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1 Preface

The world of laboratory automation is at a turning point: advances in technologies such as robotics, artificial intelligence and data integration have revolutionized the ways in which research and development are conducted. At the same time, however, I observe that many companies and professionals lack a clear direction on how to effectively and sustainably integrate these innovations into their labs.

I was driven by the desire to make this knowledge more accessible and to build a bridge between technological progress and practical implementation. With my many years of experience in laboratory process automation, combined with my background in various industries, I have been able to identify numerous challenges and best practices. I still remember my first exposure to a high throughput system of Labman at AkzoNobel in Slough, UK, in 2008. That's when I caught the virus and started implementing it at Omya.

My aim with this book is to share knowledge. To make the complex possibilities and challenges of laboratory automation understandable for a broad audience. I also want to provide inspiration and motivate readers to see automation not just as a tool, but as a strategic advantage. The presentation of practice-oriented solutions ranges from planning to implementation, with a special focus on efficiency, quality and sustainability. This book is aimed at anyone who is professionally involved in any way with laboratory processes for coating materials. Beginners and students will get a comprehensive overview of the field, while experienced developers will find practical details relevant for solving their daily challenges in the future.

This book is intended to help guide companies and laboratories on their way into the future. As I firmly believe that laboratory automation is not only a tool for increasing efficiency, but also a pioneer for innovation and scientific progress. For this reason, I have used a lot of visual material to describe the possibilities that already exist today in order to show the reader in a simple way that the introduction of automated laboratory processes also requires a rethink. Manual processes and practices used up to now cannot always be automated 1:1. This is particularly the case for antiquated, historical measuring and testing methods, which are being replaced by modern instrument technology for characterizing the properties of paints and coatings.

It is important to mention that in my more than 15 years of experience in laboratory automation, there was never any thought of cutting jobs. Unfortunately, this is often the first thought in many people's minds. In reality, however, many examples from different industries and professions do not show job cuts but rather changes in activities. The focus of automation is primarily on shortening time to market, standardization, reproducibility and the elimination of mindless routine work. In recent years, the baby boomer effect has also played a role. It is becoming increasingly difficult to replace this retiring generation with new, young skilled workers. This is also spurring the introduction of automation in the laboratory, as well as in many other company processes. This change will continue in the future. The frontrunners in laboratory automation are already starting to use artificial intelligence and machine learning due to the large amounts of data generated.

This book can be seen as a step towards self-employment. Through my company, PERFECO Consulting Gysau, I focus on performance, economy, and ecology, offering vendor-neutral consulting and expertise to the industry.

Detlef Gysau
Full/Switzerland, March 2025

Acknowledgement

What motivated me to write a specialist book on laboratory automation? I admit it, I was motivated by various feminine sources. The request to write the book came from Vincentz Network, who has already supported me with my filler books, now in their 3rd edition. My wonderful wife Jacqueline also played a key role in my decision. She has always had my back in my professional career and encouraged me in all my activities. At the same time, she has brilliantly managed our family with both children and many animals, from dogs to cats, goats, chickens and horses. Dear Jacqueline – you deserve my deepest thanks! I would also like to gratefully thank my fabulous children, Gian-Flurin and Mica-Ladina, for their continued understanding and patience when I was not always available (similar to writing my other books).

I would like to express my deep thanks to Hendrik Hustert, Hermine Riegler, Ian Riley, John Hesford, Natalie Kainz, Roland Emmerich, Tobias Burk and Ulf Stalmach in alphabetical order, as well as the companies Anton Paar, Chemspeed Technologies, Füll Lab Automation, Labman Automation and Orontec for their uncomplicated support with technical information and images. My thanks also go to all my companions who have supported and encouraged me in any way in my professional career.

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1 Introduction

1.1 History of automation

The first making of paints dates more than 100,000 years back and was discovered in South Africa approximately one decade ago [1]. The paints were exemplary dedicated for cultural purposes such as paintings in caves. Life was very different to what it is nowadays and there was no need to rush either for making or applying the paint. The industrial revolution was still far away as well as industry 4.0 and lab 4.0.

