(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
23 June 2016 (23.06.2016)

(10) International Publication Number
WO 2016/100752 A2

(51) International Patent Classification:
G06Q 10/08 (2012.01)

(21) International Application Number:
PCT/US2015/066527

(22) International Filing Date:
17 December 2015 (17.12.2015)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/094,037 18 December 2014 (18.12.2014) US

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU,

[Continued on next page]

(54) Title: METHODOLOGY FOR DESIGN OF A MANUFACTURING FACILITY FOR FABRICATION OF SOLID STATE ENERGY STORAGE DEVICES

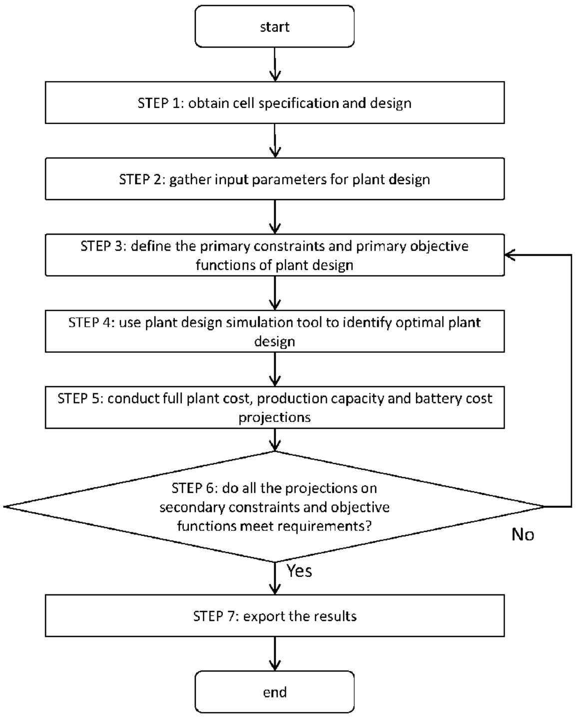

Figure 13

(57) Abstract: Techniques for designing a manufacturing facility for fabrication of solid state energy storage devices are disclosed herein. Specifically, an iterative method can be used to design a solid state battery manufacturing line considering a multitude of factors including, but not limited to: (1) how to choose battery materials and structure; (2) how to choose between crystalline and amorphous battery materials; (3) how to choose materials to avoid expensive elements and to avoid materials that are difficult to be processed; (4) whether to include interlayers; (5) whether to stack and wind the layers into cells; and (6) how to terminate and package cells.

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LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

METHODOLOGY FOR DESIGN OF A MANUFACTURING FACILITY FOR FABRICATION OF SOLID STATE ENERGY STORAGE DEVICES

REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 62,094,037, filed December 18, 2014, the content of which is incorporated herein in its entirety by reference.

BACKGROUND OF THE INVENTION

[0002] This present disclosure relates to manufacture of electrochemical cells. More particularly, the present disclosure provides techniques, including a method and device, for a solid state battery device. Merely by way of example, the invention has been provided with use of lithium based battery cells, but it would be recognized that other battery cells made from materials such as zinc, silver and lead, nickel could be operated in the same or like fashion. Additionally, such batteries can be used for a variety of applications such as portable electronics (cell phones, personal digital assistants, radio players, music players, video cameras, and the like), tablet and laptop computers, power supplies for military use (communications, lighting, imaging, satellite, and the like), power supplies for aerospace applications (aero plane , satellites and micro air vehicles), power supplies for vehicle applications (hybrid electric vehicles, plug-in hybrid electric vehicles, fully electric vehicles, electric scooter, , underwater vehicle, boat, ship, electric garden tractor, and electric ride on garden device), power supplies for remote control devices (unmanned aero drone, unmanned aero plane, an RC car), power supplies for a robotic appliances (robotic toys, robotic vacuum cleaner, robotic garden tools, robotic construction utility), power supplies for power tools (electric drill, electric mower, electric vacuum cleaner, electric metal working grinder, electric heat gun, electric press expansion tool, electric saw and cutters, electric sander and polisher, electric shear and nibbler, and routers), power supply for personal hygiene device (electric tooth brush, hand dryer and electric hair dryer), heater, cooler, chiller, fan, humidifier, power supplies for other applications (a global positioning system (GPS) device, a laser rangefinder, a flashlight, an electric street lighting, standby power

supply, uninterrupted power supplies, and other portable and stationary electronic devices). The method and system for operation of such batteries are also applicable to cases in which the battery is not the only power supply in the system, and additional power is provided by a fuel cell, other batteries, an IC engine or other combustion devices, capacitors, solar cells, combinations thereof, and others.
Common electro-chemical cells often use liquid electrolytes. Such cells are typically used in many conventional applications. Alternative techniques for manufacturing electro-chemical cells include solid state cells. Such solid state cells are generally in the experimental state, have been difficult to make, and have not been successfully produced in large scale. Although promising, solid state cells have not been achieved due to limitations in cell structures and manufacturing techniques. These and other limitations have been described throughout the present specification and more particularly below.

[0003] Solid state batteries have been proven to have several advantages over conventional batteries using liquid electrolyte in lab settings. Safety is the foremost one. Solid state battery is intrinsically more stable than liquid electrolyte cells since it does not contain a liquid that causes undesirable reaction, resulting thermal runaway, and an explosion in the worst case. Solid state battery can store over 30% more energy for the same volume or over 50% more for the same mass than conventional batteries. Good cycle performance, more than 10,000 cycles, and a good high temperature stability also has been reported.

[0004] Despite of these outstanding properties of solid state batteries, there are challenges to address in the future to make this type of batteries available in the market. To exploit the compactness and high energy density, no metal housing or excessive substrate should be used. To be used in variety of applications such as consumer electronics or electric vehicle, large area and fast film deposition techniques at low cost should be developed. Also, a solid state, hybrid thin film energy storage and conversion device, such as solid-a state battery, a solid oxide fuel cell, a capacitor, a photovoltaic cell and a hybrid device of these, consists of several components of thin film layers. These thin film layers are made from different materials and of different thicknesses. The deposition rate of laying down a material using a physical vapor deposition technique to form the thin film layer varies with the material and the processing technique used. Each individual layer requires a different time to finish to make a thin film device.

[0005] The production rate of solid state batteries, in terms the number of device units made per unit time, depends on the slowest, rate-limiting processing step for the layer with the largest thickness to deposition rate ratio. Multiple deposition zones and multiple deposition chambers are used to speed up the rate-limiting processing step by distributing the deposition task in parallel to the assigned multiple zones and chambers. However, the added deposition zones and chambers increase the total capital and operational expenditure for the manufacturing facility. It is necessary to optimize the number of deposition zones and chambers to balance the competition between cost and production rate. The same optimization necessity exists for other solid state, hybrid thin film energy storage and conversion device manufacturing processing steps including chemical vapor deposition, physical vapor deposition, atomic layer deposition, winding, slitting, packaging using a technique of at least but not limited to dip coating, and robotic arm operations for attaching leads, wiring, moving, handling and electronic control component assembling.

[0006] However, the existing manufacturing facilities for solid state, hybrid thin film energy storage and conversion devices, including solid-state batteries, solid oxide fuel cells, capacitors, photovoltaic cells and hybrid devices of these, are designed in an arbitrary and subjective intuition-based fashion without conducting a systematical and mathematical analysis to identify the optimal design.

[0007] From the above, it is seen that techniques for improving the manufacture of solid state batteries are highly desirable. The present invention provides techniques for design of a manufacturing facility for fabrication of solid state energy storage devices. There are unexpected benefits by using the techniques provided in this invention. The present invention provides directions on (1) how to choose battery materials and structure; (2) how to choose between crystalline and amorphous battery materials; (3) how to choose materials to avoid expensive elements and to avoid materials that are difficult to be processed; (4) whether to include interlayers; (5) whether to stack and wind the layers into cells; and (6) how to terminate and package cells.

