D6.4 - System integrated readily to be placed within a sterile enclosure to accommodate all of the hardware required to automate the sterile testing.

Deliverable 6.4

Deliverable Title	System integrated readily to be placed within a sterile enclosure to accommodate all of the hardware required to automate the sterile testing.
Deliverable Lead:	ASTECH PROJECTS LIMITED
Related Work Package:	WP6: Integration & Evaluation
Related Task(s):	WP2-WP3-Wp4-WP5-WP6
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Abstract	Brief explanation of the system readiness for rapid integration and deployment into a sterile environment within the industry.

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Versioning and Contribution History

Version	Date	Modified by	Modification reason
v.01	15/11/2024	William Speed (AST) Nirmal Raveendran (AST)	First Issue ready for first internal review
v.02	03/12/2024	Anthony Remazeilles (TECN) Patrick Mania (UOB)	Internal revision
V.03	08/01/2025	Nirmal Raveendran (AST)	Revision according to internal review
V.04	09/01/2025	Anthony Remazeilles (TECN)	Final version ready for submission

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1 Executive Summary

This deliverable describes in detail the steps involved for the rapid integration and readiness of the TraceBot system for direct deployment into any sterile environment to start an automated sterility test. As explained in our previous deliverables 6.2 [2], and 6.3 [3], the TraceBot system integration has two main parts: the hardware integration and the software integration. The hardware integration consists of all the hardware component assembly and testing whereas the software integration consists of the steps required for the software setup to communicate with the hardware. The last step before deploying the system into any sterile environment would be to test for the system's capabilities to be accepted for a sterility certification test. The rapid integration of the TraceBot system is possible because of its modular and robust software and hardware architecture as explained in deliverable 6.3 [3]. This deliverable will be elaborating and building insights on the steps for integrating all the hardware components and the software components such that it can be dismantled and shifted to different places as required and also the methods that would be implemented on the system to make it possible to pass any standard sterility certification tests.

The mechanical and electrical design and construction performed to assemble the TraceBot physical platform has already been described in detailed in the D6.2 [2] deliverable. Hence this document is an extension to the deliverables from D6.1 [1] to D6.3 [3], respectively.

The integration efforts for this year mainly consisted of three main phases: (i) the start of the acceptance testing process of the system, (ii) the manipulation of the sterility testing pump with the robot arms and finally (iii) the complete integration of the two dexterous grippers developed by one of our partner CEA of the Tracebot consortium. This integration of the complete system is the main target for achieving the Milestone 4.

The integration efforts this year were focused on the adaptation of the two robotic arms of the TraceBot system for the proposed dexterous gripper developed by work package two leader CEA, along with the development of the test scenarios for the acceptance testing of the traceability and verification capabilities of the TraceBot system. The complete integration and testing of the gripper was achieved by the end of this year which was a key task for the completion of Milestone 4 of this project. The acceptance testing is scheduled to be carried out by the end of next Milestone.

Throughout the year periodic bi-weekly and weekly integration meetings were organized, in addition to presential integration workshops. These events enables us to identify the potential issues raised by such integration, to define the adjustments required, and to monitor the progress of the integration effort. This year is also significant as it witnessed the entire consortium gathering for the integration progression review at Konstanz this year in the month of September 2024.

The efforts by all our partners this year have resulted in the quick adaptation of the TraceBot demonstrator system with the two CEA dexterous grippers. The upgraded system is now able to showcase the canister insertion into the pump tray, tube insertion into the pump and the needle cap removal and the needle insertion into the bottle use-cases which are currently the three sequential processes that has been well integrated into the system.

All the works that were carried out in this year were strongly in line for the final achievement of the Milestone 4 by the end of the year.

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2 Introduction

This document gives an overview of all the integration outcomes achieved during this fourth year of integration of the TraceBot project, in the continuity to the activities conducted during the first, second and third years, reported in deliverable documents D6.1 [1], D6.2 [2], and D6.3 [3] respectively.

After having showcased the canister insertion and needle cap removal and bottle insertion use cases demos with a single CEA dexterous gripper integrated towards the end of the year 2023 on the physical demonstrator as part of the Milestone 3, the fourth year of integration started off as a follow up of the Milestone 3 integration efforts. The main objective of integration efforts for this year was to start the “Verification and Acceptance Testing” of the TraceBot system as mentioned in deliverable 6.3 [3]. This was especially important because it helps to highlight the robustness of the TraceBot system.

After having conducted the series of acceptance testing scenarios with the system at the beginning of the year, the outcome was distributed internally within the consortium. Discussions were then carried out within the integration group with respect to the test results to increase the robustness of the entire system as a whole. After this, integration efforts at Astech were concentrated on the process of integrating the sterility pump with the TraceBot system. This was a challenging task as the pump that we currently use did not come with a supportive API which would help for software integration. Due to this challenge after a detailed internal discussion with the consortium it was decided to proceed with the manual manipulation of the pump using the robotic arms of the TraceBot system. Finally, towards the end of the year the integration efforts were concentrated on the integration of the second CEA dexterous gripper onto the TraceBot system. This integration efforts were conducted in the month of November 2024 with an intense integration workshop held at Astech where all the developers from each partners of the consortium came to Astech and carried the works required for the clean integration of the grippers into the system. During this integration workshop at Astech we also managed to integrate a third process into the system which was the tube insertion into the pump. Hence currently by the end of this year we have completely integrated four main processes into the system which are, the canister insertion into the drain tray of the pump, tube insertion into the pump, the needle cap removal and insertion into the bottle and finally the pump manipulation with the two CEA dexterous grippers.

