Towards Robotic Laboratory Automation
Plug & Play: Teaching-free Robot Integration with the LAPP Digital Twin

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Abstract
The Laboratory Automation Plug & Play (LAPP) framework is a high-level abstraction layer that makes the autonomous operation of life science laboratory robots possible. The plug & play nature lies in the fact that the manual teaching and configuration of robots is not required. A digital twin (DT) based concept is proposed that outlines the types of information that has to be provided for each relevant component of the system. In particular, for the devices that the robot interfaces with, the robot positions have to be defined beforehand in a device-attached coordinate system (CS) by the vendor. This CS has to be detectable by the vision system of the robot by means of optical markers placed on the front side of the device. With that, the robot is capable of tending the machine by performing the pick-and-place type transportation of standard sample carriers. This basic use case is the primary scope of the LAPP-DT framework. The hardware scope is limited to simple benchtop and mobile manipulators with parallel grippers at this stage. This paper first provides an overview of relevant literature and state-of-the-art solutions, after which it outlines the framework on the conceptual level, followed by the specification of the relevant DT parameters for the robot, for the devices and for the facility. Finally, appropriate technologies and strategies are identified for the implementation.

Keywords: Laboratory Automation, Mobile robotics, Autonomous manipulation, System integration, Plug and Play, Digital Twin

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1. Introduction

This article is the second in the series *Towards Robotic Laboratory Automation Plug & Play*. The first paper outlined the concept in a high-level fashion and stated the fundamental goal for the Laboratory Automation Plug & Play (LAPP) framework: to provide a comprehensive high-level technical abstraction for robot-focused laboratory automation [1]. The top level in this context is considered to be the process representation and scheduling layer, which serves the orchestration of the laboratory workflows. This includes communication and control aspects considering various types of (semi-)automated laboratory devices and robots.

The framework aims to simplify the integration and set-up process for these types of robots by freeing the integrator/user from the burden of manually setting up the communication and teaching the robot motions. As a crucial part of the LAPP framework, the digital twin (DT) layer enables the storing and sharing of the robot-relevant information in regard to the various components of the system. Most importantly, the positions for navigation and arm control have to be stored in a standardized fashion and provided with the device out-of-the-box. Using these pieces of information a mobile manipulator (MoMa) will be - after localizing the device with a fiducial marker - capable of tending the device in a plug & play manner.

Both the over-arching LAPP framework and the DT layer are created in a scalable and extendable manner throughout an evolutionary development process. This approach can be outlined with the following bullet points:

- The concept is first formulated in an abstract and high-level fashion and will be concretized and adapted with the involvement of the professional community throughout continuous evolution.

- The definition of the framework fundamentally focuses on the already existing and established building-block technologies but will be suitable to incorporate new developments, such as advances in collaborative robotics.

- Initially, a limited set of typical laboratory tasks that are already subject to a certain level of automation/robotization will be considered. Later, as the point above suggests, new technologies will enable covering more complex tasks that the framework also has to be able to incorporate.
The LAPP framework focuses at first on a specific type of MoMa that is now used by multiple solution providers for sample transportation in automated laboratories. For this, the typical lab automation MoMa anatomy is considered. Such a robot consists of a wheeled autonomous mobile base capable of simultaneous localization and mapping (SLAM), a robot arm of four to seven degrees of freedom (DoF) and a vision system that aids the fine position detection for gripping and manipulation planning. A MoMa can be considered as the most complex robot system in our scope, which represents the broadest variety of components. As such, simpler robots (e.g., stationary or rail-mounted arms) can be derived from this set by omitting certain components (e.g., mobile navigation).

On the use case side, the concept is developed at the first stage for simple pick-and-place type sample transportation and machine tending without any physical interaction with the equipment. Complex robot-equipment interactions will be elaborated in follow-up articles.