BRIEF SUMMARY OF THE INVENTION

[0008] According to the present disclosure, techniques related to manufacture of electrochemical cells are provided. More particularly, the present disclosure provides techniques, including a method and device, for a solid state battery device. Merely by way of example, the invention has been provided with use of lithium based battery cells, but it would be recognized that other battery cells made from materials such as zinc, silver and lead, nickel could be operated in the same or like fashion. Additionally, such batteries can be used for a variety of applications such as portable electronics (cell phones, personal digital assistants, radio players, music players, video cameras, and the like), tablet and laptop computers, power supplies for military use (communications, lighting, imaging, satellite, and the like), power supplies for aerospace applications (aero plane , satellites and micro air vehicles), power supplies for vehicle applications (hybrid electric vehicles, plug-in hybrid electric vehicles, fully electric vehicles, electric scooter, , underwater vehicle, boat, ship, electric garden tractor, and electric ride on garden device), power supplies for remote control devices (unmanned aero drone, unmanned aero plane, an RC car), power supplies for a robotic appliances (robotic toys, robotic vacuum cleaner, robotic garden tools, robotic construction utility), power supplies for power tool (electric drill, electric mower, electric vacuum cleaner, electric metal working grinder, electric heat gun, electric press expansion tool, electric saw and cutters, electric sander and polisher, electric shear and nibbler, and routers), power supply for personal hygiene device (electric tooth brush, hand dryer and electric hair dryer), heater, cooler, chiller, fan, humidifier, power supplies for other applications (a global positioning system (GPS) device, a laser rangefinder, a flashlight, an electric street lighting, standby power supply, uninterrupted power supplies, and other portable and stationary electronic devices). The method and system for operation of such batteries are also applicable to cases in which the battery is not the only power supply in the system, and additional power is provided by a fuel cell, other batteries, an IC engine or other combustion devices, capacitors, solar cells, combinations thereof, and others.

[0009] Common electro-chemical cells often use liquid electrolytes. Such cells are typically used in many conventional applications. Alternative techniques for manufacturing electro-chemical cells include solid state cells. Such solid state cells are generally in the experimental state, have been difficult to make, and have not been successfully produced in large scale. Although promising, solid state cells have not been achieved due to limitations in cell structures and manufacturing techniques. These and other limitations have been described throughout the present specification and more particularly below.

[0010] Solid state batteries have been proven to have several advantages over conventional batteries using liquid electrolyte in lab settings. Safety is the foremost one. Solid state battery is intrinsically more stable than liquid electrolyte cells since it does not contain a liquid that causes undesirable reaction, resulting thermal runaway, and an explosion in the worst case. Solid state battery can store over 30% more energy for the same volume or over 50% more for the same mass than conventional batteries. Good cycle performance, more than 10,000 cycles, and a good high temperature stability also has been reported.

[0011] Despite of these outstanding properties of solid state batteries, there are challenges to address in the future to make this type of batteries available in the market. To exploit the compactness and high energy density, no metal housing or excessive substrate should be used. To be used in variety of applications such as consumer electronics or electric vehicle, large area and fast film deposition techniques at low cost should be developed. Also, a solid state, hybrid thin film energy storage and conversion device, such as solid-a state battery, a solid oxide fuel cell, a capacitor, a photovoltaic cell and a hybrid device of these, consists of several components of thin film layers. These thin film layers are made from different materials and of different thicknesses. The deposition rate of laying down a material using a physical vapor deposition technique to form the thin film layer varies with the material and the processing technique used. Each individual layer requires a different time to finish to make a thin film device.

[0012] The production rate of solid state batteries, in terms the number of device units made per unit time, depends on the slowest, rate-limiting processing step for the layer with the largest thickness to deposition rate ratio. Multiple deposition zones and multiple deposition chambers are used to speed up the rate-limiting processing step by distributing the deposition task in parallel to the assigned multiple zones and chambers. However, the added deposition zones and chambers increase the total capital and operational expenditure for the manufacturing facility. It is necessary to optimize the number of deposition zones and chambers to balance the competition between cost and production rate. The same optimization necessity exists for other solid state, hybrid thin film energy storage and conversion device manufacturing processing steps including chemical vapor deposition, physical vapor deposition, atomic layer deposition, winding, slitting, packaging using a technique of at least but not limited to dip coating, and robotic arm operations for attaching leads, wiring, moving, handling and electronic control component assembling.

[0013] However, the existing manufacturing facilities for solid state, hybrid thin film energy storage and conversion devices, including solid-state batteries, solid oxide fuel cells, capacitors, photovoltaic cells and hybrid devices of these, are designed in an arbitrary and subjective intuition-based fashion without conducting a systematical and mathematical analysis to identify the optimal design.

[0014] From the above, it is seen that techniques for improving the manufacture of solid state batteries are highly desirable. The present invention provides techniques for design of a manufacturing facility for fabrication of solid state energy storage devices.

[0015] A method for design of a manufacturing facility for fabrication of solid state hybrid thin film energy storage and conversion devices has been described in (Sastry et al. U.S. Pat. App. No. US 20120130522), and assigned to Sakti3, Inc. of Ann Arbor, Mich., which is hereby incorporated by reference in its entirety. However, this method is not an iterative process and does not accommodate multiple constraints and objective functions. The present invention provides an iterative method for designing a solid state battery manufacturing line considering significantly more factors. There are unexpected benefits by using the techniques provided in this invention. There are unexpected benefits by using the techniques provided in this invention. The present invention provides directions on (1) how to choose battery materials and structure; (2) how to choose between crystalline and amorphous battery materials; (3) how to choose materials to avoid expensive elements and to avoid materials that are difficult to be processed; (4) whether to include interlayers; (5) whether to stack and wind the layers into cells; and (6) how to terminate and package cells. As one example, when lithium cobalt oxide can not be selected along with a polymer substrate because the high temperature treatment required by the lithium cobalt oxide annealing pyrolyzes the polymer substrate. Of course, there can be other variations, modifications, and alternatives. The present disclosure achieves these benefits and others in the context of known process technology. However, a further understanding of the nature and advantages of the present disclosure may be realized by reference to the latter portions of the specification and attached drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] The following diagrams are merely examples, which should not unduly limit the scope of the claims herein. One of ordinary skill in the art would recognize many other variations, modifications, and alternatives. It is also understood that the examples and embodiments described herein are for illustrative purposes only and that various modifications or changes in light thereof will be suggested to persons skilled in the art and are to be included within the spirit and purview of this process and scope of the appended claims.

[0017] FIGURE 1 is a simplified illustration of pyrolysis of polymer substrate during thermal treatment.

[0018] FIGURE 2 is a simplified illustration of a multi-drum design configuration.

[0019] FIGURE 3 is a simplified diagram of a solid state battery manufacturing plant layout according to an embodiment of the present invention.

[0020] FIGURE 4 is a simplified diagram of a solid state battery manufacturing cluster tool according to an embodiment of the present invention.

[0021] FIGURE 5 is a simplified diagram of a solid state battery manufacturing cluster tool according to an embodiment of the present invention.

[0022] FIGURE 6 is a simplified diagram of a solid state battery manufacturing inline tool according to an embodiment of the present invention.

[0023] FIGURE 7 is a schematic illustration of multiple stack solid-state batteries by winding according to an example of the present disclosure.

[0024] FIGURE 8 is a schematic illustration of procedure to fabricate multiple stack solid-state batteries by cutting after winding according to an example of the present disclosure.

[0025] FIGURE 9 is a schematic illustration of multiple stack solid-state batteries by z-folding according to an example of the present disclosure.

[0026] FIGURE 10 is a schematic illustration of procedure to fabricate multiple stack solid-state batteries by cutting after z-folding according to an example of the present disclosure.

[0027] FIGURE 11 is a schematic illustration of procedure to fabricate multiple stack solid-state batteries by cutting and stacking according to an example of the present disclosure.

[0028] FIGURE 12 is a schematic illustration of stacked solid state batteries by consecutive deposition processes according to an example of the present disclosure.

[0029] FIGURE 13 is a simplified flow diagram describing how to use plant design modeling and simulation tool according to an embodiment of the present invention.

[0030] FIGURE 14 is a simplified diagram of modules of the code included in the manufacturing plant design system according to an embodiment of the present invention.

[0031] FIGURE 15 is a simplified diagram showing winding solid state battery cells on arbitrary shape of mandrel according to an embodiment of the present invention.

[0032] FIGURE 16 is a simplified diagram showing winding on arbitrary shape of mandrel according to an embodiment of the present invention.

[0033] FIGURE 17A is a schematic representation of multiple stacked solid state battery integrated into the ring shape frame of a portable fan according to an embodiment of the present invention.

[0034] FIGURE 17B is a list of simplified illustrations of arbitrary configuration of a multiple stacked solid state battery cells according to an example of the present disclosure.

