Current developments in the Target Array Assembly System

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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 (CLF) to autonomously assemble microtarget arrays. The project is being developed to support the future solid target demands of the 'Extreme Photonics Applications Centre' (EPAC) facility, which will be operational in 2025 [1].

The TAAS will also be able to support target assembly for other high-repetition laser facilities, such as the 'Extreme Light Infrastructure' (ELI) facilities or the 'European X-Ray Free-Electron Laser Facility' (XFEL). Additionally, the 'Gemini' and 'Vulcan 20-20' laser systems at CLF will be able to utilise these array targets.

The TAAS prototype reached TRL 6 (Technology Readiness Level) [2] with the semi-automated production of targets for XFEL by Christopher Gardner in 2022. A full system will be developed and validated to move up to TRL 7, requiring a prototype to be demonstrated in an operational environment. By completing, testing, and demonstrating the actual technology, the TAAS will reach TRL 8. Reaching TRL 9 requires the completion of successful mission operations.

This article will detail the current functionality of the TAAS, as well as the development goals for the future.

System Requirements

The following system requirements have been developed from both the performance of the TAAS prototype and the needs of the Target Fabrication Group.

ID	*System Requirement*
1	The system shall be able to manipulate target foils and array target frames with a 90% success rate.
2	The system shall be able to identify target foils on a backlight and load them into any palette slot with a repeatability of 500µm
3	The system should be able to enable or disable the backlight automatically, based on the required operation.
4	The system shall be able to load target foils from the palette to any positions on an array frame assembly slot with a repeatability of 500µm.
5	The system shall be able to load an array frame from a motorised holder to any array frame assembly slot with a repeatability of 500µm.
6	The system shall be able to unload an array frame from any array frame assembly slot to an array frame holder with a repeatability of 500µm.
7	The system should be able to prevent the assembled targets from being damaged during manipulation or storage.
8	The system shall be able to adjust the height of a motorised array frame holder, based on the required operation.
9	The system shall be able to detect if a target foil or array frame has been dropped during operation.
10	The system shall be able to dispense glue onto specific positions of any array frame with a repeatability of 500µm.
11	The system shall be able to UV cure glue in specific positions on any array frame, for at least 10 seconds.
12	The system shall terminate all operations within 1s if any door interlock or emergency stop button is triggered.
13	The system shall ensure that any robot does not unintentionally collide with any part of the environment.
14	The system shall ensure that any intentional contact by the robots with the environment does not cause damage to the robots, environment, or assembly components
15	The system shall allow a user to control all operations and input parameters from a Human Machine Interface (HMI)
16	The system shall bring any operation to a controlled stop if the HMI stop button is pressed.
17	The system should always provide an indication of the system status.
18	The system shall be able to safely home all robots from any point in the operation, when instructed to do so.
19	The system shall be able to safely perform a warm-up routine when instructed to do so
20	The system shall not start an assembly operation until the temperature of the robot arm servos is above a user-defined threshold.
21	The system should be able to produce 2 'full' targets per hour (containing 32 foils)

Overview of Current Functionality

Currently, the TAAS can assemble an array target containing 32 foils in 27 minutes, as seen in Figure 1. All foils were deemed to be placed within acceptable positional tolerances by an experienced microtarget fabricator in the Target Fabrication Group.

Figure 1 - *A '32-foil' array target*

The main components of the TAAS are a Programmable Logic Controller (PLC), a Human Machine Interface (HMI) Panel, a 6-axis robot arm and a Cartesian glue dispensing/UV curing robot. An image of the system can be seen in Figure 2 and a full representation of the system layout can be seen in Figure 4.

