

Óbuda University

PhD Thesis Booklet



**Integration framework for robotics
in life science laboratories
Laboratory Automation Plug and Play**

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1 Antecedents and background

Automation and its corresponding supportive technologies are set to become prevalent across the life science laboratory landscape. This thesis focuses on creating an integration framework targeted at these ecosystems. By unifying semantics, information models, and system architecture, the aim is to facilitate the interoperability of supportive subsystems within the overarching automation systems.

Modern-day pharmacy operates within a highly regulated global industry. Advanced technologies, stringent quality control measures, and extensive Research and Development (R&D) ensure the safety, efficacy, and accessibility of medications worldwide. Throughout the process development cycle, several scale-up stages can be observed, transitioning from laboratory through pilot to manufacturing scale. At each stage, regulatory requirements progressively increase, ultimately reaching a Good Manufacturing Practice (GMP)-ready stage.

Both Process Analytical Technologies (PATs) (sensing) and mechanical (actuation) technologies play a critical role in this progression, representing the manufacturing and laboratory system's "senses" and "muscles." Additionally, analytical technologies are vital for Quality Control (QC), where a variety of predefined and regulated tests must be performed on samples from various production stages.

In R&D, specifically, a constant decline in efficiency can be observed since 1950 [1]. This is attributed to factors such as market saturation, stricter regulatory requirements for new drugs, and inefficient resource allocation. Eroom's law states that the number

of drugs developed per billion US\$ is declining logarithmically [2]. To address this decline in efficiency, advanced technologies such as robotics have emerged as promising tools to enhance productivity and streamline processes in research and development.

Robots are used for a wide range of tasks in life science laboratories [3, 4, 5] [WA1]. While many laboratory devices are already automated as standalone units, most are not optimized for integration into overarching automation systems [6]. These devices are often designed for human operation with interfaces such as touch screens and keyboards [7], necessitating human intervention for tasks such as loading samples and transporting them between devices.

Fleischer et al. define flexible robots as systems that, beyond transportation, also perform other laboratory tasks such as sample manipulation [8]. According to Fleischer et al. [3], laboratory robotics solutions can be categorized into two configurations:

- Fixed-position robots surrounded by all devices, tools, lab-ware, and consumables.
- Mobile manipulators that approach different stations while transporting and manipulating samples, enabling an open automation system.

In laboratory automation systems, supportive robots and peripherals play a crucial role in material flow between individual stations. Bench-top robot arms, whether stationary or rail mounted, are now offered by multiple integrator companies. These systems typically focus on handling standardized sample carriers, such as ANSI/SLAS-conform¹ microplates. Scheduler and orchestrator

¹Meets the Standards ANSI/SLAS 1-2004 through ANSI/SLAS 4-2004

software manage both laboratory devices and transportation robots, initiating procedures and monitoring their states. This approach allows devices to be integrated into automated islands, with the robot serving as the transportation backbone. However, this method introduces spatial constraints, significantly limiting flexibility [WA1].

Mobile Manipulator robots (MoMas) consist of a mobile base (Autonomous Mobile Robot (AMR)), one or more robot arms, and typically a range of sensors, including laser scanners and cameras [9, 10, 11]. Unlike fixed-base or rail-mounted robots, MoMas can cover larger areas, including multiple laboratories across different floors of the same building, thereby increasing system flexibility.

Fiducial markers play a crucial role in many state-of-the-art MoMa applications. Using computer vision algorithms, these markers are detected in calibrated camera images, allowing their position and orientation to be calculated relative to the camera's coordinate system (frame) [12].

The blueprint for equipping a mobile platform with at least one robot arm and a vision system capable of fiducial-based pose detection is already well-established and widespread in laboratory automation.

In addition to implementing the automated flow of materials (e.g., via robotic solutions), enabling interoperability of these units through an overarching orchestration and scheduling system is essential. Laboratory devices can be controlled via specific Application Programming Interfaces (APIs), which trigger commands representing functionalities and steps in an experimental sequence (assay). Developing and adopting standardized interfaces could eliminate repetitive work in this area. Standardisation in Laboratory Automation Consortium (SiLA) and Open Platform Commu-

nications - Unified Architecture (OPC-UA) Laboratory and Analytical Device Standard (LADS) are two prominent examples in laboratory automation standardization.

