

**AUTOMATED CONTROL OF MULTI-PROCESS USING ROBOTIC EQUIPMENT
FOR COMPLEX WORKFLOWS**

CROSS REFERENCE

[001] This continuation-in-part application claims the benefit of priority and is entitled to the filing date pursuant to 35 U.S.C. § 120 of U.S. Non-Provisional Patent Application 16/674,704, filed November 5, 2019, the content of which is hereby incorporated by reference in its entirety.

FIELD

[002] The present invention relates to the field of robotics and integrating robotic processes. Specifically, the present invention relates to a system and method of integrating multiple processes performed by robotic equipment, and scheduling of the integrated processes, for automated control of workflows involving such robotic equipment, particularly in the performance of laboratory tasks and experiments in the field of life sciences.

BACKGROUND

[003] There are many existing approaches to automating activities, such as laboratory tasks and experiments, that involve robotic equipment. These existing approaches are generally focused on automating performance of a single workcell or a single robot, and are constrained by a difficult setup process, regardless of whether the activity involves the use of one or more robotic devices. These existing approaches are limited in scalability as they do not account for integration of multiple devices and identifying and scheduling multiple paths along which robotic activity must be accomplished for carrying out a sophisticated workflow or process involving different workstations performed by different types of robots. These existing approaches are further constrained by difficulties in pooling of robotic equipment and in allowing for fully interleaved processes, where a set of instruments can be shared by multiple methods running simultaneously.

[004] Existing approaches are restricted by their limited throughput or volume capability, large walk-away times requiring due to extensive human oversight needed, and laborious set up time and limited expansion capabilities as noted above. Where such approaches are utilized in specific life sciences applications, they are further hampered by limitations in tracking of laboratory samples and equipment used, handling of liquids, and simplification of assays with complicated requirements. Additionally, life sciences applications often involved handling of sensitive material, making automation of workflows difficult due to the monitoring and diligence required in

maintaining a reliable, accurate process. Further, where workflows have been successfully automated, the transportation paths are fixed to a single path and do not support dynamic just in time calculation and reprioritization of paths.

SUMMARY

[005] It is therefore one objective of the present invention to provide a system and method for integrating workflows involving robotic equipment. It is another objective of the present invention to provide a system and method of scheduling integrated tasks in the performance of such workflows. It is still another objective to provide a system and method for automated control of workstations in the performance of complex processes that is agnostic as to hardware devices such as the type or manufacturer of robotic equipment. It is still a further objective of the present invention to provide a system and method of integrating and scheduling performance of such workflows that includes an interface that enables users to quickly design and modify processes and access analytical data relative to such workflows.

[006] It is still a further objective of the present invention to provide a system and method of integrating and scheduling performance of workflows in life sciences applications involving the performance of laboratory tasks. It is yet another objective of the present invention to enable users to manage complex liquid handling protocols in workflows involving such laboratory tasks and robotic equipment, and still a further objective to automate such workflows for diverse life sciences applications, including compound management, high throughput and content screening, cell and tissue culturing, genomic sequencing, and tracking and compiling immunoassays.

[007] It is a further objective of the present invention to automate the integration and scheduling of robotic workflows for applications outside the field of life sciences. Examples of such non-life sciences applications include, but are not in any way limited to, packaging and shipping of consumer goods, facilitating safe and effective human transportation, and managing the manufacturing of highly complex, multi-part industrial products such as airplanes, automobiles, and commercial ships.

[008] The present invention provides an approach for fully automating both the integration of multiple robotic devices in the performance of a laboratory workflow, and the scheduling of tasks or workcells that together comprise a process in executing such workflows. This approach is performed in one or more systems and methods that allow users to define equipment and operations to be performed in the multiple tasks or workcells that encompass such workflows. The present invention is therefore a tool for automating control of the devices and resolving

pathways for executing operations defining such laboratory workflows. The present invention may be used in single or multiple robot configurations, and may involve resolution of workcell tasks in a single path or in multiple paths.

[009] The present invention also provides an easy-to-use interface, in which a user drags and drops devices or robots to automatically configure them, defines operations to be performed by these devices, and then runs the process encompassing these operations. The interface also provides the ability to monitor progress of the process, and make modifications and adjustments as needed during performance.

[010] The present invention is also widely applicable to robotic workflows in activities other than those involving the completion of complex life sciences tasks. For example, the present invention's scheduling and integration aspects may be applied to the performance of any industrial activity involving multiple pieces of robotic equipment or process performed by such equipment, such as packaging consumer goods and preparing and delivering a package for shipment in response to a customized order, or in human transportation systems.

[011] Other objects, embodiments, features and advantages of the present invention will become apparent from the following description of the embodiments, taken together with the accompanying drawings, which illustrate, by way of example, the principles of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[012] The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate several embodiments of the invention and together with the description, serve to explain the principles of the invention.

