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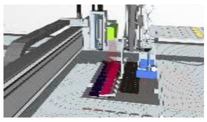

CHANGE INDEX

Issue	Date	Description of Change
1	04.02.2022	Initial issue
2	14.09.2022	Update of copyright mark

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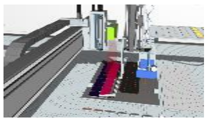


1 INTRODUCTION

1.1 Scope

The scope of this document is to summarize the work on the implementation and validation of the in-situ process monitoring and control for the highly automated space solar generator manufacturing.

1.2 Applicable, Reference, and Normative Documents

Documents identified here below are applicable or reference for the present document and are considered part of it to the extent specified herein.

For dated references, subsequent amendments to or revisions of any of these apply to this document only when incorporated in it by amendment or revision.

For undated applicable documents, the latest edition of the applicable document referred to applies.

1.2.1 Applicable Documents

[AD 01] ESA-GSTP-TECEPG-SOW-014850, Implementation and validation of in-situ process monitoring and control for highly automated space solar generator manufacturing, Appendix 1 to ESA RFQ 3-15995/19/NL/FE Statement of work

[AD 02] GSTPII-STI-OF-043, Issue 2, 23.10.2019

Implementation and Validation of In-Situ Process Monitoring and Control for Highly Automated Space Solar Generator Manufacturing, ESA RFQ 3 – 15995/19/NL/FE, Activity No.: 1000025567

1.2.2 Reference Documents

[RD 01] GSTP-STI-RP-003, Issue 4/draft 13.03.2019

De-Risk Activity Study Report

[RD 02] GSTP2-STI-TN-0002 D1 Inspection Head Technical Description and Operation Manual, Issue 4 Draft

[RD 03] GSTP2-STI-TN-0003 D2 Inspection Head DAQ Software Technical Description and Validation Procedure, Issue 2 Draft

[RD 04] GSTP2-STI-TN-0014 D5 Inspection Head Management Software Technical Description and Validation Procedure

[RD 05] GSTP2-STI-TN-0013, D4 Preliminary Catalogue of ELM and PL Defects, Issue 1

[RD 06] GSTP2-STI-PL-0009 MAIT Plan, Issue 1

[RD 07] GSTPII-STI-TN-0003 D3 Inspection Head DAQ Software Validation Report, Issue 2

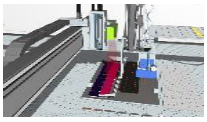
[RD 08] GSTP2-STI-TN-0015
D6 Management Software Validation Report and User Manual, Issue 1

[RD 09] GTSP2-STI-TN-0016, D7 SCA Repair Process Procedure, Issue 1

[RD 10] GSTP2-STI-TN-0017, D10 Solar cell Coupon(s) fatigue life test reports, Issue 1

[RD 11] GSTP2-STI-TN- 0019, D11Catalogue of ELM and PL Defects, Issue 2

1.2.3 Normative Documents



2 INTRODUCTION

The design, building and testing of space solar cells, is one of the core business of STI. At the beginning, STI used external service providers for the laydown of solar cells on the substrates. Starting from 2018, STI applied its own cell laydown process, which had been developed since 2015, mainly with own funding and with support from ESA and DLR for partial aspects.

Due to its innovative laydown process, SpaceTech has drastically increased its throughput for solar generators and has successfully entered into series production. Furthermore, SpaceTech is extending its capacities with a new fully automated PVA laydown production line. An automated process serves both, a demand of cost reductions in volume manufacturing of hundreds or thousands of individual, identical satellites (OneWeb Gen1, Telesat LEO, Starlink, Kuiper) as well as highly reliable modules for most sensitive science missions of multinational institutions (e.g. ESA Copernicus).

Regarding constellations, the recurring cost and production time of an individual satellite is the key driving factor for the viability of the business case. Currently, solar arrays are major schedule and cost factors for the satellites (~ 10 % - 20 % of total recurring satellite cost).