Times have changed, not only but tremendously with the beginning of the industrial revolution in the 18^{th} century. Industry and society strove for growth by the revolutionary technology enabling mass production. And thus, the need for higher speed was also necessary for development and innovation in the field of science. Tools such as stirrers became operated by transmission received from water or steam power. Later, these became useable and thus mobile at other locations by electrification. It is hard to say that this is automation with the understanding of the 3^{rd} millennium after Christi.

Before electronic components became widely available after World War II, laboratory automation was constructed by end users and designed for specific tasks such as filtration and washing operations. The earliest mention of automation in the United States chemical literature dates to 1875, when a device for unattended washing of filtrates was announced, see Figure 1.1.

In the following years, a small number of automated devices were sold, including large mills for preparing coal samples. By 1900, power plants began using automated carbon dioxide analysis, see Figure 1.2 and Figure 1.3.

Around the time of World War I, the development of electrical equipment for conductivity measurements made possible the first commercial automated gas analyzers for laboratory and field use. The growth of industrial production in the 1920s led to a need for automated test equipment, and the growing rubber industry was among the most successful early

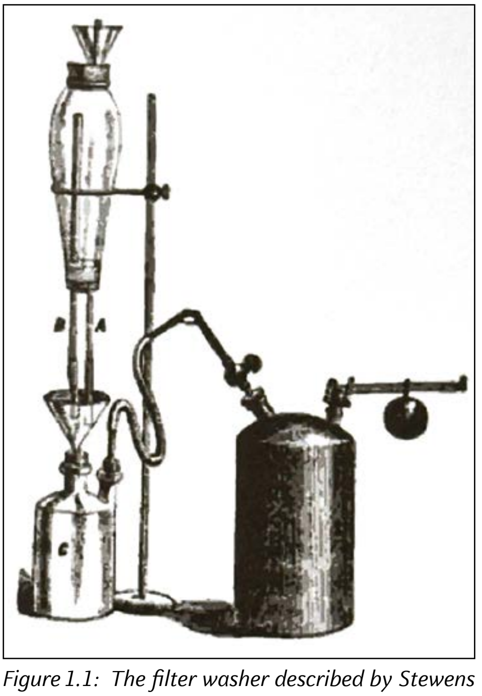

Figure 1.1: The filter washer described by Stewens in 1875 used a lamp chimney with water and closed at both ends to drip rinse water over a filtrate. The canister at the right of the device is a steam trap that was used to create vacuum
Source: Google Books

adopters. The beginning of the Second World War saw a further surge in the development of automation solutions in process control. The background to this was, on the one hand, the increased requirements to produce war-related goods and, on the other hand, the shortage of qualified workers [2]. Particular attention was paid to the development of semi-automatic distillation apparatus [3]. By the end of World War II, the use of automated systems had become routine in the chemical industry. Electronic components were increasingly used to control valves. The development of automated titrators was advanced; in 1948, a device was developed that used a motor-driven syringe to add the titrant. Innovative technologies in liquid dosing were essential for the further development of laboratory automation. In 1957, Schnitger developed a new type of pipette that already had all the features of today's modern piston-stroke pipettes. Today's mechanically adjustable micropipettes can be traced back to a development by *Gilson*, which he patented in 1974 [4]. Technical advances in the development of small motors and valves led to the introduction of semi-automatic syringe-based pipetting systems in the 1970s. The development of microprocessor technology enabled the creation of program sequences to control the motors and valves, leading to the first fully automated pipetting systems. In the 1980s, further developments in electrical engineering resulted in the first automated liquid handling systems.

In the early 1980s a revolution took place; the first fully automated laboratory was opened by *Dr. Masahide Sasaki* [5, 6]. One of the world's first clinical automated laboratory management systems were developed at the University of Nebraska Medial Center by *Dr. Rod Markin* in 1993 [7]. In addition to the requirements of clinical laboratories, the development of high-throughput screening (HTS) methods in the pharmaceutical industry has been of particular importance for the development of laboratory automation. Parallel sample processing has been increasingly used in bio screening automation. Test methods based on microtiter plates were first introduced in 1986 [8]. With interchangeable hands, the systems could perform various laboratory processes such as pipetting, washing the plates, or adding reagents. The use of articulated robots was a very costly way of automating such processes and therefore not generally applicable. Numerous companies have therefore developed specialized liquid handling systems based on a "Cartesian" robot structure. The first 96-channel pipetting system was developed by TomTec in 1990 [9], followed later by a variant with a 384-pipetting head. Developments in the field of collaborative robots in recent years are increasingly enabling the use of cost-effective automation solutions in small and medium-sized enterprises, see Figure 1.4.

