Review Article

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Considerations on automation of coating machines

Abstract: Most deposition chambers sold into the optical coating market today are outfitted with an automated control system. We surveyed several of the larger equipment providers, and nine of them responded with information about their hardware architecture, data logging, level of automation, error handling, user interface, and interfacing options. In this paper, we present a summary of the results of the survey and describe commonalities and differences together with some considerations of tradeoffs, such as between capability for high customization and simplicity of operation.

Keywords: automation; controls; equipment; optical coating machines.

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1 Introduction

Early optical coating machines were operated fully manually. After machine setup, a skilled operator turned on the vacuum pumps and operated the valves in the right sequence to reach the required vacuum level. During the deposition, the operator opened and closed the shutters, switched on the power supplies, and then adjusted the potentiometers and other dials to keep operating conditions stable. Early thickness termination cutpoints were made by time or in some cases when the optics had a certain visual appearance [1].

The industry has come a long way since these early days. Today, many systems are fully automated. Powerful computers and sophisticated control loops are employed to control the sequences and regulate the operating conditions. Many machines use advanced cutpoint control techniques to guarantee the proper quality of the coating. Figure 1 shows an impressive example of a coating design, together with the measurement of a fabricated filter. This filter is used in a Raman application where a sample is excited with laser light at 488 nm. Raman Stokes photons lose a small amount of energy and need to be detected only a few nanometers above the laser line. The long-wave-pass filter is employed to separate the scattered light from the laser light. At the laser wavelength, the filter blocks light almost completely. The optical density (OD) is 6 (transmission <0.0001%). Yet, just 2 nm above the laser wavelength, the filter allows above 80% transmission. The transmission across the passband is close to 100% for the entire region of the detector's sensitivity. The design of the filter consists of 402 alternating Ta_2O_5 and SiO_2 layers with a total physical thickness of 23 µm. Further details and other examples can be found in [2]. While there are many factors contributing to this success, including a stable, low-absorption, low-defect process, a capable automation system is one of the pillars to producing such a filter. It would be impossible to coat such a filter manually.

Automation ensures that the process is repeatable. To scale up production, multiple machines can be installed with the same automation.

While automation is enabling, automation can also be a significant hindrance. Trying something different can be a difficult task if the automation system does not support the new sequence or process. Where a few words to an operator would have allowed exploring a sequence differently in a manual machine, now an automation engineer needs to change the code. Bugs in the automation can introduce systematic or sporadic errors. Software and process engineers often have to spend hours of detective work to find out what went wrong. When something in the equipment setup, the process, or a component goes wrong, a human operating the machine may easily recognize the situation and stop. However, an automation

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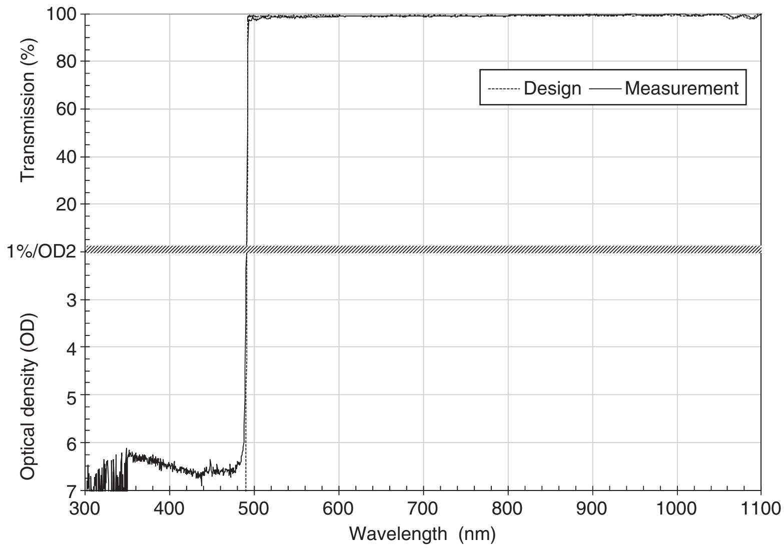

Figure 1: Design and measurements of a long-wave-pass filter for Raman spectroscopy with a laser at 488 nm.

system, left alone, only relies on the feedback it receives and responds the way it is programmed.

