Control Of Critical CPV Panel Assembly Parameters Through Manufacturing Automation

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Abstract. In order to produce a repeatable, high quality and reliable product, there are multiple critical manufacturing parameters to control in CPV assembly. To maintain design performance with a tight distribution, repeatable placement and orientation of optical components must conform to a well understood tolerance budget. Product reliability requires controlled dispense, mixture and cure of adhesives and coatings. Efficient throughput requires rapid-cure adhesives, high-speed robotics and a short quality control loop. The size and weight of panels requires high-payload robotics, and ergonomic lifting devices where human intervention is needed. Product verification requires repeatable and validated testing methods.

Keywords: Adhesives, robotics, manufacturing, high-concentration photovoltaic, HCPV, CPV.
PACS: 42.79.Ek, 88.40.-j, 88.40.F-, 07.07.Tw

INTRODUCTION

SolFocus has designed and deployed an efficient automated panel assembly factory for its second-generation CPV panel, the SF-1100S. From the design onset, the SF-1100S was continually evaluated against manufacturability and reliability requirements. Components and process methodologies were selected accordingly. As a result, every critical aspect of the product is controlled and evaluated through automated assembly automation and test equipment.

Optical alignment requirements within the SF-1100P panel are typically 0.1 mm over the entire panel. To meet this end, all critical alignment tools are stationary and rigid. Only the component being assembled is moved from station-to-station. After initial acquisition, the optical glass assembly remains locked to its tooling until the assembly process is completed. Each station contains datum features to ensure part-to-part repeatability.

Adhesive dispense and cure is controlled through automotive-industry dispensing tools. Temperature, mix ratio, and flow rate are all closely controlled and monitored. The assembly system includes alarms to stop production if any dispense parameters vary outside of accepted norms.

The SF-1100P panel is 1.1 m by 1.4 m with a mass of 32 kg. Therefore, any carrying mechanism which will transfer panels or panel-sized subassemblies should have reach of 2.8 m or more. Payload capability in order to ensure rapid accelerations and motions should be at least 100 kg. As a result, SolFocus selected Kuka KR150L130-2 robots with 2.9 m reach and 130 kg load capacity.

Panels manufacturing efficiency is created through a multi-robot assembly line approach. Each robot serves a specified set of assembly operations within its reach, and where longer adhesive cures are required, extra stations are used. Patterned adhesives are synchronized in flow rate to robotic motion. Multiple end-of-arm tools ensure that minimal time is spent blocked waiting for an available operation.

PANEL DESIGN

The SolFocus SF-1100P panel design concept is shown in Figure 1.

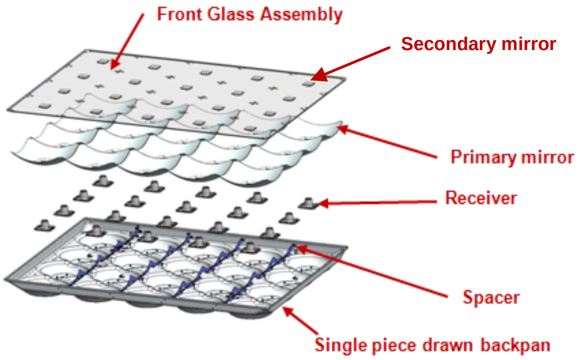

Figure 1. SF-1100P Panel Design

Concentrating on the key manufacturing aspects, the principal alignment tolerances are: secondary mirror to primary mirror, secondary mirror to receiver and front glass to backpan. Each power unit must be aligned with similar tolerance, such that the combined effect results in expected panel performance, and furthermore that the combination of panels aligned in an system result in expected system performance.

We employed a Monte Carlo methodology to create an alignment error budget, which was used in the development of all manufacturing tooling, tracker frame design and system assembly methodologies. Each step from optical alignment of mirrors through to panel assembly into an system is treated as a manufacturing operation, with an allocation of tolerance applied to each component, alignment tool and process, and variation over operating conditions and lifetime. Using the error budget model, the effect any given tolerance or uncertainty can be assessed against product performance.

Assembly Sequence

The SF-1100P panel is assembled by placing secondary mirrors onto the glass sheet, followed by primary mirrors. The receivers are manufactured and in parallel, they are attached to the backpan. The glass subassembly (with attached mirrors) is then placed into the backpan-receiver subassembly. A simplified assembly flow chart and line views are shown in Figures 2 and 3.