DETAILED DESCRIPTION OF THE INVENTION

[0035] This present invention relates to manufacture of electrochemical cells. More particularly, the present disclosure provides techniques, including a method and device, for a solid state battery device. Merely by way of example, the invention has been provided with use of lithium based battery cells, but it would be recognized that other battery cells made from materials such as zinc, silver and lead, nickel could be operated in the same or like fashion. Additionally, such batteries can be used for a variety of applications such as portable electronics (cell phones, personal digital assistants, radio players, music players, video cameras, and the like), tablet and laptop computers, power supplies for military use (communications, lighting, imaging, satellite, and the like), power supplies for aerospace applications (aero plane , satellites and micro air vehicles), power supplies for vehicle applications (hybrid electric vehicles, plug-in hybrid electric vehicles, fully electric vehicles, electric scooter, , underwater vehicle, boat, ship, electric garden tractor, and electric ride on garden device), power supplies for remote control devices (unmanned aero drone, unmanned aero plane, an RC car), power supplies for a robotic appliances (robotic toys, robotic vacuum cleaner, robotic garden tools, robotic construction utility), power supplies for power tool (electric drill, electric mower, electric vacuum cleaner, electric metal working grinder, electric heat gun, electric press expansion tool, electric saw and cutters, electric sander and polisher, electric shear and nibbler, and routers), power supply for personal hygiene device (electric tooth brush, hand dryer and electric hair dryer), heater, cooler, chiller, fan, humidifier, power supplies for other applications (a global positioning system (GPS) device, a laser rangefinder, a flashlight, an electric street lighting, standby power supply, uninterrupted power supplies, and other portable and stationary electronic devices). The method and system for operation of such batteries are also applicable to cases in which the battery is not the only power supply in the system, and additional power is provided by a fuel cell, other batteries, an IC engine or other combustion devices, capacitors, solar cells, combinations thereof, and others.

[0036] The production rate of solid state batteries, in terms the number of device units made per unit time, depends on the slowest, rate-limiting processing step for the layer with the largest thickness to deposition rate ratio. Multiple deposition zones and multiple deposition chambers are used to speed up the rate-limiting processing step by distributing the deposition task in parallel to the assigned multiple zones and chambers. However, the added deposition zones and chambers increase the total capital and operational expenditure for the manufacturing facility. It is necessary to optimize the number of deposition zones and chambers to balance the competition between cost and production rate. The same optimization necessity exists for other solid state, hybrid thin film energy storage and conversion device manufacturing processing steps including chemical vapor deposition, physical vapor deposition, atomic layer deposition, winding, slitting, packaging using a technique of at least but not limited to dip coating, and robotic arm operations for attaching leads, wiring, moving, handling and electronic control component assembling.

[0037] However, the existing manufacturing facilities for solid state, hybrid thin film energy storage and conversion devices, including solid-state batteries, solid oxide fuel cells, capacitors, photovoltaic cells and hybrid devices of these, are designed in an arbitrary and subjective intuition-based fashion without conducting a systematical and mathematical analysis to identify the optimal design.

[0038] From the above, it is seen that techniques for improving the manufacture of solid state batteries are highly desirable. The present invention provides techniques for design of a manufacturing facility for fabrication of solid state energy storage devices.

[0039] A method for design of a manufacturing facility for fabrication of solid state hybrid thin film energy storage and conversion devices has been described in (Sastry et al. U.S. Pat. App. No. US 20120130522), and assigned to Sakti3, Inc. of Ann Arbor, Mich., which is hereby incorporated by reference in its entirety. However, this method is not an iterative process and does not accommodate multiple constraints and objective functions. The present invention provides an iterative method for designing a solid state battery manufacturing line considering significantly more factors. There are unexpected benefits by using the techniques provided in this invention. The present invention provides directions on (1) how to choose battery materials and structure; (2) how to choose between crystalline and amorphous battery materials; (3) how to choose materials to avoid expensive elements and to avoid materials that are difficult to be processed; (4) whether to include interlayers; (5) whether to stack and wind the layers into cells; and (6) how to terminate and package cells. As one example, when lithium cobalt oxide can not be selected along with a polymer substrate because the high temperature treatment required by the lithium cobalt oxide annealing pyrolyzes the polymer substrate.

[0040] FIG. 1 is a simplified illustration of pyrolysis of polymer substrate during thermal treatment. 101 and 102 are two solid state batteries deposited on a polymer substrate. 106 shows how these two batteries 101 and 102 looked like before any thermal treatment. A thermal treatment was applied by heating the batteries in a tube furnace from the room temperature to 400°C in half an hour. The batteries were then kept at 400°C for an hour, followed by a one hour cooling in air. After this thermal treatment, the polymer substrate was pyrolyzed. 107 shows how battery 103 and 104 looked like after the thermal treatment. Deposited battery materials (in thin film structure) over the active area remained after pyrolysis of the substrate. However, the films broke into pieces when the batteries were transferred out of the tube furnace, as shown in 105. This experiment demonstrates that not all the materials are compatible with all desirable processes. In other words, a polymer substrate cannot be used along with a cathode material that requires thermal annealing as proved by this experiment because the thermal treatment pyrolyzes the polymer substrate and destroy the integral structure of the deposited films. This further makes fabrication of multiple layer batteries impossible. Therefore, polymer substrates can only be used when the cathode does not require thermal treatment after deposition and the overall processing temperature during deposition is relatively lower than the pyrolysis temperature of the said polymer substrate. This is important because polymer substrates are desirable because its flexibility and makes winding and rolling of battery layers possible to form larger capacity cells. On the other hand, for cathode materials that do require thermal annealing, substrates such as glass or ceramic materials can be used instead of polymer substrates.

[0041] Tools used for deposition of solid state battery materials come in various types. The tools provided in this invention can be used for making multiple layer solid state batteries with the number of layers ranging from 1 to N, where N is a integer number greater than 1. Different tool configurations and designs include, but not limited to, multi-drum design, roll-to-roll design, cluster design, and in-line design.

[0042] FIG. 2 is a simplified illustration of a multi-drum design configuration. It is also called carousel design. In the carousel design, a drum stays in each processing tool for a certain period until the processing task is finished and moves to the next process tool. In this design, the number of drums is equal to the number of total processing tools and all the processing tools are arranged along a circular line. There can be other variations, modifications, and alternatives. One with normal skill in the art would be able to design single drum systems with multiple sources arranged circumferentially around the drum to create multiple layers in a single chamber or to design any arbitrary combination of sources in single or multiple chambers to create specific layers on a rotating substrate. One with normal skill in the art would be able to design a rotating substrate with flat surfaces or curved surfaces, or any combination thereof, or to design a rotating surface of arbitrary shape which would serve as a mandrel for battery production. Conformally coating battery cells onto such a shape would be used to create devices with complex shapes that do not require separate packs, or packaged batteries, either singly or multiple cells. One with ordinary skill in the art would be able to design chambers of varying size and shape as needed for a variety of processes used in production of solid state battery cells.

[0043] FIG. 3 is a simplified diagram of a thin film battery manufacturing plant layout according to an embodiment of the present invention. This diagram is merely an illustration and should not unduly limit the scope of the claims herein. As shown, the plant layout includes several rotating units that control a moving surface, such as a conveyer belt or web. This design can be called a roll-to-roll design. Batteries or other sources of energy can be used to drive the rotating units. The moving surface runs through several tools, each with a specified function. In a specific embodiment, the PVD Coater tools can be configured to for physical vapor deposition of one or more materials to form thin film layers for a battery device. Also, the slitter may be configured to remove excess portions of deposited layers, and the winder may be configured to coil the thin film layers. The packaging tool can encapsulate the electrochemically active materials in a sealed unit. One of ordinary skill in the art would recognize many variations, modifications, and alternatives to such a lay out, such as adding or removing chambers and adding or removing functions for individual chambers. One with ordinary skill in the art would be able to design chambers of varying size and shape as needed for a variety of processes used in production of solid state battery cells.

[0044] FIG. 4 is a simplified diagram of a thin film battery manufacturing facility layout according to an embodiment of the present invention. This diagram is merely an illustration and should not unduly limit the scope of the claims herein. As shown, the tool consists of a cluster of thin film deposition vacuum chambers. This configuration is called cluster design. In this design, substrates are loaded into a loadlock chamber 401 and further transferred to each individual processing chambers 402, 403, 404, 405, 406, and 407, by a robotic arm 408. As substrates move through chambers, battery materials are deposited onto the substrate sequentially and form batteries. After all the layers required for the batteries are completed, substrates with finished batteries exit the cluster tool through loadlock 401. One with ordinary skill in the art would be able to design multiple loadlocks or distributed loadlocks, gas gates or other transitional chambers enabling due control of pressure and composition of gasses and particles in and among the chambers. One with ordinary skill in the art would be able to design chambers of varying size and shape as needed for a variety of processes used in production of solid state battery cells.