In this paper, we discuss a list of factors to consider when automating an optical coating machine or looking for a machine with suitable automation. We received input from nine well-known equipment suppliers. Our discussion of the information documents the state of the art in automating optical coating machines in the year 2014. This information will be helpful to users who are looking to acquire a new system or upgrade an existing system, as well as for vendors in their efforts to offer a state-of-the-art, competitive system.

2 Details on our approach

We created the list of the following seven questions on automation aspects of coating chambers. The questions below are phrased as we sent them to equipment suppliers:

- What hardware model is your automation built on, and where is the intelligence?
- What kind of logging does your system employ?
- What is automated?
- How does your system deal with errors/abnormal conditions?
- What is the user interface?
- What connections does your system have/allow?
- What standards and literature apply?

We initially approached two equipment manufacturers and asked under which conditions they would be willing to help with the paper. The consensus was that we should gather inputs from multiple companies; however, we should present and discuss the information anonymously from a pool of answers. We sent the seven questions to 15 equipment manufacturers around the globe. The nine companies listed in Table 1 responded, and their answers created the main basis of this paper. We supplemented the information with some of our experiences and added further references.

Several of the equipment suppliers offer various models of optical coating machines for different applications and industries. Even within one company, different automation approaches may be employed. The answers to our questions were given at a company summary level, not at a model-by-model level. In the discussion below, we quantify things with words like 'many', 'all', and 'some' to identify trends as we do not have exact quantitative data.

Table 1: List of nine equipment manufacturers who provided input to this paper by answering our seven automation questions.

Company	Headquarter
Applied Materials	USA
Dynavac	USA
Evatec	Europe
Leybold Optics	Europe
Optorun	Japan
Shincron	Japan
ULVAC	Japan
Veeco	USA
VPT	USA

Table 2: Definition of intelligence levels, employed in the automation of a coating machine.

Level	Description	Example
Run level	High-level sequence steps	Pump down, precoating steps, layer 1, layer 2, …, postcoating steps, vent
Layer level	Details how to coat a layer	Close shutter, set gas flow, configure optical monitor, turn on power supply, …
Device level	Details on how to perform a specific task	Regulate temperature, control power, measure voltage
Logging	Data recording	Alarms, events, process variables

3 Results and discussions

3.1 What hardware model is your automation built on, and where is the Intelligence?

The answers to this question were quite diverse. The following models allow a classification of the approaches and highlight some tradeoffs. In 3.1.1, we define several levels of intelligence. In 3.1.2, we introduce two hardware elements. In 3.1.3, we discuss the architectures (models) consisting of the hardware and where the intelligence resides.

3.1.1 Intelligence

Intelligence, as it relates to optical coating machines, can be classified into hierarchical levels as defined in Table 2. The higher levels instruct and rely on the execution at the lower levels. Logging is an important service that runs in parallel and applies to all levels.

3.1.2 Hardware for the run level and layer level intelligence

We found that all companies employ an industrial personal computer (PC). An industrial PC puts emphasis on a more rugged design compared to a consumer PC. The case is more robust and mounts in a standardized industrial rack system. It is well-cooled with filtered air. The power supply is of a higher grade, and prime components are used.

Some equipment manufacturers make use of a programmable logic controller (PLC). A PLC is a special purpose computer developed for industrial process control. PLCs are designed for multiple analog and digital inputs and outputs, extended temperature-operating ranges, immunity to electrical noise, and resistance to vibration and impact. Programs to control machine operation are typically stored in battery-backed-up or nonvolatile memory. A PLC has a real-time operating system. Output results must be produced in response to input conditions within a limited time, otherwise, unintended operation could result. Further information can be found in [3].