2 Objectives

The primary objective of this research is to establish a standardized interoperability framework for laboratory automation, specifically targeting the integration of various automation units to form end-to-end automated workflows. This framework aims to enhance automation platforms in modern laboratories by focusing on supportive lab robotics.

In this dissertation, I present the Laboratory Automation Plug and Play (LAPP) framework for integrating supportive robotics technologies into laboratory automation ecosystems. The scope and focus of LAPP are defined around orchestrated analytical assays that are labware-based (typically plate-based).

3 Scientific methods

In this dissertation, the research methodology is structured into two main stages. First, the LAPP framework is developed and analyzed conceptually, establishing its three foundational pillars, as follows.

- Semantics of laboratory workflows (Chapter 4)
- Digital twin framework for laboratory robotization (Chapter 5)
- Reference architecture model for the integration of laboratory robots (Chapter 6)

This conceptual analysis forms the theoretical basis for the framework and defines its scope, principles, and applications.

Second, the framework's practical feasibility is demonstrated through two case studies, implemented with increasing Technology Readiness Level (TRL). The first demonstration focuses on validating the core concepts and functionalities at a lower technology readiness level (TRL 4), emphasizing feasibility and proof-of-concept experiments. The second demonstration advances the implementation towards higher TRL (5), highlighting scalability, robustness, and performance under more complex and realistic conditions.

Together, these stages provide a comprehensive evaluation of the LAPP framework, bridging theoretical development with practical implementation and validation.

4 Thesis 1 - Semantics

4.1 Preliminaries

To automate labware-based analytical assays, the workflows must be decomposed in a hierarchical fashion. This way, the suitable units of activities can be assigned to specific actors (devices or humans) in the lab.

For an overview of the state-of-the-art, first, let us consider the commercial scene, where laboratory automation device vendors, system integrators and software companies provide their own scheduler and orchestrator software. These software usually come with a built-in workflow representation solution. However, these are almost always based on a proprietary format/language and are limited in functionality, logic, and breakdown possibilities.

The second category comprises academic initiatives that aim to create open-source and independent frameworks. One such example is the LARA suite [13, 14], which features its own process description framework. As an elemental part of the LARA suite, the PythonLab language represents the laboratory process using the Python syntax. Another example of an independent laboratory process representation protocol is Laboratory Open Protocol (LabOP) [15]. LabOP is responsible for representing biological workflows, where the implementation of a laboratory primitive is considered a device-dependent black box. Lab robots are used in most cases for supportive actions (e.g., labware transportation), which are not explicitly represented in the biological protocols. As such, neither does LabOP's Autoprotocol library include a specific primitive for labware transportation, nor does LabOP's extension.

To overcome the limitations of state-of-the-art laboratory workflow representation approaches, I introduce a new approach that draws inspiration from project management, industrial automation, and robotics to create a semantic workflow description framework.

Hierarchical decomposition is an effective way of comprehending the vertical of complex multilevel systems in different domains. First, I consider two examples from project management. As I define LAPP-Reference Architecture Model (RAM) I adopt certain principles of Work Breakdown Structure (WBS) [16, 17] and draw inspiration from issue trackers such as Jira [18, 19].

When it comes to robotic activities, it is important to define the different levels of representation. Chu [20] and D. Nagy et al. [21] both provide hierarchical decompositions in this regard, while Vedula et al. [22] analyze the structure of robotic surgical activities from the perspective of a human surgeon. Although the field of application and the nomenclature are different, the corresponding levels can be identified, as presented in Table 1. The table covers surgical operations, robotic surgery, service robotics, and laboratory robotics, respectively. It follows the consistent leveling scheme used throughout the thesis, which is why the top row is intentionally left blank.

Laboratory automation formulates special needs towards robotic solutions concerning the complexity and variability of tasks [3]. Chu proposes the concept of Motion Elements (MEs) specifically for the automation of a complex sample preparation laboratory workflow [20]. They consider robot movements from one position to another as a *motion step* and group them in reusable units called *motion elements*.