The paper starts with section 2 which provides an overview of the relevant literature and state-of-the-art solutions in regard to the vertical of robot-centered laboratory automation systems. Starting with the top-level concepts, section 2.1 reviews different standard solutions for representing the laboratory workflows on the high level. Then, section 2.2 takes a step towards the lower-level aspects of representing robot behaviors. With section 2.3 the lowest level is reached by reviewing how prevalent manual teaching approaches work. To conclude the literature and state-of-the-art review, the digital twin (DT) approach is reviewed, which will serve as the basis of the LAPP-DT proposal. In section 3, a systematic distinction is provided for the various levels of automated laboratory workflows. The proposed LAPP-DT concept is elaborated in section 4, followed by identifying and discussing key challenges and enablers in section 5. For implementing the concept, pieces of the technological stack are discussed in section 6. Finally, the next steps are introduced in section 7 and the paper is concluded in Section 8.

2. Literature and the state-of-the-art

2.1. Workflow representation approaches

As discussed in [1], the representation of laboratory workflows is a very important aspect in automation. Ultimately, a process can only be automated if it is adequately described by a machine-readable format. For that, not only the sequence of actions has to be prescribed but also their input parameters, conditional relations and the control flow. This section provides an overview of the relevant state-of-the-art solutions that address this problem. As such, the process modeling language BPMN provides a general high-level solution for this purpose by implementing a graphical (flow-chart like) representation with a back-end that enables executing it on process engines.
Biological protocols have special requirements that general solutions may fail to fulfill. After all, a biological protocol is very different from a business- or a manufacturing process both in the subject of the actions and in the required parameters. The Protocol Activity Markup Language (PAML) provides an open representation for biological protocols [2]. The framework aims to make it possible to communicate and reproduce the representations across different projects and even different laboratories with different equipment. For that, the representation has to be unambiguous but abstract enough to enable reuse. Also, both automation systems and humans have to be able to interpret it. PAML is based on well-established technologies, such as UML, Autoprotocol and Synthetic Biology Open Language (SBOL). It provides representation not only for protocols, execution records and the resulting data, but also for the requirements towards the execution framework. UML is used for semantically modeling the behavior in a domain-independent manner. In the PAML representation, the basic building block is a Behavior, which is an abstract specification on how the state of a system changes over time. An Activity, on the other hand, represents the sequence of steps behind that change. Flow control is implemented by token-passing, which enables serial, parallel, non-deterministic and distributed execution. The representation of laboratory primitives, such as liquid handle and incubate is implemented with Autoprotocol. A protocol is defined as a sequence of instructions. An extensible SBOL-based data model is used to store the UML and Autoprotocol elements in an object-oriented fashion. The extendable library of laboratory-independent primitive behaviors aligns the primitives with equipment that is capable of performing them. With that, the execution environment can be defined by the set of primitives that it supports. SBOL is used for unambiguously identifying and defining the compounds, such as strains, reagents, media and sample designs. Specifications, samples and data are linked via traces of activities. These are stored in a serialized format, which enables versioning.

On one hand, PAML serves for the LAPP framework as a reference regarding the technical implementation. On the other hand, PAML is considered as a layer in the automation hierarchy that resides above LAPP. PAML is in fact responsible for representing the biological workflows, where the implementation of a laboratory primitive is considered as a black box. The implementation of the laboratory primitives can take place by the means of robotic actions, which are an essential part of the LAPP framework.

When it comes to robotic activities, it is important to distinguish the different levels. Chu [3] and D. Nagy et. al [4] both provide hierarchical decompositions in this regard. Although the field of application and the nomenclature is different, the corresponding levels can be identified, as presented in Table 1. In the fourth column, the levels of the LAPP hierarchical decomposition are shown that are discussed in detail in section 3.
Table 1: Hierarchical decomposition of robotic activities in different nomenclatures, from lowest (bottom) to highest (top) level

| Vedula | D. Nagy | Chu | PAML | LAPP |
|--------|---------|-----|------|------|
| Procedure | Operation | Autoprotocol lab primitives | Process |
| Task | Task | Task | Subtask |
| Maneuver | Subtask | Task motion | Subtask |
| Gesture | Surgeon | Motion element | Action primitive |
| Motion primitive | Motion step | Motion primitive |

Table 2: Types of conventional robot movements

| Name | Meaning | Characteristics |
|------|---------|-----------------|
| MoveJ | Joint move | Optimal joint-based movement with non-prescribed path |
| MoveL | Linear move | Prescribed linear path |
| MoveC | Circular move | Prescribed circular path |
| MoveP | Process move | Defined path and velocity (e.g., for welding or dispensing) |

2.2. Representation of robot actions

As discussed above, the robotic actions are on the low-level side of the automation system and are considered as the means of implementing higher-level tasks. In this subsection, various robot behavior representation approaches will be discussed.