An automated process increases not only throughput but yield of production, too. This is due to tighter control and higher repeatability of the process, associated with lower risk of cell damage within production.

The activity “implementation and validation of in-situ process monitoring and control for highly automated space solar generator manufacturing” is part of this strategy and dedicated to enable an automated process for the manufacturing of photovoltaic assemblies. It is part of ESAs General Support Technology Programme (GSTP) with Kick-off in January 2020.

In the first phase of the project, a technical inspection head, that measures the PVA hardware at each productions step, has been implemented. The analysis of multispectral 2D and 3D data from image capturing devices is at the core of the development. Dedicated software, that analyses these measurements, is monitoring the PVA laydown process. It is signalling if non-conformities are occurring and is guiding the operator of STI’s production line through manufacturing. Software and hardware, both have been disseminated speedily from development to the actual production for fast feedback and validation.

To date, the automated in-situ process monitoring is

- monitoring the automated process, by checking for violation of process parameters
- providing data for the automated process to work, e.g. by supplying movement commands
- monitoring the integrity of parts and sub-assemblies of SCA-S
- providing quick and easy to use tools for verifying newly developed manufacturing process.

3 SUMMARY OF INLINE MONITORING TASKS

The goal of the current activity is to monitor the space solar generator manufacturing and enable its automation with a verified process. This includes the following main tasks:

- Implement sensor and develop appropriate software
- Software verification with implemented automated reporting and pass fail criteria
- Manufacture and testing of DVT Coupon for process verification

For those tasks, a dedicated software has been generated. It features a graphical user interface that guides through the entire manufacturing process. At the end, a final PVA laydown report is generated. It includes data and derived visualization, to document the manufacturing process. The developed key measurement tasks and respective visualization of the results, are presented in the following sections.

3.1 3D Analysis

The used 3D imaging system is implemented in line scanning modus. Output of the device consists of fully extrinsic and intrinsic calibrated images. Hence, distances and height measured in the image, correspond to real world distances and images. A typical scan duration for a string of solar cell assemblies of 1 m length, lasts 25s.

3.2 Substrate Flatness Measurement and Acceptance

The measurement of the planarity of the CFRP substrate is part of the incoming inspection of the panel. It is part of the 3D analysis and it is measured for several reasons. First, to ensure peak-valley difference within a SCA and a SCA-S are in acceptable regime, second, check for dents/damages in the substrate.

An exemplary result from the DVT Coupon is given in the figure below. The scan of the entire panel is performed fully automated. Resulting images are stitched together from several scans, centred around the position of the later SCA-S.

Key results are:

- Lateral resolution < 50 µm
- Height resolution < 10 µm
- Full automation
- Image processing including, calibration, filtering and stitching
- Automated reporting with pass/fail notification