[013] **FIG. 1** is a system diagram for a process for integrating multiple tasks or workcells performed by robotic equipment, and for scheduling and automated control of workflows, according to one aspect of the present invention;

[014] **FIG. 2** is a flowchart of steps performed in the process for integrating multiple tasks or workcells performed by robotic equipment, and for scheduling and automated control of workflows, according to one aspect of the present invention;

[015] **FIG. 3** is a flowchart of steps performed in the process for integrating multiple tasks or workcells performed by robotic equipment, and for scheduling and automated control of

workflows, according to another aspect of the present invention; and

[016] FIG. 4 is a flowchart of steps performed in a process for resolving paths and prioritizing transfers in performing a workflow according to one aspect of the present invention.

DETAILED DESCRIPTION

[017] In the following description of the present invention reference is made to the exemplary embodiments illustrating the principles of the present invention and how it is practiced. Other embodiments will be utilized to practice the present invention and structural and functional changes will be made thereto without departing from the scope of the present invention.

[018] FIG. 1 is a system diagram of a process 100 for integrating multiple tasks or workcells 102 performed by robotic equipment 112, and for scheduling and automating control and performance of workflows 104 involving such integrated workcells 102. The process 100 of the present invention is performed within one or more systems and/or methods that includes several components, each of which define distinct activities and functions the different devices and operations involving in performing a complex laboratory workflow 104 involving multiple tasks and experiments.

[019] The process 100 receives, ingests, requests, or otherwise obtains input data 110 that includes multiple types of information relative to integrating, scheduling, and executing workflows 104 performed by robots 106. Input data 110 may include equipment data 111, which defines and identifies pieces of automated equipment 112 for performance of a robotic workflow 102. Equipment data 111 may further include device drivers 113 and device specifications 114, or provide reference markers for the process 100 to obtain such information when the equipment data 111 has been received and the process 100 initiated. The input data 110 may also include operational data 115, defining one or more specific tasks, workcells, or workstations 102 required in the performance of a workflow 104. Operational data 115 may further include an identification of one or more parameters relative to the pieces of equipment 112 used for each of the one or more tasks 102, and/or at that to be used at each stage of a workflow 104, and may also include identification of placement nests, stations, and transport modes or vehicles (including humans) used in performing the one or more tasks 102, identification of labware or other items used in the performance of the one or more tasks 102, identification of plate load orientation in the placement nests, and identification of grip specifications for transferring the labware or other items from, to, and between placement nests, stations and transport modes. Input data 110 may also include biological or other content data 116, which may include content or material specifications 117, or

provide reference markers for the process **100** to obtain such information when the content data **116** has been received and the process **100** initiated. By way of example, such content data **116** include a sample identification, such as one comprising tissue, blood, urine or sample, or other type of biological material to be tested. Where the content **116** is related to a laboratory or life sciences workflow **104**, it is to be understood that any type of biological content or material may be identified, and therefore the present invention is not to be limited to any specific type of content or material described herein.

[020] The input data **110** may further include other items attendant to performing a workflow **104**, such as for example timing data **118**. Timing data **118** may be included to define when the one or more tasks are performed within the workflow **100**, for example to ensure that content **116** is analyzed before it deteriorates to a point where an outcome of the workflow **104** is no longer valid. Timing data **118** may be entered by a user on an interface **190**, or derived from one or more of the other types of input data **110**, for example from the content or material specifications **117**.

[021] Other input data **110** may include third-party data such as LIMS (Laboratory Information Management System) data **119**, and ELN (electronic laboratory notebook) data **120**. The process **100** may be configured to import input data **110** from such third-party sources, as well as to export output data **170** to such third-party sources as noted further herein.

[022] The input data **110** is applied to a plurality of data processing components **140** within a computing environment **130** that also includes one or more processors **132**, a plurality of software and hardware components, and one or more modular software and hardware packages configured to perform specific processing functions. The one or more processors **132**, plurality of software and hardware components, and one or more modular software and hardware packages are configured to execute program instructions to perform algorithms for various functions within the process **100** that are described in detail herein, and embodied in the one or more data processing modules **140**.

[023] The plurality of data processing components **140** include a data reception and initialization component **141** configured to receive, ingest, request, or otherwise obtain the input data **110** as noted above, and to initialize the process **100**. The plurality of data processing components **140** also include an integration component **142**, configured to compile device and operational information for performing the workcells **102** within the workflow **104**, and generate get, handoff, and put sequences **143** that together define how a particular robot (or robots) **106** operates in the performance of a workflow **104**. The integration component **142** includes an execution engine **144** which begins generating these sequences **143** by creating a transportation request **145**, which

specifies an origin, a destination, an item identifier **157** for each robot **106**.

[024] The plurality of data processing components **140** further include a path resolution component **146**, within which origin and destination information from the integration component **142** are evaluated for each workstation or workcell **102** and robot **106**. The path resolution component **146** receives the transportation request **145** from the integration component **142** and executes one or more path resolvers **158**, which include queries of datasets for solving the transportation request **145**, and analyzes the outcomes from the path resolvers **158** and the information obtained from dataset queries to determine an optimal path **147** and segments **148** thereof comprising the get, handoff and put sequences **143**. Path resolvers **158** may include data relative to a single robot **106** or multiple robots **106**, and may define handoff protocols between robots **106** as well as accounting for characteristics such as robot tracks, robot mobility, human involvement, etc., as discussed further below.