In its simplest form, a robot program is just a sequence of pre-taught movements and I/O operations, potentially with some basic logic operations, branching and loops. Table 2 shows the various types of conventional robot movements (using Universal Robot’s nomenclature).

In more complex robot applications, simple movements might need to be grouped and organized for modular reusability. This enables a sequence of movements to be performed throughout the robot program multiple times, potentially on multiple different objects.

Besides industrial robotics, an increasing number of new application fields are arising. One of these is robotic surgery, which represents a radically different set of requirements but utilizes many advantages of the fundamentals. As such, the accuracy and repeatability of robots is a key factor when it comes to teleoperated or (semi-)autonomous robotic surgery. The latter application means that during a robot-actuated surgery - i.e., when the surgeon controls the robot’s movements - the robot could take over some simple tasks to relieve the surgeon. To achieve this, the tasks have to be defined in the fully descriptive manner. As the basis of these representations, analyzing how a human surgeon...
performs the task can be considered [5]. Nagy et al. propose a framework for surgical subtask automation based on the Da Vinci surgical robot, for which they provide a hierarchical structure to handle the different granularity levels of surgical motions [4].

Laboratory automation represents special needs towards robotic solutions concerning the complexity and variability of the tasks [7]. Chu proposes the concept of Motion Elements (ME) specifically for the automation of a complex sample preparation laboratory workflow [3]. He considers robot movements from one position to another as a motion step and groups them in reusable units termed as motion elements. A motion element can either be of path-type (P-element) or relative (R-element). The former is composed of fixed motion steps, while the latter is composed of changeable motion steps. P-elements can be used to move the robot arm/arms to a suitable position for executing relative motion elements while avoiding collisions and singularities. R-elements, on the other hand, are relative to a certain CS and are suitable of performing repetitive tasks. An R-element, also referenced as "Motion Frame", consists of motion steps, a variable interface and a reference point. Reference points can be predefined statically or dynamically, or relative to the actual position of the robot arm, in which case they are referred to as a virtual reference point. A static reference point can be for example a fixed user CS corresponding to a fix-mounted shelf or platehotel. On the other hand, a dynamic reference point can correspond e.g., to a microplate, which can be placed on multiple bench positions. Virtual reference points can be used e.g., for dual-arm tasks, such as unscrewing a vial cap with one arm while holding the vial with the other arm. To store the motion elements, Chu proposes a so-called motion database.

2.3. Manual teaching

At the current state of technology, robotic manipulators in laboratory automation are mostly intended for transporting standard SBS-format microplates between different laboratory devices. To make this possible, in most cases, online teaching takes place when setting up the robotic system. This means that the positions are manually set either by moving the robot by hand or by jogging it with the controller. Figure 1 shows the coordinate systems (frames) and positions that are typically used in laboratory robotics scenarios.

In the case of stationary robots, either the robot configuration is stored for each position in the form of joint values, or the position is directly prescribed in relation to the robot’s base CS (r in Fig. 1a). Between these taught positions, different types of movements are possible, as presented in Section 2.2. Usually a sequence of intermediary approach positions are defined for the robot, before it reaches a final hand-over site with its gripper TCP. This is to make sure that no collisions occur between the robot and its surroundings, including the device it is supposed to load with samples. A typical sequence of steps for a pick-and-place task from site 1 (s1) to site 2 (s2) is presented below, using the coordinate systems in Fig. 1a.
Figure 1: Coordinate systems in the LAPP environment, d: device CS, g: robot’s tool center point (TCP), h: home position for robot m: fiducial marker for device; r: robot’s base, PoI: base pose for station, s: hand-over site (plate nest) of device, sd: device approach position, ss: site approach position, u: stand-by position for robot, w: world.
• The robot starts in its home position (h)
• Performs a MoveJ-type movement to "untangle" itself and arrive to the standby configuration at the position u)
• Moves linearly (MoveL) to a device-approach position (s1d)
• MoveL to a site-approach position (s1s)
• MoveL to the final site hand-over position (s1)
• Grips the plate
• MoveL back to s1s
• MoveL back to s1d
• MoveL to s2d (not displayed)
• MoveL to s2s (not displayed)
• MoveL to s2 (not displayed)
• Releases the plate
• MoveL back to s2s
• MoveL back to s2d
• MoveL to u and returns to standby/ready state