[0045] FIG. 5 is a simplified diagram of a thin film battery manufacturing facility layout according to an embodiment of the present invention. This diagram is merely an illustration and should not unduly limit the scope of the claims herein. As shown, the tool consists of two clusters of thin film deposition vacuum chambers. This configuration is called cluster design. In this design, substrates are loaded into a loadlock chamber and further transferred to each individual processing chambers by robotic arms. As substrates move through chambers, battery materials are deposited onto the substrate sequentially and form batteries. After all the layers required for the batteries are completed, substrates with finished batteries exit the cluster tool through loadlock. One with ordinary skill in the art would be able to design multiple loadlocks or distributed loadlocks, gas gates or other transitional chambers enabling due control of pressure and composition of gasses and particles in and among the chambers. One with ordinary skill in the art would be able to design chambers of varying size and shape as needed for a variety of processes used in production of solid state battery cells.

[0046] FIG. 6 is a simplified diagram of a thin film battery manufacturing facility layout according to an embodiment of the present invention. This diagram is merely an illustration and should not unduly limit the scope of the claims herein. As shown, the tool consists of multiple thin film deposition vacuum chambers and a loadlock. Substrates on which batteries are deposited move inside these chambers and the loadlock. This configuration is called an in-line design. Substrates move continuously through the chambers carried by conveyor belts or other conveying mechanisms. Chambers are connected by gates or other intermediate chambers. This process could be either a continuous or a sequence process in which substrate either moves continuously or has a certain residence or variation of transfer time in any chamber. As substrates move through chambers, battery materials are deposited onto the substrate sequentially and form batteries. After all the processes are completed for forming batteries, the substrates exit from the loadlock. One with ordinary skill in the art would be able to design multiple loadlocks or distributed loadlocks, gas gates or other transitional chambers enabling due control of pressure and composition of gasses and particles in and among the chambers. One with ordinary skill in the art would be able to design chambers of varying size and shape as needed for a variety of processes used in production of solid state battery cells.

[0047] There are multiple methods that can be used to build multiple stack solid state batteries. As one example, multiple stack solid state batteries are built by winding: the present invention provides a method of using a flexible material that has a thickness in the range between 0.1 and 100 μm as the substrate for the solid state batteries. The flexible material can be selected from polymer film, such as PET, PEN, or metal foils, such as copper, aluminum. The deposited layers that comprise solid state batteries on the flexible substrate, then can be wound into a cylindrical shape or wound then compressed into a prismatic shape. FIG. 7 shows the image of the wound cell as an example of the present invention. The wound cells can further be processed by cutting the round corners to maximize the energy densities as shown in FIG. 8.

[0048] As another example, multiple stack solid state batteries are built by z-folding: the present invention provides a method of using a flexible substrate that can be a part of solid state batteries. As shown in FIG. 9, the deposited layers of solid state batteries on the flexible substrate can be stacked by z-folding. The z-folded cells can further be processed by cutting two sides of cells and terminating them to maximize the energy densities as shown in FIG.10. By alternating the process sequence, another configuration of multistack battery can be made by cutting the individual layers and then stacking them as illustrated in FIG.11.

[0049] As another example, multiple stack solid state batteries are built by iterative deposition process: As an example, the present invention provides a method of building multiple stack solid state batteries by moving a substrate through a number of deposition processes. By repeating a sequence of processes by N times, the solid state battery device has N number of stacks as shown in the schematic diagram in FIG.12.

[0050] As discussed above, there are various design configurations for solid state battery deposition tools, and there are multiple methods to make multiple stack solid state batteries. These make the decision making process on how to design these tools nontrivial. This is further complicated by the battery layer design. In solid state batteries, there are multiple stacks of battery materials. One battery stack consist of at least a first current collector layer, a cathode layer, an electrolyte layer, an anode layer. One stack can further include an interlayer, a second current collector layer, and a barrier layer. These layers can be in thin film form factor and deposited in vacuum chambers. Each layer can have different thicknesses based on the specific battery design targeted for different applications. Additionally, the deposition speed (how fast the battery materials can be laid down on the substrate) varies a lot for different layers because of the different kind of materials are used. As one example, current collectors are metals; cathodes are metal oxides; electrolytes are glassy or ceramic materials; and interlayers are polymer materials. Last, but not least, different deposition methods can be used for making different films based on the materials. As one example, thermal evaporation can be used for metals; and flash evaporation can be used for metal oxides to form cathode layer. Different deposition speeds and different deposition methods for different materials of various thicknesses renders the decision-making process regarding how many deposition unit operations need to be assigned to each layer extremely complicated and non-obvious. The present invention addresses this design process by providing an integrated plant design modeling and simulation tool. The provided technique and plant design modeling and simulation tool take into account all the above-mentioned factors and identify an optimal tool design configuration for the specific battery design targeted for a specific application.

[0051] FIG. 13 is a simplified flow diagram describing how to use plant design modeling and simulation tool according to an embodiment of the present invention. This diagram is merely an illustration and should not unduly limit the scope of the claims herein. In STEP 1, the battery design specifications targeted for a specific application are first obtained by using multiphysics modeling and simulation tool and a design optimization process. As one example, this multiphysics modeling and simulation tool and a design optimization process have been described in (Wang et al. U.S. Pat. No. 7,945,344 B2 and Zhang et al. U.S. Pat. No. 8,301,285 B2), and assigned to Sakti3, Inc. of Ann Arbor, Mich., which is hereby incorporated by reference in its entirety. As one example, the battery specifications include information regarding (1) layers in each battery stack including type of materials, pricing of materials, and thicknesses of materials, (2) the footprint (in-plane area) of the battery, (3) number of stacks in a battery, and (4) if the battery design is of a single battery type or a hybrid design consisting of different types of batteries. After all the battery design related information is collected, plant design related input parameters are gathered next in STEP 2. As one example, the information needed in this step includes, but not limited to, capital expenditure of each type of processing tools, depreciation rate of each type of processing tools, speed of each type of processing tools (as one example, the speed comprises deposition speed, winding speed, slitting speed, folding speed, cutting speed), operational expenditure of each type of processing tools (as one example, the operational expenditure comprises electricity consumption rate and cost, required facility area and footprint, required number of operators and associated cost, tool maintenance cost), and yield of processes. STEP 3 defines the constraints and primary objective functions of the plant design. As one example, the constraint is that the total capital expenditure of the manufacturing facility including all tools has to be lower than a targeted value. In another example, the constraint is that the total annual production capacity of the manufacturing facility has to be higher than a targeted value. Objective functions are normally target financial variables including at least the internal rate of return (IRR), modified internal rate of return (MIRR), net present value (NPV), and the weighted average cost of capital (WACC). As one example, the target financial variable is simplified as the ratio of capital expenditure over production capacity for a first-order analysis. In STEP 4, the plant design simulation tool is used to identify the optimal plant design. In this step, the collected information on battery design and processing tools is first represented in a tensor format. The plurality of variables in the tensor relationship can be processed to reduce a magnitude of the target objective variable. Through the processing, an optimized set of the plurality of processing tools and respective configuration with the plurality of tools associated with the reduced magnitude of the target variable can be determined. STEP 5 uses the identified optimal tool design to conduct detailed projections including at least plant cost, production capacity, battery cost projections, IRR, MIRR, NPV, and WACC. In STEP 6, the projections on secondary constraints and secondary objective functions that where not used in the optimization process were checked against requirements. If all the requirements are met, one can proceed to STEP 7 to export the results on plant design and associated projections. If there are requirements that are not met, one needs to go back to STEP 3 for one more iteration by redefining the primary constraints and primary objective functions.

[0052] As an example describing the iterative process of plant design, assuming a capital expenditure was originally set up being less than10 million US dollars, as a primary constraint. The objective function was to minimize the cost of goods sold (COGS) of batteries made. The optimization process identified an optimal design which yields only 2 million batteries annually, while a secondary constraint requires 3.5 million batteries produced annually. When this happens, STEP 6 in FIG. 13 triggers another iteration by going back to STEP 3 to redefine the primary constraints and primary objective functions. For the new iteration, capital expenditure constraint is modified to being less than 4 million US dollars. After going through STEPS 4 to 6, it was found that the annual production capacity for the new optimal design based on the modified constraints is now 3.9 million batteries, which exceeds the secondary constraint on annual production capacity. The annual production capacity was not included in the primary constraint in the first place because more constraints make the optimization problem more complicated and time consuming to solve. This is also the reason why we categorize objective functions into primary and secondary ones. To simplify the optimization problem, secondary constraints and objective functions can be left out and considered later. Secondary constraints and objective functions are also generally less important than primary ones in the plant design project.

[0053] In a specific embodiment, the processing tool configuration tensor is an n-order tensor with n dimensions to index a plurality of specifications including at least the processing step, allocated locations for tools inside the processing step, processing tool type, and the type of facility used inside a processing tool. The processing tool configuration tensor also includes elements which have binary values of zero and one. An element has the value of one if and only if the specified allocated location for the specified processing step is occupied by the specified processing tool including the specified processing facility. Otherwise, the tensor element has the value of zero.

