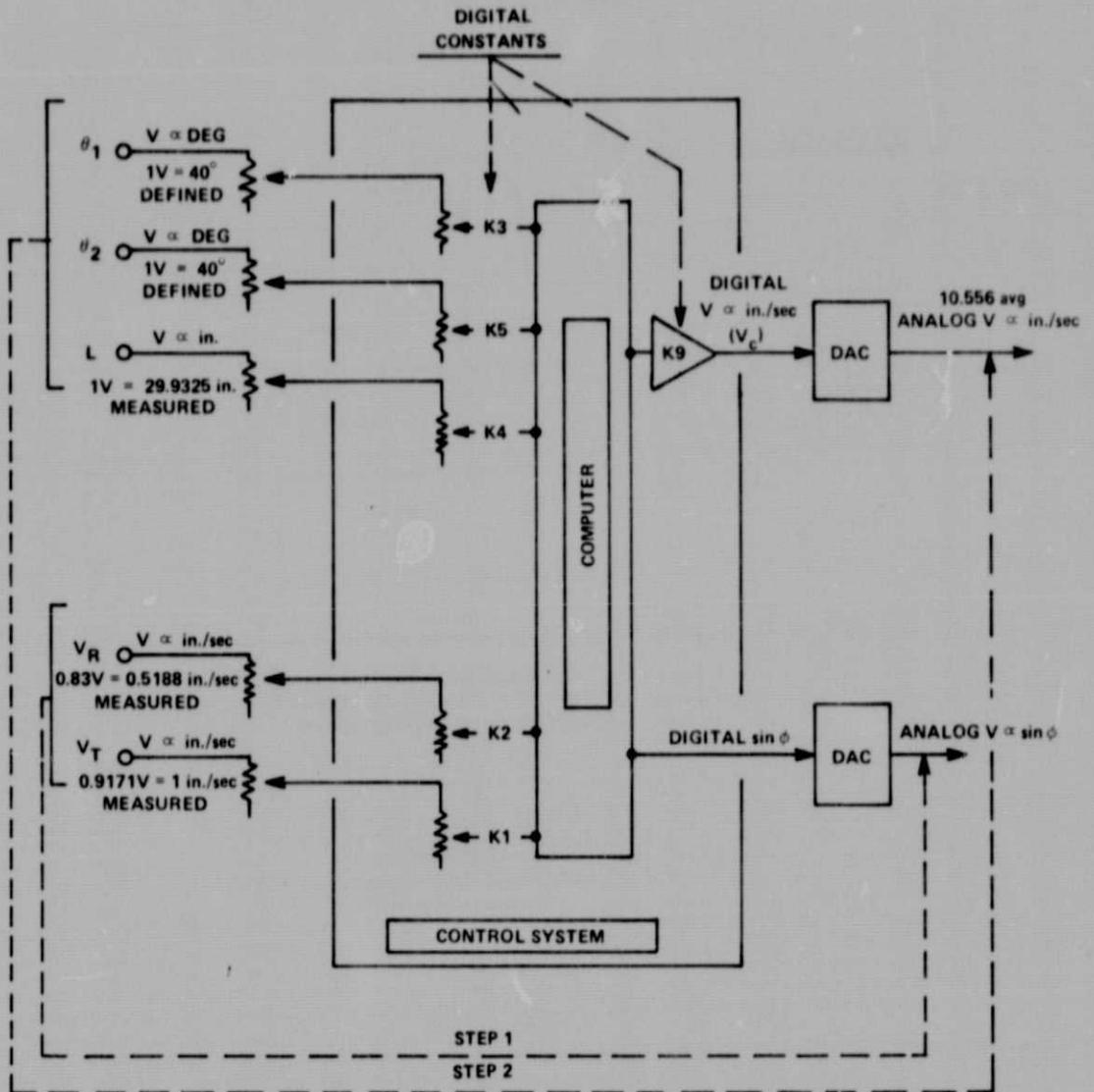
$$V_T : V_c : 10$$

$$\text{Velocity Error} = 2.2466\%$$

APPENDIX B

MARK III WELD SKATE COMPUTER PROGRAM 1002 SCALING FACTORS AND FLOW CHART

SCALING FACTORS FOR PROGRAM 1002 AND MARK III SKATE



DIGITAL CONSTANTS (DECIMAL)