This achievement was obtained thanks to a significant integration effort by all of our work package partners involved in the periodic integration follow-ups and several integration workshops.

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3 Description of work & main achievements

3.1 Hardware Integration

This section explains in detail all the follow-ups that have been done on the hardware build of the TraceBot system with respect to the final build of the demonstrator showcased in the deliverable D6.3 [3], last year. Most of the system's global hardware architecture remains the same as that of the one detailed in the deliverable D6.2 [2] and D6.3 [3].

With the project entering into D6.4 deliverable phase this year, the only new hardware modification made to the system was the integration of the second CEA dexterous gripper on the TraceBot system. The rest of the entire system has been kept as described in the deliverable 6.3 [3] last year. The following figure illustrates the system with the two dexterous gripper from CEA, mounted onto the ASTECH demonstrator. The experience acquired during the installation of the first gripper last year enabled to make a swift physical integration, without requiring the presence of the CEA team.

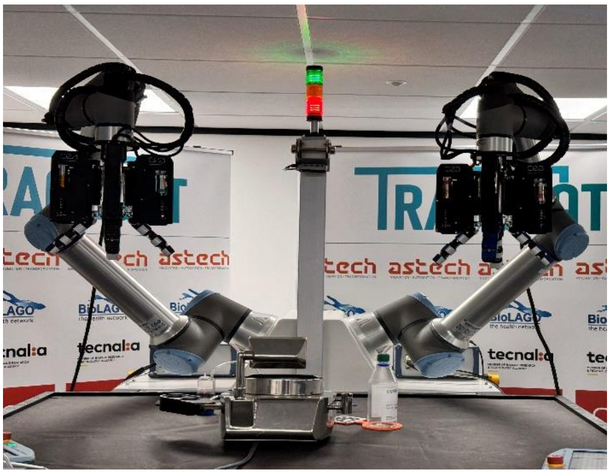

Figure 1: TraceBot System with the two CEA Gripers integrated

The on-site CEA dexterous gripper integration efforts started from the mid-week of November 2024 and continued until the end of November 2024. The adaptation of the TraceBot system from the existing configuration of two Robotiq 2F grippers on each robotic arm to the new configuration of the two CEA dexterous grippers on each robotic arm was a fairly straightforward implementation and installation. This is mainly due to the modular software architecture of the system with ROS middleware. The communication with the two grippers is handled seamlessly by the usage of a ROS gripper driver node which interface was already agreed and validated by the developers. This way the system evolution was significantly easier and faster. The entire process of installing the two new grippers onto the TraceBot's UR10e arms was done within a timespan of one day after the gripper being available at the Astech facility by the middle of the month of November 2024 (ref. Figure 1).

This hardware and software integration was done during the physical integration workshop hosted by Astech during the month of November 2024. During this integration workshop the members from Tecnalia, CEA, TUW and UOB where present physically throughout the integration week.

Through this teamwork and efforts, we were able to achieve the objective of installing, testing, and recording the working of the TraceBot System with the two CEA dexterous grippers with the two of

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the most mature use cases we have integrated within the system namely the Canister insertion into the Pump tray and the Needle cap removal and insertion into the bottle. There was also few test runs of the third process namely the tube insertion into the pump as well (this latter process is still under final tunning to improve its robustness).

Grippers: - The grippers are the most integral part of the TraceBot system as it is responsible for the grasping of objects to be manipulated during the use case processes of the TraceBot System. These dexterous grippers are the state-of-the-art custom machine with 18 DOF in total on one gripper which is specially designed for the TraceBot system alone such that it can bio mimic the human palm to a certain extent. These grippers are also enhanced with piezo electric tactile sensors that are present on each finger as a white plastic sticker layer. These tactile sensors can function as the touch verifiers once these are integrated into the system (ref. Figure 2).

Figure 2: CEA Dexterous Gripper Fingers

All of the gripper specifications are discussed in detail, in the documentations produced by the working partner CEA within Work Package 2.

Motor Driver Units: - These units are responsible for driving all the motors that are embedded in the gripper's fingers for producing the actuations of the fingers and also control the motors on the 3rd wrist joint to produce the rotation motion of the gripper. These units are attached onto the body of the UR10e arms of the TraceBot system using custom 3D printed brackets and holders (ref. Figure 3). More detailed electrical and mechanical architecture of these units are discussed in the documentations produced by the working partner CEA.