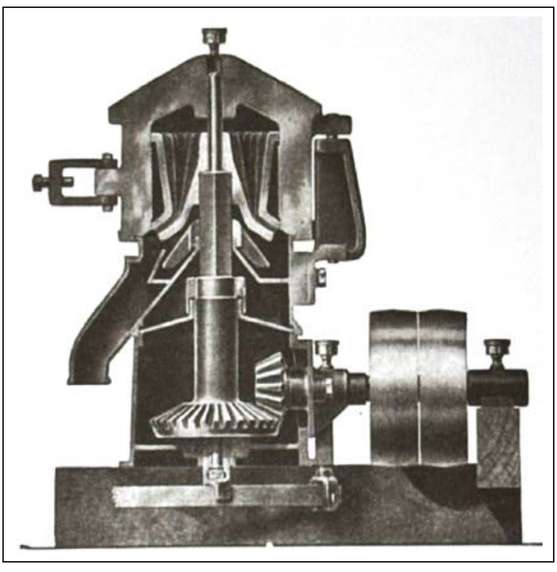

Figure 1.2: The "Sturtevant Automatic Coal Crusher" could reduce large pieces of coal to a size more suited for laboratory analysis and partition out a representative sample. This greatly improved the efficiency of coal analysis
Source: Google Books

The automation of paint labs, like many other industries, began in the mid-20th century. The specific timeline for the introduction of automation in paint labs can vary depending on the level of automation and the processes involved. In the early stages, automation may have been limited to simple machinery and equipment to aid in mixing and dispensing paint ingredients. Parallel operation of stirrers in a lab refers to the practice of using multiple stirrers simultaneously to mix or agitate multiple samples or solutions at the same time. This technique is commonly employed in laboratories, especially when researchers or technicians need to process multiple samples efficiently and uniformly. The parallel operation of stirrers offers several benefits:

- **Timesaving:** Using multiple stirrers allows researchers to process several samples simultaneously, reducing the overall time required for experiments or preparations.
- **Consistency:** Parallel operation ensures that all samples experience similar stirring conditions, resulting in more consistent and reproducible experimental outcomes.
- **Increased throughput:** Laboratories with a high sample workload can benefit from parallel operation as it enables the processing of a larger number of samples in a shorter time frame.
- **Resource optimization:** Instead of dedicating one stirrer for each sample, parallel operation enables researchers to use fewer stirrers while achieving the same results.
- **Flexibility:** Different stirrers can be set to different speeds and configurations, allowing researchers to tailor the stirring conditions to the specific requirements of each sample.

