A Systems Engineering Architecture for Robotic Microtarget Production

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Introduction

The Target Array Assembly System (TAAS) is a robotic system that is being developed by the Target Fabrication Group of the Central Laser Facility to autonomously assemble microtarget arrays. The project is being developed to supply the future target demands of the Extreme Photonics Applications Centre (EPAC) facility which will be operational in a few years.

EPAC will house a petawatt-class laser that can shoot laser pulses 10 times a second (10 Hz) which is a major increase in shot repetition rate compared to the current Gemini Laser which delivers one shot every 20 seconds (0.05 Hz). The Target Fabrication Group will supply microtargets for the new EPAC facility when it is operational. In order to prepare for the increase in shot rate the target production rate will need to have a similar increase. Currently all targets made by the group are assembled by hand but a single target array (of 60 microtargets) can take at least two hours for the assembly step [1]. Clearly the manual assembly strategy for target arrays will introduce a bottleneck in the supply of microtarget arrays for EPAC. The assembly process for these target arrays involves highly repetitive tasks that can be performed with the help of robots. Consequently the Target Fabrication Group has initiated a programme of using robots for the automated assembly of microtarget arrays.

For continuous development of the TAAS it is imperative to take a Systems Engineering approach. The approach provides a systemic understanding of the project and hence identifies the main objectives and requirements that can later be verified. A waterfall model of project management has been chosen (given the overall project structure of successive one-year placement student working on it). Work includes building an understanding of the objective(s) and narrowing down requirements followed by the integration, testing, and verification of the requirements. This report outlines the main objective and requirements for the first TAAS prototype. From the design, integration and testing of the prototype, the Group will gain a deeper understanding of the assembly process and the upgrades required to move up in Technology Readiness Level (TRL) [2].

The TAAS will continue its yearly development cycle to support EPAC target needs and furthering research into the robotic assembly of complex 3D microtargets.

Objective

The main objective of the TAAS is to utilise and integrate a six-axis industrial robot arm with a Cartesian glue dispensing robot to automatically assemble target arrays populated with thin foil microtargets. The requirements listed in the next section are used to specify a system and architecture to meet the objective.

Main Requirements

The requirements discussed below are divided into Functional Requirements (FR) in Table 1, Performance Requirements (PF) in Table 2, Design Requirements (DR) in Table 3, and Operational Requirements (OR) in Table 4. All the requirements have an ID assigned to them.

ID	Functional requirement
FR1	The robot arm shall be able to pick up targets
FR2	The robot arm shall be able to place targets above known locations
FR3	The robot arm shall pick up targets using a pneumatic vacuum suction device
FR4	The pneumatic suction device shall be able to detect successful pick-up of targets
FR5	The pneumatic suction device shall be able to clear its nozzle to eject stuck target foils.
FR6	The robot shall be able to reach the pick-up tray and glue dispenser tray
FR7	The TAAS shall be able to terminate its operation if an emergency stop button is pushed
FR8	The TAAS shall be able to terminate its operation if a safety door interlock has been triggered
FR9	The glue dispensing robot shall be able to dispense lines and dots of glue
FR10	The glue dispensing machine shall be able to cure the adhesive

Table 1: Functional requirements: These requirements outline the basic functions of the TAAS

ID	Performance requirement
PR1	The robot arm shall be able to pick up targets with a repeatability of 50 µm
PR2	The robot arm shall be able to place targets above known locations with a repeatability of 80 µm
PR3	The robot arm shall pick up targets using a pneumatic vacuum suction device producing at least 15 kPa of vacuum pressure
PR4	The pneumatic suction device shall be able to detect successful pick-up of targets within a range of 15 kPa and 35 kPa.
PR5	The pneumatic suction device shall be able to clear its nozzle to eject stuck target foils by ejecting at least 10 kPa of compressed air
PR6	The glue dispensing robot tray and the pick-up tray need to be within 400 mm radius of the robot arm
PR7	The glue dispensing robot shall be able to dispense lines of glue with a bead width of up to 500 µm
PR8	The glue dispensing machine shall be able to cure the adhesive by switching on the UV lamp for at least 10 seconds to begin the UV curing process
PR9	The TAAS shall be able to complete the assembly of a single microtarget array in under 15 minutes