$$K1 = 1.0904 \text{ in./sec/V}$$

$$K2 = 0.6100 \text{ in./sec/V}$$

$$K3 = 40.0 \text{ deg/V}$$

$$K4 = 29.9325 \text{ in./V}$$

$$K5 = 40.0 \text{ deg/V}$$

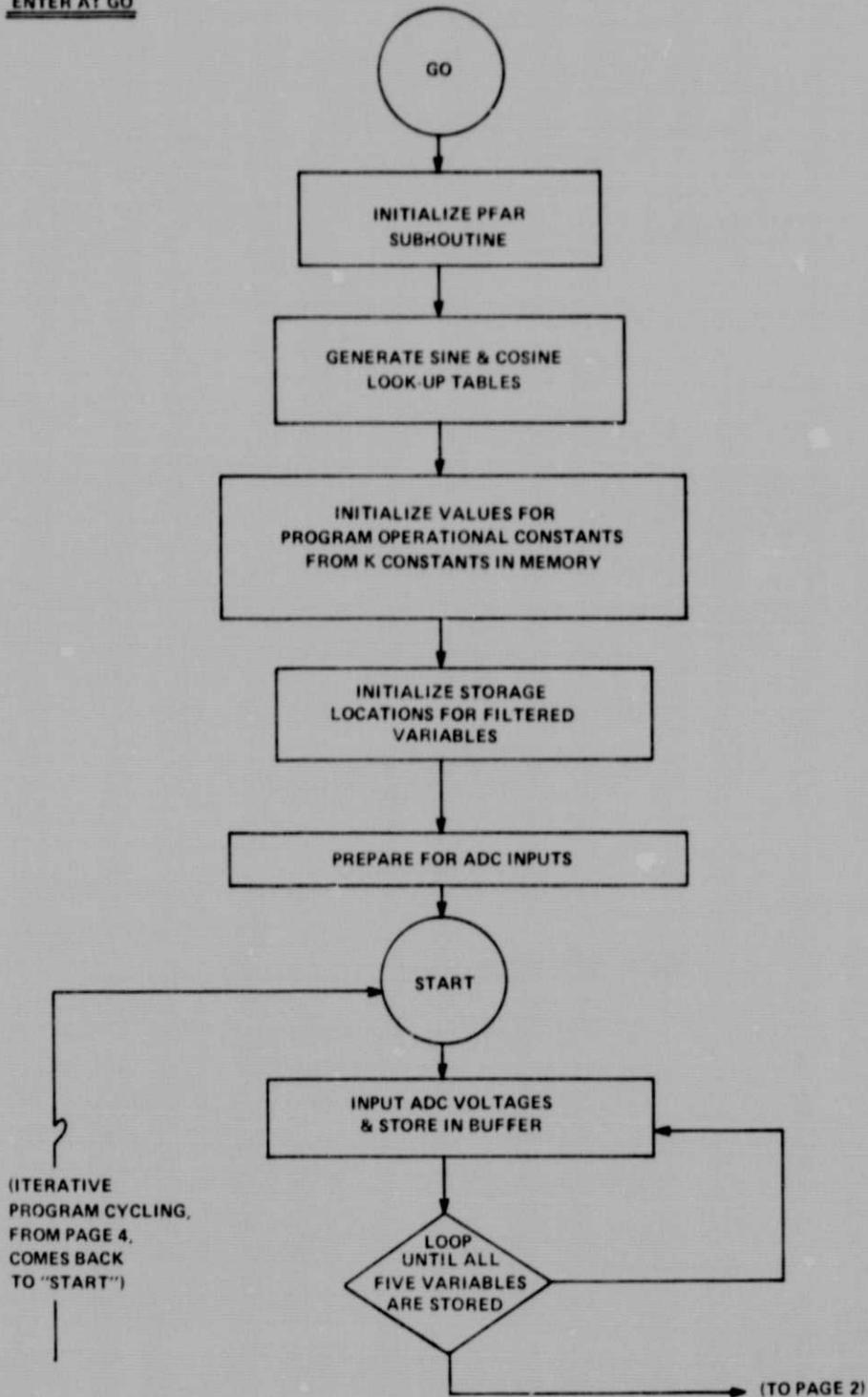
$$K9 = 1.177 \text{ V/in./sec}$$