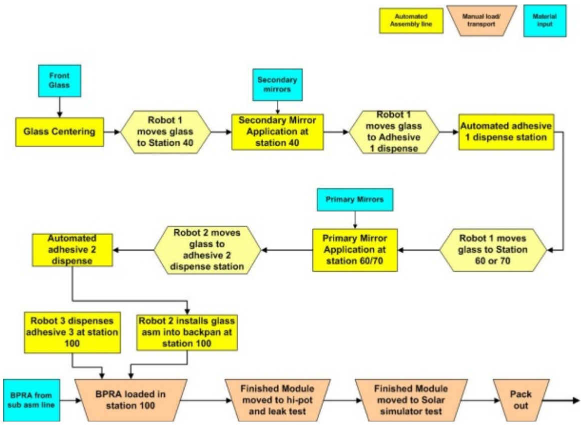

Figure 2. Simplified Assembly Flow Chart

Figure 3. Assembly Line View

Required Tolerances

According to the developed error budget, the alignment ("boresight") error allocated for assembly is 0.1 deg (1 sigma). Secondary mirror to primary mirror alignment determines the pointing direction for the individual power unit. Pointing is a strong function of mirror to mirror alignment. Secondary mirror to receiver alignment also determines the pointing direction for the individual power unit. Pointing is a weaker function of mirror to receiver alignment, front glass to backpan alignment carries two effects: it determines mirror to receiver alignment, and it determines the gap that the perimeter sealant must fill in order to form a water-tight seal.

The effect of pointing variations between individual power units is that they will not each be operating at their peak power efficiency at any given incidence angle of the sun. In the extreme, it would be possible for collection power units to have such variation in their pointing angles that the maximum achievable electrical power output would be at an incidence angle where one power unit would be completely misaligned and therefore contributing negligible output. The panel pointing direction being given as the incidence angle at which panel electrical output power is maximized.

Similarly, the effect of differences in pointing of a complete panel relative to another panel is to reduce the power achieved by the combination, whether they are wired in parallel (due to reduced voltage of a misaligned panel) or series (due to reduced current from a misaligned panel).

An example of the major factors contributing to boresight error is shown in Figure 4, and the individual assembly/tooling contributions to each of these major factors. The allocated error for boresight of 0.1 deg was achieved.

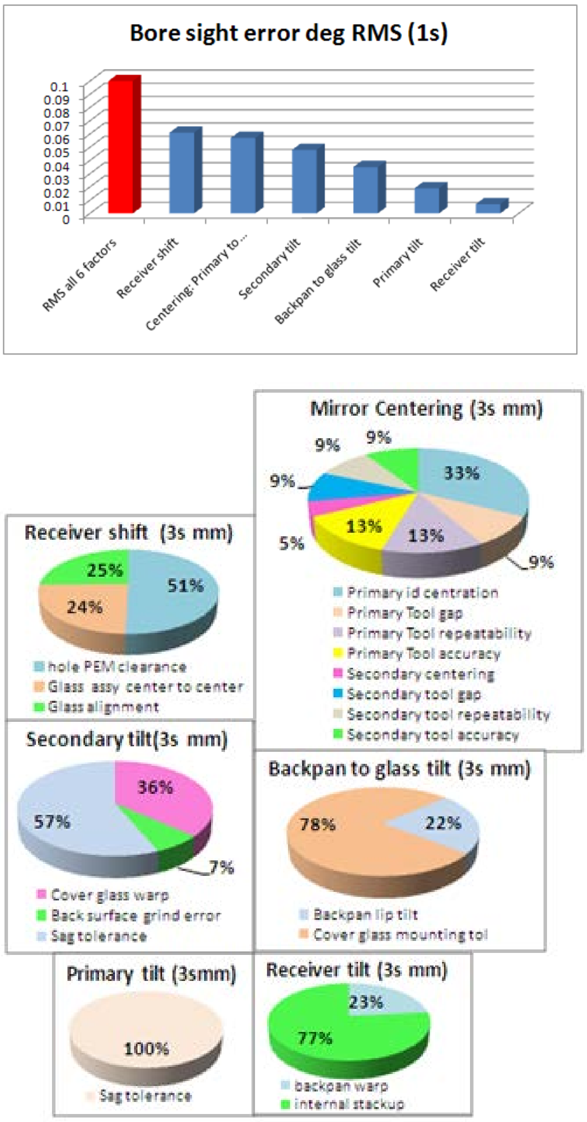

Figure 4. Boresight Alignment Error Analysis

Periodic assembly line tooling calibration is also necessary to maintain these alignments. A recent full calibration was done on the automated assembly line, and showed some minor adjustments were necessary. Figure 5 shows the alignment "stack" before and after the adjustment. The result was an increase in power by 2.9%.