[025] Paths **147** are resolved, prioritized, and evaluated in the present invention by the path resolution component **146**, together with the integration component **142**. It is to be understood that a path **147** both begins and ends at instruments comprising such equipment **112**, and the path resolution component **146** executes the path resolvers **158** to accomplish path resolution, prioritization and evaluation using different steps to arrive at a set of get, handoff and put sequences **143** for carrying out a transportation request **145**. This involves querying properties of each equipment **112** identified in a path **147** to determine which, if any, robots **106** will have access to nests, as well as if any stations are accessible to robots **106** directly or accessible via other robots. Stations refer to any non-instrument pickup/drop-off location, and are used by track or conveyor systems, autonomous vehicles, other robots, or people that are part of a path **147** for passing labware off between path segments **148**.

[026] Paths **147** are resolved by a collection of available path resolvers **158**, which are algorithms configured to analyze the available paths **147** that can be taken to transfer an item from one instrument or piece of equipment **112** to the next in the get, handoff and put sequences **143**. These path resolvers **158** include a single robot path resolver, in which the origin instrument and destination instrument are checked to determine if a single robot transfer can be used to access both pieces of equipment **112**. If so, the path resolution component **146** returns a path **147** defined as a simple combination of sequences **143** for that robot **106**. This provides the optimal transfer time in executing the transportation request **145**, and the present invention therefore gives such a path **147** priority in the path resolution profile **150**.

[027] The path resolvers **158** also include a multi-robot path resolver, which determines if the

path **147** can be created using multiple robot-to-robot handoff segments **148**. To determine valid paths, the origin robots **106** are each evaluated based on the handoff stations that are accessible to other robots, recursively without backtracking, until all possible paths to the destination are found. All available paths are then considered and ordered in priority by applying a pathfinding algorithm such as A* or the like, and the path resolution component **146** returns a prioritized path **147** for the path resolution profile **150**.

[028] The path resolvers **158** also include an advanced transfer resolver, which evaluates the same robot transfer capabilities of the multi-robot path resolver, and further includes station-to-station transfers for track/conveyor transport (where labware can be transferred from station to station using linear track-based systems), autonomous vehicles that are used to transfer labware from station to station, and humans that can be instructed to transfer labware from station to station. In such an advanced transfer resolver, default prioritization is ordered as follows. A track/conveyor path **147** has priority over a multi-robot path **147** if it requires fewer robot transfers (where the number of robots **106** that need to be locked for this transportation to be successful is minimized, in order to maximize throughput on busy platforms). A robot and track/conveyor path **147** has priority over any other path **147** involving an autonomous vehicle or a human. Also, any path **147** not involving humans has priority over any path **147** involving humans. In this manner, the path resolution component **146** is able to prioritize paths **147** resolved by applying the path resolvers **158**. It is to be understood that these prioritization rules may be amended, adjusted, added or overridden for special cases, or for unique configurations, for example using the support tool **191** and/or the user interface **190**.

[029] As noted above, the path resolution component **146** returns a prioritized path **147** for the path resolution profile **150** by applying one or more algorithms to model a shortest possible path **147**, such as for example graph and tree node, or tree searching, algorithms. Examples of such algorithms which may be utilized by path resolvers include A*, Dijkstra's algorithm, variants thereof, and other similar approaches that resolve paths under constraints, particularly where temporal constraints are being modeled. Constraints in the present invention include prioritization of temporal characteristics where robots in a path **147** that perform tasks in a shortest amount of time are assigned a greater weight for priority, over spatial constraints such as a physical distance between robots. These algorithms resolve paths according to the default prioritization rules described above regarding a number of robots needed, whereby a single robot path is prioritized over a multi-robot path **147**, which has priority over a track/conveyor path **147**, but only where the multi-robot path requires greater than two robot transfers. A multi-robot path **147** and track/conveyor path **147** both have priority over any other path **147** involving an autonomous ground vehicle (AGV) or a human. For example, as to default prioritization that considers the

number of robots needed, the path resolution component 146 calculates a shortest distance, measured by how many robot handoffs are needed to get from a starting point to an end point. Where temporal measurements are added as constraints, the process 100 may ingest and analyze historical time records representing how long each robot 106 needs to transfer a plate, and adds those times, in conjunction with the number of robots 106 needed, to evaluate the length of each path 147.

[030] For each path 147, the present invention also performs several evaluations to determine additional aspects for completing the sequences 143 to carry out a transportation request 145 and build a path resolution profile 150. These include evaluating labware parameters for each robot transfer along a path 147. In evaluating labware parameters, for each labware or item type identified, and present invention determines a grip force. If a grip force is specified and the robot 106 is capable of an adjustable grip force, then each grip operation in the sequences 143 is parameterized with the specified grip force rather than the default robot grip force. A further parameter determined is a grip offset for each labware or item type. Any specified grip offset is added to associated points during the sequences 143 to ensure the labware can be properly gripped at the right location. For most labware this is simply a grip height difference, but full cartesian x, y, z, yaw, pitch, roll points may also be specified to carry out the specific grip necessary for the workcells 102.