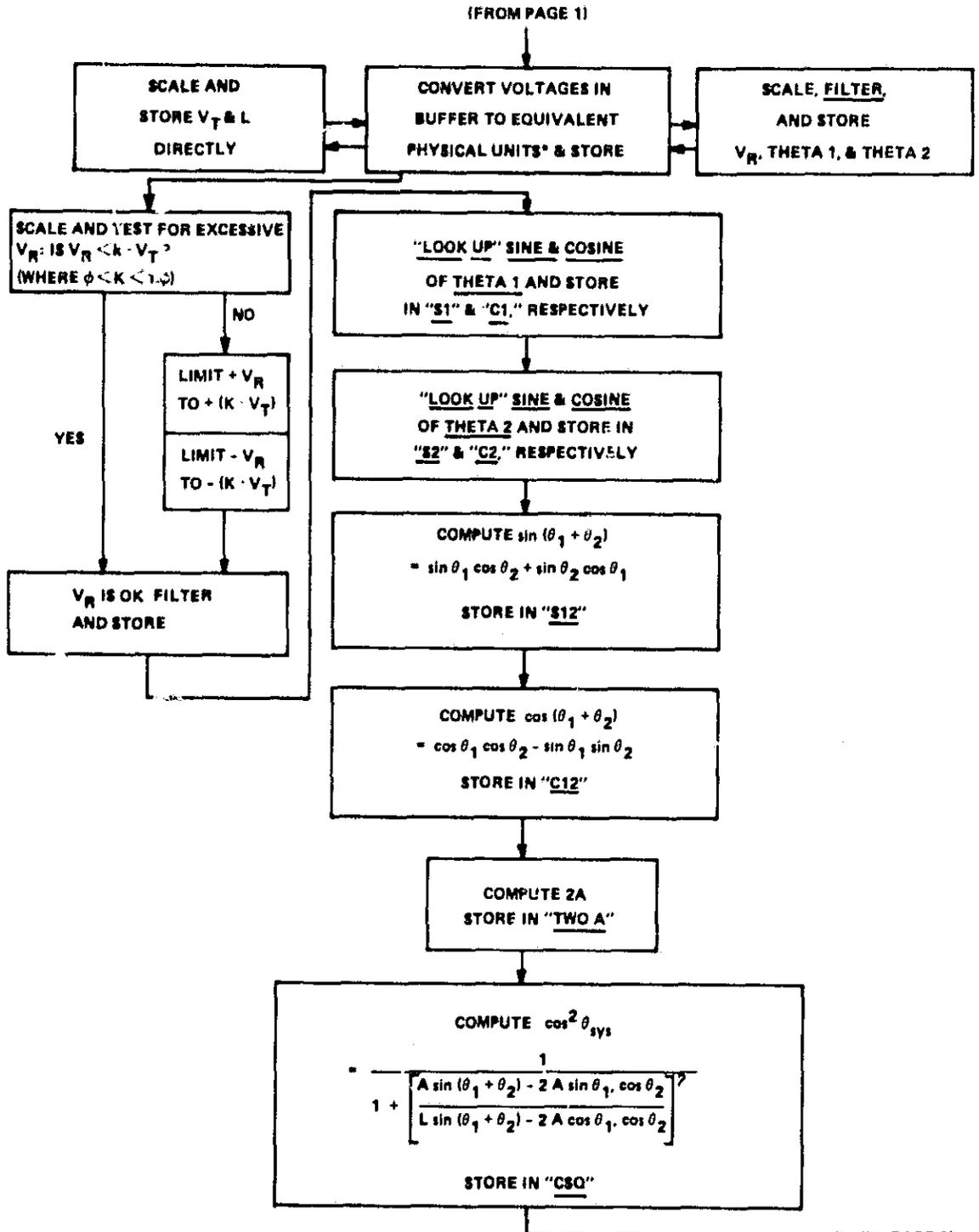
K	OCTAL VALUES	LOCATIONS
	042711	003267
	016402	003270
	047024	003271
	075400	003272
	050000	003273
	000014	003274
	073672	003275
	160412	003276
	050000	003277
	000014	003300
	045523	003307
	174002	003310