3.1.3 Hardware and intelligence architectures

Figures 2–4 depict three hardware and intelligence architectures. All descriptions that we received from companies map into one of the following three scenarios.

In all cases, the run level intelligence resides in an industrial PC. The logging intelligence is also anchored in the industrial PC.

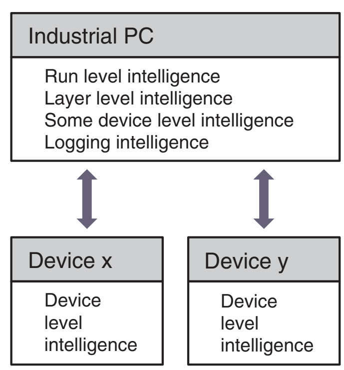

Figure 2: Architecture, employing only an industrial PC.

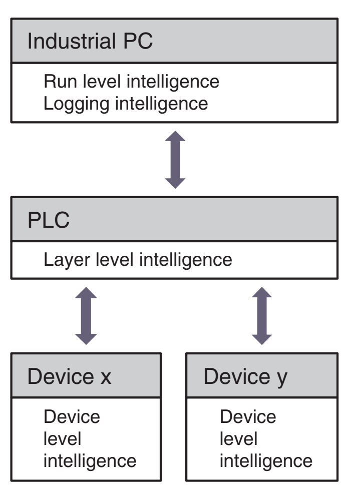

Figure 3: Architecture, using a strict division between industrial PC intelligence and PLC intelligence.

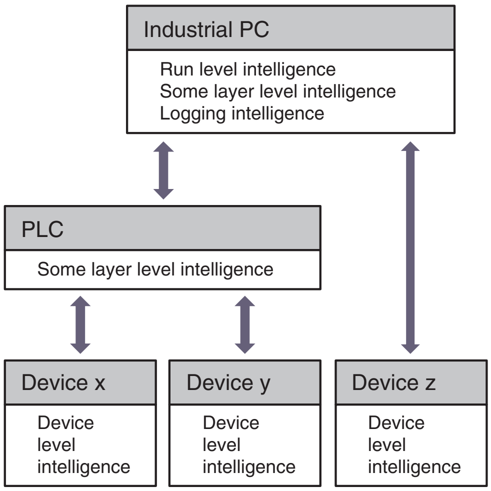

Figure 4: Architecture, employing industrial PC and PLC with distributed layer level intelligence.

Some coating machines do not employ a PLC. That scenario is shown in Figure 2. The layer level intelligence and even some device level intelligence reside together with the run level intelligence and logging in the industrial PC. Further devices are connected directly to the industrial PC. Such a control system is enabled by the high processing power of today's PCs. As many critical software elements execute in the same platform, this can be a very flexible architecture. The logging function can have access to all data at a high frequency. The challenge in this architecture is to manage the resources so a critical cutpoint does not get delayed because of an unexpected interrupt, for example, from a virus scanner. In some installations, a soft PLC, operating on a real-time component is installed to address the concern of latency.

Some coating machines only have the run level and logging intelligence in the industrial PC and have all layer level intelligence in a PLC. Figure 3 shows that architecture. All further controlling devices are attached to the PLC. This is a classical model and can be a very robust architecture. All inputs and outputs are synchronized allowing for best possible control. While a layer is being coated, all required intelligence is in the PLC, and all devices are under its control. This means the industrial PC could be turned off and the machine would still finish coating the current layer. For process monitoring and logging, a service needs to be installed to upload the critical parameters to the PC. Compared to the 'all PC' option from Figure 2, logging sequence events in rapid succession can be more challenging. Trying out a new control concept requires adherence to the rules of PLC programming, which may be more challenging and time consuming than programming something in the PC.

Most of the coating machines fall somewhere between the two discussed scenarios. Figure 4 depicts this architecture. These systems use a PLC for many tasks; however, some additional devices are connected to the PC in parallel to the PLC. This requires that the layer level intelligence is distributed between the PLC and the PC. This may be the most pragmatic approach to automation. Sometimes new algorithms are first prototyped in the PC and once developed are coded and moved into the PLC. The dangers with this type of system are when the distributed intelligence is not sufficiently synchronized, and the robust features of the PLC are lost.