[031] If specific grip offsets are defined on a nest-by-nest basis, and the grip offsets differ between origin nest and destination nest, a re-grip sequence in the sequences 143 is calculated and used, rather than standard or pre-defined pick-and-place sequences. If a re-grip sequence is necessary, then the availability of a re-grip nest is determined, and if available, the following re-grip steps are queued up: pick from origin nest with source nest labware grip offset; place on re-grip nest with source nest labware grip offset; pick from re-grip nest with destination re-grip offset, and place on destination nest with destination re-grip offset. Otherwise, if there is no re-grip nest and there are no matching orientations, the path 147 is determined to be impossible and will not be available for execution in the path resolution profile 150.

[032] The present invention also performs an evaluation of plate load orientation in nests. The origin nest orientation (for example, portrait, landscape, reverse portrait, reverse landscape) is identified and compared with destination orientation. If either origin or destination supports multiple orientations and there are matching orientations available, these matching orientations are used to prevent the need for a re-grip. If the origin and destination do not match and there is a re-grip nest is available, the following re-grip steps are queued up to change the plate orientation in the gripper, rather than the standard pick-and-place steps: pick from origin in origin orientation;

place on re-grip in origin orientation; pick from re-grip nest destination orientation; and place from destination nest in destination orientation. Otherwise, if there is no re-grip nest and there are no matching orientations, the path **147** is determined to be impossible and will not be available for execution in the path resolution profile **150**.

[033] The path resolution component **146** may further include a path execution manager **149**, which reserves or locks required devices (such as robots **106**, vehicles, or other devices involved in the transport and conveyance of labware and other items between nests, stations and vehicles/devices) and defines one or more segments **148** of a path **147** for execution within the workflow **104** within a path resolution profile **150**. The path resolution profile **150** defines how a workflow **104** is performed according to the optimal path **147** and segments **148** calculated in the path resolution component **146**. The path resolution profile **150** is used to fulfill the associated transportation requests **145** by specifying the get, handoff, and put sequences **143** for each workcell **102** and between each robot **106** involved in a path **147**.

[034] The path resolution profile **150** may include instructions for execution **160** of a workflow **104** that performs the get, handoff, and put sequences **143** for workcells **102** in the one or more transportation requests **145** within the process **100**, as well as generation of other output data **170**. The path resolution profile **150** is sent to a scheduling component **151**, which prepares a schedule **152** for the execution **160** of a workflow **104** in a workflow execution component **153**.

[035] The path resolution component **146** evaluates transportation requests **145** to enable the get, handoff, and put sequences for each workcell **102**, and provides for simultaneous transport that minimizes delays in handoffs between workcells **102** and robots **106** to improve throughput. **FIG. 2** shows stages of an exemplary get, handoff, and put sequence **200** defined by the path resolution component **146** in response to a transportation request **145**. In **FIG. 2**, the transportation request **145** is queued at step **210**, and a robot **106** or workstation **102** evaluation is initiated at step **220**. The path resolution component **146** evaluates each workstation **102** and robot **106** and resolves a path **147** at step **230**. A workflow execution component **153** then executes the workflow **104** according to the path resolution profile **150** by getting a plate or other item from its origin at step **240**, and initiating the actions involved in transporting the item between workstations **102** at step **250**. During the workflow **104**, at each handoff between stations **102**, the process **100** retracts the item from its prior workstation **102** at step **260** and waits for arrival of the item at its destination at step **270**. The process **100** then puts the item in place at the next or destination workstation **102** at step **280**.

[036] The plurality of data processing components **140** may further be configured to provide

information **171** to a user interface **190** relative to carrying out a workflow **104**, or other output data **170**. For example, the present invention may display information **171** such as instrument settings, a liquid handling status, error data, simulation outcomes, log files, LIMS and ELN data, a workflow performance status, plate location, assay details, etc. on the user interface **190**. Such information **171** may also be exported to third-parties or other users.

[037] The plurality of data processing components **140** may also include a simulation component **155**, configured to simulate integration of workcells and the use of robots **106** to improve determination of get, handling and put sequences **143** and resolving paths **147** for different types of workflows **104** and involving different workcells **102** and robots **106**.

