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PROCESS DEVELOPMENT FOR AUTOMATED SOLAR CELL
AND MODULE PRODUCTION

Task 4: Automated Array Assembly. Quarterly Report No. 5

By
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PROCESS DEVELOPMENT FOR AUTOMATED SOLAR CELL AND MODULE PRODUCTION

TASK 4: AUTOMATED ARRAY ASSEMBLY

Quarterly Report No. 5

JPL Contract No. 954882

PREPARED BY: JOHN J. HAGERTY

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ABSTRACT

Construction of an automated solar cell layup and interconnect system is now complete. This system incorporates a Unimate 2000 B industrial robot with an end effector consisting of a vacuum pick up and induction heating coil. The robot interfaces with a "smart" cell preparation station which correctly orients the cell, applies solder paste and forms and positions the correct lengths of interconnect lead. The system is controlled and monitored by a TRS-80 micro computer.

The first operational tests of the fully integrated station have been run. These tests proved the soundness of the basic design concept but also pointed to areas in which modifications are necessary. These modifications are nearly complete and the improved parts are being integrated. Development of the controlling computer program is progressing to both reflect these changes and reduce operating time.

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1.0 INTRODUCTION

The objective of this program is to develop techniques for the automated placement and interconnection of solar cells using an industrial robot.

The previous Quarterly Report, dated 15 October 1979, discussed the design chosen to meet this objective and the progress in constructing the actual machine.

The construction and integration of all phases of this automated system are now complete. This includes the mechanical preparation station, the interface electronics package and the robot end effector.

The first tests of the fully integrated system were run and proved the soundness of the basic design. These tests also pointed out areas where modifications were necessary. These modifications have been fabricated and are currently being integrated.

The machine is now considered to be in its final configuration and although the basic design concept has not changed, there have been some subtle modifications. This report, therefore, contains a complete description of both the hardware and sequence of operation of the machine in this final configuration. It also contains the results of the first operational tests showing where improvements were necessary and the changes to make these improvements.

2.0 TECHNICAL DISCUSSION

The following discussion begins with a detailed description of the electronic hardware in the cell preparation station. The mechanical hardware was described in detail in the previous Quarterly Report (15 October 1979) and remains largely unchanged. Any recent changes from this description will be discussed in section 2.3 "Test Results and Modifications". Section 2.2 gives a detailed description of the current operation sequence.

2.1 Electronics Package

The electronics package performs three distinct interfacing functions with the TRS-80; mechanical equipment interface, optical position sensor interface and robot interface. Figure 1 shows the information flow in the preparation station.

It is necessary to convert the parallel 8 bit data and address information from the computer's output buss into discrete on/off commands for each of the devices controlled by the computer. This is accomplished by an Intel 8255 peripheral interface chip designed for this purpose. A second 8255 is used as an input for feedback signals. The 8255's, in turn, interface with the following equipment.

2.1.1 Mechanical Equipment Interface

The on/off commands from the 8255 cannot be connected directly to the solenoid valves and stepper motors as its current capacity is far too low. In order to operate these high current devices, an intermediate driver board must be used. This board contains 22 driver circuits (only 19 are presently used) which use Darlington 2N 6055 power transistors to switch the necessary current on and off. In between each driver and the 8255 is a Monsanto 4N33 Optical Isolator. This device (which is essentially an LED connected to a photo transistor) allows information signals to travel without direct electrical connections. In this way large current surges (such as during solenoid valve operation) are prevented from reaching the 8255 thus avoiding potential damage. For the input 8255, the signals pass through

FIGURE 1
PREPARATION STATION DATA FLOW

a conditioning network consisting of a pair of blocking diodes and fusing resistors. This protects the 8255 in a manner similar to the optical isolators.