A very important consideration on any of the three architectures is maintenance of the automation system. Optical coating tools often last a decade and longer, but modern innovation cycles of technology are much faster. Network components and protocols, bus systems, operation systems, applications software, and device drivers are upgraded and, in some cases, obsoleted all the time. This rapid evolution of technology poses significant challenges to keeping automation systems operational, especially when PC components are employed. Running a component to failure and then finding that it cannot be replaced, or rebuilding a computer with a new operating system in an emergency and then finding that prior drivers do not work, can be a costly disruption to the operation of the machine. Companies should, therefore, devise strategies for maintaining the automation system and keeping it current.

In summary, we found that there is no one dominant architecture used in the automation of coating machines. All three discussed scenarios can be successful. It is advisable for each company to have a philosophy on the architecture and intelligence distribution, which guides the development and ensures the risks are properly understood and managed. Enough resources should be committed to keeping the automation system maintainable, especially in light of the rapid advances in computer technology.

3.1.4 Connections and communication

Table 3 shows the main currently used technologies to connect devices to the PC or PLC. We list the advantages and disadvantages for each type and what kind of device is required for troubleshooting.

We found a trend toward using more data bus technology, where adding devices or functionality means less connection hardware, but more software work. The user's maintenance department should be trained to trouble

Table 3: Connection types for connecting device to PLC or PC.

Connection type	Advantages	Disadvantages	Trouble shooting with
Digital I/O	Fast, simple	Wire for each signal	Voltmeter
Analog I/O	Fast, simple	Noise, scaling, wire for each signal	Voltmeter
Serial (RS-232, RS-485, USB)	Can exchange huge amount of data within a few wires	Increased engineering work for data handling, legacy hardware	Laptop with HyperTerminal, etc.
Parallel (GPIB)	Fast	Legacy equipment	Computer with GPIB port
Profinet, Profibus, TwinCAT, DeviceNET	High-speed data exchange with devices, expandable	Trained, qualified personnel to support, engineering work for data handling	BUS diagnostics

shoot connection problems with the respective bus technology. It is helpful if the vendor includes trouble shooting screens in the human machine interface (HMI) to shorten down time when a problem occurs.

3.2 What kind of logging does your system employ?

All coating systems employ two types of logs: event based and continuous. We discuss the two types in 3.2.1 and 3.2.2.

3.2.1 Event-based logs

Event-based logs include messages like 'recipe loaded', 'start layer 1', 'start machine vent'. Each event has a time stamp. Warning and alarms are event based. Warnings, errors, and other events may be stored together or in separate logs, categorized according to type. During manual operation, some systems consider every user keystroke an event, which gets recorded in a log. This helpful feature allows a troubleshooter to reconstruct the user input in response to an abnormal condition or any other input that led up to a specific system state.

3.2.2 Continuous logs

Scientists and process engineers are often interested in having a record of key variables over time. Examples include the cathode voltage in a sputter system with the cathode power held constant or the chamber temperature throughout a coating run. Continuous logs provide that feature.

Ideally, all control system information is archived at a very high speed. There are, however, limitations. Digital devices update their data at a given rate. A new cathode voltage may only be acquired by the driver every second. Information from the device must first be transmitted to the PLC and then transmitted to the PC before it can be recorded by the logging service. Each layer adds some latency. The latency may also vary as upload services may be interrupted and delayed. In addition, different data types may get separated and transmitted sequentially. Thus, the data that is stored in a given PC log cycle may not describe the machine state at a specific time. In most cases, it has little practical meaning to log data more frequently than once every second.