External Control Units: - These units act as the external brains of the grippers, since currently the control modules are developed externally by CEA with respect to the TraceBot system (ref. Figure 3). This controller is connected to the same local area network as the TraceBot using an RJ45 ethernet cable and an ethernet switch. The controller is commanded by the CEA ROS server node that is embedded into the TraceBot software architecture. There is a detailed explanation about the development of these controllers in the documentation of the work package partner CEA.

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Figure 3: External controller unit and the motor driver of the CEA Gripper

3.2 Software Integration

The software part of TraceBot also follows the same basic architecture as shown previously in the deliverable D6.2 [2].

The integration effort consists of (i) validating the development at the partner site, (ii) deploying the developments made by the partners on the physical demonstrator located at the Astech site, and (iii) making sure the combination with the other components is effectively functional.

This year the software integration efforts were mainly concentrated on (i) perfecting the perception node with the new "Gdrnpp" model, (ii) having the pump manipulation process integrated into the TraceBot system, (iii) integrating the 2nd CEA dexterous gripper, and (iv) integrating a bimanual manipulation with the dexterous grippers for the tube insertion process. There have also been significant efforts to update the Digital Twin (DT) according to the gripper evolution and to the additional operations covered by the system, while keeping up to date the audit trail generation. The main role of Astech as integrator was to deploy all these developments made by the partners onto the demonstrator and test it functionalities throughout the development phase.

Perception Integration: - This year also witnessed the first full implementation of the new Reflow6d technique, an evolution of the "Gdrnpp" model used for locating objects which would mainly be used for locating and pose estimation of the canister and the needle and other objects that are in the area of interest of the camera vision. This change in method is due to the reason that "Gdrnpp" method is a more refined and precise model for pose estimation and object recognition (ref. Figure 4). More details about this method can be obtained from the TUW deliverable D4.2 [4] and the paper Reflow6d [5].

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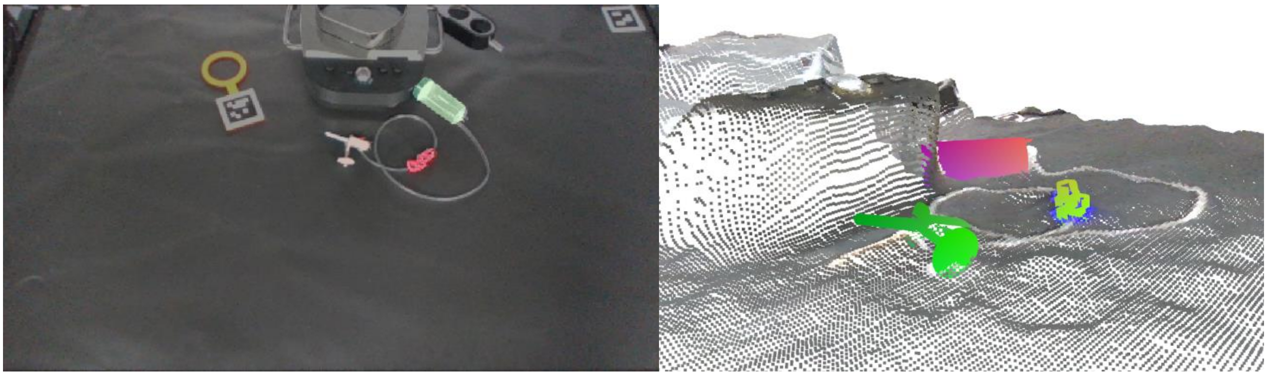

Figure 4: Objects located using Gdrnpp method and rviz point cloud

Verification of Locate Object: - This node is responsible for the verification and refinement of the output of the locate object node. It works as a background verifier for the locate object system. This node uses a "Silhouette" methodology for verification. The integration of the verifier layer has helped to improve the TraceBot system robustness in the perception/vision areas. This node helps the locate object confirm that the objects recognized are really the objects of interest for manipulation with the TraceBot system as it also uses the same point cloud data as that of the locate object method (ref. Figure 4). As seen from the figure the point cloud (right side image), is a projection of the real image captured by the camera sensor for the pose estimate. Thanks to this verification layers, the resulting pose estimation has been improved. This added verification helps boosting the confidence level of the locate object in the audit tail that will be generated at the end of each process.

CEA Dexterous Grippers: - This year we also managed to integrate the 2nd CEA dexterous grippers onto the 2 arms of the TraceBot system (ref. Figure 1). The integration efforts for achieving this milestone were similar to the efforts put forward to the integration of the 1st CEA dexterous gripper last year. The software integration of the CEA grippers started with the modification of the URDF model of the TraceBot system to reflect the upgraded system. This is required to update accordingly the grasping functionality, but also to keep the DT model up to date with the actualized real robot. The next step consisted in connecting the output of the updated gripper node to the rest of the TraceBot system. This was achieved by an appropriate remapping of the joint state information provided by the gripper was done to complete the overall joint state status of the TraceBot. This work was mainly carried out by our partners CEA and TECN, during the integration week.