As described in 11, in the case of mobile manipulators, on the other hand, the positions are defined in relation to a fiducial marker, which is in most cases an optical augmented reality (AR) marker 8 (Fig. 1b m). This is necessary because the precision of the mobile base (Fig. 1b r) is not sufficient for the positions to be defined in a word-fixed CS (Fig. 1b w).

The robot itself is keeping track of its coordinate systems (frames) by maintaining a transfer tree, where relations between the frames are expressed. For example the pose of the camera frame and the TCP are both known in relation to the robot’s base frame. When the arm is moving, the system regularly updates the corresponding chain of frames based on the kinematic model and the joint angles (forward kinematics).

The teaching process for marker-guided MoMas typically consists of the following steps, as deduced from the feature definitions for Astech Projects’ MoMa 9 and from the Fraunhofer IPA’s Kevin Webinar 10 (Markings of Fig. 1b are used):
• The operator drives the robot to the station and makes sure the marker is in the camera’s field of view

• This pose of the mobile robot is stored as a point of interest (PoI) with the station’s name $T_0(w \rightarrow PoI)$

• The vision system determines the transformation from the camera frame to the marker frame: $T_1(c \rightarrow m)$

• The operator moves the arm to the hand-over position so that the TCP and the site coordinate systems align: $T_2(g = s)$

• Based on the robot kinematics model, the relation between the camera frame and the TCP ($T_3(c \rightarrow g)$) is determined

• The relation between the marker and the hand-over site is calculated: $T_4(m \rightarrow s)$

Similarly to stationary robots, the intermediary positions (ss and sd in Fig. 1b) can be taught additionally. The concept proposed in this paper provides a solution for eliminating the need for manual teaching and setup. For that, the standardized representation of the teaching positions and other relevant parameters based on the digital twin approach is presented in section 4.

2.4. The Digital Twin approach

One of the most important aspects of the LAPP framework is that it provides an information layer of the assets of the laboratory. As proposed in [4], a LAPP-enabled laboratory device has a DT representation containing its parameters. These include both parameters that are constant and assigned when the device is manufactured as well as parameters that change during the operation of the device and that describe the current state. The approach of a virtual representation of physical entities aligns with the digital twin (DT) concept. In this section, an overview of the DT concept is provided and the relevant nomenclature is specified. Originally, this concept was proposed by Michael Grieves at NASA [11] for product life cycle management purposes. Maintaining a virtual representation of a physical entity and implementing bi-directional data connections enables a variety of virtual operations ranging from modeling through testing to optimisation. All of these operations correspond to a specific sub-space of the digital twin. Generally, data is fed from the real space to the virtual space, and information is fed back alongside with processes. A DT accompanies the product throughout its entire life cycle and, according to the specific stage, can take up different forms. In parallel to the design phase of the product, a prototype of the DT is also developed, which is then instantiated for each physical product individually. The whole set of these instances make up the aggregate and they all reside in the corresponding environment. The state of both the physical and the virtual entities are stored in the form of parameters. These can be either static parameters, so-called prototype parameters that have
Table 3: Parameters of the digital twin [12]. Elements that are relevant to the LAPP framework are underlined.

| Parameter   | Characteristics                                                                 |
|-------------|----------------------------------------------------------------------------------|
| Form        | The geometric structure of the entity Can contain dimensions, CS definitions and 3D models |
| Functionality | The entity’s capabilities, movement or purpose, Definition of the control interface and parameters |
| Health      | State of the entity with respect to its ideal state                                |
| Location    | Position and orientation (pose) With respect to the environment, layout or other entity |
| Process     | Activities in which the entity is engaged, Scheduling parameters and models        |
| Time        | Duration to complete an activity, Timestamp                                        |
| State       | Measured (live) values of entity and environment parameters                         |
| Performance | Measured operation with respect to the optimal operation                           |
| Environment | The physical and virtual environment as a parameter                                |
| Miscellaneous | Requirements Qualification                                                        |

the same value for each piece of the same product, or instance parameters that correspond to a specific physical specimen.