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PROGRAM 1002 FLOW CHART

ENTER AT GO

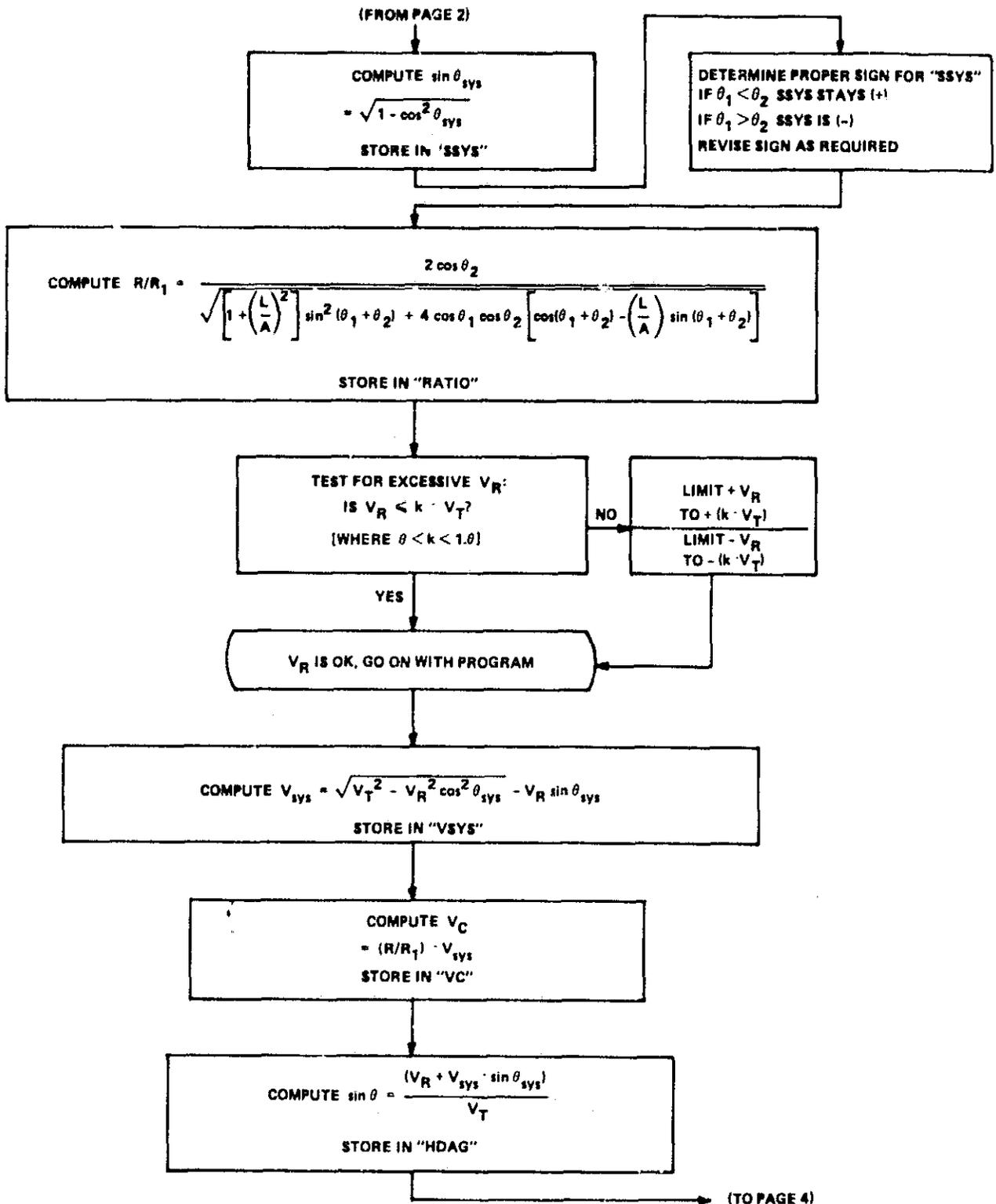




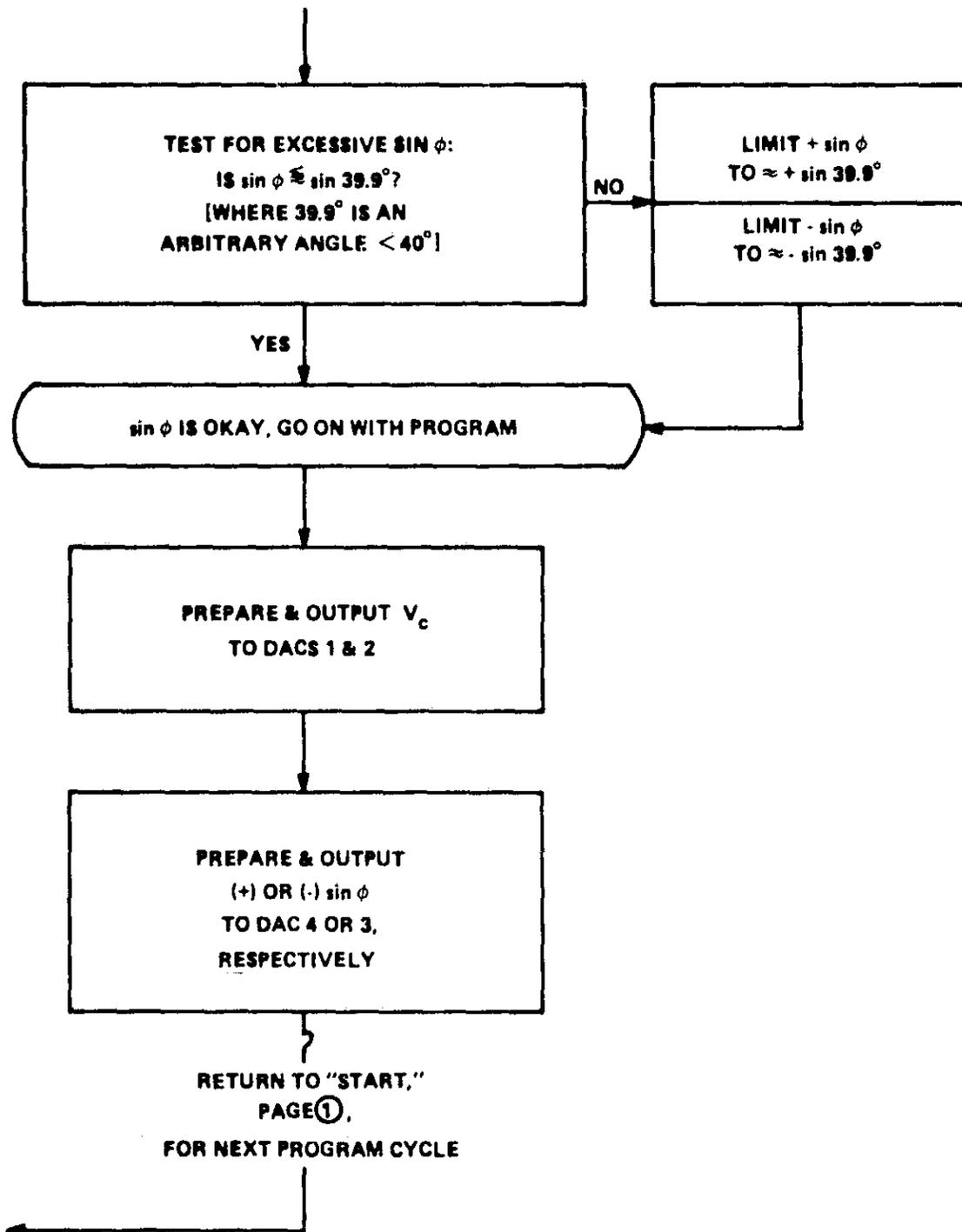
*PHYSICAL UNITS ARE DEGREES, INCHES, & INCHES/SEC.

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APPROVAL

COMPUTERIZED ADAPTIVE CONTROL WELD SKATE WITH CCTV WELD GUIDANCE PROJECT – STATUS REPORT

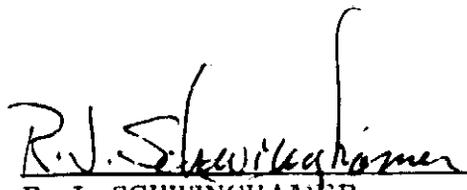
By W. A. Wall

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.



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