[0054] In a specific embodiment, the tensor operation modules comprises adding two tensors, multiplying two tensors, transposing first-order and second-order tensors, contracting a tensor and finding the maximum or minimum element of a tensor or a subset of the tensor along with specified dimensions. In a specific embodiment, the optimization module includes one or more codes directed to an integer programming optimization process applying enumerative techniques, branch-and-bound techniques, or cutting planes techniques, or directed to a genetic algorithm based optimization process.

[0055] In a specific embodiment, the post-processing module includes importing the optimal configuration tensor, identifying the non-zero elements which have exactly values of one and outputting the optimal configuration information with specifications of which type of and how many processing tools are used for each processing step associated with which type and how many processing facilities are used inside each processing tool.

[0056] In a specific embodiment, the enumerative optimization procedure comprises a parallelized implementation of the enumeration of the feasible possibilities to speed up the computation process on a shared memory and multi-processing unit computing system. Of course, those skilled in the art will recognize other variations, modifications, and alternatives.

[0057] In a specific embodiment, the optimization procedure comprises a genetic algorithm based technique implemented in parallel. The approach populate the (integer) number of unit operations for each processing step randomly and maintain a fraction of the population and genetically modify the rest of the population from one generation to the next. The technique gives at least a local optimal design for the production plant when the stop criteria are met after several generations. For most of the cases, the technique can also easily identify the global optimal solution.

[0058] FIG. 14 is a simplified diagram of modules of the code included in the manufacturing plant design system according to an embodiment of the present invention. The system comprises codes of data acquisition and pre-processing module, tensor operation module, financial modeling module, optimization module, an evaluation module, and post-processing module. Of course, those skilled in the art will recognize other variations, modifications, and alternatives for modules of code to be incorporated into the manufacturing plant design system.

[0059] FIG. 15 shows winding solid state battery cells on arbitrary shape of mandrel. FIG. 15 shows schematically the winding solid state battery cells on mandrel **1501**, and deposition means. This is as an example of deposition of multiple stack solid state battery cells with arbitrary shape of mandrel, but it is not limited to the shape illustrated here. In this example, the cross section of 8-shape can be as vacuum cleaner handle part. The vacuum cleaner handle part can be used as the substrate for solid state battery cells. In one of the specific embodiment of current invention, the multiple stacked solid state battery cells can be achieved by depositing each cell components sequentially, from first current collector, cathode, electrolyte, anode, second current collector, and insulating interlayer. This deposition sequence will be repeated 1 to N times until desired total capacity achieved. Because of the thin layer characteristics, the increased volume of the stick vacuum would be minimized compared to conventional liquid or polymer gel types of battery cells. In this example, there are needs to have push rollers as **1504, 1505** and **1506** to assist the deposition battery cells **1503** conformably stick on the mandrel. As the mandrel rotating, the push rollers would need to move along the surface so that they would not be on the way of the rotation. Furthermore, the deposition sources are located under the mandrel as an example. However, the location of the deposition source can be located in any location around the mandrel to achieve uniformity of the multiple stacked solid state battery cells. The required deposition sources will be moved into the positions when they are needed. The deposition sources can also be positioned based the shape of the mandrel. For example, the two different layer deposition sources can be position on the opposite side of the 8 shape mandrel due to wide shade shielding characteristics to minimize the deposition time.

[0060] FIG. 16 shows winding on arbitrary shape of mandrel. FIG. 16 shows schematically the winding on mandrel **1603**. This is as an example of deposition of multiple stack solid state battery cells with arbitrary shape of mandrel, but it is not limited to shape illustrate here. In this example, the cross section of 8 shape can be as a vacuum cleaner handle part. In one of the specific embodiment of current invention, the multiple stack solid state battery cells can be achieved by depositing each cell components sequentially on another drum or mandrel **1601**, from first current collector, cathode, electrolyte, anode, second current collector, and insulating interlayer. This deposition sequence will be repeated 1 to N time until desired total capacity achieved. Once the desired total capacity achieved, rolled solid state battery cells will be move to winding station. On the winding station, the desired shape mandrel will be used to load the solid state battery cell. The deposited solid state battery cells will be unloaded from the cylindrical drum and winded to the desired shape mandrel, as in this example, 8-shape mandrel. After wounded to the 8-shape mandrel, the final packaging layer will be layered on top of the battery to provide insulation to environment. Because of the thin layer characteristics, the increased volume of the vacuum cleaner handle would be minimum compared to conventional liquid or polymer gel types of battery cells. In this example, there are needs to have push rollers as **1664, 1605** and **1606** to assist the winding battery cells **1602** conformably stick on the mandrel surface. As the mandrel rotating, the push rollers would need to move along the surface so that they would not be on the way of the rotation.

[0061] FIG. 17A shows integrating the multiple stack solid state batteries to the structural and/or decorative space of application device: In one example as shown in FIG. 17A, a multiple stack battery device **1705** is wound on a hollow core to be used within a housing **1702** of a bladeless fan or an air blower **1701** as shown in Figure 22. Multiple stack battery **1705** integrated to the structure, for example the rim of the fan head **1704**, eliminates the need of having a separate space for storage, allowing design only needed for the function of the appliance while enabling portability. The solid state batteries on a flexible substrate disclosed in this present invention can form any arbitrary shape. FIG. 17B demonstrates some of the example form factors that the flexible batteries may have, such as a torus, a coil, a circular cone, a trapezoidal cone, a tetrahedron.

[0062] In an embodiment, the present invention provides an iterative method for forming a manufacturing facility. The method can include providing a plurality of processing tools for arrangement within a predetermined spatial region of one or more manufacturing facilities. A plurality of variables can be assigned, respectively, for the plurality of processing tools. These variables can be provided in a tensor format. A target financial variable can be defined to evaluate different manufacturing processing tool configurations. The plurality of variables in the tensor relationship can be processed to reduce a magnitude of the target variable. Through the processing, an optimized set of the plurality of processing tools and respective configuration with the plurality of tools associated with the reduced magnitude of the target variable can be determined. The optimized set of the plurality of processing tools in the respective configuration can be used in the one or more manufacturing facilities. Furthermore, the optimized set of tools can be operated for the manufacture of a solid state thin film battery device. Those skilled in the art will recognize other variations, modifications, and alternatives.

[0063] In an embodiment, the present invention provides a multi-layered solid-state battery device comprising: an equivalent circuit numbered from 1 through N associated with, respectively, a plurality of solid state battery cells numbered from 1 through N, each of the solid state battery cells comprising a first current collector overlying the substrate member, a cathode device overlying the first current collector, an electrolyte device overlying the first current collector, an anode device overlying the electrolyte device, and a second current collector overlying the anode device, each of the plurality of solid state battery cells being operable at a state of charge between a lower bound to an upper bound; an energy density of greater than 50 watt hour per liter and greater characterizing the plurality of solid state battery cells; and a plurality of collimated pillar structures characterizing each of the cathode devices, each of the plurality of collimated pillar structures comprising an amorphous cathode material.

[0064] In an embodiment, the present invention provides a multi-layered solid-state battery device comprising the state of charge with lower bound ranging from 0.5% to 75%, wherein the state of charge upper bound ranging from 25% to 99.5%.

[0065] In an embodiment, the present invention provides a multi-layered solid-state battery device comprising the cathode device characterized by an amorphous or crystalline structure.

[0066] In an embodiment, the present invention provides a multi-layered solid-state battery device comprising the anode device comprising of metal film.

[0067] In an embodiment, the present invention provides a multi-layered solid-state battery device comprising cathode device has a thickness ranging from 0.05 to 200 microns; and the anode device has a thickness ranging from 0.02 to 200 microns.

[0068] In an embodiment, the present invention provides a multi-layered solid-state battery device comprising a plurality of battery cells that are wound or stacked.

[0069] In an embodiment, the present invention provides a multi-layered solid-state battery device comprising a substrate made of at least one of a glass structure, a conductive structure, a metal structure, a ceramic structure, a plastic or polymer structure, or a semiconductor structure, or one or more active may comprise the substrate layer.

[0070] In an embodiment, the present invention provides a multi-layered solid-state battery device comprising a termination which is configured in a parallel or a serial arrangement using either a self-terminated or post-terminated connector configuration.

[0071] In an embodiment, the present invention provides a multi-layered solid-state battery device comprising a local conductivity characterizing the region of the cathode device and a bulk conductivity characterizing the cathode device.