Since the proposal of the original concept, the DT notion has been adapted to a broad variety of use-cases. Jones et al. [12] provide a systematic review of the related literature by means of a thematic analysis and characterisation. The paper also consolidates the terminology in regard to the terminology, which will be followed in the context of the present article. Jones et al. also specify the parameters that are often used for digital twins, which is summarized in table 3.

The DT concept is broadly applied for smart manufacturing use cases [13, 14, 15, 16], and there are also numerous examples of robotics applications, where the DT may have different goals. These range from the education of future engineers [17, 18] through human-machine interactions [19, 20, 21] and control [22] all the way to programming [23, 24]. Tipary and Erdős propose a design approach that utilizes parametric digital twins of robotic workcells for planning and programming [25, 26]. To adapt the off-line created robot program to the physical workcell, calibration and manual adjustments are needed in on-line mode most of the time. To bridge this gap, they define the so-called Digital twin closeness as the measure of the “geometric difference between the digital and physical counterparts of Digital Twins for robotic workcells”. Their DT comprises the models in table 4. The LAPP-DT concept presented in this paper
Table 4: Models in Tipary’s robot cell DT

| Model            | Content                                                                 |
|------------------|-------------------------------------------------------------------------|
| Kinematic model  | Geometry, kinematic behavior and component relations                    |
| Grasp model      | Workpiece - manipulator relation through the gripper                    |
| Path model       | Manipulation sequence and manipulator motion                            |
| Servo model      | Condition-based manipulation (observation-based)                       |
| Metrology model  | Providing information to other models and planner tools                 |
| Tolerance model  | Represent the tolerance stack-up of the operation to assess its feasibility |

follows an approach that shares many aspect with Tipary’s DT. See section [4]

3. Hierarchical decomposition of automated laboratory processes

To bring the various layers and components of laboratory automation into a cohesive system, this section presents a hierarchical decomposition approach. According to this, a laboratory workflow can be decomposed along five hierarchical levels, as shown in Fig. [2]. In regard to automation, these correspond to different levels of process control. In the last column, the span of existing workflow representation and control approaches are displayed. In this context, the focus is laid on robotic actions, but general aspects are also briefly mentioned without elaborating them in detail. Liquid handling tasks, for example, lie outside the scope of this paper. These are covered by numerous commercial solutions, for example gantry-type liquid handlers, such as those from Tecan, Hamilton, Beckman Coulter or OpenTrent, and flexible liquid handlers, such as the Andrew+. On the other hand, multiple research projects focused on fulfilling this task with robots [28]. Section [2.3] discusses the robot-related aspect in detail.

In the proposed hierarchy, the highest level is the process/workflow, which covers the entirety of the process, such as an experiment or assay. The processes are different depending on the context, i.e. which discipline of life sciences the laboratory serves. In biological laboratories, these mostly revolve around cell culture processes, ranging from upstream through downstream to analytics. As an example for the latter, a high pressure liquid chromatography (HPLC) workflow is considered. On the high level, entire workflows can be represented by BPMN or PAML, as discussed in section [2.1].

The next level is that of the task, which is carried out by components of the system, i.e. by a certain device. An example is the HPLC method itself, which is carried out by the HPLC system. On this level, the control is implemented by the device controller, which runs on the built-in or stand-alone dedicated computer [29].
The subtask level is considered as an intermediary layer that corresponds to activities of a component accomplishing minor landmarks, such as picking up a microplate as a part of a transport task.

The most important level in this context is that of the robotic action primitives (RAP). RAPs describe a robotic activity, which is considered to be elemental from the perspective of the laboratory automation controller. These parameterizable abstract actions accomplish meaningful outcomes on the lowest level, e.g., by gripping a plate. The navigate activity is also assigned to the RAP level, although it does not directly belong to a subtask but is part of the transportation task. Establishing a comprehensive canonical set of these action primitives is the subject of future work.

In the context of this article, the focus is laid on the actions that belong to the simple transportation task of standardized microplates. Section 4 presents the proposed teaching-free (plug & play) robot control strategy based on this use case.