TABLE 1
HIERARCHICAL DECOMPOSITION FRAMEWORKS

Lvl	Vedula [22]	D. Nagy [21]	Leidner [23]	Chu [20]
7				
6	Procedure	Operation		
5	Task	Task	Action template	Task motion
4	Maneuver	Subtask		
3	Gesture	Surgeme	Operations	Motion element
2		Motion prmtv.	Geometric level	Motion step
1				

For robots to be able to achieve similar flexibility in performing actions with tools, suitable knowledge representations and the corresponding planning framework are needed, which utilizes these representations. Leidner addresses these needs [23, 24].

I conducted a targeted survey with the participation of seventeen experts in the field of laboratory automation. The majority of the participants identified themselves as *Users*, *laboratory experts* (seven), and *Robotics researchers* (six). In addition, the following groups were represented by one participant each: *Robot vendors*, *Lab software vendor*, *System integrator*, *Lab equipment vendor* and *Application engineer*. Twelve participants were active in the *Industry*, while five were in *Academia*. Fourteen were in *Research and development*, two in *Manufacturing*, and one in *Quality control*. The *Biologics* (six) and *Chemistry* (five) fields were represented by the majority, but *Software engineering*, *Bioinformatics*, *Biochemistry*, *Robotics*, *Mechanical engineering* and *Lab automation* were also marked. See the detailed analytics in the supplementary materials S1.

4.2 New Scientific Results - Thesis 1

I created a semantic decomposition scheme of workflows in life science laboratories, based on assessing the manual and semi automated tasks in pharmaceutical process development laboratories.

Sub-thesis 1.1

I defined a general framework for the hierarchical decomposition of laboratory workflows, considering their automation and robotization. The framework characterizes the layers of the decomposition using the basic principles of Mutually Exclusive and Collectively Exhaustive (MECE). It draws inspiration from other domains and comprehends state-of-the-art laboratory automation capabilities.

I define the general layers of the hierarchical decomposition as follows:

- 7) **Service** refers to the entirety of the laboratory's capabilities, e.g., high throughput and/or microscale services.
- 6) **Procedure** is an experiment, an assay, or a repetitive/continuous laboratory process.
- 5) **T** **Task** is an elemental action item that is carried out by a human or a certain device.
- 4) **S** **Subtask** is an intermediary layer that represents parts of a task, that accomplishes minor landmarks.
- 3) **Q** **Motion sequence** is defined for the specific case of robotics, whereby the robot performs a sequence of motions, for example, to approach a handover site.

- 2) **M** **Motion primitive** is an elemental motion of a robot or other mechanism.
- 1) **A** **Actuator primitive** is an output excerpted by a certain actuator, e.g., robot joint, pump, etc.
- 0) **P** **Physical process** refers to the actual subject of the laboratory activity, e.g., a set of samples, buffers and/or reagents.

Sub-thesis 1.2

I created a comprehensive breakdown of the primary supportive laboratory robot activity of pick-and-place labware transportation, as seen in Table 2. I defined exhaustive Robotic Activity Representations (RARs) for each level and formulated the compositional and sequential relations between them. In addition, I constructed an extended taxonomy of laboratory robot activities, including activities, that are not yet covered by existing solutions.

Related publications: [WA1, WA3, WA5, WA6, WA7].

RAR					
Task	Subtask	Internal subtask	Motion sequence		
				Motion primitive	
LabwareTransfer	PrepareForInput	-	Undock	DriveToBaseWaypoint	
			DriveThroughSequence	DriveToBaseWaypoint	
			Dock	DriveToBaseWaypoint	
			MoveThroughSequence	-	
			-	-	
			-	-	
			OpenGripper	SetFingers	
			MoveThroughSequence	MoveToArmWaypoint	
			-	MoveToArmWaypoint	
			Grip	SetFingers	
			MoveThroughSequence	MoveToArmWaypoint	
			Internal Place	MoveThroughSequence	-
	OpenGripper	SetFingers			
	MoveThroughSequence	-			
	PrepareForOutput	-	Undock	DriveToBaseWaypoint	
			DriveThroughSequence	DriveToBaseWaypoint	
			MoveThroughSequence	-	
			Dock	DriveToBaseWaypoint	
			-	-	
			-	-	
			MoveThroughSequence	-	
			-	-	
			Grip	-	
			MoveThroughSequence	-	
PutLabware			-	MoveThroughSequence	MoveToArmWaypoint
				-	MoveToArmWaypoint
	OpenGripper	SetFingers			
	MoveThroughSequence	MoveToArmWaypoint			
-	-	-			