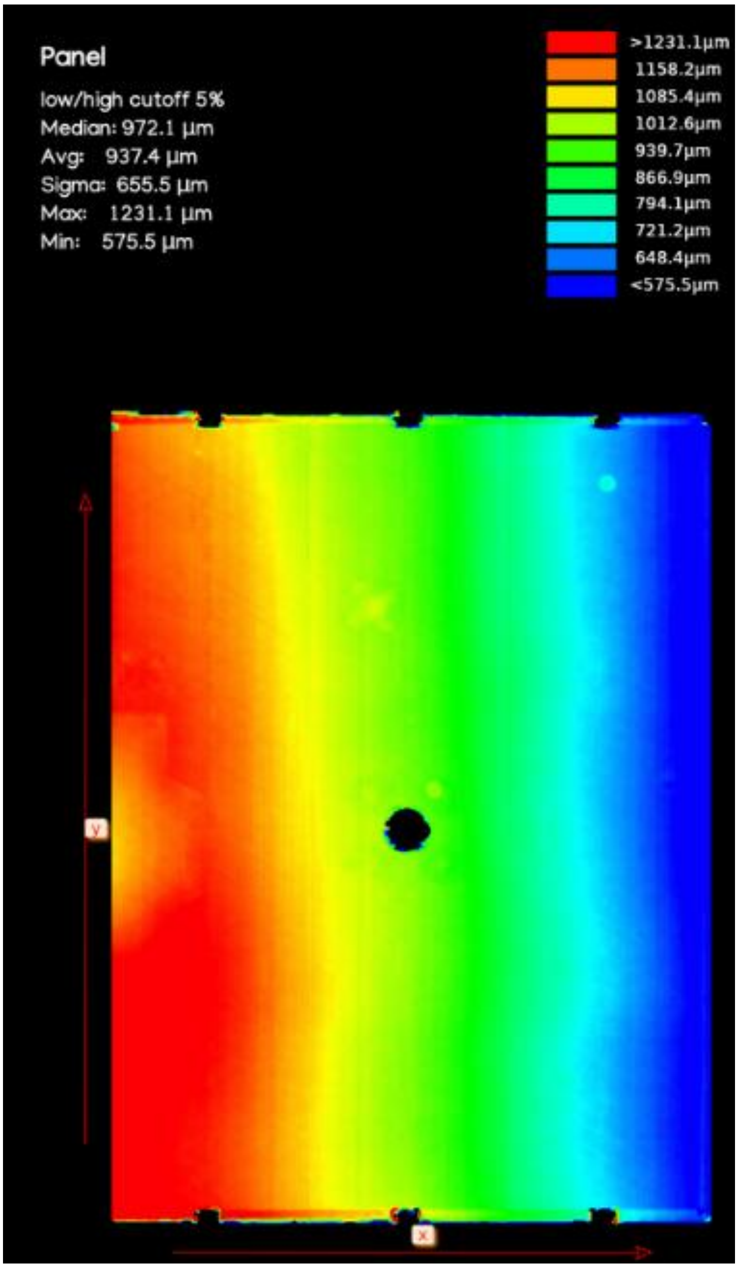


Figure 1 Result of the CFRP panel flatness measurement of the DVT Coupon

3.3 Adhesive Gap between Solar Cell and Substrate

The adhesive gap is one of the key acceptance criteria of a solar panel. It ensures, that the thermal and mechanical contact between panel and solar cells is in the optimal range. The process parameters regarding bonding of the cell to substrate have been verified by dedicated pull tests and x-ray imaging of the panel. The sensitivity of the measurement is illustrated with visualization of the analysis in Figure 2. A kinked interconnect slightly increases the adhesive gap between solar cell and panel. In consequence an automated alarm is triggered.

Summary of key improvements

- Height resolution < 10 µm, lateral resolution < 50 µm
- Assessment of area of glued surface
- Implementation of process windows with pass/fail notification
- Automated measurement and reporting