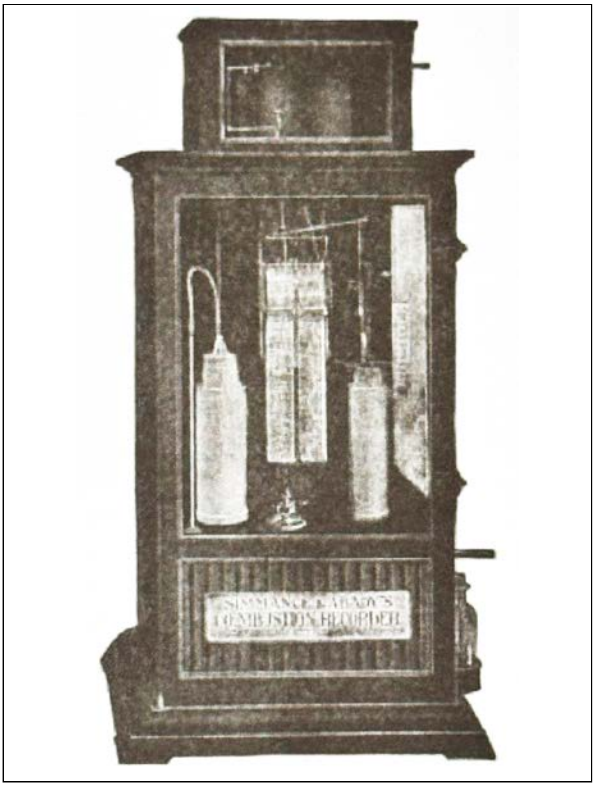

Figure 1.3: The "Autolysator" was one of the first automated analysis instruments ever sold commercially. This 1912 model used a complex system of clockwork, counterweights, and a chart recorder to provide real-time measurements of carbon dioxide in flue gas Source: Google Books

Figure 1.4: Olympus America OLA2500 Ô lab automation system has a maximum sorting throughput of 800 tubes per hour and aliquoting throughput of 650 tubes per hour.
Source: Olympus America, INC., Center Valley, PA

When implementing parallel operation of stirrers, it is essential to ensure that each stirrer is properly calibrated, and the stirring conditions (such as speed, direction, and time) are standardized for all samples. Additionally, proper lab safety protocols should be followed to prevent any accidents or mishaps during the simultaneous operation of multiple stirrers.

As technology advanced, more sophisticated automated systems were developed to handle various aspects of paint manufacturing, quality control, and testing. In the early 21^{st} century, with the rapid advancements in robotics, computer control systems, and artificial intelligence, paint labs saw a significant increase in automation capabilities. These advancements allowed for greater precision in color matching, faster production rates, improved quality control, and reduced human intervention in certain tasks. It's worth noting that the adoption of automation in paint labs, as in other industries, is an ongoing process, and new technologies continue to be integrated to optimize manufacturing processes and overall efficiency. In the meantime, automation in paint labs is well-established with large, financially strong paints and coatings manufacturers and the corresponding raw material industry, and it's likely that further advancements have occurred since then.

1.2 Needs for laboratory automation

Laboratory automation refers to the use of technology, robotics, and software to perform various tasks and processes in a laboratory setting. There are several reasons why laboratory automation is increasingly adopted. Some of the drivers, without representing completeness, for the increasing interest and thus the next step of the digital transformation are highlighted in the following sub chapters.

1.2.1 Increased efficiency

Lab automation allows for the simultaneous processing of multiple samples or experiments, significantly increasing the number of tests or analyses that can be conducted in a given timeframe. Automation can significantly speed up repetitive and time-consuming tasks, allowing scientists and researchers to focus on more complex and creative aspects of their work. Automated systems can work around the clock without breaks, leading to higher productivity.

1.2.2 Improved accuracy and precision

Improved accuracy and precision are crucial goals in scientific research, testing, and development. Accuracy refers to the closeness of a measurement or result to the true value, while precision refers to the consistency and repeatability of measurements. Automated equipment can carry out tasks with high precision and accuracy, leading to more reliable and reproducible results. Automation often includes integrated data collection and analysis, leading to more accurate and reliable data. This can improve the quality of research and decision-making processes.

1.2.3 Enhanced data quality

Enhanced data quality refers to the improvement and optimization of various attributes and characteristics of data to ensure that it is accurate, reliable, consistent, and fit for its intended purpose. Data quality is a critical aspect in scientific research and laboratory environments. When data quality is enhanced, it leads to greater confidence in the data's accuracy and the insights derived from it. Automation reduces the potential for manual data entry errors and ensures that data is recorded consistently and accurately. This leads to better data quality and more robust scientific conclusions. Thus, it is crucial for making informed decisions, drawing meaningful insights, and deriving reliable conclusions from data-driven analyses. It requires careful attention to data collection methods, processes, validation, and maintenance throughout the data lifecycle.

1.2.4 High throughput

High throughput in a laboratory context refers to the ability to process many samples, experiments, or analyses simultaneously in a relatively short period of time. It involves automating and streamlining laboratory processes to achieve a rapid and efficient workflow. High throughput is particularly valuable in research, diagnostics, drug discovery, and other industries where the volume of samples or data to be processed is substantial. The goal of high throughput is to increase efficiency, reduce turnaround times, and accelerate the pace of scientific discovery, development, and decision-making. While high throughput offers numerous benefits in terms of speed and efficiency, it is important to carefully design and validate high-throughput processes to ensure data quality, reproducibility, and accuracy. Real high-throughput workflows require typically investment in specialized equipment, automation technology, and data management solutions.