Digital Twin Integration: - With respect to the digital twin interface node of the TraceBot system the focus was to integrate the URDF model with 2 new CEA grippers into the Digital Twin virtual environment (ref. Figure 5). There has also been work carried out this year to incorporate the DT with the URDF model of the tube which is used in the use case of tube insertion into the pump. There has been extensive work carried out in the DT to encapsulate the visual verifiers required by the KnowRob data base to generate the audit trail. This year the DT is integrated with the capabilities of the tactile verification as the two new CEA grippers provide tactile information that can be processed. This will help in generating a much more accurate audit trail document to showcase the traceability functionalities of the TraceBot system.

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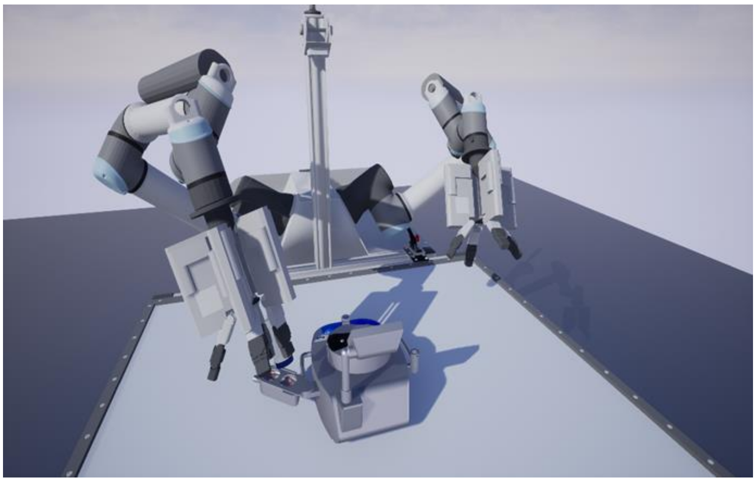

Figure 5: Digital Twin with two new CEA grippers integrated

<u>Sterility Pump Manipulation</u>: - This year there were efforts carried at Astech to integrate the sterility pump from Merck with the TraceBot system, but during this task we were facing many challenges since the pump that is currently used with the TraceBot system does not have an active API which restricts our capabilities to manipulate the pump digitally via software communication protocols. This issue was brought to several contacts in the manufacturer company, but unfortunately, we did not manage to convince them to give us access to their proprietary interface. This issue was raised and addressed by the middle of this year and the solution that the TraceBot consortium came up with was to use the pump through robotic manipulations, i.e. the TraceBot arms will move to push down the physical buttons of the pump to control the interaction with the device. A test demo of the TraceBot system with the robotiq 2f gripper configuration has been showcased in the TraceBot Symposium held at Konstanz in the month of September this year. The process needs to be re taught with the CEA gripper this year, but we do not foresee any major issue. In order for the CEA gripper to perform the physical motion of pressing the buttons, the pump needs an addon part with bigger buttons as the actual button's surface area is too small for the CEA gripper to accurately perform the motion. Hence Astech has developed such addon (ref. Figure 6). This addon will help in performing the pump manipulation task with the CEA Gripper. This will be completely integrated with the TraceBot system by the start of next year.

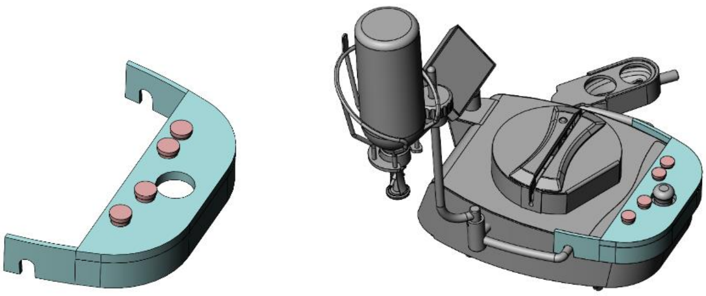

Figure 6: Pump Add-On part

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Tactile Verification and Audit Trail Generation:-

This year we also managed to integrate both the visual verifier and the tactile feedback functionality from the CEA grippers on the TraceBot system to generate the non-verbal audit trail that was mentioned in the previous deliverable 6.3 [3]. The works to achieve this integration was jointly carried out by CEA, TUW and UOB. Sensor data is recorded and the KnowRob framework triggers related verification layers to deduce the operation status, information that is used also for the generation of the audit trail, with the confidence level corresponding to the precision provided by these verifier layers (ref. Figure 7). A prior collection of tactile and detection data was carried out by the partners TUW and CEA at the CEA facility in Paris, in the months of July and August 2024. This initial data capture and study enabled to smooth the activity during the integration workshop at Astech in the month of November 2024. This prerecording helped for a faster integration of the system as a whole.

More details about the representation and generation of Audit Trails in the TraceBot system can be found in the Deliverable 5.3 by UOB [6].