In an embodiment, the present invention provides a multi-layered solid-state battery device comprising cathode device is made from a material selected from lithiated or non-lithiated transition metal oxide and lithiated transition metal phosphate, wherein the metal is in Groups 3 to 12 in the periodic table, including but not limited to lithium manganese oxide, lithium nickel oxide, lithium cobalt oxide, lithium nickel-cobalt-manganese oxide, lithium nickel-cobalt-aluminum oxide, lithium copper-manganese oxide, lithium iron-manganese oxide, lithium nickel-manganese oxide, lithium cobalt-manganese oxide, lithium nickel-manganese oxide, lithium aluminum-cobalt oxide, lithium iron phosphate, lithium manganese phosphate, lithium nickel phosphate, lithium cobalt phosphate, vanadium oxide, magnesium oxide, sodium oxide, sulfur, metal (Mg, La) doped lithium metal oxides, such as magnesium doped lithium nickel oxide, lanthanum doped lithium manganese oxide, lanthanum doped lithium cobalt oxide..

[0072] In an embodiment, the present invention provides a multi-layered solid-state battery device comprising anode device is made of a material selected from lithiated or non-lithiated transition metal oxide, including but not limited to lithium titanium oxide, germanium oxide, or graphite, lithium, silicon, antimony, bismuth, indium, tin nitride, or lithium alloys, including but not limited to lithium magnesium alloy, lithium aluminum alloy, lithium tin alloy, lithium tin aluminum alloy

[0073] In an embodiment, the present invention provides a multi-layered solid-state battery device comprising electrolyte device is selected from lithiated oxynitride phosphorus (LIPON), poly(ethylene oxide) (PEO), lithium lanthanum zirconium oxide, lithium lanthanum titanium oxide, lithium sodium niobium oxide, lithium aluminum silicon oxide, lithium phosphate, lithium thiophosphate, lithium aluminum germanium phosphate, lithium aluminum titanium phosphate, LISICON (lithium super ionic conductor, generally described by LixM1-yM′yO4 (M = Si, Ge, and M′= P, Al, Zn, Ga, Sb)), thio-LISICON (lithium super ionic conductor, generally described by LixM1-yM′yS4 (M = Si, Ge, and M′= P, Al, Zn, Ga, Sb)), lithium ion conducting argyrodites (Li6PS5X (X = Cl, Br, I)), with ionic conductivity ranging from 10-5 to 10-1 S/m.

[0074] In an embodiment, the present invention provides a multi-layered solid-state battery device comprising a bonding material in between each pair of the plurality of solid state battery cells.

[0075] In an embodiment, the present invention provides a multi-layered solid-state battery device comprising cathode device that is characterized by a material comprising a plurality of pillar-like structures, each of which extends along a direction of the thickness, and substantially normal to a plane of the thickness of material and surface region.

[0076] In an embodiment, the present invention provides a multi-layered solid-state battery device comprising the cathode device that comprises a plurality of pillar structures, each of the pillar structure having a base region and an upper region, each of the pillar structures comprising a plurality of smaller particle-like structures, each of the smaller particle like structures being configured within each of the pillar structures.

[0077] In an embodiment, the present invention provides a multi-layered solid-state battery device comprising the cathode device that comprises a plurality of pillar structures, each of the pillar structure having a base region and an upper region, each of the pillar structures comprising a plurality of particle-like structures, each of the particle like structures being configured within each of the pillar structures, each pair of pillar structures having a plurality of irregularly-shaped polyhedral structures provided between the pair of pillar structures.

[0078] In an embodiment, the present invention provides a multi-layered solid-state battery device comprising an appliance coupled to the plurality of battery cells, whereupon the application is selected from at least one of or more of at least a smartphone, a cell phones, personal digital assistants, radio players, music players, video cameras, tablet and laptop computers, military communications, military lighting, military imaging, satellite, aero-plane, satellites, micro air vehicles, hybrid electric vehicles, plug-in hybrid electric vehicles, fully electric vehicles, electric scooter, , underwater vehicle, boat, ship, electric garden tractor, and electric ride on garden device, unmanned aero drone, unmanned aero-plane, an RC car, robotic toys, robotic vacuum cleaner, robotic garden tools, robotic construction utility, robotic alert system, robotic aging care unit, robotic kid care unit, electric drill, electric mower, electric vacuum cleaner, electric metal working grinder, electric heat gun, electric press expansion tool, electric saw and cutters, electric sander and polisher, electric shear and nibbler, electric routers, an electric tooth brush, an electric hair dryer, an electric hand dryer, a global positioning system (GPS) device, a laser rangefinder, a flashlight, an electric street lighting, standby power supply, uninterrupted power supplies, and other portable and stationary electronic devices.

[0079] In an embodiment, the present invention provides a configuration tensor **T** that is set up with binary values of zero and one. Take a third-order tensor for example, a respective element T_{ijk} is one when a certain tool type (index k) is assigned to a certain position (index j) for a certain processing step (index i).

$$\mathbf{T}_{ijk} = \begin{cases} 1 & \text{when position j at step i is occupied by tool type k} \\ 0 & \text{otherwise} \end{cases}$$

[0080] The advantage of this setup of configuration tensor is that the parameters such as capital expenditure and throughput rate can be easily obtained using tensor multiplication. For example, the capital expenditure $\mathbf{X}^c_{ij}$ of the processing tool located at position j at processing step i is obtained by:

$$\mathbf{X}^c_{ij} = \left(\mathbf{x}_c\right)_{\underline{k}} \mathbf{T}_{ij\underline{k}} = \mathbf{x}_c^T \mathbf{T}(:, i, j)$$

[0081] where $\mathbf{x}_c$ is a K by 1 vector defining the capital expenditure of K types of processing tools and $\left(\mathbf{x}_c\right)_{\underline{k}} \mathbf{T}_{ij\underline{k}}$ defines a the multiplication along the dimension indexed by *k*. Similarly, the throughput rate $\mathbf{R}_{ij}$ at position j at processing step i is obtained by:

$$\mathbf{R}_{ij} = \left(\mathbf{r}\right)_{i\underline{k}} \mathbf{T}_{ij\underline{k}} = \mathbf{r}(i, :)\mathbf{T}(:, i, j)$$

[0082] where $\left(\mathbf{r}\right)_{i\underline{k}}$ is a I by K matrix (2$^{\text{nd}}$ order tensor) and $\left(\mathbf{r}\right)_{i\underline{k}} \mathbf{T}_{ij\underline{k}}$ defines a multiplication along the dimension indexed by *k*.

To calculate the throughput of thin film deposition processing tools (thin film coaters), first consider the time required to deposit the component layer required for a whole battery τ,

$$\tau = \frac{LW\delta}{rA}\frac{1}{zm}$$

[0083] where L is the length of the battery component layer, W is the width of battery component layer, r is the rate, in angstrom per second, for the component layer material to be deposited by the specified processing tool with the specified processing facility, A is the effective deposition area of the processing tool, and z is the number of deposition zones inside one coater, δ is the thickness of the battery component layer and m the number of processing tools used for the battery component layer. The throughput of the coater for this specific battery component layer is then:

$$R = \frac{N}{\tau} = \frac{NA}{LW}\frac{rzm}{\delta}$$

[0084] where N is the machine running time in a year.

[0085] The total expenditure of the all the processing tools used is calculated by:

$$\mathbf{X}_{total}^{c} = \sum_{j=1}^{J}\sum_{i=1}^{I}\mathbf{X}_{ij}^{c}$$

[0086] The production rate of the whole line, in number of units made per year, is determined by the rate-limiting step:

$$\mathbf{R}_{total} = \min_{1\le i\le I}\left\{\sum_{j=1}^{J}\mathbf{R}_{ij}\right\}$$

[0087] The described configuration tensor is expandable to include a fourth dimension to index the facility type.

$$\mathbf{T}_{ijkl} = \begin{cases} 1 & \text{when position j at step i is occupied} \\ & \text{by tool type k with processing facility type l} \\ 0 & \text{otherwise} \end{cases}$$

[0088] The corresponding calculations for expenditure and rate are:

$$\mathbf{R}_{ij} = (\mathbf{R})_{i\underline{kl}}\mathbf{T}_{ij\underline{kl}} = \sum_{k}\sum_{l}\left[\mathbf{R}(:,i)\mathbf{T}(:,i,j)\right]_{kl}$$

$$\mathbf{X}_{ij}^{c} = \left(\mathbf{x}_{c}\right)_{\underline{kl}} \mathbf{T}_{ij\underline{kl}} = \sum_{k}\sum_{l} \mathbf{x}_{c}\mathbf{T}(:,i,j)$$

[0089] where $\mathbf{R}_{ikl} \in \mathbb{R}^{I \times K \times L}$ is the production rate when processing tool k with facility l is used for step I and $\left(\mathbf{x}_{c}\right)_{kl} \in \mathbb{R}^{K \times L}$ is tool capital expenditure for processing tool type k equipped with processing facility l.