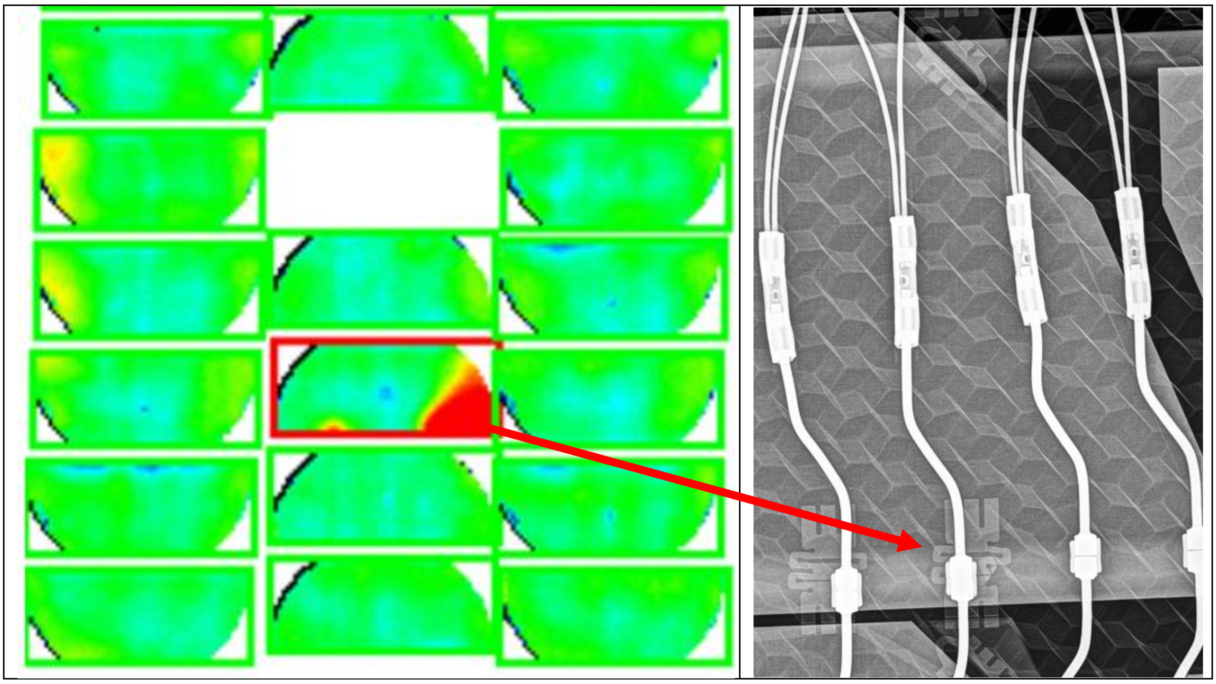
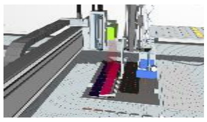


Figure 2 Demonstration of the sensitivity of the adhesive gap measurement. Left: visualization of the adhesive gap measurement. An alarm is triggered. Right: x-ray image of the marked cell. Root cause of the elevated adhesive gap is found to be a kinked interconnect.



3.4 2D Analysis

For even faster computation, some inline monitoring tasks are conducted in 2D. This includes the positioning of the solar cells and its components as well, as the cell to cell distances.

3.5 Alignment of the Solar Cells

The *alignment* feature is used on multiple occasions. It analyses the position of the solar cells with respect to the design. First, it is part of the incoming inspection of a string of solar cells. Its purpose is to check if the criteria of minimal specified cell distances (in all directions), projected on the panel, can be met. In a next step, the output of the alignment procedure is used, to calculate movement commands for the laydown. Finally, the feature is applied, to calculate the ESD distances for all solar cells on the panel and compare results with the given process window.

Main achievements during the activity:

- Automated measurements
- Real time feedback (processing time of 5 sec)
- High precision with respect to global coordinates (50 µm)
- Generation of calibrated movement commands over entire axis travel range
- Shape matching working on all type of cells (DXF drawing input)
- Automated calculation of ESD gap after laydown.

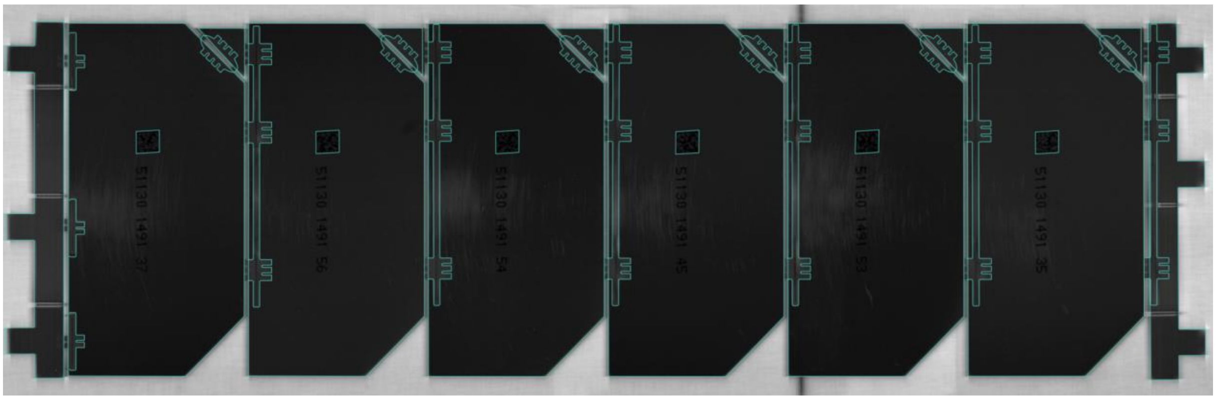
Figure 3 ESD gap measurement of DVT Coupon