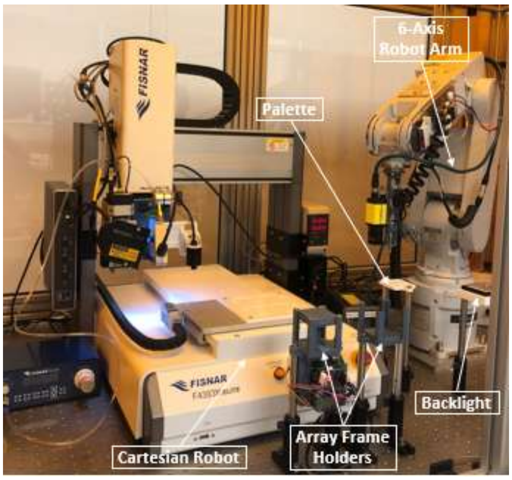

Figure 2 - *The Target Array Assembly System (TAAS)*

The robot arm can manipulate array target frames, allowing them to be loaded into any of the four assembly slots from the array frame holder. Once an array frame has been loaded, the robot arm can signal the motorised array frame holder to raise the stack of array frames.

A camera attached to the robot arm enables the use of 2D image recognition to identify and load randomly placed foils into a palette. The robot arm can also activate the backlight on the platform when required.

During the palette loading process, the glue dispensing robot applies glue to the foil positions on the array frames. The foils from the palette are then placed on the array target frames.

Once the foils have been placed onto frame, the UV lamp on the cartesian robot is used to cure the glue. Finally, once all loaded array targets have been assembled, they are unloaded into the static array frame holder. A diagram of the logic flow for the assembly process above can be seen in Figure 3.

With foils on array target mounts, the chance of a laser interaction damaging the neighbouring foil is substantially high, particularly at thicknesses under 5µm. To prevent shock damage from destroying nearby targets and to limit the effects of fratricide, the foils are assembled in a chequerboard pattern on the array.

Up to 30 array targets can be made in one run, with the only limitation being the maximum number of foils that can fit on the backlight. To expand this limitation, 64 foils can also be manually loaded into the palette, and a setting used to bypass the palette loading process.

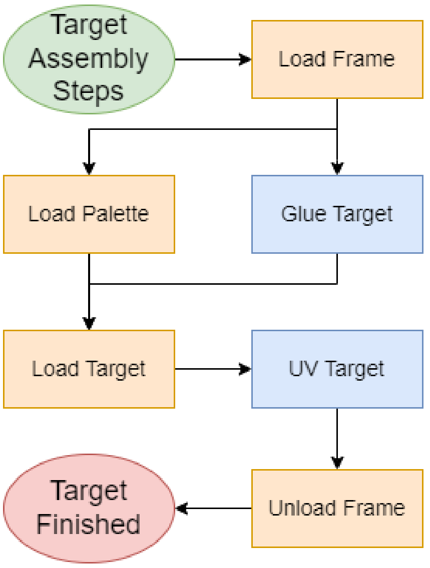

Figure 3 *- Array Target assembly logic flow diagram.*

System Design

The TAAS contains the following subsystems:

- Siemens PLC S7-1214C DC/DC/DC [3]
- Siemens TP1200 Comfort Panel [4]
- Mitsubishi RV-2FRLB Robot [5]
- Mitsubishi C800 Series Controller [5]
- SMC ZK2 Vacuum Controller [6]
- Fisnar F4303N Elite Robot [7]
- Fisnar SL101N Dispenser [8]
- OmniCure LX500-4 UV Curer [9]
- Array Storage with Motorised Lift (using Arduino UNO [10])
- TPL Vision SBACKII050502 Backlight [11]

The diagram in Figure 4 illustrates how the different subsystems within the TAAS connect.