TABLE 2

DECOMPOSITION OF THE LABWARE TRANSFER SEQUENCE, THESIS 1.2

5 Thesis 2 - Digital twin framework

5.1 Preliminaries

Setting up the physical and logical interface between the laboratory robots and the devices includes manually teaching the positions and movements for the AMR and the robot arm, setting up the corresponding control sequence. To achieve this, I propose an information model based on the Digital Twin (DT) approach and an operating model for the set-up procedure.

To make robotic labware transfer possible, in most cases, on-line teaching is performed when the robotic system is deployed. This entails that the positions are manually set by moving the robot by hand or jogging it with the controller.

In the case of mobile manipulators, the positions are defined in relation to Fiducial Markers (FMs), which are in most cases optical Augmented Reality (AR) markers [12]. This is necessary because the precision of the mobile base is insufficient for the positions to be defined in a world-fixed Coordinate System (CS).

To overcome the limitations of manual teaching, an asset-centric information representation framework must be introduced. The approach of a virtual representation of physical entities aligns with the DT concept.

Originally, this concept was proposed by Michael Grieves at NASA [25] for product life cycle management purposes. Maintaining a virtual representation of a *physical entity* and implementing bidirectional data connections enables various virtual operations ranging from modeling through testing to optimization.

In parallel to the design phase of the product, a *prototype* of

the DT is developed, which is then *instantiated* for each physical product individually. The *state* of both the entities are stored in the form of *parameters*. These can either be static (so-called *prototype*) parameters which have the same value for each piece of the same product, or they can correspond to a specific physical specimen, in which case they are called *instance* parameters.

Since the proposal of the original concept, the DT notion has been adapted to a wide variety of use cases. Jones et al. [26] provide a systematic review of the related literature by thematic analysis and characterization. The paper also consolidates the terminology that I will follow in the context of the present thesis.

Tipary and Erdős propose a design approach that utilizes parametric DTs of robotic workcells for planning and programming [27, 28]. To adapt the offline-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 measuring the "geometric difference between the digital and physical counterparts of DTs for robotic workcells".

5.2 New Scientific Results: Thesis 2

I propose an information model and an operating model for facilitating the integration of laboratory assets with automation systems and robots.

Sub-thesis 2.1

Based on the DT concept, I created an information framework to represent the parameters of laboratory assets, allowing their integration into an automated robotized ecosystem.

I adopted the canonical DT nomenclature and categorized the specific *functional*, *form*, and *miscellaneous* parameters for laboratory assets. Furthermore, I redefined the distinction between prototype and instance parameters.

Parameters that belong to the *functionality* category include:

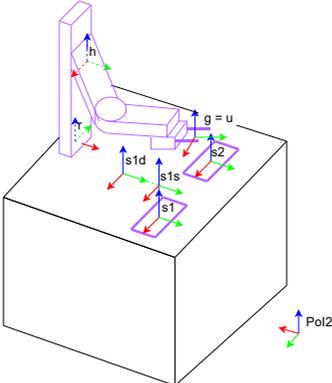
- The semantic description of the asset's capabilities may include RARs in the form of a control protocol's API definition (e.g., SiLA feature definitions or LADS models).
- The specification of labware that the device can process or handle.

I consider the following *Form* parameters:

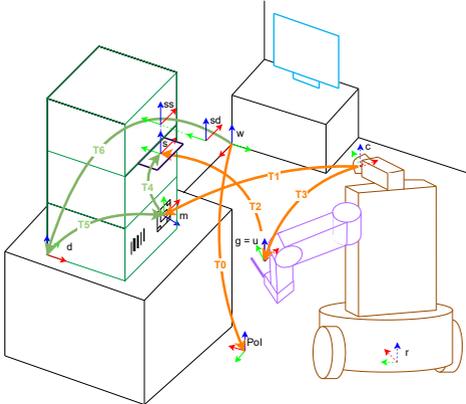
- Position definitions within the bounds of the device.
- Collision geometry of the device, to enable dynamic robot motion planning.