1.2.5 Standardization

Standardization in laboratories refers to the establishment and implementation of consistent protocols and standard operating procedures (SOP), practices, and guidelines to ensure uniformity, reliability, and accuracy in experimental processes, data collection, and analysis. It involves defining clear and agreed-upon methods that all personnel follow when conducting experiments, handling samples, using equipment, and recording data. Standardization is essential to maintain the quality and integrity of research, ensure reproducibility of results, and facilitate comparisons between different experiments or laboratories. Standardization is particularly important in the paints and coatings industry, where accurate and reliable results are critical for making informed decisions that impact performance, durability, application but also health, safety, and regulatory compliance. It ensures that experiments can be repeated, validated, and built upon, contributing to the advancement of scientific knowledge and technological innovations.

1.2.6 Cost savings

Achieving cost savings in research and development (R&D) is a priority for many organizations, as R&D activities can be resource intensive. It is essential for optimizing resources, maximizing efficiency, and ensuring sustainable innovation. One of the means could be the identification and elimination of inefficiencies in R&D processes. Streamlining workflows, reducing unnecessary steps, and optimizing resource allocation can lead to significant cost savings. Lab automation is indeed a strategy that can contribute significantly to cost savings in R&D. While setting up automated systems may require an initial investment, the long-term cost savings can be significant. Automation reduces the need for manual labour and minimizes the consumption of reagents and materials. Its implementation requires careful planning, investment in equipment and technology, training of personnel, and ongoing maintenance. Organizations need to consider the specific needs of their R&D processes and balance automation with other strategies to achieve optimal cost savings and research outcomes.

1.2.7 Safety

Lab automation can significantly increase safety in laboratory environments. Automation technologies are designed to minimize or eliminate various risks associated with manual laboratory processes, thereby enhancing the overall safety of researchers, technicians, and the surrounding environment. For example, reduced human interaction with hazardous materials considered toxic, mutagenic, cancerogenic and irritating, automation minimizes direct human contact with these substances, reducing the risk of exposure and contamination. Automated systems handle samples, reagents, and chemicals with precision, reducing the likelihood of accidental spills, leaks, and releases that could pose safety hazards. Lab automation is also designed to prevent cross-contamination between samples, ensuring that hazardous or infectious materials are contained and isolated. Automation can decrease the need for researchers to wear extensive "personal protective equipment (PPE)", making it easier to follow safety protocols and reducing the likelihood of human error due to discomfort or restricted movement. While lab automation can significantly improve safety, it is important to note that the design, implementation, and operation of automated systems should be approached with careful consideration of safety guidelines and regulations. Proper training and maintenance are also crucial to ensuring the continued safety of personnel and the environment in automated laboratory settings.

1.2.8 Integration and connectivity

Integration and connectivity play a crucial role in the effectiveness and efficiency of lab automation. Integration of various instruments, devices, and software platforms allows for seamless movement of samples and data between different steps of the workflow. This improves overall efficiency, reduces the risk of errors, and accelerates the pace of research and analysis. Automation systems with robust connectivity features enable easy sharing and collaboration of data within the lab and even across different locations. Researchers can access and share experimental data, results, and protocols, facilitating better communication and cooperation among team members. Integration and connectivity allow lab personnel to remotely monitor and control automated processes. This is particularly important for experiments that require constant monitoring or adjustments. Researchers can access real-time data, receive alerts, and make necessary changes without being physically present in the lab. Automation systems often come with built-in data logging and traceability features. Integrating various components of the lab setup ensures that data is accurately captured and attributed to the right source. This traceability is important for maintaining data integrity, complying with regulations, and ensuring the reproducibility of experiments. In addition, automation systems can be integrated with data analysis and reporting tools. This integration facilitates the efficient extraction of insights from large datasets, speeding up the decision-making process and enabling researchers to focus on interpreting results rather than data processing.