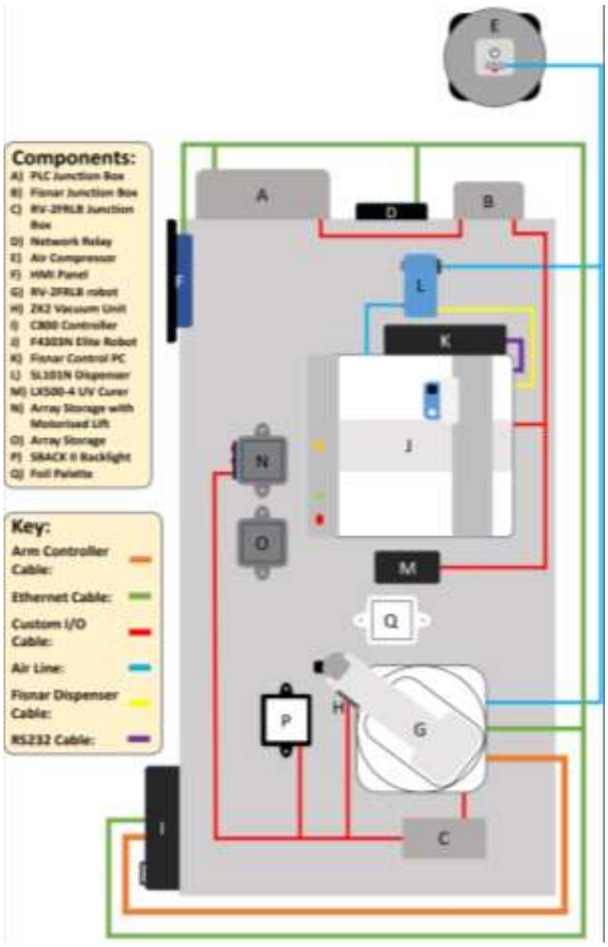

Figure 4 *- A representation of the TAAS layout and connections.*

The diagram in Figure 5 shows the UML state diagram for the TAAS. Identifying the local states of both machines as well as the overall system state, is vital for ensuring safety and reliability. The system states are:

0) Manual mode: Enclosure key turned to manual. The robot arm can only be moved manually with a teaching pendant.
1) Error mode: An error signal is detected from any source within the TAAS.
2) Automatic mode: Enclosure key turned to automatic. The robot arm can run automatic programs.
3) IO Write Enabled: ‘IO Write Enable’ signal active. The robot arm can be controlled by the PLC.
4) Invalid Start mode: The robot arm servos and main program are activated. The cartesian robot moves to home position. Assembly prerequisites are not met.
5) Valid Start mode: The robot arm servos and main program are activated. The cartesian robot is in the home position. Assembly prerequisites are met.
6) Homing: The robot arm and cartesian robot are moving to home positions.
7) Operating: The system is performing assembly operations.
8) Warm-Up: The robot arm is performing a high-speed movement routine to increase the motor and encoder temperatures.

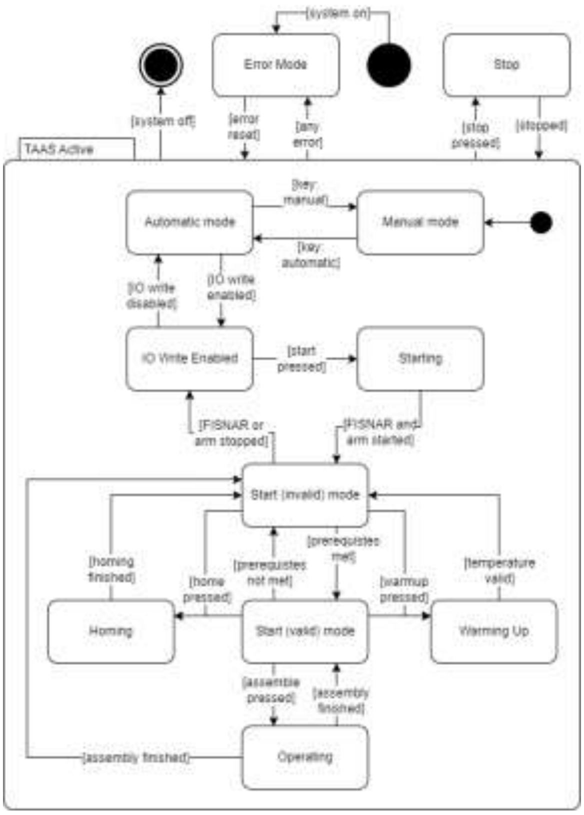

Figure 5 *- TAAS high-level state diagram.*

The diagram in Figure 6 shows how the different program blocks in the PLC are used to control the TAAS.