[038] The plurality of data processing components **140** may also include an artificial intelligence engine **156** configured to apply one or more machine learning techniques within the process **100** to improve an understanding of get, handling and put sequences and predict paths **147**. Predictions developed by the artificial intelligence engine **156** may be applied to the simulation component **155** to improve simulation outcomes and the determination of get, handling and put sequences and resolution of paths **147**. The present invention contemplates that many different types of artificial intelligence may be employed within the scope thereof, and therefore, the artificial intelligence engine **156** may include one or more of such types of artificial intelligence. The artificial intelligence engine **156** may apply techniques that include, but are not limited to, k-nearest neighbor (KNN), logistic regression, support vector machines or networks (SVM), and one or more neural networks. Regardless, the use of artificial intelligence in the process **100** of the present invention enhances the utility of output data **170** by automatically and heuristically constructing appropriate relationships, mathematical or otherwise, relative to the interactions required between workcells **102** and robots **106**, and the resolution of optimal paths **147** between them for performance of workflows **104**.

[039] For example, the artificial intelligence engine **156** may be utilized to improve an understanding of get, handling and put sequences **143** and predict paths **147** by examining outcomes of prior, known paths to build a model that identifies unknown paths **147** based on those outcomes. The artificial intelligence engine **156** may be comprised of, in one embodiment of the present invention, one or more neural networks that are instantiated to further evaluate input data **110** to perform the specific algorithms (and increase their accuracy) comprising the path resolvers **158** and generate, in conjunction with one or more of the path resolution component **146** and the simulation component **155**, a prediction for an unknown path **147** by analyzing the outcomes of the prior, known paths. The artificial intelligence engine **156** may therefore apply prioritization rules to determine the most appropriate path **147** in response to a

transportation request **145**, based on prior instances where those rules resulted in outcomes that produced the most appropriate get, handling, and put sequences **143** for similar workcells **102**, workflows **104**, and robots **106** (and numbers thereof), as well as for similar temporal constraints, where applicable.

[040] Neural networks generally are comprised of nodes, which are computational units having one or more biased input/output connections, which are transfer (or activation) functions that combine inputs in some way, and an output connection. Nodes are then organized into layers that form a neural network. There are many types of neural networks, which are computing systems that "learn" to perform tasks, such as solving transportation requests **145** and resolving paths **147**, without being programmed with task-specific rules, based on examples. Neural networks generally are based on arrays of connected, aggregated nodes (or, "neurons") that transmit signals to each other in multiple layers over connections. Connections as noted above are activation or transfer functions that "fire" these nodes and combine inputs according to mathematical equations or formulas. Different types of neural networks generally have different configurations of these layers of connected, aggregated nodes, but they can generally be described as an input layer, a middle or 'hidden' layer, and an output layer. These layers may perform different transformations on their various inputs, using different mathematical calculations or functions. Signals travel between these layers, from the input layer to the output layer via the middle layer, and may traverse layers, and nodes, multiple times.

[041] Signals are transmitted between nodes over connections, and the output of each node is calculated in a non-linear function that sums all of the inputs to that node. Weight matrices and biases are typically applied to each node, and each connection, and these weights and biases are adjusted as the neural network processes inputs and transmits them across the nodes and connections. These weights represent increases or decreases in the strength of a signal at a particular connection. Additionally, nodes may have a threshold, such that a signal is sent only if the aggregated output at that node crosses that threshold. Weights generally represent how long an activation function takes, while biases represent when, in time, such a function starts; together, they help gradients minimize over time. At least in the case of weights, they can be initialized and change (i.e. decay) over time, as a system learns what weights should be, and how they should be adjusted. In other words, neural networks evolve as they learn, and the mathematical formulas and functions that comprise neural networks design can change over time as a system improves itself.

[042] Neural networks instantiated as part of the artificial intelligence engine **156** may be applicable in one or more of the integration component **142**, path resolution component **146**, and

simulation component **155** of the process **100**, particularly where it constraints such as temporal characteristics related to performance of tasks in a shortest amount of time involve determining and assigning weights for evaluating priority. For example, a neural network trained on historical time records representing how long each robot needs to transfer a plate may improve the resulting processing required to correctly resolve a future path **147** according to prioritization rules that involve such temporal constraints, and calculate a length of each path **147**. This may be particularly important where paths **147** must be resolved in time-sensitive situations that require a fast and accurate response.

[043] The artificial intelligence engine **156** may also be applied to evaluate other aspects of a workcell **102**, workflow **104**, or robot **106**. One or more neural networks may be instantiated to evaluate historical performance of robots **106** and model labware parameters for each robot transfer along a path **147**, for example to determine a grip force, where a robot **106** is capable of an adjustable grip force. Neural network(s) can be applied to model each grip operation in the sequences **143** with a specified grip force. Neural network(s) may also be applied to evaluate a grip offset for each labware or item type to ensure the labware can be properly gripped at the right location. For example, x, y, z, yaw, pitch, roll points may also be modeled to ensure that a required grip necessary for the workcells **102** is properly applied.

[044] The data processing components **140** are configured to generate output data **170** that may take many different forms. Output data **170** may include, in addition to the execute instruction **160** and visualized information **171** as noted above, a label **172**, a compliance report **173**, an audit report **174**, an output to a LIMS **175**, an output to an ELN **176**, and deadlock detection **177**. The output data **170** may also include video **178** of a workflow **104** being performed, either as a live stream or fixed in time. The output data **170** may also include an alarm **179** such as a verbal, visual, aural, or other indication, for example to indicate that an incident or problem has been detected in the performance of a workflow **104**, or that a workflow **104** has been successfully completed.