3.6 Presence Check of Solar Cell Components

On the rear side, most of the components of the SCA-S are accessible. This comprises the interconnects, the busbars, the diodes and diode interconnects. Presence and position checking of those components was successfully developed and demonstrated in the current activity. The data code contains a unique identifier number. This is read and processed as well, increasing traceability of the single SCAs.

Key achievements are:

- Detection of components
- Position check of the components according to input drawings
- Pass/fail criteria based on presence and position of components.



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Cells  ID-06, 51130 1491 35

Presence inspection
  Component       |          Diode |  Diode_Interconnect |      Interconnect |
  Result          |            1.0 |                 1.0 |               1.0 |
  Score           |           0.84 |                0.90 |              0.88 |
  Delta Position  |          0.417 |               0.178 |             0.208 |

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Presence inspection for bottom and top of string

  Component      |      Busbar_Bottom |      Busbar_Top |       Interconnect |
  Result         |                1.0 |             1.0 |            1.0 |
  Score          |               0.96 |            0.95 |           0.91 |
  Delta Position |              0.522 |           0.606 |          0.695 |

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String summary:

Overall string result: 1.0
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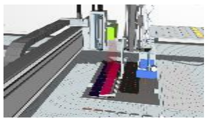
Figure 4 Presence check of components. The SCA-S is searched for its constituents and for the unique identifier. The software performs presence and position checking of the parts



3.7 High Speed Luminescence Measurement of Solar Cells

Electro- and photoluminescence is integrated within STI's SCA inspection process. Recognizing defective solar cells before laydown, is crucial to reach a high yield in manufacturing and prevent costly and risky repair process. In addition, it is a valuable monitoring tool in the process development, where poor setting of parameter or tools, manifest in damage of the cell.

Within the activity, photoluminescence and electroluminescence imaging on all three junctions are successfully demonstrated. Furthermore, luminescence images of most common cell types are post processed automatically and a data collection of defects, detected within the production of solar generators, has been established. It shall serve as starting point for AI based defect detection. The luminescence measurement on top and middle junction is implemented at scanning speeds > 8 m/min.

Key achievements are:

- Implementation of high resolution electroluminescence and photoluminescence imaging of top, middle and bottom junction

- Automated defect detection

- Defect catalogue of STIs' defects, detected by luminescence measurements.