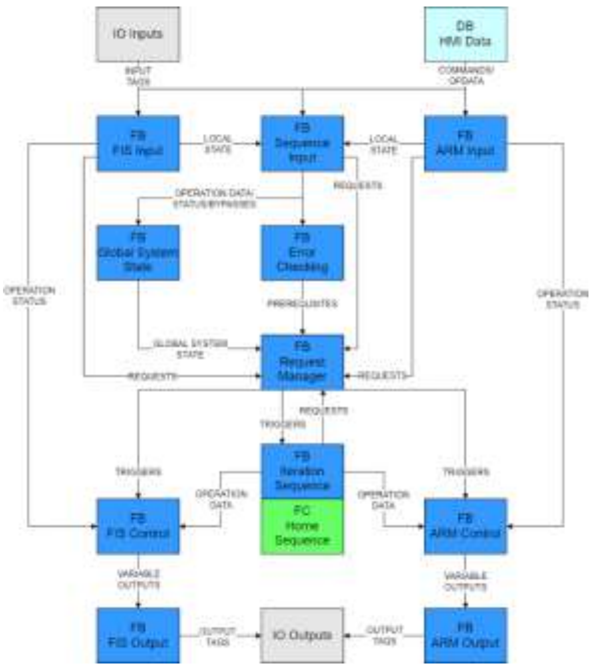

Figure 6 *- PLC function block flow diagram.*

The PLC uses different methods for controlling the robot arm and cartesian robot.

To control the robot arm, triggers are used to start pre-set programs, with the relevant parameters sent to these programs. The detailed program logic is then calculated by the arm controller during operation, using the parameters and other inputs to the robot arm. A high-level flow diagram for one of the programs can be seen in Figure 7.

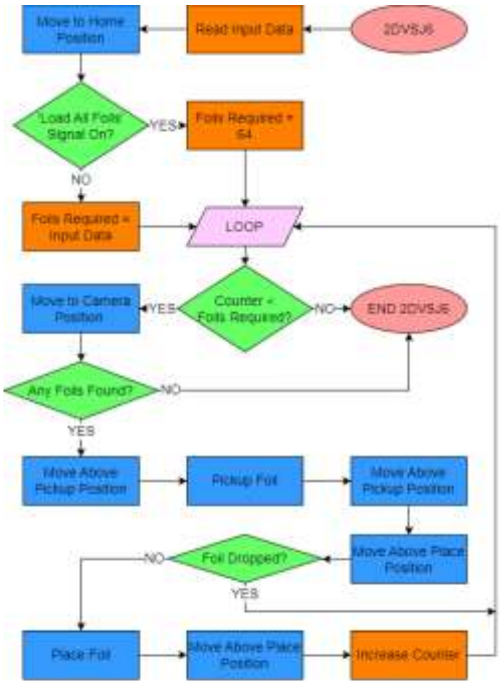

Figure 7 *- '2DVSJ6' logic flow diagram.*

Integrating the cartesian robot into the system was a challenge as it cannot perform variable based logic and has a limited number of commands. Therefore, the PLC must calculate all program logic and issue action instructions to the cartesian robot.

An example of the Dispense Routine logic flow on the PLC can be seen in Figure 8.

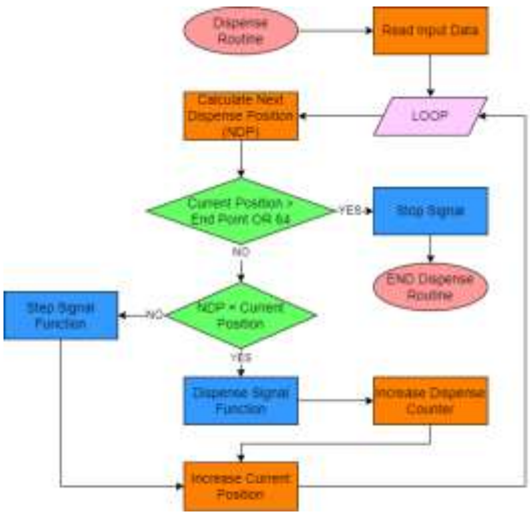

Figure 8 *- 'Dispense Routine' logic flow diagram.*

Display

To allow a user to interact with the system, the TAAS Control Interface has been designed and implemented. This interface has three main areas, the Control area, the Tools area, and the Toolbar, as shown in Figure 9 below. Each of the menus contain faceplates, allowing for modular interface construction as well as the combination and cleaning of relevant data.