2.1.2 Optical Position Sensor Interface

The optical positioning sensor (Figure 6 in Quarterly Report, dated 15 October 1979) is an analog device and its data must be converted to digital form in order to be used by the TRS-80. We are using a National Semiconductor ADC 1210 analog to digital converter for this purpose. However, the output from the sensor is so extremely low that considerable amplification (on the order of 10^6 times) is required. A two stage amplifier using a pair of Motorola MC 1556 op-amps raises the signal to a level detectable by the 1210.

2.1.3 Robot Interface

The Unimate Robot was designed for use in industry where hard-wired limit switches are used to signal the completion of external tasks. Due to this "switch closure" logic, the robot is unable to understand the "binary voltage level" logic used by the electronics package. We are therefore using reed relays, driven by the 8255, to give the robot the "switch closure" it is looking for. This also applies to the Siltec cassette unloader since it also uses "switch closure" to initiate its function.

The robot uses this switch closure two ways: for input and output. When the input or "Wait External" (WX in Figure 1) is programmed into the robot it will wait at that step until it receives a switch closure signifying the completion of the external task. The output or "Operate External" (OX in Figure 1) closes a relay inside the robot presenting a switch closure to whatever external device is being operated.

Being a piece of industrial equipment, the induction heater also uses switch closure to start. As such, it could be operated directly by the TRS-80 via the reed relays. It was decided, however, that since

the robot and heater were bound in such a lock-step relationship (the heater cannot start until the robot has picked up the cell and the robot cannot release the cell until the heater has finished) that they would be considered a single unit. The induction heater is controlled only by the robot's internal program. The "heat-on" duration is controlled by the heater's built-in timer.

2.1.4 Component Layout

The majority of the electronics is placed on the main interface board. This contains the two 8255 peripheral interface chips, the ADC 1210 A to D converter, the reed relays, as well as all of the support electronics and necessary connectors. A second smaller board contains the MC 1556 amplifiers used by the optical positioning sensor. The largest, although electrically simplest board, contains the 2N 6055 high current drivers and optical isolators. It is made of aluminum to provide an adequate heat sink for the drivers. There are two power supplies; one regulated (for the electronics) and one unregulated (to power the solenoids and stepper motors). They are mounted on the equipment shelf next to the Siltec unloader.

2.2 Operation Sequence

This description of the sequence of operations for the preparation station will begin with a discussion of interface network's actions. The reader should realize that when a description says "the computer commands..." or "the valve is commanded ..." that this refers also to the interface network in operation.

2.2.1 Command and Feedback Data Flow (Figure 1).

The system is initialized by having the TRS-80 send out an address on its output buss that the 8255 recognizes as "itself". It is then ready to accept commands from the TRS-80. A command comes in two parts: address and data. The address tells the 8255 which of its 24 output "ports" are to be used. The data says whether the ports chosen by the address will output a high or low (on or off). Each port is connected to a 4N33

optical isolator which electrically separates the 8255 from the power transistors. A "high" output from a 4N33 is enough to cause a power transistor to switch, turning on the current to the chosen device. A "low" output is insufficient and the transistor will switch off, turning off the current.

Each stepper motor requires four driver circuits (hence four optical isolators and four ports on the 8255) and each solenoid valve needs one. Since there are three motors and seven valves, this means a total of 19 drivers, etc. are required. The driver board presently has 22 power transistors on it and some room for expansion. The optical isolator board has 24 circuits available to match the 24 ports on the 8255 although only 22 are currently used.

The feedback from the limit switches and robot OX relays works in a similar manner. The switches and relays present high or low voltage levels (for closed or open contacts respectively) to the input ports of the second 8255. When the TRS-80 interrogates the 8255 with an address, the 8255 can respond with data indicating whether the input ports at that address are high or low.

Data from the optical positioning sensor is processed the same way. The output of the analog to digital converter is connected to 12 of the input ports on the 8255. This, in effect, is a 12 digit binary number representing the analog data from the optical sensor.

2.2.2 Sequence Steps

Following is a step-by-step description of the cell preparation, placement and interconnection cycle. Figure 2 is a time line representation of the process.