Table 2: Performance requirements: These outline the performance requirements for the functions providing a metric on how the latter are met

ID	Design requirement
DR1	The robot arm, glue dispensing robot and peripheral devices should be able to fit within the safety enclosure
DR2	The digital input/output (IO) signals between devices should be via relays or opto-isolators
DR3	The Programmable Logic Controller should have an RS232 communication module attached, to communicate with the robot arm controller

Table 3 Design requirements: These requirements outline the design of TAAS to meet the functional requirements

ID	Operational requirement
OR1	The TAAS shall be able to terminate the process if an emergency stop button is pushed
OR2	The TAAS shall be able to terminate the process if a safety interlock has been triggered
OR3	Terminating the process shall stop the robot arm
OR4	Terminating the process shall stop the glue dispensing robot and the disarm the UV lamp
OR5	The TAAS shall be able to run all steps of the assembly process autonomously
OR6	The TAAS shall have a Human Machine Interface (HMI)
OR7	The TAAS shall have a visual indication of the state of operation at all times
OR8	TAAS software shall be maintainable by the CLF Electrical Group

Table 4: Operational requirements: These outline the requirements to make the TAAS operational

TAAS Prototype

From the requirement tables, the necessary hardware was identified and purchased including a Siemens PLC and a Mitsubishi HMI for industrial standardisation and future-proofing. Figure 1 shows the final version of the prototype which includes the following parts:

- A: Pneumatic suction device
- B: The robot arm
- C: Human Machine Interface (HMI)
- D: Pick-up Tray
- E: UV curing station and UV lamp
- F: The Cartesian glue dispensing robot
- G: Programmable Logic controller (PLC)

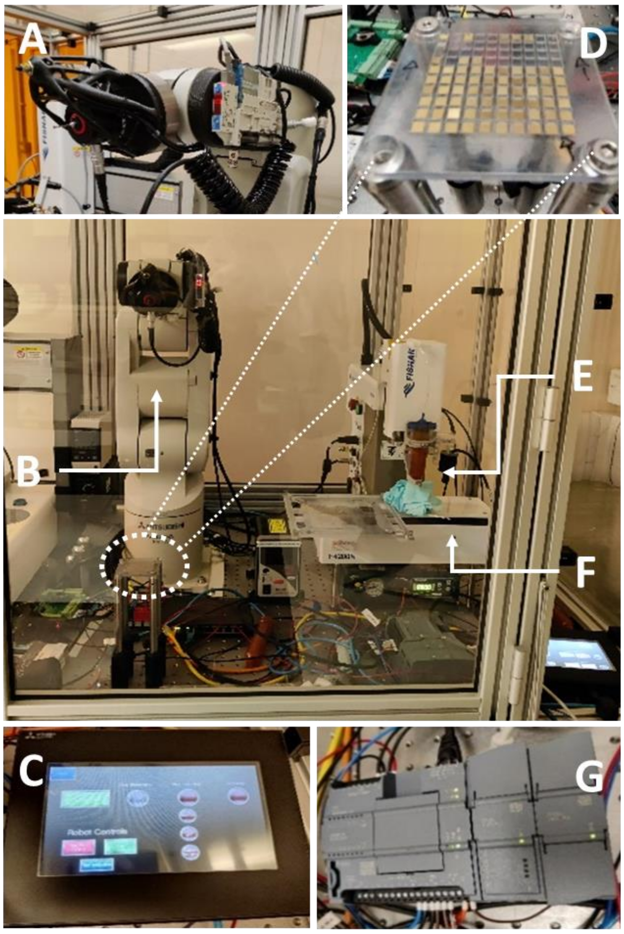

Figure 1: TAAS Prototype

TAAS Systems Architecture Diagram

The systems architecture diagram outlines the communication, power, and software architecture for all the devices in the TAAS. Figure 2 shows the communication architecture of the TAAS. Two subsystems can be identified within the TAAS which are:

- Subsystem A: Glue Dispensing and Curing
- Subsystem B: Pick and Place

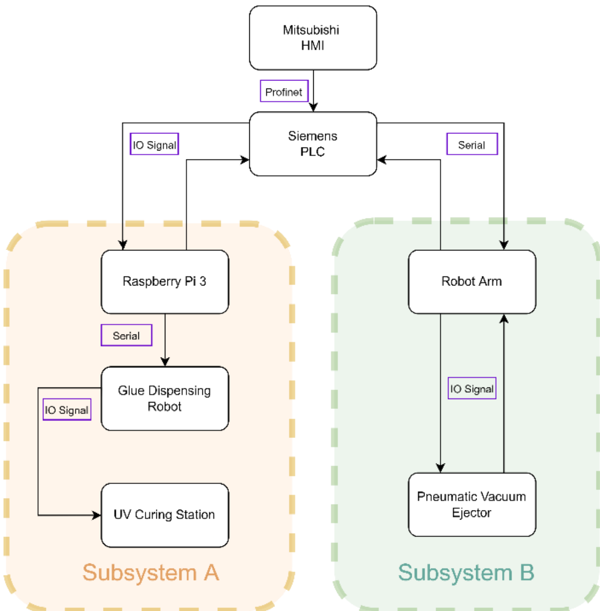

Figure 2: Communication System Architecture Diagram

TAAS High Level Logic Flow

The high level logic flow of the TAAS includes all the steps to meet the operational requirements. The logic flow is controlled by the PLC on a system level and by the robots on a subsystem level. Three main steps can be identified for assembling a single microtarget array, which are repeated for every array that needs assembling, as follows:

- Step 1 - Glue dispensing: Lines of glue are dispensed between the apertures of the array.
- Step 2 - Pick and Place: The robot arm picks foils from a pre-assembled tray of 2.8 mm square foils, and then places the thin foil over the aperture and on the glue line.
- Step 3 - UV Curing: The Cartesian robot then moves the assembled target array under a UV lamp to cure the adhesive.

Figure 3 shows a flow diagram of the high level logic flow of the TAAS. Figure 4 shows the target array after each step of the process.