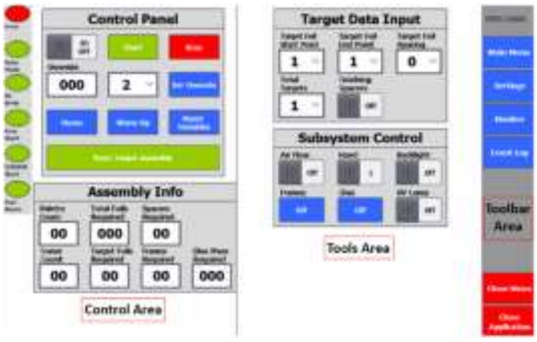

Figure 9 *- Prototype HMI layout*

The Control area is responsible for the core commands sent to the robot arm and the cartesian robot. The user can begin the three operations using buttons and switches: 'Warm-up', 'Home' and 'Assembly'. This area also contains key information about the assembly process, as well as status indicator lights. The buttons in this area are always visible to ensure that the user can safely control the system.

The Tools area is responsible for displaying one of 5 menus. These menus are named as follows: Default, Main, Settings, Monitor and Event Log.

The Default menu displays a representation of the system and runtime information.

The Main menu allows the user to input assembly information and manually trigger control arm functions. This menu is visible but disabled during operation, to prevent parameters being changed.

The Settings menu is responsible for controlling behaviours of the system. It allows the user to bypass selected steps in the assembly process, to adapt to different assembly needs. This menu can also disable certain functions, such as array frame lifting or pressure monitoring. Finally, the minimum joint temperatures required for operation are set here.

The Monitor menu is used to view various information about the system. The user can see the current position (in Cartesian and Joint coordinates); the current temperature of each robot arm joint; as well as the manipulator status for both the robot arm and cartesian robot.

The Event Log menu is used to view the history of actions the system has performed.

The Toolbar area is used to select which menu appears in the Tools area or close the application.

Reducing sources of positional placement error

During system development a coordinate drift was observed in the robot arm, causing unreliable and inaccurate foil placement. Several experiments were conducted to identify the source of this drift. After initial experimentation, it was suggested that thermal expansion in the arm's chassis or motors could cause coordinate drift. An experiment to investigate the effect of thermal expansion on the robot arm was conducted. [12]

The results of this experiment led to the addition of a 'Warm-up' operation, to increase the temperature of the robot arm's joints. The system also prevents an assembly operation unless the arm's joint temperatures are above user-specified values.

Future work

The future aims of the TAAS focus on adaptability and reliability. Due to the nature of the Target Fabrication Group's requirements, the designs of the targets assembled by the system will vary extensively. The system must be able to adapt to these variations to remain useful, while remaining user-friendly.

Firstly, a simple improvement to the TAAS would be a larger backlight. This would allow a user to assemble more array targets before needing to stop and add more foils.

Another future aim would be to create a "User mode" for the HMI, preventing the user from changing core settings and processes. By providing a simpler layout, user error will be reduced.

A core aim for future development is a robust error management system. Currently, a disruption in one of the robots does not stop the operation of the whole system. Also, different error events need to be classified with respect to their effect on the wider assembly process. This would make the system more reliable and safer.

A potential future development would be the addition of a second, upward facing camera. This camera would be used to adjust for any positional inaccuracies when manipulating foils, reducing cumulative manipulation error during assembly.

Another area for future development would be the handling of thinner and more fragile foils. These foils are more prone to damage, being dropped or electrostatic adherence. Investigations and developments into soft, anti-static manipulation methods would be required to handle these foils.

Conclusions

Initial automated assembly processes were run on the TAAS, with 'wet' and 'dry' testing. The wet runs included glue dispensing and UV curing, whereas dry runs did not. These tests, as well as the verification of assembled targets were used to assess the basic functionality of the TAAS.

Currently, the system requirements for the TAAS are all met except for requirements 2 and 7. Investigation and tuning of the 2D Vision system is required to ensure a sufficient manipulation repeatability. Also, spacers between finished targets need to be implemented to ensure array target frames are not damaged.

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