[0090] To evaluate different manufacturing processing tool configurations, at least one target financial variables are used. The target financial variable comprises at least internal rate of return (IRR), modified internal rate of return (MIRR), net present value (NPV) and weighted average cost of capital (WACC). The net present value (NPV) is calculated by:

$$\mathrm{NPV} = -\mathbf{X}_{total}^{c} + \sum_{y=1}^{n} \frac{1}{\left(1 + r_{dis}\right)^{y}} \left[p \cdot \mathbf{R}_{total} - \mathbf{X}_{total}^{o} \right]$$

[0091] where r_{dis} is discount rate, p is the profit for one unit of the product, $\mathbf{X}_{total}^{o}$ is the total operational cost per year and n is the duration of the project in years. The internal rate of return (IRR) is obtained by finding the exact discount rate r_{dis} which satisfies that the net present value (NPV) is zero,

$$-\mathbf{X}_{total}^{c} + \sum_{y=1}^{n} \frac{1}{\left(1 + r_{dis}\right)^{y}} \left[p \cdot \mathbf{R}_{total} - \mathbf{X}_{total}^{o} \right] = 0$$

[0092] Due to the intrinsic drawbacks of the internal rate of return, two other financial variables, modified internal rate of return (MIRR) and weighted average cost of capital (WACC), are also used to evaluate processing tool configurations and the manufacturing facility design. Modified internal rate of return (MIRR) is obtained by:

$$\mathrm{MIRR} = \left(\frac{\mathrm{FVCF}}{\mathrm{IO}} \right)^{\frac{1}{n}} - 1$$

[0093] where FVCF is the total future value of the cash flows, IO is the cost of investment, and n is the duration of the project in years. The total future value of the cash flows is obtained by summing the future values of the individual cash flows (CF).

$$\mathrm{FVCF} = \sum_{i=1}^{n} \mathrm{CF} \cdot (1 + r)^{n-i}$$

[0094] The cost of investment is obtained by summing the present values of the individual investment.

[0095] In an embodiment, the present invention provides a method for designing a anufacturing facility for fabrication of solid state batteries of single design.

[0096] In an embodiment, the present invention provides a method for designing a manufacturing facility for fabrication of solid state batteries of hybrid design. As an example, the hybrid design consists of cells made of different cathode thicknesses to deal with different power consumptions, namely, thin cathode cells are high power cells and thick cathode cells are high energy cells. Power cells are used to deliver energy during peak power consumption, and energy cells are used to deliver energy during baseline power consumption. As another example, the hybrid cell design consists of cells made of different cathode thicknesses to deal with different operating temperatures. Thin cathode cells are low temperature cells which are capable of delivering high energy at low operating temperature, and thick cathode cells are room temperature or abovr cells which are capable of delivering high energy at room temperature or above.

[0097] While the above is a full description of the specific embodiments, various modifications, alternative constructions and equivalents may be used. Therefore, the above description and illustrations should not be taken as limiting the scope of the present invention which is defined by the appended claims.

In an embodiment, the present invention provides a plurality of processing tools comprising physical vapor deposition based thin film coater, chemical vapor deposition based thin film coater, atomic layer deposition thin film coater, conveyor, transport robot, winder, slitter, slitter using laser ablation and/or cutting, packaging machine using a technique of at least but not limited to dip coating, and robotic arms for attaching leads, wiring, moving, handling and electronic control component assembling; wherein the thin film coaters are also equipped with film thickness monitors including at least quartz crystal thickness monitors.

[0098] In an embodiment, the tools are specified with capital cost of the tool, speed of the tool, downtime of the tool, yield of the tool, efficiency of the tool, material load and unload time of the tool, preparation time of the tool, work in process for the tool and operational cost of the tool including labor and electricity cost.

[0099] In an embodiment, the present invention provides a technique using tensors to represent a plurality of processing tools comprising physical vapor deposition based thin film coater, chemical vapor deposition based thin film coater, atomic layer deposition thin film coater, conveyor, transport robot, winder, slitter, slitter using laser ablation and/or cutting, packaging machine using a technique of at least but not limited to dip coating, and robotic arms for attaching leads, wiring, moving, handling and electronic control component assembling; wherein the thin film coaters are also equipped with film thickness monitors including at least quartz crystal thickness monitors.

[0100] In an embodiment, the present invention provides optimization module comprising one or more codes directed to an integer programming optimization process applying enumerative techniques, branch-and-bound techniques, or cutting planes techniques; the wherein the optimization module comprising one or more codes directed to an optimization process applying genetic algorithm techniques.

[0101] In an embodiment, the present invention provides a system for designing a manufacturing plant. This system can include a computer readable memory device, one or more codes directed to a plurality of variables, a tensor operation module, a financial modeling module, an optimization module, and a post-processing module. The computer readable memory device can include one or more codes directed to a plurality of tool parameters corresponding respectively to a plurality of processing tools for arrangement within a predetermined spatial region of one or more manufacturing facilities. The one or more codes directed to a plurality of variables, respectively, can be for the plurality of processing tools, whereupon the plurality of variables are arranged in a tensor format, with the one or more codes directed to a processing tool configuration tensor. The tensor operation module can be configured to process the plurality of variables and the configuration tensor to obtain the production rate, capital expenditure, and operation expenditure. The financial modeling module can be used to reduce a magnitude of a target financial variable associated with a set of the plurality of variables and the configuration tensor. The target financial variable can include at least the internal rate of return (IRR), modified internal rate of return (MIRR), the net present value (NPV), and the weighted average cost of capital (WACC). The optimization module can be configured to output an optimized configuration tensor associated with the optimal target financial variable value. The post-processing module can be configured to convert the optimal configuration tensor to output the optimized set of tools and associated configuration of the set of tools. Those skilled in the art will recognize other variations, modifications, and alternatives.

[0102] In an embodiment, the present invention provides an iterative method for forming a manufacturing facility for solid state batteries comprising: providing a battery design for a targeted application; providing a plurality of processing tools for arrangement within a predetermined spatial region of one or more manufacturing facilities; assigning a plurality of variables, respectively, for the plurality of processing tools; providing the plurality of variables in a tensor format; defining primary constraints for the manufacturing facility; defining primary objective functions to evaluate different manufacturing processing tool configurations; processing the plurality of variables in the tensor relationship to reduce a magnitude of each primary objective function; determining an optimized set of the plurality of processing tools and respective configuration with the plurality of tools associated with the reduced magnitude of the target variable; determining if the secondary constraints and objective functions meet the requirements; if the secondary constraints and objective functions do not meet the requirements, redefining the primary constraints and primary objective functions to repeat the optimization process and identify an updated tool design; if the secondary constraints and objective functions do meet the requirements, proceed to the next step in this method; using the optimized set of the plurality of processing tools in the respective configuration in the one or more manufacturing facilities; and operating the optimized set of tools for the manufacture of the solid state thin film battery device.

[0103] In an embodiment, the present invention provides an iterative method for forming a manufacturing facility for solid state batteries comprising primary constraints for designing the manufacturing facility comprising at least total capital expenditure being lower than a target value, annual production capacity in number of batteries made per year being higher than a target value, annual production capacity in total capacity in million ampere hour made per year being higher than a target value, annual production capacity in total energy in million watt hour made per year being higher than a target value, battery cost of goods sold (COGS) being lower than a target value, battery cost in dollar per kilowatt hour being lower than a target value.

[0104] In an embodiment, the present invention provides a system for iteratively designing a manufacturing plant for fabricating multiple stack solid state batteries, the system comprising: a computer readable memory device, the computer readable memory including: one or more codes directed to a plurality of battery specifications and one or more codes directed to a plurality of tool parameters corresponding respectively to a plurality of processing tools for arrangement within a predetermined spatial region of one or more manufacturing facilities; one or more codes directed to a plurality of variables, respectively, for the plurality of processing tools and the plurality of battery specifications; one or more codes directed to a plurality of primary and secondary constraints; whereupon the plurality of variables and constraints are arranged in a tensor format; one or more codes directed to a processing tool configuration tensor; one or more codes directed to a battery specification tensor; a tensor operation module configured to process the plurality of variables and the configuration tensor to obtain production rate, capital expenditure, and operation expenditure; a financial modeling module to reduce a magnitude of a target financial variable associated with a set of the plurality of variables and the configuration tensor; the target financial variable comprising at least internal rate of return (IRR), modified internal rate of return (MIRR), net present value (NPV) and weighted average cost of capital (WACC); wherein these financial variables are primary objective functions; wherein these financial variables are secondary objective functions; an optimization module configured to output an optimized configuration tensor associated with the optimal target financial variable value; a post-processing module configured to convert the optimal configuration tensor to output the optimized set of tools and associated configuration for the set of tools; and an evaluation module which determines whether secondary constraints meet the requirements and secondary objective functions meet the requirements and further determines if the iterative design process continues or terminates.