Finally, as a *miscellaneous* parameter, I consider the positional precision requirements specific to the device and specific robotic actions.

I created a specific information model for hierarchically representing geometric information to enable offline teaching of laboratory robots, as shown in figure 1.



(a) Benchtop robot



(b) Mobile robot

Fig. 1. Coordinate systems in the LAPP environment.

Fig. 1. Coordinate systems (i.e. frames of references) in the LAPP-DT environment. Coordinate frames are indicated with red, green, and blue axis triplet with their names indicated in black script. Arrows that connect these represent transformations, i.e., the expression of one frame relative to another.

Frames: d – device CS, g – robot’s tool center point (Tool Center Point), h – robot home position, m – fiducial marker of the device, r – robot base, Point of Interest (PoI) – base pose for station, s – device handover site (plate nest), sd – device approach position, ss – site approach position.

Transformations: T0 - world-to-PoI, T1 camera-to-marker, T2 - Tool Center Point-to-site, T3 - camera-to-Tool Center Point, T4 - marker-to-site, T5 - device-to-marker, T6 - world-to-device), u – robot stand-by position, w – world. Transformation color coding and line types: Orange – live robot-level transformations; Green – transformations stored in the LAPP-DT. Dashed – inaccurate transformations (from base odometry); Solid – accurate transformations (from robot kinematics, marker detection, or DT-stored positions).

Sub-thesis 2.2

I derived a harmonized operation model for the DT-based setup and operation of supportive laboratory robots. An autonomous offline teaching procedure is enabled by utilizing the information models of sub-thesis 2.1 (see table 3).

Related publications: [WA3, WA4].

TABLE 3

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	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 Point of Interest (PoI) d is now defined in w .	$T_6(w \rightarrow d)$	Location	Device (instance)
The handover 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)

6 Thesis 3 - Reference architecture model

6.1 Preliminaries

Unlike industrial automation, the laboratory domain lacks a standardized reference architecture model, which would prescribe a canonical architecture and outline the best practices.

Many similarities and analogies can be drawn between industrial production and laboratories [WA2]. At the highest level, Enterprise Resource Planning (ERP) has to take place, while underneath a Distributed Control System (DCS) or a Supervisory Control and Data Acquisition (SCADA) resides. These systems feature several layers of scheduling, control and supervision ranging all the way down to the individual machines as the elemental components of the system.

End-to-end digitalization and equipment integration are key in industrial automation and the process industry. OPC-UA, introduced in 2008, is a global standard for client-server communication, enabling vendors to model control and data structures in an OPC-UA name-space [29]. Collaborations with societies like International Society for Pharmaceutical Engineering (ISPE), German Mechanical Engineering Industry Association (VDMA), and Zentralverband Elektrotechnik- und Elektronikindustrie (ZVEI) focus on creating Companion Specifications for various domains [30], with ISPE Pharma 4.0 addressing GMP manufacturing requirements.

The Reference Architecture Model Industrie 4.0 (RAMI4.0) framework uses a DT approach to represent physical and virtual assets, organizing them in a three-dimensional structure linked to

the automation pyramid's layers and life cycles [31]. Building on RAMI4.0, the I4.0 Asset Administration Shell (AAS) concept connects physical assets by encapsulating data into admin shells. This inspired the creation of the LAPP DT concept.

Multi-level architectures are standard in industrial automation, as outlined by the ISA-95 model, which integrates ERP, Manufacturing Execution Systems (MES), and SCADA systems [32]. The hierarchy spans from physical processes, sensors, and actuators at the *Field* level, through Programmable Logic Controller (PLC)-based *Direct Control* and Human-Machine Interface (HMI)-enabled *Process Supervisory*, up to *Production Supervision* and *Plant Management*. Similar principles are applied to laboratory automation [WA2].

Industry 4.0 demands flexibility beyond these rigid layers [33]. Schnicke et al. propose a peer-to-peer Service-oriented Architecture (SoA) with stateless services organized into sequences using a DT framework [34]. Services, described via *ServiceTags*, enable high-level process changes without manual reprogramming. Hierarchical relationships allow nesting of services, device-agnostic recipes, and adaptable execution plans. These concepts are foundational also for laboratory automation frameworks like SiLA 2, which facilitates service-oriented communication [35].