A RAP serves as an abstraction layer that comprises the low-level robotic motions. These are considered as the lowest level in the hierarchy: the motion primitives. They can be represented as simple robot movements, as discussed in section 2.2. Section 4 presents the motions needed for performing a pick-and-place task.

| Level                    | Example                             | Technology                  |
|--------------------------|-------------------------------------|-----------------------------|
| Process/Workflow         | Chromatography workflow             | PAML, BPMN                  |
| Task                     | Liquid handle                       | ME                          |
| Subtask                  | Pick up microplate                  | SILA, LSS                   |
| Action Primitive         | Approach plate                      | Robot control: ROS, LAPP-AP |
| Motion primitive         | Grip plate                          |                            |
|                          | Navigate                            |                            |
|                          | MoveLs2d                            |                            |
|                          | MoveLs2s                            |                            |
|                          | MoveLs2d                            |                            |

Figure 2: Hierarchical semantic decomposition of laboratory activity
4. Teaching-free operation with the LAPP Digital Twin

As outlined in [1], the LAPP framework aims to make the whole set-up process fully automatic, all the way from map generation with simultaneous localization and mapping (SLAM) to determining the above-mentioned coordinate frame transformations. According to the LAPP approach, the positions (s, ss, sd in Fig. 1b) have to be defined in relation to the marker frame (m in Fig. 1b) in cartesian space. To make this possible, first the workpiece CS has to be defined. Since the most common workpiece in this context is an SBS-format microplate, this is taken as a basis. In Fig. 3 the axes are defined, as overlaid on the drawing from the ANSI/SLAS standard [30].

Figure 3: Definition of the plate CS (Overlaid on [30]) (US projection). Viewing from an upper view, the origo is placed to the centerpoint of the plate, whereas the height is set to the middle of the bottom rim. When looking at the plate from above with well A1 being on the top left, the x axis points to the right, the y upwards, and z outwards. The TCP for the gripper and the CS of the hand-over site are defined in a way that their origo aligns with the plate CS and the axes either align or are rotated 90 degrees along the z axis (e.g., in portrait mode gripping, as seen in 4). The site CS is defined similarly, derived from the plate CS.

As discussed above, in the LAPP framework the positions are defined in relation to the marker frame in cartesian space and not in the robot’s CS in joint space. This enables a robot-independent implementation of the movements thanks to the fact that the positions belong to a certain site of a workstation or device and not to one specific robot. This makes sharing the positions between multiple robots possible. Ultimately, it can be assumed that a certain model of a laboratory device always has the same geometry, i.e. the hand-over site is at a pre-defined location of the device. Supposing that the marker is also at a fixed and known position, the transformation T5 (as displayed in Fig. 1b) can be deduced. The LAPP framework thus requires the device vendor to include the marker in the design of the device. The marker must be in a visible location, on the same side from where the robot has to access it. It is also the vendor’s responsibility to provide the information shown in Table 5 as part of the digital twin prototype of the device (See section 2.4 and Table 2 in [1]).
In general, DT parameters are distinguished in the LAPP framework as follows:

- **Prototype parameters** are unified for all specimens of the same make and model. See Table [5]
- **Instance parameters** override and extend the prototype parameters with instance-specific data
  - **Static parameters** remain unchanged during the entire lifecycle of the instance. E.g. serial number
  - **Volatile parameters** represent the current state of the instance
    - **Observable properties** represent real-time or semi real-time data streams. E.g. sensor streams, continuous progress updates
    - **Unobservable properties** are updated only upon specific request. E.g. calibrated positions

With the help of this information, a LAPP-enabled MoMa with a calibrated camera system will be capable of performing the setup fully autonomously, as presented in Fig. 1 of [1]. After that, in ideal circumstances, the pre-defined robotic actions can be performed right away, without requiring any manual input from the integrator or operator. This is the functionality referred to as plug & play. As a part of the sequence presented in [1], the coordinate transformations are determined and the digital twin instances are parameterized, as presented in table [6]
The relation between the frames and positions in such a system depend on each other in that one frame is defined as a transformation of another frame. This means that the frames can be represented in a graph structure, such as in Fig. 5, where the nodes are the frames and the edges are the transformations. The fact that fairly long chains of interlinked frames can form means that the uncertainties of each transformation can accumulate. These uncertainties are inevitably present both in the form of mechanical imperfections causing deviations from ideal geometries and in the inherent inaccuracies of the metrology systems [31]. These have to be taken into account by storing the uncertainty for each transformation in the digital twin. Also, a requirement in regard to precision has to be specified for the specific robot action. This enables the process controller to match the requirement with the actual precision and determine if the specific system is capable of performing the requested action.