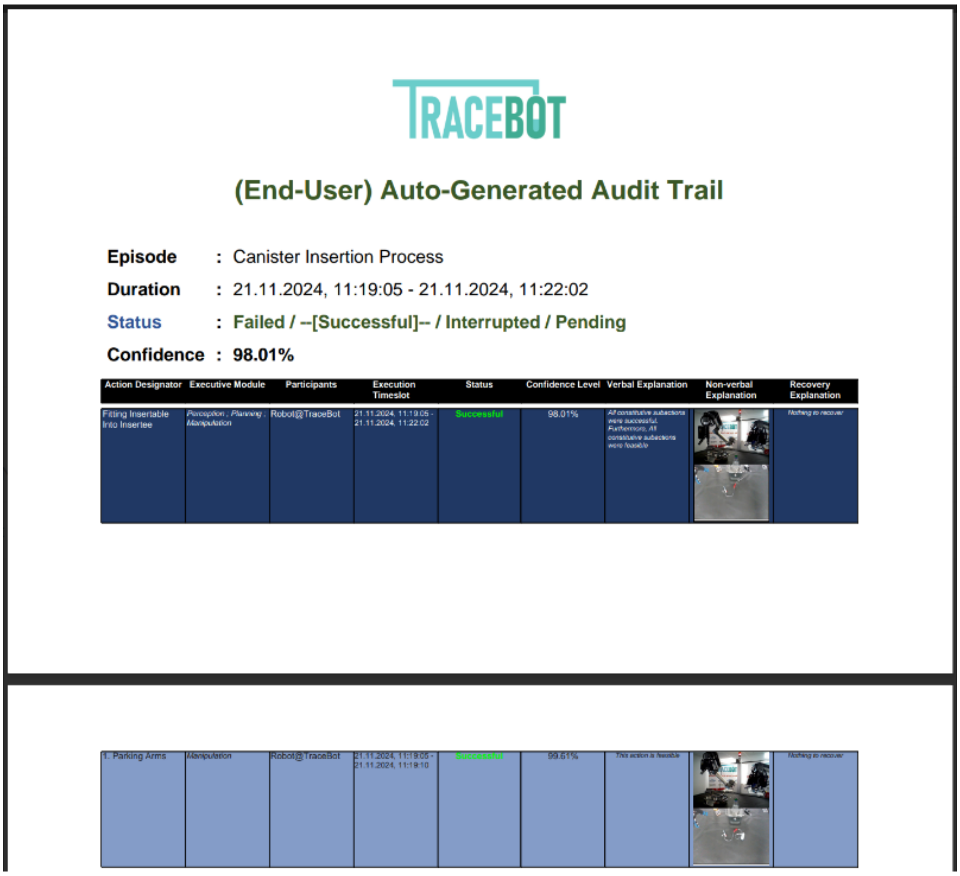

Figure 7: Improved Audit Trail

Use Case Demonstrator States: - After showcasing the combined integration of the use cases, Canister insertion into pump tray holes and the Needle Cap removal and insertion into the bottle during the D6.3 [3] deliverable with the demonstrator last year. The works were continued for

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implementing the integration of the third and fourth use cases, namely the Tube insertion into the pump and the pump manipulation with the CEA grippers from the beginning of this year. In the tube insertion process the tube is stretched and with bi-manual motion of the two robotic arms of the TraceBot system, it is then being inserted into the pump's tube cavity and the pump is locked with the pump manipulation process. After the tube is inserted, the needle is detected using the camera. This information is passed into the Digital Twin (DT) action server to spawn the needle into the DT virtual environment. This step also makes use of the pose estimate and verification function embedded into the DT. Once the pose is verified the position coordinates are passed into the Joint controller for the arm manipulation action which makes the arm move towards the needle object both in the real world as well as the virtual world in the Digital Twin in real time. Once the arm reaches the grasp position the needle is grasped and then placed onto a safe place to perform the cap removal sequence of this process. Once the cap removal is executed successfully the left arm of the robot moves to grasp the bottle to secure it for the needle insertion and then the right arm moves towards the bottle to insert the needle into the bottle cap and then the right arm moves back, and the left arm inverts the bottle into a position that enables for the liquid transfer once the pump is turned on. The final process would be to turn on the pump such that the liquid start to flow from the bottle into the canister via the pump.

Hence at this point of integration there are three processes or uses cases combined, namely the "Canister Insertion", the "Tube Insertion" and the "Needle insertion". They are fully integrated into the TraceBot system demonstrator at Astech and each of these use cases makes use of both of the CEA grippers mounted on the TraceBot system. The combined use cases have been recorded and showcased as a single sequential process/use case at the end of the integration workshop.

Future works on the demonstrator for the next year consists of the integration of the pump manipulation with the CEA gripper available at Astech. This would probably be the final process to be integrated as it will then allow the liquid transfer to happen between the bottle and the canister.

The final acceptance and verification testing will also be done on the process during the course of next month as the project comes to the end of life by March 2025.

3.3 Acceptance Testing and Verification Methodology

The main goal for the deliverable D6.3 [3] was to define the "Failure Mode and Effects Analysis" (FMEA) tests for the TraceBot demonstrator built. Indeed, as it is to be placed in a sterile environment in a pharmaceutical industry, it must follow the standard industrial procedures. Acceptance testing must be carried out before commissioning such a system into a critical environment. The acceptance test in industrial standards is known as the "Failure Mode and Effects Analysis Test (FMEA TEST)." Since Astech is the leading automation partner for the laboratory and pharmaceutical automation, we are more than capable of design a wide range of processes to evaluate the robustness and acceptance capabilities of the TraceBot system as a whole.