The gross steps involved in cell preparation and interconnection are as follows:

- 1) Initialize System
- 2) Dispense Cell

FIGURE 2
CELL PREPARATION ON PLACEMENT CYCLE

- 3) Orient Cell
- 4) Apply Solder Paste to Cell
- 5) Form Interconnect Leads
- 6) Robot Pickup (Preparation Station returns to 2 and repeats cycle).
- 7) Transport and Heat
- 8) Placement and Reflow (Robot returns to 6 and repeats cycle).

A detailed explanation of each of these steps follows.

- 1) Initialize System - This series of commands sets the preparation station to its initial conditions: The vacuum chuck is rotated until the locating pins are opposite the cassette unloader (also called the home position), the moving solder paste dispenser arm is fully retracted, the interconnect ribbon cutter is cycled to trim any excess lead and the Siltec unloader lowers the cassette to the first cell. All valves are commanded to the off position. The robot's cycle must also be started but this is not externally commandable and must be done by the operator.
- 2) Dispense Cell - The cassette unloader is commanded to dispense a cell. The system turns on the air to the chuck and pauses about 2 seconds to allow the cell time to travel down the belts and settle against the locating pins.
- 3) Orient Cell - The cell is now clamped to the chuck's surface by shutting off the air and turning on the vacuum to the chuck. The cell is then rotated 360° in order to scan its entire surface and determine the location of the contact pads. The analysis of optical sensor data is done real time (while the cell is rotating) so that once the scan is completed the chuck can proceed immediately (at its highest speed) to the correct orientation without stopping.

- 4) Apply Solder Paste to Cell - The moving solder paste dispenser arm is extended over the cell at maximum speed until the limit switch is reached. Air is turned on to dispense the paste while the arm retracts. The speed of retraction is calibrated (empirically) to the maximum that the flow rate of the nozzle will allow (see section 2.3.1.4). This continues for a preset distance until the nozzles reach the end of the contact pads. Air to the dispenser is turned off and the arm retracted at maximum speed until the limit switch is reached.
- 5) Form Interconnect Leads - The ribbon is fed at full speed until it is in the correct position for crimping. Air to actuate the crimp die is commanded on for approximately 0.25 seconds and the ribbon is again fed at maximum speed until the crimp clears the paste dispensing nozzles. Air to lead paste dispensers is turned on and the ribbon feed rate slowed to match the flow rate of the nozzle. This continues a preset distance until the tip of the lead reaches the far end of the cell. At that point the ribbon feed is stopped, air to paste dispenser is commanded off and the lead hold downs are activated. The cutter is operated for approximately 0.5 seconds to insure a good clean cut.
- 6) Robot Pickup - The TRS-80 now interrogates the robot to see if it is ready. When it is, a signal is sent that starts the robot's program and it moves into position over the cell. The robot signals the TRS-80 that it is in position and at the same time opens the valve creating a vacuum at the end effector. The computer then turns off the vacuum to the chuck. The lead hold downs are commanded to release and the robot lifts the cell.

- 7) Transport and Heat - After the robot has lifted the cell clear (about 6") it signals such to the TRS-80. The computer then commands the chuck back to the "home" position at top speed and returns to step 2 of this sequence to repeat the cycle. The robot then starts the induction heater which is under the robot's program control.
- 8) Placement and Reflow - The robot transports the cell to its proper position in the panel being assembled. After positioning the cell in place the robot waits for the heating cycle to finish. This cycle is controlled by the induction heater's internal timer. When the timer clocks out, the heater signals the robot which then commands the vacuum off, releasing the cell. The robot then moves back to its wait position in front of the preparation station and signals the TRS-80 that it is ready. It waits until signaled that a cell is ready to be picked up. The robot then repeats the cycle from step 6 of this sequence.