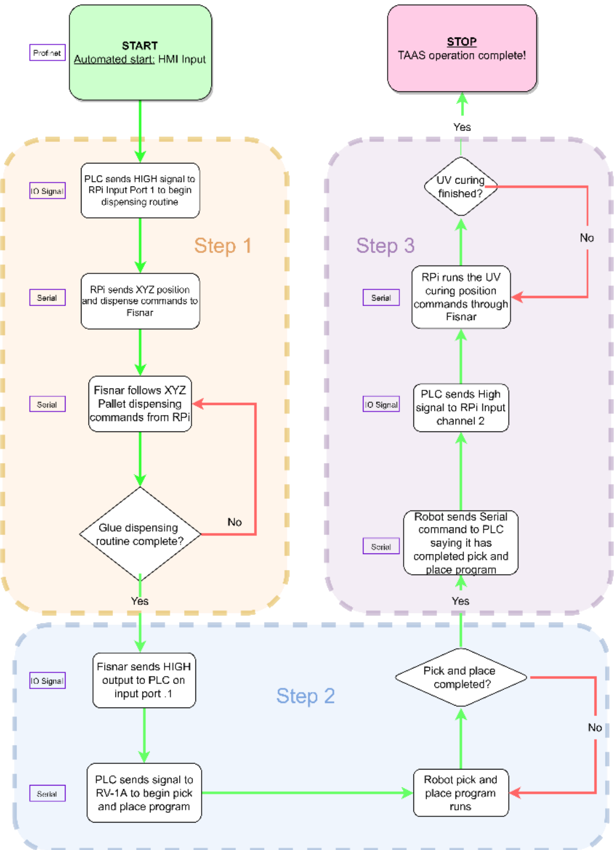

Figure 3: TAAS Logic Flow

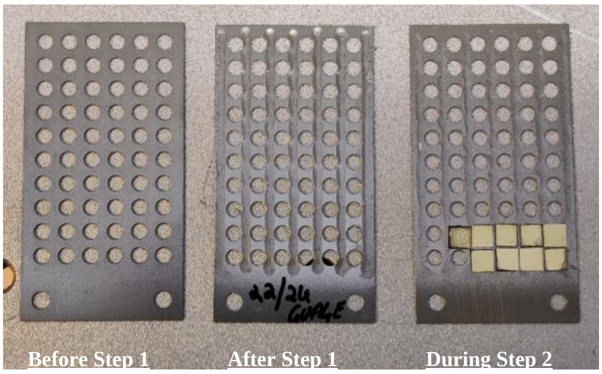

Figure 4: Target Array during the TAAS operation

Results

Initial test runs using 30 µm gold foils, laser machined by Scitech Precision Ltd to 2.8 x 2.8 mm, delivered an average success rate of 80% for the combined pick-up and deposition of the foils. Investigations to improve the success rate discovered it is crucial that all components that come in contact with the foils are electrically grounded. Grounding all individual components resulted in a near 100% success rate of pick and place operation. The target array in Figure 5 (top) shows the result of a full run of the TAAS with 100% success of pick and place. The criterion for calculating the success rate depends on whether individual apertures on the target array have been covered by individual gold foil targets (Figure 5 (bottom)). Although a slight deviation in the angle of the foils is observed in the top image the foils fully cover the apertures which is considered to be a successful assembly.

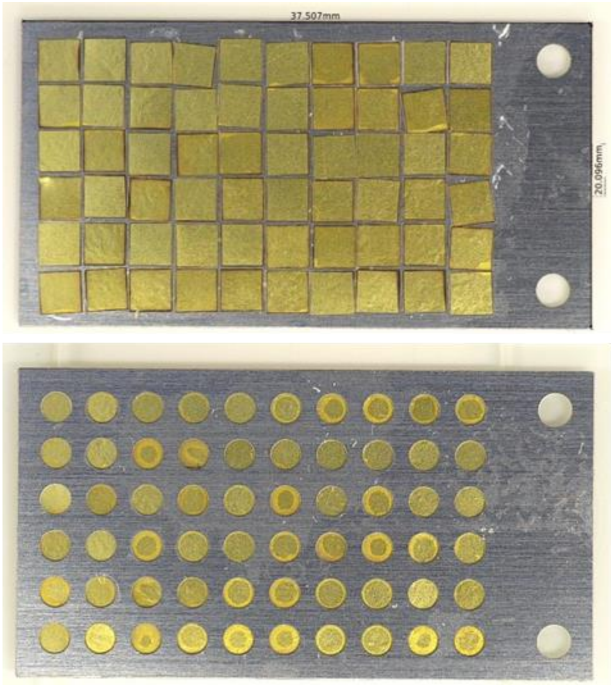

Figure 5: (top) Upper side of target array with sixty 2.8 mm square gold foil targets that are 30 µm thick; (bottom): Laser-facing side of (same) target array

The assembled target in Figure 5 was characterised using a White Light Interferometer to obtain a surface profile of individual gold foil targets when viewed from the laser-facing side of the aperture. The results from the characterisation indicate if the positional surface deviations of the surface of the mounted gold foils are within acceptable limits (determined by the Rayleigh range of experimental area laser systems). The results can be seen in Figure 6.

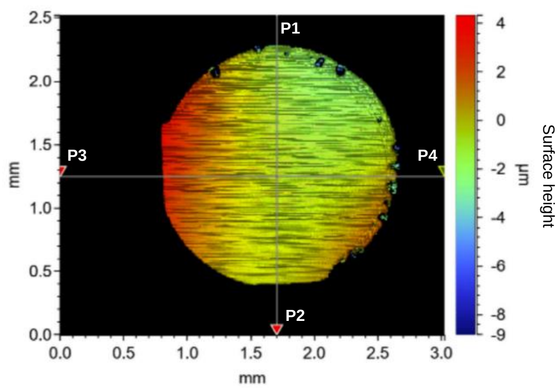

Figure 6: Foil position and topography of a single aperture in an assembled target array (from laser-facing side)