In laboratory automation, Knobbe et al.'s AILaboratory integrates Industry 4.0 principles with robotic systems for precision pipetting [36]. Similarly, ARChemist provides a flexible, reconfigurable platform for chemistry experiments, combining Robot Operating System (ROS)-based middleware with DT frameworks for resource state tracking [37]. Both systems share conceptual overlap with LAPP, which incorporates hierarchical decomposition,

detailed labware handling, and flexible operation models. The LAPP RAM bridges traditional industrial automation and modern, service-oriented approaches.

In laboratory automation, two major sub-domains must be distinguished: Advanced Process Control (APC) and workflow orchestration, each with distinct system architectures and some overlaps.

APC involves continuous or batch-operated systems using pipes and tubes for material transport, focusing on time-series data and feedback control via advanced PATs like High-performance Liquid Chromatography (HPLC) or mass spectroscopy. Specialized tools, such as PharmaMV [38], enable multivariate analysis and real-time pharmaceutical process control. These systems adopt SCADA principles and protocols like OPC-UA. For multi-step at-line or offline PATs, samples undergo workflows resembling orchestration systems.

Workflow orchestration involves sample transport in containers (labware) between stations to complete sequential assay steps. An orchestrator interprets experiment recipes, assigning tasks to devices and managing material flow with supportive systems like conveyors and robots.

While workflow orchestration can complement APC for at-line analytics, the two are typically built on distinct paradigms with separate software tools.

6.2 New Scientific Results: Thesis 3

I created a generic architecture model (LAPP-RAM) for the integration and automation of equipment in life science laboratories. I demonstrated its applicability on the basis of a prototype and an industrial pilot implementation (see chapter 7).

I showed that hierarchical function-centric models can be combined in a single generic architecture model (LAPP-RAM) by mapping the layers of the semantic decomposition to the layers of the control architecture, as shown in table 4. The table follows the consistent leveling scheme used throughout the thesis, which is why the top row is intentionally left blank.

The protocols are:

- Service Protocol (SP)
- Experiment Design Language (EDL)
- Laboratory Process Language (LPL)
- Modular Robot Program (MRP)
- Low-level Robot Program (LRP)
- Joint trajectories and IO (JTIO)

The technical layers are:

- Laboratory Information Management System (LIMS)
- Electronic Lab Notebook (ELN)
- Laboratory Execution System (LES)
- Device-level Control Unit (DCU)
- Embedded Controller (EC)

Related publications: [WA2, WA3, WA5, WA6, WA7].

TABLE 4
THE THREE HIERARCHICAL ASPECTS OF LAPP-RAM, MAPPED AGAINST
EACH OTHER

Level	Process	Protocol	Technical
8			
7	Service	SP	LIMS, ELN
6	Procedure	EDL	LES
5	Task	LPL	DCU
4	Subtask		
3	Motion sq.	MRP	EC
2	Motion prim.	LRP	
1	Actuator pr.	JTIO	
0			

7 Possibility of exploiting the results

This chapter presents experimental demonstrations and validation of the concepts that I introduced in chapters 4, 5, and 6. I demonstrate the feasibility of two of the main conceptual pillars (the semantics and the system architecture). First, a research-oriented platform was used to create a prototype, followed by a pilot with an industrial-grade mobile manipulator.

7.1 Preliminary steps

The first preliminary step was to manifest the semantics of chapter 4 in the form of a service description, more specifically in the form of a SiLA feature definition. This was done by the SiLA

Robotics Working Group (SRWG) ². After the feature definition has been unified, the SRWG created reference implementations for stationary robots, as a part of the BioLAGO SiLA 2 An-iML Serial Hackathon (BioSASH). During the third installment of this series, the goal was set out to the SiLA-based communication to the robots' driver software. The result can be found on GitLab [39] as the SiLA-ROS bridge. The fourth BioSASH included a working group focused on demonstrating the unified feature definition's capabilities with fixed-base robots. Using the `LabwareTransferManipulatorController` and `LabwareTransferSiteController` feature definitions [40], the group implemented a pick-and-place task for Universal Robots UR3 and PreciseFlex 3400 arms. The robots transferred plates via a shared handover site, demonstrating the first unified feature definition for labware transfer. The project and its final presentation are available online [41, 42].