2.3

Test Results and Modifications

The first tests of the fully integrated, automated cell layup system were completed during this period. Following is a detailed discussion of the performance of each of the components along with any problems encountered and the modifications being made to solve those problems.

2.3.1 Preparation Station

2.3.1.1 Vacuum Chuck

The vacuum chuck performed as designed with only two minor problems. When accepting the cell from the Siltec cassette unloader, the chuck (acting as an air table) proved to be quite sensitive to the alignment of the unloader. If the output belts of the unloader were directly perpendicular to the center line of the preparation station, then the cell would contact all four locating pins simultaneously and settle almost immediately. If it were even slightly out of alignment, however, the cell would rock back and forth against the pins for a considerable time (over a second) before settling. The other problem was the high vacuum leakage rate around the retractable locating pins. This tended to overwhelm the vacuum pump leading to a loss of hold down force. The solution to this problem, was to replace the vacuum pump with a commercial eductor or venturi-type vacuum generator. This device uses a compressed air stream to "generate" a high flow-rate, low grade vacuum. This is precisely what is required in our high leakage rate situation. The main drawback is that the hold down force is reduced to 5-10 lbs., although this is sufficient for our purpose. Early tests of the vacuum chuck (see Quarterly Report dated 13 July 1979) showed hold down forces of approximately 70 lbs. but those tests were made before the locating pins were installed. The two big advantages to using the eductor are 1) The vacuum is constant (the vacuum pump would start at very high vacuum levels, approximately 28 inch Hg, but would leak to 0 long before the cell was prepared) and 2) it does away with the external vacuum source requirement simplifying the plumbing and making the station more self sufficient. The only external requirements now are a single AC line plug and one shop air connection.

2.3.1.2 Cell Orientation

The optical orientation system was made fully operational during this period. It now works flawlessly and will consistently orient cells to within $\frac{1}{2}^{\circ}$, which is the positional limit of our turntable.

The crystalline nature of the cell's surface causes secondary reflections at about 45° from the vertical. If the light source is placed at or near this angle it causes a contrast reversal as seen by the sensor, i.e. the metalization appears as a dark pattern against a bright surface. This is easily prevented by careful lamp positioning. An other problem is that there is a 60 Hz "hum" superimposed on all lamps that use line current, even incandescents. Experiments with various lamps showed regular room lamps with low temperature filaments to be the worst. In some cases the amplitude change due to the hum was greater than that we were trying to measure due to the cell rotating. It was found that higher temperature filaments (higher wattage bulbs) suffered less from this problem so we are using a 600 W movie illumination lamp w/reflector as a light source. A better solution for a production machine would be to use a focused DC lamp of much lower wattage as 600 W is five to ten times more power than necessary to make the sensor work.

2.3.1.3 Ribbon Feed and Forming

This mechanism has been essentially trouble-free from the beginning. It will reliably and repeatedly feed, crimp, feed, clamp, cut and release parallel leads which are all uniform. One small problem was that some of the fasteners have worked loose under repeated, high speed operation. A little Lock-Tite solved this.

The only difficulty of note is one of alignment. When feeding the leads across the cell, they had a tendency to wander slightly left or right of the intended path. It was determined that the lead guides were too short. New, longer guides were installed that constrain the leads along their entire travel from the exit of the solder paste bridge to the edge of the vacuum chuck. Even the longer guides, however, did not solve the

the alignment problem. While the #1 (outside) lead lined up over the pads perfectly, the other would be offset about half a lead width. Careful inspection of the ribbon feed and forming mechanism showed that the entire #2 (inside) ribbon path was offset $\approx 0.053''$. Milling of the mounting block was all that was needed to bring both sides into perfect alignment. Now that the ribbons could be fed repeatedly with good accuracy, they once again moved off line when subjected to the crimping and cutting processes. From the supply spool to the cell's surface, the ribbon passes through eight forming and/or guiding mechanisms. Each of these is capable of having an adverse effect on alignment but the crimping die is the only one designed to cause plastic deformations. Upon inspection it was found that one tooth of the #2 crimping die had a slight flat spot causing the outer edge of the crimp to be approximately 1 mil. shallower than the inner edge. This slight difference (undetectable to the eye) was sufficient to splay the lead enough to miss the last contact pad by nearly half an inch. The dies of this prototype machine were made of aluminum for ease of fabrication. A piece of production equipment would have to use steel for durability.