The FMEA test document is a well-accepted data within the pharmaceutical industries and laboratories. It helps us to verify the compliance and the repeatability of a system when conducting a particular process at a closed or confined environment.

In the case of TraceBot the challenges that can be thrown towards the system is to challenge the vision system of the machine by removing the canisters and needle while a canister manipulation or needle manipulation processes are being executed. The expected outcome of these challenging situations is

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that the TraceBot must identity missing objects and the entire process must be stopped immediately or should be designed in a way that the system automatically recovers from this challenging position and returns to a safe position/configuration.

The FMEA test were conducted in accordance with the methodology proposed in the deliverable 6.3 [3], from last year. The testing began early this year from January 2024 and was continued until the end of April with a total of two full sessions of testing of the TraceBot system with its most mature process that is the Canister insertion process. This process alone can challenge the TraceBot system's vision system, the manipulation system and also the verifiers.

A new session of testing is planned to commence from the beginning of next year before the final integration and review to test the system for the tactile verification and reasoning capabilities as well. This testing will also follow the same methods provided in deliverable 6.3 [3].

4 Sterility Certification of the System

This section of this 6.4 deliverable document tends to throw light into the modifications that need to be made at the hardware level to make the TraceBot system capable of passing a standard Sterility certification test. This testing is required before deploying it into any sterile environment across the industry. Until such test is successfully done, the TraceBot system cannot be deployed into any such environment.

A thorough and close examination of the system was conducted by a team of experts from Astech's applications team and the Quality manager who are responsible for validating and creating testing scenarios for any systems build at Astech. Several recommendations were suggested by them to make TraceBot system suitable for a sterile environment. They are described in the following items.

1. The UR10e arms needs to be replaced with a suitable ISO certified robotic arm of same reach and payload carrying capacity. This is due to the fact that UR arms are technically not certified for a sterile environment. There is also an option to cover the arm with a protective cover that is ISO certified for the sterile environment. The UR company claims that their products are class 5 clean room compatible, but a clean room and a sterile environment are entirely two different environments. Hence, we cannot use an UR arm for this purpose. Thus, the arms need to be replaced with proper ISO rated arms for the sterility testing.
2. The CEA Grippers are the most challenging part of this build as it has many open and exposed parts which makes it impossible to be washed or cleaned with liquids that would be used in a sterile environment for disinfecting and sanitation purposes. A complete redesign of the gripper is thus required for it to pass a sterility certification test. This is the best recommendation we have for the CEA grippers because it would not be possible to build any sort of enclosure for it with the current design of grippers.
3. The final recommendation made was to build a complete enclosure after the redesign and rebuild of the system to make it compatible for a sterile environment.
4. This redesign and rebuild of the TraceBot system will enable to be a production capable unit rather than a demonstration unit.

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5 Link To Milestone 4

The integration of the most recent developments, as described in this document, is directly connected to the completion of Milestone 4. As each milestone is defined with a set of means of verification, we provided here additional information related to these points. Some videos demonstrating the achievements are collected in a YouTube playlist[1].

[WP2] Second Multifingered hand used in bimanual manipulation

A second 18-dof multi-fingered gripper has been fully designed and assembled by CEA. This newly developed, task-oriented gripper delivers high performance with advanced multimodal sensitivity and dexterity. In addition to providing haptic feedback through backdrivable actuators, it integrates tactile sensors. These sensors combine two sensing technologies, enabling the detection of both high-frequency touch events via a piezoelectric (piezoE) sensor layer and pressure distribution through a piezoresistive (piezoR) sensor layer. Both of the CEA four-fingered grippers have been successfully mounted at the tips of collaborative robot arms at ASTECH facilities, creating an advanced, dexterous bimanual setup.

[WP2] Hand controller implemented & used in the manipulation

The controllers for the two CEA multi-fingered grippers have been developed within a real-time software architecture. These controllers leverage backdrivable, low-friction, and low-inertia motor-to-joint mechanical transmissions to offer both position and torque control capabilities. Additionally, the controllers incorporate tactile sensor data to estimate the contact points with the held object, compute its pose within the gripper, and detect critical events during manipulation, such as object slipping and verification. These features are made accessible to other components of the entire demonstration setup through a connection to the ROS middleware and the simulation verification supervision process. The controller also proposes admissible grasps for all objects involved in the use case. Dexterous grasping capabilities were successfully demonstrated at ASTECH during Milestone 4, replicating the bimanual operations required by the use case.