1.2.9 Serendipity

Serendipity refers to the unexpected discovery of valuable insights, knowledge, or results while pursuing a different research goal or conducting routine experiments. While lab automation is often associated with planned and controlled experiments, it can still play a role in facilitating serendipitous discoveries. Lab automation can significantly increase the speed at which experiments are conducted. Researchers can run more experiments in a shorter amount of time, increasing the chances of encountering unexpected outcomes or phenomena. Automation allows the researcher to think out of the box, and to try out ideas, and experiments that otherwise would not have been conducted. The Edisonian approach, also known as accelerated serendipity, to innovation is characterized by trial-and-error discovery rather than a systematic theoretical approach. Thus, the accelerated pace of experimentation provides more opportunities for serendipitous discoveries. Automation allows for high-throughput screening of many variables, compounds, or conditions. This process can reveal unexpected correlations, interactions, or effects that might not have been anticipated. These discoveries can lead to new research directions and unexpected breakthroughs. Automated systems generate a substantial amount of data. While the initial goal might be to analyze specific parameters, researchers can also explore the data for patterns, anomalies, or interesting observations that were not part of the original research plan. While lab automation can certainly enhance the potential for serendipitous discoveries, it is important to note that serendipity often relies on the open-mindedness and creativity of researchers to recognize and interpret unexpected results. Automation can provide tools and opportunities, but the human element of curiosity and critical thinking remains essential for transforming unexpected observations into valuable insights.

1.2.10 Flexibility and customization

Lab automation can have both positive and potentially limiting impacts on the flexibility and customization of experiments. Many automated systems are designed to be modular and easily configurable. This flexibility allows laboratories to adapt the automation to their specific needs and accommodate various types of experiments. Lab automation can improve the reproducibility of experiments by precisely controlling variables and minimizing human error. This reliability is particularly important when aiming to replicate experiments for validation or further investigation. It also enforces standard protocols, reducing variability between experiments. This is beneficial when consistent experimental conditions are required for comparisons, quality control, or regulatory compliance. Depending on the design of lab automation systems, some automation systems are optimized for specific protocols and may not easily accommodate deviations or customizations. This can limit researchers' ability to explore novel experimental setups.

1.2.11 Addressing labour shortages

Laboratory 4.0 can contribute to overcoming labour shortages representing the integration of digital technologies, automation, data exchange, and advanced analytics into various industries, including laboratories and research facilities. Lab 4.0 technologies enable the automation of repetitive and manual tasks in laboratories, reducing the need either for many skilled personnel or compensating recruiting shortages. Robots and automated systems can handle tasks like sample preparation and formulation including dispensing steps, application and testing, data collection, and basic experiments, freeing up the limited resources of skilled researchers for more complex and interesting tasks. Laboratories and research facilities that adopt cutting-edge Lab 4.0 technologies may attract a younger and tech-savvy workforce. This can help address labour shortages by appealing to a new generation of researchers. While Lab 4.0 technologies can contribute to overcoming labour shortages in laboratories, it is important to note that their successful implementation requires careful planning, investment, and consideration of the specific needs and challenges of your organization. The early involvement of the dedicated personnel for the future operation of the lab automation systems, starting from planning and designing, setting up, installation,

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Detlef Gysau

LAB AUTOMATION AND DIGITALISATION IN COATINGS

The Mission
This book makes lab automation and digitalisation in the coatings industry understandable. It combines technological advancements such as robotics, AI, and data integration with practical solutions to enhance efficiency, quality, and sustainability in lab processes, while leveraging automation as a strategic advantage for innovation and scientific breakthroughs.

The Audience
The book targets a wide audience involved in lab processes within the coatings industry. It is suitable for beginners and students seeking an overview of lab automation, as well as experienced professionals and developers looking for practical solutions to daily challenges. It is especially relevant for companies and labs aiming to modernize their processes and leverage automation and digitalisation in research and development.

The Value
The book provides valuable insights into the practical aspects of lab automation and digital solutions, offering both technical details and strategic implementation perspectives. It highlights automation as more than just a tool – it is a catalyst for innovation and scientific progress. Additionally, it emphasizes the potential for serendipitous discoveries through automation, making it a key resource for scientific research and the development of new technologies in the coatings industry.

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