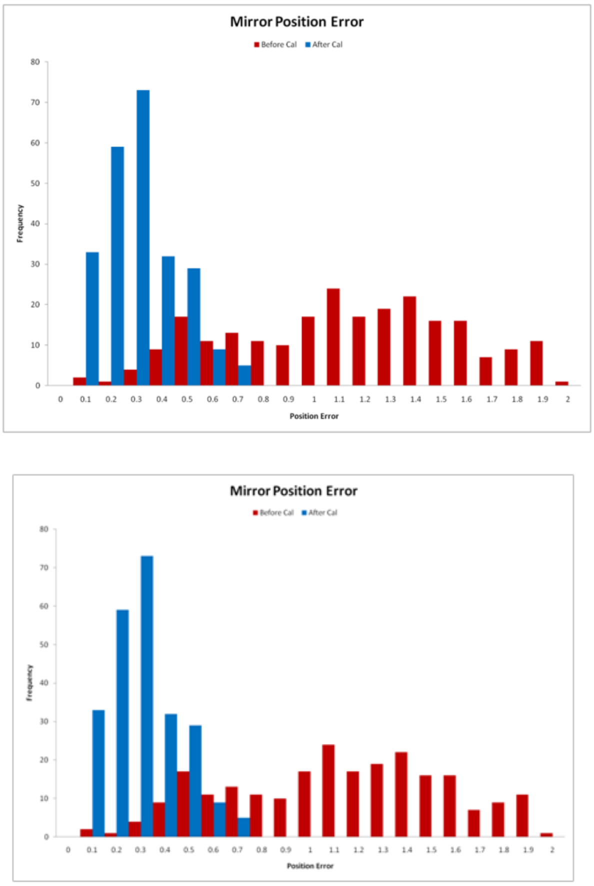

Figure 5. Results of Periodic Recalibration

Joints

The joints examined in this presentation are the primary mirror to front glass, secondary mirror to front glass, and front glass to backpan. The locations of each element are controlled in manufacturing by a combination of robotic tooling and designed reference features on each part. Each assembly joint is provided by a rapid-cure adhesive to allow for manufacturing throughput.

The secondary mirror to front glass joint is formed by a self fixturing bonding agent, which provides nearly instantaneous joint formation. The primary mirror to front glass joint is formed by a rapid-cure liquid adhesive. The tip of the primary mirror is suspended in the adhesive while it cures, so that undesirable glass to glass contact and associated stress-risers is avoided. The front glass to backpan joint is formed by a combination of double sided adhesive tape and a compliant silicone water seal. The tape allows rapid manufacturing while the weather-resistant silicone creates a reliable seal.

MANUFACTURING REQUIREMENTS

Throughput

The panel assembly line is designed for a two minute assembly cycle time. The multiple dispense and attach steps have been broken into an assembly line where each step must complete within the allotted two minutes. Where two minute throughput was not possible, additional stations were used to create an effective two minute throughput.

A systematic approach to cycle time reduction was taken. The first step was to optimize the movement and synchronization of the 3 robots. The process requires complex motions and tool handoffs between 2 robots. A typical path involves positioning a pick up tool within 0.1mm to pick up a ~65kg load (glass plus tool), a 3 dimensional translation/rotation over a span of ~3 meters, and repositioning within 0.1mm in less than 6 seconds. The Kuka robots had to be sized to provide this motion with margin. Using motion modeling software (Arena), the timing for all 3 robots was optimized reducing cycle time by 14 seconds.

The 2nd step was to optimize the adhesive dispense and cure processes for the 3 different systems on the panel line. A precise balance of dispense parameters (flow, temperature, dispense path) and cure time resulted in a total cycle time reduction of another 14 seconds.

The 3rd step was to add/modify the line hardware to further reduce cycle time, however, this required additional capital expenditures, so amortized cost per panel was also part of the optimization model. The additional cost of cycle time reduction had to be offset by lower cost of higher line thruput.

Figure 6 shows a snapshot of the Arena line modeling.

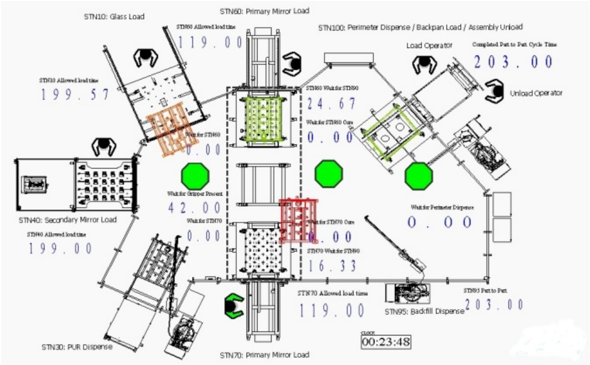

Figure 6. Assembly Line Timing Model

Figure 7 shows the progression of activities and the additional cost per panel required.