2.3.1.4 Solder Paste Dispensing

There are two separate paste dispensing systems. In one, the dispensing tips are extended out over the cell then retracted while laying down parallel beads solder paste on the cell's two rows of contact pads. In the other, the dispensing tips are fixed and each lays a bead of paste on one of the interconnect ribbons as they pass beneath the dispensing tips. Both dispensers were originally designed with remotely located tips to allow changing of the solder supply tubes without disturbing the alignment of the dispensing tips. It also meant that much less weight need be handled by the moving paste mechanism. The largest problem encountered during these tests came as a result of this remote locating concept.

In order to connect a moving tip to the fixed supply, the tubing has to be very flexible. This flexibility, however, led to a two-fold problem. When pressure was applied to dispense the paste, the tubing would begin to expand radially. This, combined with the surface friction inside

the tube, caused a considerable time lag (4 or 5 seconds) before the paste began dispensing. Conversely, when the pressure was removed, the tubing began to shrink to its original size causing the tip to continue dispensing (at an exponentially decreasing rate) for up to a minute. Although this tube expansion/contraction problem is not insoluble, it was decided that a faster and less expensive solution would be to find ways of attaching the paste supply tubes directly to the dispensing tips.

For the fixed dispenser this means mounting the supply tubes directly over the ribbon path. Also a means of aiming the dispensing tip that allows it to be quickly removed and replaced without loss of alignment is required. The result is shown in Figure 3. The previous nozzle holders were lightweight structures cantilevered out from the cutter block. These have been replaced by a substantial bridge which mounts directly to the station's baseplate. The supply tubes are mounted in clips supported by uprights while the nozzles ride in carriers in the bridge surface. For fast changing of the supply tubes the nozzles can be removed and inserted in the carriers without disturbing the aiming alignment. Both carriers are spring loaded towards the center with adjusting screws on the outside. Once correctly aligned, jam nuts maintain the adjustments. This new mechanism is quite flexible as the paste can be easily aimed to fall anywhere on the ribbon. Also, by varying either the air pressure and/or ribbon feed rate, the .015" bead of solder (other nozzle sizes are .020" and .030") can be made to form dashes (when the solder flow rate is less than ribbon feed rate), solid lines (when the rates are equal) or even swirls (when the flow rate exceeds the feed rate).

The moving paste dispenser also required a redesign. The original design has the dispensing tips mounted on the end of a cantilevered screw drive with a single guide rod on the side. This lightweight mechanism is inadequate for supporting two 30cc paste reservoirs. In addition, it is slow (over 12 sec. cycle time), mechanically inefficient (the losses in the screw drive causes the motor to stall occasionally) and inaccurate due to excessive backlash and bearing slop when fully extended (which caused binding further increasing the load to the motor). It is being replaced by a rack

FIGURE 3
IMPROVED SOLDER PASTE DISPENSER

0350-16939

and pinion drive attached to a commercial ball slide. The ball slide has a much larger load capacity than the screw drive and can operate at much higher speeds. Other advantages to the ball slide are much higher mechanical efficiency (approximately 90% compared to 40%) and much greater tracking accuracy. The total sideways deviation is only 0.005" at full extension compared to more than 0.1" for the screw drive. (Note: contact pad width is 0.1"). For clearance purposes, the supply tubes are laid back at approximately 45° with a short piece of hard pipe between the tube and nozzle. This pipe is very short (≈1") and should have none of the expansion/contraction problems exhibited by the flexible tubing.