7.2 Academic prototype

As the second major step, an academic prototype was implemented using a research-oriented MoMa platform, TIAGo ++ [11]. Based on ROS, the software stack was adapted to reflect the layers of the LAPP RAM (as presented in chapter 6). Implementing a SiLA-ROS bridge, the labware transfer functionality was exposed towards a SiLA based scheduler. This study served as a prerequisite for the next phase.

²The SRWG is lead by *Ádám Wolf* since March 2022 and as of the time of writing this present thesis.

The system architecture is based on the integration of the ROS and SiLA frameworks. Figure 2 describes the connection between the ROS and SiLA ecosystems at the level of the main components. The contract for communication between the SiLA server and SiLA client is the *feature definition*. The bridge represents the SiLA-ROS bridge package [43], which is based on a reference implementation published on the SiLA GitLab [39]. On the ROS side, communication is managed through the standard concepts: topics, services, and actions.

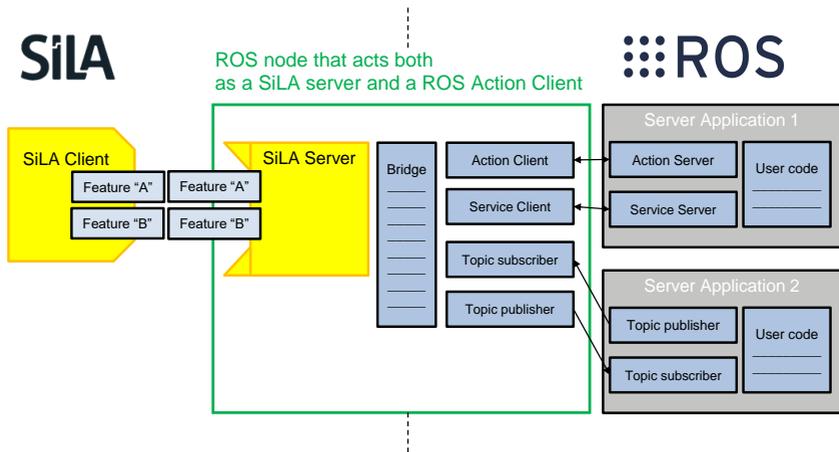


Fig. 2. Conceptual software architecture of the SiLA-ROS hybrid system.

We tested different **S** Subtask-level sequences multiple times, namely the navigation, the picking and placing separately and the **T** Task-level sequence as a whole. Our testing showed that the bottleneck lies in navigation inaccuracy, as malfunctions occur when the robot traverses on an uneven surface. The 6-wheel de-

sign of the AMR proved to be a sub-optimal setup for this application. Despite the difficulties with the hardware, the setup proved to be a sufficient platform for a prototype implementation to demonstrate the LAPP concept.

7.3 Industrial prototype

As the third step, a market-ready implementation followed with an industrial-grade MoMa of EngRoTec, called mobERT [44]. First, the hardware was adapted to the labware transfer task by developing an end effector for microplate manipulation. The robot was equipped with on-board storage (hotel) and a tool changer to handle various types of labware. Based on the LAPP semantics, the `Labware-Transfer` sequence was implemented and exposed via a SiLA driver as a wrapper over EngRoTec's ERTmiral middleware. The control architecture follows the concept outlined in chapter 6, retaining the high-level role of the scheduler, using an interoperability protocol to trigger the **Ⓡ** and **Ⓢ** commands, and a middleware translating these into low-level functionalities, such as **Ⓚ** motion sequences and **Ⓟ** motion primitives.

Together, the academic prototype and the industrial pilot implementations demonstrate the feasibility of the LAPP concept. These efforts constitute a multi-step endeavor ranging from the scientific conceptualization of the general semantics, information models, and RAM, incorporating these concepts in harmonized industrial standards, to implementing an early-stage prototype and a real-life industrial setup.

Related publications: [WA6, WA7]

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