It is important to consider the format (decimal vs. scientific notation, text, how to save dates and times?) and precision at which the data is stored. Saving a pressure in mbar or Torr as an integer will result in a lot of zeros once high vacuum is reached. Such a variable should be saved in scientific notation. Large amounts of data may be accumulated in short periods of time if all available data is logged at high precision or logged too frequently. Stored data means nothing unless it is accessible. The user needs to have effective tools to withdraw the relevant information from the data log.

3.2.3 Log format

We found that a few systems log to an ODBC [4]-compliant database such as Microsoft Access (Microsoft, Redmond, WA, USA) or Wonderware Historian (Schneider, Rueil-Malmaison, France). A standard set of commands and functions can be used to manipulate and access the data. That allows storing data at a high frequency and storing different data at different frequencies. The database service retrieves only the requested data at the requested frequency. Data will be interpolated as required. For an overview, only key data can be retrieved at fairly low frequency, which allows effective manipulation. More detail can be added as required. Interestingly, several equipment manufacturers reported that, currently, most users of optical coating machines request log files to be written as text files in a folder structure. This allows the users to open the files in common desktop tools such as Microsoft Excel (Microsoft, Redmond, WA, USA). In this format, files written at a high frequency with many parameters can be quite cumbersome to manipulate. Care should be taken to determine the right critical parameters, the adequate logging frequency, precision, and format of the data. Often, suppliers allow the user to configure the logging parameters. One way to reduce the amount of storage and, in some cases, to enhance performance is to save the data in the less user-friendly binary format. The tradeoff is that the supplier must provide the tools to access the data.

3.2.4 Other logging considerations

Certain critical information may be of interest at a very high data rate. For example, raw optical monitoring information may be acquired and processed many times per second. One reported technique is to log the data at a moderate speed in the log described above, but to retain the data at a high speed in memory in a large ring buffer. The data can be displayed in full detail, and on demand, the recent history can be saved to a file at high resolution for a detailed analysis.

3.3 What is automated?

3.3.1 Deposition process

Modern coating machines use electromechanical components that can be remotely controlled and provide feedback. Every vacuum, motion, and process component is connected to the control system. As such, most coating machines are capable of controlling a coating run from pump down through coating to venting without any human intervention.

Sometimes, the entire sequence is not fully automated, and humans are necessarily part of the process. For example, a person may be prompted to confirm that the right gas bottle is connected and has the required minimum pressure. There may be some hardware exceptions where a user has to perform an operation that is not automated. For example, the correct grating and slit need to be installed in a monochromator. There may be some fault conditions in the management of the source system that either the vendor or the user are not comfortable with, so a user is requested to look through a port window and acknowledge a condition or even interfere and make a correction.

3.3.2 Loading and unloading

Many custom coating operations need to coat different substrates everyday. In these cases, substrates are generally loaded and unloaded manually.

Specialized high-throughput systems and systems that have extreme low defect requirements, however, include automatic loading and unloading. In these cases, the substrate sizes are very well standardized. Examples for standardized substrates include 100 mm and 200 mm wafers. Some tools provide cassette-to-cassette processing. Other examples can be found in display and architectural sheets and solar cells. Some systems load individual substrates, others load 'pages' of some intermediate size, and some even load the full motion system. The user may have different pages for different substrates or different motion system layouts, which allows some customization in an automated loading system.

3.4 How does your system deal with errors/abnormal conditions?

3.4.1 Detection

All coating machines look for abnormal conditions. When a valve setpoint is set, it is expected that the feedback will match the setpoint within a certain amount of time. When a sputter cathode is requested to maintain a setpoint, it is expected to report feedback within a defined tolerance interval of the setpoint. Such component level checks are standard, and the user may have the option to configure tolerances, time delay until an event is triggered, and the severity classification of the event. There are higher-level checks that follow more complex logic. For example, when gas is flowing, current to an electromagnet is on, and RF power is delivered, a plasma is expected to be sensed through on optical detector. Another example may be that when a pump is turned on, the pressure is expected to fall at an expected rate. Typically, an equipment manufacturer will start with standard error detection, and as the coating processes evolve, the error detection and alarm signaling will also change and become more complex and customized to meet the needs of the user.