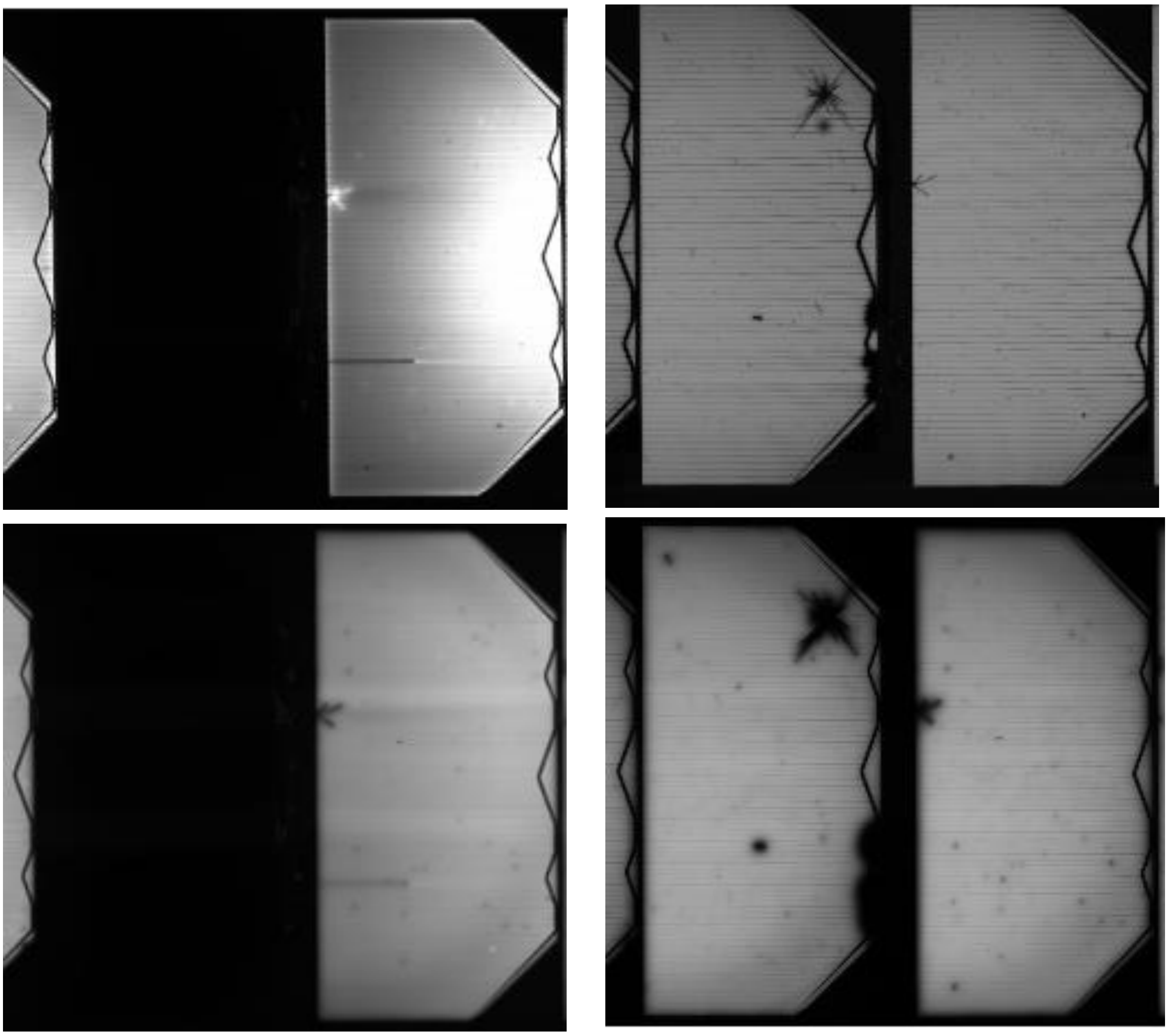
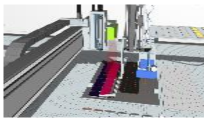


Figure 5 Comparison of electro- and photoluminescence images. Left column, electroluminescence of top and middle junction. Right column, photoluminescence of top and middle junction. Cells not electrically connected, are only visible in photoluminescence.



4 CONCLUSION

At the proposal stage of the current activity, several key requirements, regarding analysis output and scanning speeds have been established. All of them were successfully tested and implemented within the current activity. The developed software comes with a graphical user interface and guides the operator through the process of automated PVA laydown on SpaceTech's PVA pilot line. For the operator, no detailed software engineering knowledge is required. Furthermore, key process parameter are constantly monitored and non-conformances, are signalized. This includes monitoring of relevant parameter during manufacturing:

- peak-valley height of panel
- adhesion of solar cells on panel
- ESD distances of solar cells
- position of constituents of solar cell assembly
- electrical health of solar cell

Finally, the novel process was used to manufacture a dedicated DVT coupon. The Coupon successfully completed a test campaign including environmental and performance testing, whilst closely monitoring its electrical and mechanical health.

The findings and software of the activity are currently implemented in STI's new PVA Assembly Line, to be completed in Q1 2022. With this new production line, SpaceTech GmbH is further increasing the depth of automation in manufacturing, together with increasing its production output of solar panels with sizes up to 4 x 2.5 m.