[WP3] Learning implemented and used in the manipulation

In the context of task 3.5, cognitive learning by demonstration, we developed different approaches to utilizing Learning by Demonstration for transferring skills from human operators to robot machines. Both approaches consider a setting where the behaviour demonstration is performed using a teleoperation scheme, as the robotic system may be deployed in hazardous environments. The first approach involves learning a complete motion pattern, relying on Dynamic Movement Primitives (DMP). Although the DMP approach can learn a motion pattern from a single demonstration, we have investigated how to extract a nominal behaviour from multiple demonstrations [7]. A video illustration of this solution was presented during the second review, and this functionality was already

[1] https://youtu.be/Ilz5HyD0Pe0?si=j8F9ELno-qms-WUa

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mentioned in the previous milestone. It was related to learning how to move a bottle from a table to a bottle holder, where the bottle needs to be inserted upside down. With this approach, the robotic system can learn new motion patterns and expand its bank of skills.

In some cases, even if a manipulation skill is already known, it may be necessary to adjust its tunning for a specific application case. This is the second learning process we have implemented. In this case, an admittance controller is used, designed to control the gripper velocity direction while opening the sterility kit, containing the canisters and other consumables. During the demonstration phase, the velocity magnitude and direction, as well as the perceived interaction forces, are measured. This information is used to fine-tune the generic controller, allowing it to specialize in the current task. The provided illustrative video demonstrates the successful execution of the process. Further details on the implementation will be provided in the related deliverable, D3.3 (Intuitive programming interface framework).

[WP3] Cognitive programming interface allowing to program a new task as a sequence of skills

The graphical interface developed in WP3 is providing two means of programming. The first is a manual selection of the successive skills to be executed while the second method is manual kinaesthetic teaching to show the required manipulation, letting the system recognize the skills that are involved in the demonstrated session.

An autocompletion feature has been developed to optimize and ease the user experience. Indeed, the sequences of skills created by the users are saved in a database that is exploited to find the most likely next skill. This feature relies on a statistical method using Markov Networks.

Finally, modalities increasing the flexibility have developed in a wizard that guides the user to add a new object definition in the knowledge base. This allows the user to add semantic description of new objects simply by answering questions like “what is the global shape of the object (cylinder, box, ...) ?”

[WP4] Traceability framework assessed on second product set

The traceability framework is responsible for producing an audit trail and any proof necessary to demonstrate the correct execution of the task at hand. As such, its two main elements are saving all relevant data during the execution of the task and checking that it is correctly done.

The framework itself has been designed in a task-agnostic manner. Once the process is defined and annotated, the relevant topics are automatically saved, and the corresponding feasibility and success checking actions are inferred. This lets the process report success and failure dynamically during the execution and adapt its approach using recovery actions.

The feasibility and success checking actions have been defined by all partners and leverage their expertise on the specific sub-task. All those actions have also been defined in a generic manner, within the context in which they are applicable. For example, the vision-based pose verification checks the consistency between the detection and pose prediction by comparing the silhouettes produced by both, as well as the physical plausibility of the pose (touching the support plane or the gripper tactile

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sensor). It is only performed after object poses are estimated by the system and only requires a 3d model of the objects involved in the scene, but no object-specific training.

[WP5] TST used to create Audit Trail and recovery from errors

The goals of WP5 for this milestone have been successfully achieved through a series of technical implementations and system adaptations. Audit Trails have been established for selected processes by modelling and grounding the process steps into the ontology of the Traceable Semantic Twin (TST). This enables systematic tracking and semantic annotation of actions, supporting the verification and validation of task completion. The simulation framework has been updated to incorporate newly integrated use cases and hardware, including the installation of the new gripper by our partner CEA. These enhancements ensure that the system is reflecting the actual robot platform to support the reasoning processes about robot manipulation actions by representing a digital twin of the employed robot.

Moreover, reasoning mechanisms for error detection and recovery have been developed and integrated into the system. These mechanisms allow the robotic platform to handle failures arising during object manipulation, enabling the system to identify, analyse, and address errors autonomously. This reduces the dependency on human intervention and enhances the robustness of the process, which is especially critical in the medical lab automation domain. All actions conducted are logged into the generated Audit Trail and allow for an introspection of the whole process to trace task execution steps and the related beliefs of the robot.

[WP6] Final version of HW integration and software architecture

This document has highlighted all the latest developments in the hardware and software integration of the TraceBot demonstrator at ASTECH. The hardware integration this year resulted in the addition of the second CEA dexterous gripper on to the TraceBot demonstrator at Astech. The software integration for this year has also resulted in a fast integration of second CEA gripper, a new locate object model for the perception node, a new and improved audit trail and finally an update to the Digital Twin (DT) as well. There have also been efforts to integrate the pump operations into the system through a manual operation of the pump with the TraceBot arm. This has been explained in detail in this document in Section 4. We were also able to test bimanual manipulation using the second gripper now being available for a new process named “Tube insertion into the pump”. This process is in initial stage and would need further fine tuning to achieve the precision we need. All of these hardware and software integrations has been done in terms of the Milestone 4 objectives.