3.4.2 Abnormal condition response

The response to an abnormal condition depends on the severity classification and sometimes on the machine or coating state.

If the abnormal condition is very severe, the coating machine immediately transitions to a 'defined state', for example, by disabling all outputs.

Some abnormal conditions are less severe and may be the result of a temporary communication interruption between components, or perhaps, a certain operation has only a 99% success rate. Consider a plasma ignition sequence with a gas pulse as an example. In such a case, the control system may reset the conditions and then retry the same operation. The plasma may ignite the second time, and the run can continue. For retries, it is important to implement a counter and set a numerical limit or program a time limit, otherwise, the system may get stuck in an endless retry loop.

Some abnormal conditions are well known, and a specific response sequence is initiated. An example could be when the filament of an electron gun burns out. We touch on this in more detail in 3.4.4.

Some abnormal conditions are at a warning level and do not require an immediate stop. An example is a low-flow water alarm where coating has already started. The system may keep operating, but a flag is set not to proceed to the next layer. In the mentioned case, there should be a second level 'no flow' water alarm that turns off the power to the component.

One company reported on a two-stage strategy to bring a machine to a safe halt state. Initially, the system transitions to the first state, where many process components are kept on. A user may be able to intervene quickly and then resume the run. However, if no help comes within a defined time, the system shuts down all of the process components.

3.4.3 Abnormal condition communication

All systems display the abnormal condition on the HMI. Such conditions are typically called alarms and show up on the alarm page. In addition some systems have audible alarms, and some have light towers. The vendors are prepared to offer further services like sending a text message or an email, but customers often are fearful of the potential consequences when connecting equipment to the internet.

3.4.4 Abnormal condition recovery

The machine is in a defined state and the HMI screen displays the alarm information. A human is expected to take things from here. In unfortunate cases, the failure resulted in destroyed substrates or a situation in which significant machine repair is needed. In most of these cases, a replacement run needs to be coated, and the knowledge on what exactly is on the substrate is of little relevancy. In other cases, after some intervention, the human may decide to continue the run. This does require exact knowledge of the coating that is on the substrate. Some systems rely on the user to determine this information from the run history. The person may have to create a new recipe for the remainder of the run. Other systems provide more support to the user and let him or her know what is coated on the substrate. In some systems, the person can just press a 'resume' button, and the system has the intelligence to continue where it left off. Providing a lot of abnormal condition intelligence can be very helpful for the user to recover effectively from a failure. However, with higher software complexity comes a higher affinity to bugs. No matter what the solution is, it is always advisable to determine the root cause of the problem and try to prevent it in the first place.

3.4.5 Robustness improvements

Using a hard disk drive RAID 1 [5] system and using uninterruptable power supplies for critical components is suggested to improve robustness and simplify error recovery.

3.4.6 Maintenance support

We found that cycle counters and component lifetime counters are standard in all coating control systems. This helps to maintain the machine and prevent some of the failures. One company reported on a tracking system that allows maintenance to keep a special eye on some selected variables. All systems have an interlock screen on the HMI that helps with troubleshooting. These screens typically have been developed over time. Information for the most probable problems are on the screen, but maintenance may need to probe the source code to find out the cause of a less frequent or unexpected issue.

3.5 What is the user interface?

3.5.1 Input and output interfaces

Every system includes at least one keyboard, mouse, display or touchscreen interface. The vendors support multiple input and output channels. Some can include remote access by devices including smart phones, tablets, and desktop devices. The user needs to balance the benefits of multiple access methods with potential privacy and safety concerns. For example, a tool may have parallel keyboards and mice in the cleanroom and on the gray side. The tool can conveniently be operated from either side. But when in maintenance mode, only the keyboard of the maintenance person should be in charge to prevent unexpected operation from the second keyboard. One way to address the concern is to allow only one station to have control at any given time. Control needs to be transferred to a different station from the control station. The downside is that someone may need to gown up and enter the cleanroom to transfer the control to the gray side.