It is also important to mention, that the parent-child relations in a transform tree can change, if a more accurate definition is available. For example the following case can be considered: When the robot moves to a certain PoI, the system can assume the approximate positions of the devices as defined in relation to the map $T_6(w \rightarrow d)$. However, the vision system can deliver a far more accurate relation between the robot and the marker ($T_1(e \rightarrow m)$), which, along with $T_4(m \rightarrow s)$ can be used for motion planning of the pick & place subtask. For this, a sub-tree from the robot frame (r) can be temporarily created, as presented in Fig. 6.
Table 6: The plug & play setup sequence, markings of Fig. 1b used

| Description                                                                 | Transform. | DT parameter type | DT instance       |
|----------------------------------------------------------------------------|------------|-------------------|-------------------|
| During the autonomous room discovery procedure, the map is generated       | $\mathcal{w}$ | Form              | Room (instance)   |
| Simultaneously, the approximate device positions are detected with the markers. Since $d$ and $m$ are already connected by the DT prototype of the device, and the robot is at the PoI $d$ is now defined in $w$. | $T_6(w \rightarrow d)$ | Location | Device (instance) |
| The hand-over site position is taken from the DT prototype of the device   | $T_4(m \rightarrow s)$ | Form              | Device (prototype) |
| If necessary, this position can be overridden (calibrated) and stored in the DT instance of the device. | $T_4, cal(m \rightarrow s)$ | Form              | Device (instance) |
| The robot kinematics can be re-calibrated and stored in the DT instance of the robot | $r \rightarrow g$ | Form              | Robot (instance)  |
5. Challenges and key enablers

Traditional laboratory robots are usually taught in joint-space, which means that the robot configuration is stored directly in the form of joint values for each position. This results in the fact that the accuracy of the robot’s kinematic model is not of crucial importance. On the contrary, when the positions are specified in world coordinates, the robot controller has to perform the inverse kinematics calculations to determine the corresponding joint values. For this, the robot’s geometry has to be precisely modeled, e.g., by Denavit–Hartenberg parameters or by the Unified Robot Description Format (URDF). These are specified initially for each robot model during the design process. Following the DT notation, this data corresponds to the DT prototype of the robot model. Due to manufacturing imperfections, however, each piece of a finished robot has slightly different geometries in reality, which has to be readjusted by the means of calibration. These new parameters are stored in the DT instance for the certain robot. To achieve the sub-millimeter precision required for efficient and reliable plate manipulation, the possibility has to be kept open for the robot to be re-calibrated.
Another distinction is between online vs. offline teaching. Online teaching means that the positions are taught directly on the physical robot by moving its end-effector to the desired positions manually. In this case, the robot’s repeatability is more important than its absolute accuracy; what matters is that the robot is consistent even if systematic error is present. Offline teaching means that the positions are defined without the physical robot, e.g., in the case of the LAPP approach by the device vendor. In this case, the absolute accuracy is just as important as the repeatability, since consistency is not sufficient if the position is off. Therefore, the precision requirements towards a LAPP-enabled robot have to be formulated adequately. For digital twin based offline teaching scenarios in particular, the digital twin closeness to measure such precision is defined by Tipary et al. [26] (see section 2.4).

Besides kinematics, the mechanics of the robot also play an important role in the robot’s precision. One such effect is that no mechanical system is perfectly rigid but flexible and compliant to a certain degree. Reasons behind this are on one hand the mechanical properties of materials: depending on a component’s shape and its elastic modulus, it bends under load. On the other hand, the joints of robots consist of bearings and gear systems, which might have mechanical play or backlash. These two effects result in the whole structure diverging from the ideal position when under the effect of internal and external forces, which could be calculated by pure kinematics. These effects have to be either mechanically minimized or countered by a suitable controller.