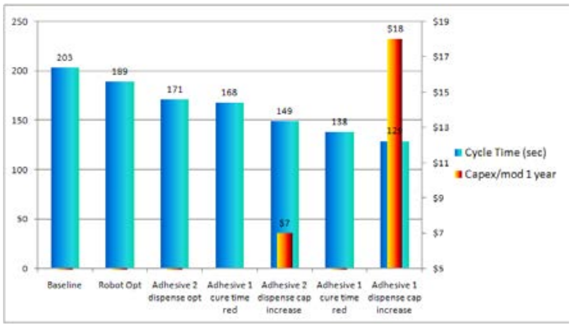

Figure 7. Throughput Optimization Progression

Process Controls

Maintaining tight controls on adhesive dispensing is essential for throughput, optical component alignment and reliability. The throughput model timing depends on the adhesive dispense parameters being within pre-set limits for factors such as dispense amount, time, temperature, viscosity and mix ratio. These parameters are monitored at least daily, more often if an out of control condition arises. Figure 8 shows a snapshot of some of the parameters monitored.

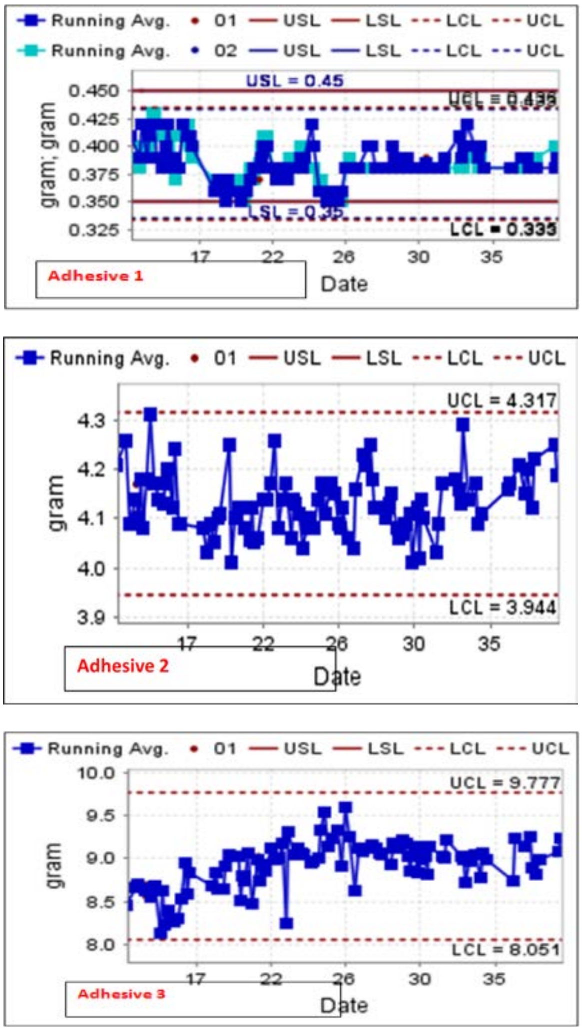

Figure 8. Adhesive Dispense Control Charts

Performance Consistency

The result of assembly line and tooling design, the disciplined monitoring of key process parameters, and the routine calibration of the system is a greater than 98% yield, and consistent power output, as shown in Figure 9.

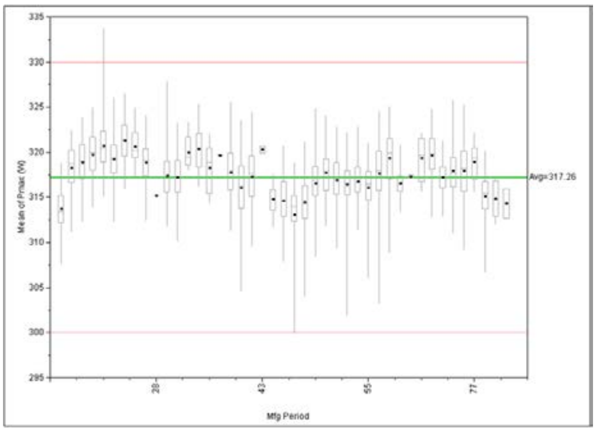

Figure 9. Performance Trend Chart

CONCLUSION

To achieve and maintain the target performance of the SF-1100P panel, the panel, assembly line and tooling were designed to consistently meet the tolerance alignment requirements outlined in this paper. In order to achieve the cost target, the assembly line and process were developed for high throughput, requiring a high degree of automation. This performance is maintained by monitoring key process parameters (adhesive dispense as the illustrated example) and periodic calibration of the tooling.

The result is a high throughput, cost effective manufacturing system, producing panels with consistency and reliability.