[045] The present invention, as noted above, includes a user interface **190**. The interface **190** enables users to track a workflow **104**, as well as samples and labware as a workflow is executed. The interface **190** may also be used to visualize information **171** and control performance of the workflow **104**, as well as to make modifications and adjustments to workflows **104** while they are being conducted. The interface **190** may include one or more support tools **191** for accessing or controlling specific functions within a process **100**. Regardless, the interface **190** may include widgets, drop-down or pull-down menus, and other indicia presented via a graphical display that enable a user to make selections and perform functions attendant to performance of workflows

104. Users may access the interface from desktop, laptop, and mainframe computing systems, as well as by using mobile telephony, tablet, wearable computing devices, augmented reality, or virtual reality device, whether via dedicated applications on such devices or via the Internet directly.

[046] As noted above, the process **100** develops a profile **150** that is used to defines how a workflow **104** is performed, according to the path **147** representing an integrated set of get, handoff, and put sequences **143** for each workcell **102** and between each robot **106**. The path resolution profile **150** therefore acts as a map and includes instructions for execution **160** of a workflow **104**. The profile **150** is also used in the process **100** to schedule workflows **104**, and is therefore used by the scheduling component **151** and the workflow execution component **153** as processes **100** are carried out within the present invention.

[047] FIG. 3 is a flowchart illustrating steps **300** in a process **100** for performing automated workflows **104** according to another aspect of the present invention. A user selects equipment for a workflow **104** by dragging and dropping devices or robots **106** for particular tasks, experiments, workstations, or other workcells **102** via the interface **190** at step **310**. The process **100** then configures these robots **106** automatically at step **320**, through their associated device drivers **113**, device specifications **114**, and any other information needed to initiate the process **100**. Alternatively, the process **100** may automatically recognize existing equipment to be used where a user simply selects the name of laboratory where a workflow **104** will be conducted, and uploads robot information according to such a selection.

[048] FIG. 3 continues at step **330**, where a user defines the operations to be performed in a workflow **104** and using the selected devices or robots **106**. This may be accomplished by dragging and dropping pre-identified operations, or by typing textual indications of operations via the user interface **190**. Regardless, the user is able to define and customize what operations constitute a workflow **104**. At step **340**, the user selects an execute function to perform the workflow **104**, and at step **350** the process **100** is able to respond to user modifications, adjustments, or other commands, and the user is able to monitor progress of the workflow **104** via the interface **190**.

[049] FIG. 4 is a flowchart illustrating steps in a process **400** of resolving paths for performing the get, handoff, and put sequences for each task in the one or more tasks, for prioritizing transfers of items in the performance of the workflow, according to another aspect of the present invention. This process **400** begins with step **410** in which the present invention analyzes a plurality of task parameters for each task. Task parameters include, as noted above, characteristics of performing

a task such as grip force, grip offset, and plate load orientation in nests, and may further include robot specifications and station characteristics.

[050] At step **420**, the process **400** according to this aspect of the present invention assesses origin, destination, and nest characteristics of the equipment **112**, and at step **430** determines the number of robots needed to carry out the get, handoff, and put sequences **143**, which may include querying properties of each equipment **112** to determine which, if any, robots **106** will have access to nests, as well as if any stations are accessible to robots **106** directly or via other robots. At step **440**, the process **400** identifies station-to-station transfers of items for each task in the one or more tasks.

[051] Once characteristics, robots, and transfer identification are assessed, the present invention is ready to proceed with finalizing the optimal path **147**. At step **450**, the process **400** defines segments **148** for executing the paths **147** in the workflow **104**, and generates a path resolution profile **150** with these segments **148**. The present invention then develops a schedule **152** for executing an automated performance of the workflow **104** from the path resolution profile **150** at step **460**. The workflow **104** may then be controlled and performed based on the schedule **152**.

[052] The user interface **190** may be configured to permit users to access multiple, additional functions in an advanced mode. Such functions may include offline instrument access, recovery features, and scripting capabilities. Additionally, users may configure the present invention to seamlessly integrate with any external LIMS/informatics or ELN platform for importing or exporting data, perform real-time positive sample tracking, track other users, instruments, and other process data, and enable advanced features such as integration of artificial intelligence and machine learning functions as noted above.

[053] It is to be understood that the present invention is not to be limited to any particular type of workflow **104** performed, and that the process **100** of the present invention may be applied to any field where automated control of robots **106** and/or tasks **102** is desired. Accordingly, the content **116** in the input data **100** may include any subject matter for which an automated process **100** is applied. For example, the content **116** may be packaging, and the automated process **100** may be a workflow for identifying an item to be shipped, preparing the item in a package, and scheduling a shipment of the package. Many types of workflows **104** are therefore possible and are within the scope of the present invention.