Most vendors offer remote support options. Remote support allows personnel from the equipment vendor to access data on a coating machine or, in some cases, to take full control of the machine and monitor its behavior. Usually, the user side needs to grant access to the vendor whenever a remote session is started. To increase security, the tool may only respond to requests from a programmed list of domain names. This can be further tightened by allowing only specific MAC addresses to access the tool.

3.5.2 Preventing unintended operations

Some commands that are initiated when pushing a button on a HMI have very significant consequences. For example, there may be a button to abort a run or to vent a chamber. One needs to be concerned that a person accidentally bumping into a touchscreen monitor or dropping a mouse does not initiate an unintended action. Depending on severity and consequence, vendors add various means of verification. Several methods are employed: One method is to open a dialog box where the user has to confirm the intention of the action. Another method requires the user to hold a key for an extended time period, e.g., 3 s. In other cases, multikey operations are employed, similar to the 'Alt+Cntr+Del' combination in Windows systems. Some actions may require entering a password, which is only given to authorized personnel.

3.5.3 User access levels

Today's coating control systems typically provide multiple user access levels such as maintenance, engineer, operator, and supervisor. This concept helps with the prevention of unintended operation as certain actions are locked out for operator access levels. The concept also allows decluttering a HMI as there may be fewer controls with less information for the operator, compared to a maintenance operation where much more data is displayed for trouble shooting.

3.5.4 Manual intervention during automated sequencing

When a coating machine operates in automatic mode, the respective intelligence is in charge and executes the programmed sequence. As an example, a process engineer may want to see whether the coating operation becomes more stable at a higher temperature. How would he go about that? Some control systems will allow the user to make adjustments 'on the fly' while being in automatic mode by changing the temperature setpoint on the HMI. Other systems require the user to abort the current sequence, change the recipe, and then restart the system with the new recipe calling for a different temperature setpoint. Allowing manual interference can be helpful during process development or even in operation, for example, to help a slow control loop. The downside can be unintended interference or the situation where operators become used to 'helping' the automation system, thus, hiding problems that would better be solved properly. Having the automation system fully in charge is the cleaner approach, but process development can be complicated. If a certain task cannot be fully automated, a method must be devised so that the operator can make periodic adjustments.

3.5.5 Scheduling functionality

Some systems allow the user to schedule an event as if a user had pressed a button at a certain time. This can be useful, for example, to start the pumping system on Sunday night before the first user comes in on Monday morning.

3.5.6 Screen architecture

Control graphical user interfaces (GUIs) have multiple pages or tabs, such as high-level overview, vacuum system, process pages, optical monitor, recipes, alarms, operator level, and maintenance support. Buttons typically at the bottom of the screen allow the user to switch between these pages. It can be difficult to monitor or operate a coating machine from a single screen, as the user has to navigate between multiple pages. In our survey, we found that vendors have installed up to four parallel displays to give the user more real estate to show and operate multiple pages in parallel.

3.5.7 HMI design and standards

Many papers have been published on HMIs. One thing they have in common is that each company should adopt a design/style standard and try to adhere to the standard across their plant and company. That helps users at all levels, machine operators, maintenance personnel, and engineering to work on various pieces of equipment. Several organizations have published standards, and here, we list a few: ISA 101 [6] and NUREG-0700 [7] give HMI design guidelines. ISO 11064 and ISO 9241 [8] focus on ergonomic aspects of control centers and office work. ASM [9] discusses effective operator design guidelines. FAA HF-STD-001 [10] is a human factor design standard. NASA [11] provides a checklist on designing a color graphics page. ANSI/HFES 200-2008 [12] cover human factors engineering of software user interfaces. EEMUA 201 [13] is concerned with process plant control desks utilizing human-computer interfaces.

3.6 What connections does your system have/allow?

Figure 5 shows several external systems that a control system may interface with.

Many systems have an interface to one or multiple design software packages. An output from the design software gets imported and linked to the correct processes for execution. Especially, systems that are used to coat custom precision designs should have that capability for rapid prototyping and to prevent data entry errors.