2.3.2 Robot End Effector

An end effector was constructed to the final design specifications. i.e. square section copper tubing for the induction coil potted in Silicone RTV with molded-in holes for the vacuum pickup all mounted on a Delrin standoff. This first end effector worked quite well for a "first cut", but did encounter some problems.

The main problem was uneven heating. This is due to the plane of the coil being non-parallel to the plane of the surface of the pottant where the cell is attached during heating. Where the coil was near the surface there was a hot spot. Where the coil was deeper there was a cold spot.

The coil was carefully broken out of the potting and tested "bare". It proved to be quite efficient (bond time ≈3 sec.) with very even heating. This further supported the sensitive nature of coupling (the distance between the coil and workpiece).

With this in mind the coil was re-potted paying very close attention to the coil depth during the molding and machining operations. The coil was left somewhat deeper (about 0.5") than final design specs to leave some margin for experimentation and error. As such the heating time has increased to approximately 5-6 sec., but the heating is now uniform.

There were two other areas where the end effector performed better than expected. The vacuum matrix on the pickup surface did an outstanding job. It never failed to achieve the pickup even with broken or partial cells that exposed more than half the vacuum holes to air. This capability is necessary for rejecting broken cells. It must be remembered also that the interconnect ribbon was between the cell and pickup, further reducing the possibility of a good seal. Additionally, no cells were broken by the robot during handling tests, not even very thin (<10 mil) cells with severe "potato chip" warping (although several were broken by human handlers!).

We attribute this performance to two factors. One is the broad surface of the end effector which supports the entire cell rather than just at one or two points. The other is that we are using an eductor, identical to the one described in Section 2.3.1.1, as a vacuum source. This low grade vacuum is very gentle on the cells and the high air flow rate makes it quite insensitive to exposed air holes.

The other area in which the end effector excelled was heat resistance. We are using General Electric RTV-11 as a potting compound which has maximum temperature limits of 400°F for continuous use and 450°F for short periods. As normal soldering operations take place at 350°F this is sufficient. However, if the cell is broken or has a crack, the induced eddy currents tend to concentrate along the discontinuity causing extreme local heating to temperatures in the neighborhood of 1500°F (based on color).

Even at these temperatures, nearly four times the design maximum for the material, the silicone did not melt, char or decompose in any manner that would damage future cells. The only damage to the end effector's surface was a dry decomposition of the silicone which ranged from a fine powder to pieces the size of eraser crumbs. Although this caused an erosion of the silicone surface, it did not seem to affect the operation of the end effector.

2.3.3 Computer Program

The controlling computer program required that the electro-mechanical portions of the machine be nearly fully developed before the program could be started. The program has, however, made great strides considering that it started from nothing at the beginning of this working period.

The first step was to write a single unifying program that would operate all of the functions of the preparation station, signal the robot and Siltec cassette unloader and do it all with the proper sequence and duration. This first program was written in the BASIC computer language for ease of programming. BASIC, however, is quite slow running for this purpose (the cell orientation alone took over 30 sec.) so the main effort now is to speed up the program. This being done by rewriting some of the subroutines of the program in much faster running assembly language. The first to be rewritten was the cell orientation routine. The assembly language routine has cut the orientation time an order of magnitude to just below 3 seconds.

3.0 CONCLUSIONS

The first tests of the fully integrated preparation station have proven the soundness of the basic design. Several problem areas have been identified and their solutions initiated. These solutions should lead to a smoother running machine capable of repeatedly producing uniform strings of interconnected cells.

4.0 FUTURE WORK

Upon completion of preparation station modifications (now nearly finished) a second round of comprehensive tests will be performed.

The computer program must be updated also to reflect these changes and reduce operating time.

5.0 NEW TECHNOLOGY

New technology was reported in the JPL New Technology report number SC1014 "Special Chuck for Orienting Cells" dated 10 December 1979.