[054] The systems and methods of the present invention may be implemented in many different

computing environments 130. For example, they may be implemented in conjunction with a special purpose computer, a programmed microprocessor or microcontroller and peripheral integrated circuit element(s), an ASIC or other integrated circuit, a digital signal processor, electronic or logic circuitry such as discrete element circuit, a programmable logic device or gate array such as a PLD, PLA, FPGA, PAL, GPU and any comparable means. In general, any means of implementing the methodology illustrated herein can be used to implement the various aspects of the present invention. Exemplary hardware that can be used for the present invention includes computers, handheld devices, telephones (e.g., cellular, Internet enabled, digital, analog, hybrids, and others), and other such hardware. Some of these devices include processors (e.g., a single or multiple microprocessors or general processing units), memory, nonvolatile storage, input devices, and output devices. Furthermore, alternative software implementations including, but not limited to, distributed processing, parallel processing, virtual machine processing, or cloud processing can also be configured to perform the methods described herein.

[055] The systems and methods of the present invention may also be wholly or partially implemented in software that can be stored on a non-transitory computer-readable storage medium, executed on programmed general-purpose computer with the cooperation of a controller and memory, a special purpose computer, a microprocessor, or the like. In these instances, the systems and methods of this invention can be implemented as a program embedded on a mobile device or personal computer through such mediums as an applet, JAVA® or CGI script, as a resource residing on one or more servers or computer workstations, as a routine embedded in a dedicated measurement system, system component, or the like. The system can also be implemented by physically incorporating the system and/or method into a software and/or hardware system.

[056] Additionally, the data processing functions disclosed herein may be performed by one or more program instructions stored in or executed by such memory, and further may be performed by one or more modules configured to carry out those program instructions. Modules are intended to refer to any known or later developed hardware, software, firmware, machine learning, artificial intelligence, fuzzy logic, expert system or combination of hardware and software that is capable of performing the data processing functionality described herein.

[057] In closing, it is to be understood that, although aspects of the present specification are highlighted by referring to specific embodiments, one skilled in the art will readily appreciate that these described embodiments are only illustrative of the principles of the subject matter disclosed herein. The specific embodiments are not intended to be exhaustive or to limit the invention to the precise forms disclosed. Therefore, it should be understood that the disclosed subject matter

is in no way limited to a particular compound, composition, article, apparatus, methodology, protocol, and/or reagent, etc., described herein, unless expressly stated as such. In addition, those of ordinary skill in the art will recognize that certain changes, modifications, permutations, alterations, additions, subtractions and sub-combinations thereof can be made in accordance with the teachings herein without departing from the spirit of the present specification. It is therefore intended that the scope of the invention is not to be limited by this detailed description. Furthermore, it is intended that the following appended claims and claims hereafter introduced are interpreted to include all such changes, modifications, permutations, alterations, additions, subtractions and sub-combinations as are within their true spirit and scope.

[058] Certain embodiments of the present invention are described herein, including the best mode known to the inventors for carrying out the invention. Of course, variations on these described embodiments will become apparent to those of ordinary skill in the art upon reading the foregoing description. The inventor expects skilled artisans to employ such variations as appropriate, and the inventors intend for the present invention to be practiced otherwise than specifically described herein. Accordingly, this invention includes all modifications and equivalents of the subject matter recited in the claims appended hereto as permitted by applicable law. Moreover, any combination of the above-described embodiments in all possible variations thereof is encompassed by the invention unless otherwise indicated herein or otherwise clearly contradicted by context.

[059] Groupings of alternative embodiments, elements, or steps of the present invention are not to be construed as limitations. Each group member may be referred to and claimed individually or in any combination with other group members disclosed herein. It is anticipated that one or more members of a group may be included in, or deleted from, a group for reasons of convenience and/or patentability. When any such inclusion or deletion occurs, the specification is deemed to contain the group as modified, thus fulfilling the written description of all Markush groups used in the appended claims.

[060] Insubstantial changes from the claimed subject matter as viewed by a person with ordinary skill in the art, now known or later devised, are expressly contemplated as being equivalently within the scope of the claims. Therefore, obvious substitutions now or later known to one with ordinary skill in the art are defined to be within the scope of the defined elements.

[061] Unless otherwise indicated, all numbers expressing a characteristic, item, quantity, parameter, property, term, and so forth used in the present specification and claims are to be understood as being modified in all instances by the term "about." As used herein, the term

"about" means that the characteristic, item, quantity, parameter, property, or term so qualified encompasses a range of plus or minus ten percent above and below the value of the stated characteristic, item, quantity, parameter, property, or term. Accordingly, unless indicated to the contrary, the numerical parameters set forth in the specification and attached claims are approximations that may vary. For instance, as mass spectrometry instruments can vary slightly in determining the mass of a given analyte, the term "about" in the context of the mass of an ion or the mass/charge ratio of an ion refers to ± 0.50 atomic mass unit. At the very least, and not as an attempt to limit the application of the doctrine of equivalents to the scope of the claims, each numerical indication should at least be construed in light of the number of reported significant digits and by applying ordinary rounding techniques.