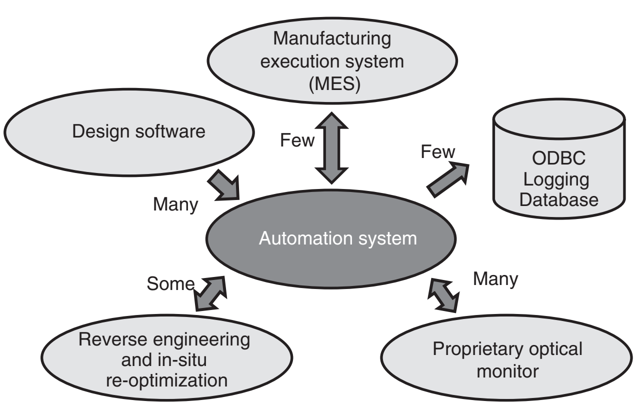

Figure 5: Automation system external interfaces.

Some control systems exchange data with an external system for reverse engineering and *in situ* reoptimization [14–17].

Some customers have developed proprietary thickness monitor systems. While vendors may have quite advanced systems and prefer employing their own system, they are prepared to integrate such a proprietary system. The user and vendor have to agree on a communication protocol. A proven way is to utilize digital lines and agree on the timing for handshake. TCP/IP protocols were also reported as being used.

We discussed in 3.2.3 that ODBC-compatible databases are supported by some vendors, but do not have widespread use in/for optical coaters today. Logging text based on file systems is more common.

A few systems, especially those being operated in concert with other semiconductor standardized tools, can have interfaces to a manufacturing execution system. Many tools in the semiconductor industry follow the communication standards of Semiconductor Equipment Communication and Standard Generic Model for Communications and Control of Manufacturing Equipment (SECS/GEM). Details can be found at SEMI [18]. Receiving electronic information about the next scheduled run and reporting progress to the manufacturing execution system can assist planning and give visibility in the factory. However, at this time, we did not find widespread use in the optical coating industry based on the information we received from the equipment manufacturers.

3.7 What standards and literature apply?

When operating any equipment, it is advisable to have a full set of configuration documents including manuals to all components for reference.

Depending on the region, municipality, or even insurance company, the equipment should adhere to one or multiple industry standards such as SEMI [18], JIS [19], NFPA [20], UL [21], CSA [22], IEC [23], VDE [24], and CE [25]. Samples of standards for safety of machinery and environment are ISO 13849-1 [7], EN 60204-1: 2006/AC:2010, EN 61000-6-4:2007, and EN 61000-6-2:2005. EN is a European standard [26]. One Equipment Communications Standard/Generic Equipment Model is SEMI SECS/GEM for displaying/logging/controlling between equipment.

IEC [23], the International Electrotechnical Commission, produces standards for programmable logic controllers and communication between automation components like IEC 61131-3 (Formerly IEC 1131-3: industrial programming standard: PLCopen) and IEC 61499 (open standard for distributed control and automation).

4 Conclusions

Today's coating machines use electromechanical components, which can be remotely controlled and provide feedback to the control system. As such, it is possible to fully automate a coating run. Pumpdown, deposition, and venting are possible to run automatically without human intervention. There are some exceptions where the vendor or user wants to have an operator verify the success of an operation or help make some decisions, at which the automation system will pause to gather user input. Loading and unloading of substrate is automated in some systems where the substrate size is sufficiently standardized and the throughput or quality gain warrants the extra investment.

We found a high variety of hardware approaches and automation implementation. No convergence on one 'winning strategy' is in sight. The user is the ultimate judge and needs to ensure that the automation approach works for the specific application that the coating machine is being used for. When buying a new coating machine, the automation system requirements should be part of the specification and not an afterthought.

Fast innovation cycles in network, bus, operation system, and hardware technology pose significant challenges to keep automation systems operational. We recommend assigning enough resources early enough to respond to the ever-changing landscape.

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