[WP6] Verification testing of Integration

This year the verification tests were conducted as planned and described in the last year Milestone 3. The tests where all conducted in the beginning of the year itself. This year more verification layers were added to the TraceBot demonstrator at Astech. The verification layers include the addition of the tactile verifiers on the CEA grippers and the service for this has also been integrated into the software framework of the TraceBot demonstrator as well. This tactile verifier along with the visual verifier adds an extra layer of confidence in predicting the feasibility of the process execution and helps improving the robustness of the TraceBot system as a whole. All these additions of the verifiers have

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been explained and discussed in detail within this document in Section 3. The testing of these new verifiers is scheduled to be done by the end of the month of January 2025, as there is a final integration workshop scheduled in the mid of February 2025. These testing methodologies will be the same as mentioned in deliverable D6.3 for Milestone 3.

The final testing of the integrated demonstrator system at ASTECH will be done after the last integration workshop in the month of February 2025, which will be the final testing in terms of Milestone 4.

[WP7] Demonstration at external conference/fair

BioLAGO: Milestone 4, as defined under Work Package 7, has been successfully achieved through the demonstration of the TraceBot system at prominent external events, underscoring the project's commitment to effective dissemination and stakeholder engagement. These activities have provided a platform to present the innovative results of the project to a diverse audience of stakeholders from the scientific, industrial, and healthcare sectors, emphasizing the transformative potential of the TraceBot system in laboratory automation.

TraceBot has been showcased at key international venues, including the Future Labs Life fair in Basel and the Life Science Open Space conference in Kraków. These events have highlighted the system's advanced capabilities, facilitating engagement with industry leaders, researchers, and potential adopters of the technology. Both events have served as critical opportunities to position TraceBot as a groundbreaking solution in healthcare and laboratory automation.

As part of further dissemination efforts under Milestone 4, TraceBot was prominently featured at the second Robotics for Lab Automation Symposium held in Konstanz, Germany. This international event, organized by BioLAGO, brought together experts in laboratory automation from across Europe to discuss innovations and advancements in robotics. The symposium included engaging sessions on current developments, with a particular focus on TraceBot's progress. Highlights included a presentation by Prof. Markus Vincze from TU Wien on breakthroughs in the perception of transparent objects and a talk by Dr. Charly Coulon from Invite GmbH on practical applications of TraceBot results for industry.

The event's keynote address, delivered by Miriam Guest from Charles River Laboratories, explored the integration of automation in GMP laboratories, providing valuable insights into the transformative impact of robotics on laboratory operations. A panel discussion featuring international experts further emphasized how modern robotic solutions enhance efficiency and safety in laboratory workflows.

In addition to these dissemination efforts, the consortium is planning an exploitation-focused event following the project's conclusion. This event will further communicate the project's results, engage with stakeholders on commercialization pathways, and explore opportunities for the sustainable application of the developed technologies. These coordinated activities reinforce TraceBot's significance in advancing robotic technologies and its contribution to the future of laboratory processes.

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6 Deviations from the workplan

The only major deviation from the proposed work plan was on completion of the pump's software integration into the TraceBot system's software environment. This delay or deviation was caused due to the lack of support of a software API for the pump. Astech did try to contact the manufacturer of the pump to obtain the API. The manufacturer "Merck" has their own proprietary software to control the pump digitally and was not ready to share the technology with Astech or the TraceBot consortium. This made controlling the pump via a software challenging as it was not an open-source software rather, an embedded operating system on the pump. Hence after raising these challenges within the TraceBot consortium, it was decided that the pump will be manipulated manually by the TraceBot robotic arms and hence a new process was designed for this purpose, called pump manipulation.

No, other major deviations in the work plan were faced within this year integration efforts for the TraceBot System.

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7 Conclusion

This deliverable presented information on the advancement of the integration process after the completion of the fourth milestone. The main outcome of this deliverable is the integration and deployment of the two CEA dexterous Grippers at the demonstrator site at Astech. The demonstrator is now able to perform the manipulation of the canister, the tube and the needle with a bi-manual system, involving the perception layers for detecting and verifying these objects, as well as the bridge with the Digital Twin to maintain an updated digital view of the overall scene. Additional verification layers, such as the tactile verifier, are now available with the new CEA grippers.

The use cases canister insertion in the pump tray, the tube insertion into the pump and the needle cap removal and bottle insertion are the three use cases combined on the demonstrator. Additional work is needed on the pump manipulation use case, as the deployed system is still pending to be tested with this use case. The object detection with the "Gdrnpp" method of perception layer is now fully functional at the demonstrator site.

The integration process and testing of the two new CEA dexterous gripper and the tube manipulation are the key advancements achieved for the completion of the fourth Milestone of TraceBot. We also provided information to describe the other items related to this milestone such as the methods needed to be followed for the sterility certification testing and normal acceptance testing.

The achievement of the integration process was ensured by following the communication dynamic used in the previous years, with periodic follow up meetings, initially every two weeks, and then every week when getting close to the Milestone period. This enabled to make the final integration session in November at Astech a successful event as the work was well prepared.

In 2025, we are approaching the end of life of the project, and we envision on maintaining the integration efforts, to continue improving the TraceBot demonstrator at Astech.

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