[062] Notwithstanding that the numerical ranges and values setting forth the broad scope of the invention are approximations, the numerical ranges and values set forth in the specific examples are reported as precisely as possible. Any numerical range or value, however, inherently contains certain errors necessarily resulting from the standard deviation found in their respective testing measurements. Recitation of numerical ranges of values herein is merely intended to serve as a shorthand method of referring individually to each separate numerical value falling within the range. Unless otherwise indicated herein, each individual value of a numerical range is incorporated into the present specification as if it were individually recited herein.

[063] Use of the terms "may" or "can" in reference to an embodiment or aspect of an embodiment also carries with it the alternative meaning of "may not" or "cannot." As such, if the present specification discloses that an embodiment or an aspect of an embodiment may be or can be included as part of the inventive subject matter, then the negative limitation or exclusionary proviso is also explicitly meant, meaning that an embodiment or an aspect of an embodiment may not be or cannot be included as part of the inventive subject matter. In a similar manner, use of the term "optionally" in reference to an embodiment or aspect of an embodiment means that such embodiment or aspect of the embodiment may be included as part of the inventive subject matter or may not be included as part of the inventive subject matter. Whether such a negative limitation or exclusionary proviso applies will be based on whether the negative limitation or exclusionary proviso is recited in the claimed subject matter.

[064] The terms "a," "an," "the" and similar references used in the context of describing the present invention (especially in the context of the following claims) are to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. Further, ordinal indicators – such as, e.g., "first," "second," "third," etc. – for identified elements are used to distinguish between the elements, and do not indicate or imply a required

or limited number of such elements, and do not indicate a particular position or order of such elements unless otherwise specifically stated. All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples or exemplary language (e.g., “such as”) provided herein is intended merely to better illuminate the present invention and does not pose a limitation on the scope of the invention otherwise claimed. No language in the present specification should be construed as indicating any non-claimed element essential to the practice of the invention.

[065] When used in the claims, whether as filed or added per amendment, the open-ended transitional term “comprising”, variations thereof such as, e.g., “comprise” and “comprises”, and equivalent open-ended transitional phrases thereof like “including,” “containing” and “having”, encompass all the expressly recited elements, limitations, steps, integers, and/or features alone or in combination with unrecited subject matter; the named elements, limitations, steps, integers, and/or features are essential, but other unnamed elements, limitations, steps, integers, and/or features may be added and still form a construct within the scope of the claim. Specific embodiments disclosed herein may be further limited in the claims using the closed-ended transitional phrases “consisting of” or “consisting essentially of” (or variations thereof such as, e.g., “consist of”, “consists of”, “consist essentially of”, and “consists essentially of”) in lieu of or as an amendment for “comprising.” When used in the claims, whether as filed or added per amendment, the closed-ended transitional phrase “consisting of” excludes any element, limitation, step, integer, or feature not expressly recited in the claims. The closed-ended transitional phrase “consisting essentially of” limits the scope of a claim to the expressly recited elements, limitations, steps, integers, and/or features and any other elements, limitations, steps, integers, and/or features that do not materially affect the basic and novel characteristic(s) of the claimed subject matter. Thus, the meaning of the open-ended transitional phrase “comprising” is being defined as encompassing all the specifically recited elements, limitations, steps and/or features as well as any optional, additional unspecified ones. The meaning of the closed-ended transitional phrase “consisting of” is being defined as only including those elements, limitations, steps, integers, and/or features specifically recited in the claim, whereas the meaning of the closed-ended transitional phrase “consisting essentially of” is being defined as only including those elements, limitations, steps, integers, and/or features specifically recited in the claim and those elements, limitations, steps, integers, and/or features that do not materially affect the basic and novel characteristic(s) of the claimed subject matter. Therefore, the open-ended transitional phrase “comprising” (and equivalent open-ended transitional phrases thereof) includes within its meaning, as a limiting case, claimed subject matter specified by the closed-ended transitional phrases “consisting of” or “consisting essentially of.” As such, the embodiments described herein

or so claimed with the phrase “comprising” expressly and unambiguously provide description, enablement, and support for the phrases “consisting essentially of” and “consisting of.”

[066] All patents, patent publications, and other references cited and identified in the present specification are individually and expressly incorporated herein by reference in their entirety for the purpose of describing and disclosing, for example, the compositions and methodologies described in such publications that might be used in connection with the present invention. These publications are provided solely for their disclosure prior to the filing date of the present application. Nothing in this regard is or should be construed as an admission that the inventors are not entitled to antedate such disclosure by virtue of prior invention or for any other reason. All statements as to the date or representation as to the contents of these documents are based on the information available to the applicant and do not constitute any admission as to the correctness of the dates or contents of these documents.

[067] Lastly, the terminology used herein is for the purpose of describing particular embodiments only and is not intended to limit the scope of the present invention, which is defined solely by the claims. Accordingly, the present invention is not limited to that precisely as shown and described.