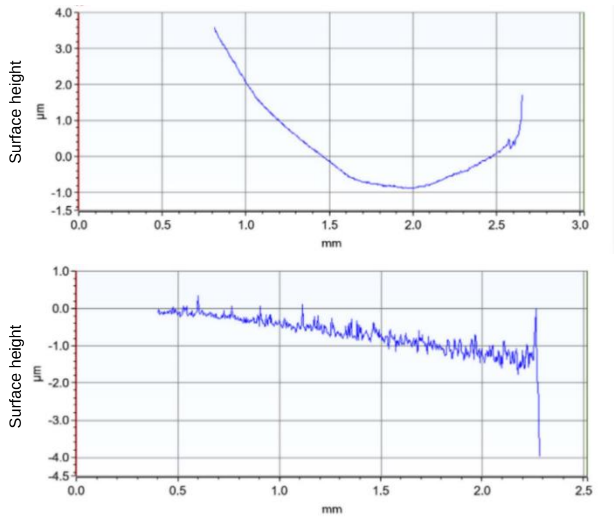

Figure 7: (top) Surface height across the line from P3 to P4 in Figure 6; (bottom) Surface height across the line from P1 to P2 in Figure 6

The results from the x and y profiles shows that the individual foil characterised is within the Rayleigh range limits of the Gemini laser [3]. Although individual foils on the array were characterised to be within the Rayleigh range a further characterisation study is needed to verify that all the foils of the array are within the Rayleigh range. The step would entail comparing the surface height difference between each aperture and ensure that the difference in height is within the Rayleigh range, rather than individual aperture surface profile measurements being within the range. The characterisation will be carried out in the future on several assembled target arrays of different foil materials to obtain statistical data on surface profile deviation during robotic assembly.

Requirement Verification

Almost all of the requirements set out in Tables 1 to 4 have been verified on the system so far. The current system does not yet fully meet the strict performance requirements; performance requirements will be further clarified during the next development iteration. A list of drawbacks and solutions are discussed below which will help in the reformulation of the objectives and requirements in the next iteration of the TAAS.

Drawbacks:

- A pick-up tray (Figure 1, D) was used for initial testing purposes to arrange the 2.8 mm target foils in a pallet formation so that the robot could pick from known (pallet) positions. Use of the tray made the whole assembly process longer and induced unwanted static charge. Long loading times arise because an operator needs to refill each individual indent in the pick-up tray which can take up to an hour. During refill of the foils they can induce a static charge caused from friction of the container in which they are stored. The static reduces the pick and place success rate because foils have a tendency to stick to the nozzle when the robot attempts to drop the foil on the target array.

- Changing the dispensing needles on the glue dispensing robot includes reprogramming the offsets of the pick and place program.

- Slight deviations in the x-y plane and in the height of the substrate/target array results from uneven lines of glue being dispensed in unwanted areas of the array. Fixing errors within the glue dispensing system may be very time consuming.

Solutions:

- An advanced assembly robot will include a vision system that will detect the x and y coordinates of individual foils and their orientation in the x-y plane. The identification will allow the robot to pick up from a tray of randomly assorted thin foils of the same material consequently removing the need to manually load foils onto a pick-up tray.

- A glue dispensing system that includes a vision system will be able to dynamically change the program offsets based on the needle height and the bead width of the dispensed adhesive.

- Additionally a glue dispensing system that includes a vision system will be able to detect the location and orientation of the target array and program the offsets accordingly.

- A glue dispensing system that includes a laser height measurement system will be able to offset any height difference of the substrate.

A new robot arm and glue dispensing robot have been procured for the next iteration of the TAAS which is currently in development. This new equipment will address the majority of the drawbacks identified to date and be able to meet specified performance requirements consequently being able to increase the system Technology Readiness Level [2].

Conclusions

From conducting an automated run of the TAAS prototype it can be concluded that a 2D microtarget array can be assembled autonomously with the aid of robotics thus meeting the project objective.

The TAAS prototype succeeded in identifying the major drawbacks of the assembly operation and suitable solutions have been implemented or proposed (which completes the first cycle of development for the system). The second cycle of development will include a re-assessment of the objectives and implementation of the solutions discussed to tackle the observed assembly issues.

Acknowledgements

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References

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