6. Technologies

To make the plug & play functionality possible, a series of complementary technologies have to be consolidated and integrated into a comprehensive stack. To this end, different competing and overlapping solutions were evaluated. Since compatibility is a crucial factor, established and widespread standardized solutions are preferred.

As described in [1], setting up a robot-based laboratory automation system begins with representing the process on the high-level to enable execution on an all-round process controller, as described in section 2.1. Below this level, the robot-specific actions have to be represented in the appropriate abstraction level, for which the LAPP RAPs are proposed and are subject to future work. On the low-level - i.e. on the robot’s side - a versatile robot control framework is needed that is capable of incorporating advanced techniques for perception, navigation and motion planning. The Robot Operating System (ROS) proves to fulfill these requirements.

To enable the communication between the different components and levels of the system, a suitable interoperability protocol is needed. The communication protocol developed by the Standardization in Laboratory Automation (SiLA) consortium provides such a solution specifically for laboratory automation purposes. The organization currently endeavors to extend the robot-related functionality, including the implementation of a SiLA-ROS bridge [32] and the unification of the feature definitions [9].
Besides that, a suitable platform is needed for the digital twin representation that can incorporate the necessary parameters. The Asset Administration Shell [33] is identified as a suitable solution.

7. Future Work

The LAPP framework, including the LAPP-DT and the RAPs, is at this point a conceptual proposal that is elaborated in the course of an article series entitled *Towards Laboratory Automation Plug & Play*. This present paper is the second in this series, which takes a step in concretizing the proposal with the focus on robotics. The series follows a top-down approach, which means that the follow-up articles will progress towards the lower technical levels of the framework and provide implementation examples and feasibility studies.

As such, the robotic action primitives are identified as the next work package to be elaborated. RAPs are considered as one piece of information that has to be represented in the digital twin. In general, the digital twin properties have to be defined for each type of component in detail, including the identification of suitable standardized representation formats. Further work has to focus on the technical implementation by utilizing the technologies discussed in section 6. Also, the challenges mentioned in section 5 have to be addressed.

The first stage of the implementation is limited to benchtop manipulators and ground-bound mobile manipulators from the hardware side, both with simple parallel grippers. On the use-case side, the scope is focused on pick-and-place type transportation of standardized objects, such as SBS-microplates. Next stages of the development may broaden this scope in regard to both aspects. On one hand, a higher diversity in lab automation robotic hardware can be covered by including emerging technologies. As such, miniature MoMas that drive on the bench or on tracks at ceiling level [34] and drones [35] open up new dimensions regarding flexibility and they also require new approaches concerning navigation. On the other hand, advanced end effectors, such as five-finger [36] or soft grippers, open up new possibilities to manipulate objects that are fragile and/or have complex geometries. Ultimately, flexible marker-less manipulation can be achieved by the means of advanced perception, such as 3D object detection [37] and tactile sensing [38, 39]. These techniques make it possible to detect the pose of the workpiece and to plan the manipulation movement without pre-taught positions. Besides that, the planning also has to consider the constraint space containing, inter alia, the obstacles around the working area. Similarly to the other DT parameters, an appropriate standardized format has to be identified to store and share this information between the different components of the system.
8. Conclusion

As a part of the Laboratory Automation Plug & Play framework, a method for teaching-free robot setup was proposed. The review of the relevant literature and state-of-the-art technologies provided an overview of the building blocks and competing technologies. A hierarchical decomposition of laboratory workflows presented a cohesive system to discuss these aspects. Based on this, a side-by-side comparison of solutions was also presented, outlining the scope of each and how LAPP and its DT framework fits in and completes the ecosystem. It can be seen that different levels of the laboratory automation pyramid are addressed by overlapping solutions. LAPP aims to serve as a conceptual framework for combining mostly existing standard solutions and extending these to achieve true plug & play integration for laboratory robots.

Conflict of interest statement

Ádám Wolf is an employee of Takeda Manufacturing Austria AG, Vienna, Austria. Stefan Romeder-Finger is an employee of Baxalta Innovations GmbH, a Takeda company, Vienna, Austria and stockholder in Takeda Pharmaceutical Company Limited.

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