EXAMPLE 1: 200 mAh battery cell

[0105] A 200 mAh cell which is 1.2 cm in width, 1.2 cm in length, and 0.32 cm in thickness. It consists of 1416 stacks of cells, with each cell comprising a cathode current collector layer, a cathode layer, an electrolyte layer, an anode layer, an anode current collector layer, and an interlayer. This cell can deliver 200 mAh at C/3 discharge, and 0.45 Wh at C/3 discharge. The battery cell can be used for wearable devices including smartwatches, smart glasses, and fitness monitoring devices. This battery has volumetric energy density of about 980 Watt hour per liter when discharge at C/3. The cell specifications also include cell layer thicknesses and material type along with material unit pricing. Deposition rates for each layer is specified as follows: 300 Å/s for cathode current collector, 1500 Å for cathode, 1000 Å/s for electrolyte, 2000 Å/s for anode, 300 Å/s for anode current collector, and 1000 Å/s for interlayer. The capital expenditure for each deposition tool is also provided in dollars per unit operation including at least the costs of vacuum pumps, cooling system, vacuum chambers, thickness monitoring devices, and control electronics. The operational costs are provided to include electricity consumption and unit pricing, operator cost, facility rental cost, and tool maintenance cost. The primary constraint is that the total capital expenditure should be less than or equal to 25 million dollars. The primary objective function is the internal rate of return, which can be approximated by the annual production capacity divided by capital expenditure. The optimization process identified that a total of 79 unit operations are needed for the production line. There should be 31 unit operations for the cathode layer deposition. The number of unit operations for all other layers are also provided. With this optimal design, it is projected that the COGS of the battery cells produced on the line is about $0.079, and about $170/kWh. The line can produce 130 million such battery cells a year.

EXAMPLE 2: high power battery cell

[0106] A high power cell which is 2 cm in width, 7 cm in length, and 0.69 cm in thickness. It consists of 6600 stacks of cells, with each cell comprising a cathode current collector layer, a cathode layer, an electrolyte layer, an anode layer, an anode current collector layer, and an interlayer. This cell can deliver 8.3 Wh at C/5 discharge. The battery cell can be used for high power consuming devices, such as power tools and vacuum cleaners. When discharge at 25 W, this cell can deliver energy continuously for 15 minutes. When discharge at 37.5 W, this cell can deliver energy continuously for 8.7 minutes. The cell specifications also include cell layer thicknesses and material type along with material unit pricing. Deposition rates for each layer is specified as follows: 300 Å/s for cathode current collector, 1500 Å for cathode, 1000 Å/s for electrolyte, 2000 Å/s for anode, 300 Å/s for anode current collector, and 1000 Å/s for interlayer. The capital expenditure for each deposition tool is also provided in dollars per meter of tool including at least the costs of vacuum pumps, cooling system, vacuum chambers, thickness monitoring devices, and control electronics. The operational costs are provided to include electricity consumption and unit pricing, operator cost, facility rental cost, and tool maintenance cost. The primary constraint is that the total capital expenditure should be less than or equal to 20 million dollars. The primary objective function is the internal rate of return, which can be approximated by the annual production capacity divided by capital expenditure. The optimization process identified that a total of 38 meters of deposition tools are needed for the production line, among which 12 meters are for the cathode layer deposition. The deposition tool length for all other layers are also provided. With this optimal design, it is projected that the COGS of the battery cells produced on the line is about $0.66, and about $79/kWh. The line can produce 13 million such battery cells a year.

CLAIMS

1. An iterative method for forming a manufacturing facility for solid state batteries comprising:

providing a multiple stack battery design for a targeted application;

providing a plurality of processing tools for arrangement within a predetermined spatial region of one or more manufacturing facilities;

assigning a plurality of variables, respectively, for the plurality of processing tools;

providing the plurality of variables expressible in a tensor format;

defining primary constraints for the manufacturing facility;

defining primary objective functions to evaluate different manufacturing processing tool configurations;

processing the plurality of variables expressible in the tensor relationship to allow reduction of a magnitude of each primary objective function;

determining an optimized set of the plurality of processing tools and respective configuration with the plurality of tools associated with the reduced magnitude of the target variable;

determining if the secondary constraints and objective functions meet the requirements; if the secondary constraints and objective functions do not meet the requirements, redefining the primary constraints and primary objective functions to repeat the optimization process and identify an updated tool design; if the secondary constraints and objective functions do meet the requirements, proceed to the next step in this method;

using the optimized set of the plurality of processing tools in the respective configuration in the one or more manufacturing facilities; and

operating the optimized set of tools for the manufacture of the solid state thin film battery device.

2. The method of claim 1 wherein the solid state batteries comprising multiple stacks of solid state electrochemical cells with the number of stacks ranging from 1 to N where N is greater than 1; wherein each electrochemical cell comprising at

least a current collector layer, a cathode layer, an electrolyte layer, an anode layer, an interlayer; wherein each electrochemical cell comprising at least a substrate and a barrier layer;

3. The method of claim 1 wherein the solid state batteries are deposited on a substrate made of at least one of a glass structure, a conductive structure, a metal structure, a ceramic structure, a plastic or polymer structure, or a semiconductor structure, or one or more active may comprise the substrate layer.

4. The method of claim 1 wherein the solid state batteries are of the same design.

5. The method of claim 1 wherein the solid state batteries are of a hybrid design; wherein the hybrid design comprising high power battery cells and high energy cells; wherein the hybrid design comprising cells designed for low temperature operation and cells designed for room temperature and above.

6. The method of claim 1 wherein the solid state batteries comprising plurality of battery cells that are wound or stacked.

7. The method of claim 1 wherein the target application is selected from at least one of or more of at least smartphones, cell phones, personal digital assistants, radio players, music players, video cameras, tablet and laptop computers, military communications, military lighting, military imaging, satellite, aero-plane, satellites, micro air vehicles, hybrid electric vehicles, plug-in hybrid electric vehicles, fully electric vehicles, electric scooter, underwater vehicle, boat, ship, electric garden tractor, and electric ride on garden device, unmanned aero drone, unmanned aero-plane, an RC car, robotic toys, robotic vacuum cleaner, robotic garden tools, robotic construction utility, robotic alert system, robotic aging care unit, robotic kid care unit, electric drill, electric mower, electric vacuum cleaner, electric metal working grinder, electric heat gun, electric press expansion tool, electric saw and cutters, electric sander and polisher, electric shear and nibbler, electric routers, an electric tooth brush, an electric hair dryer, an electric

hand dryer, a global positioning system (GPS) device, a laser rangefinder, a flashlight, an electric street lighting, standby power supply, uninterrupted power supplies, and other portable and stationary electronic devices.

8. The method of claim 1 wherein the plurality of processing tools comprising physical vapor deposition based thin film coater, chemical vapor deposition based thin film coater, atomic layer deposition thin film coater, conveyor or other transport mechanisms, transport robotic arm, winder, slitter, slitter using laser ablation and/or cutting, packaging machine using a technique of at least but not limited to dip coating, and robotic arms for attaching leads, wiring, moving, handling and electronic control component assembling; wherein the thin film coaters are also equipped with film thickness monitors including at least quartz crystal thickness monitors.

9. The method of claim 1 wherein the plurality of processing tools are arranged in a roll-to-roll configuration, a multi-drum configuration, a cluster configuration, a in-line configuration, or a combination of thereof.

10. The method of claim 1 wherein the plurality of variables comprises capital cost of the tool, speed of the tool, downtime of the tool, yield of the tool, efficiency of the tool, material load and unload time of the tool, preparation time of the tool, work in process for the tool and operational cost of the tool including labor and electricity cost.

11. The method of claim 1 wherein the primary constraints for designing the manufacturing facility comprising at least total capital expenditure being lower than a target value, annual production capacity in number of batteries made per year being higher than a target value, annual production capacity in total capacity in million ampere hour made per year being higher than a target value, annual production capacity in total energy in million watt hour made per year being higher than a target value, battery cost of goods sold (COGS) being lower than a target value, battery cost in dollar per kilowatt hour being lower than a target value.

12. The method of claim 1 wherein the secondary constraints for designing the manufacturing facility comprising at least total capital expenditure being lower than a target value, annual production capacity in number of batteries made per year being higher than a target value, annual production capacity in total capacity in million ampere hour made per year being higher than a target value, annual production capacity in total energy in million watt hour made per year being higher than a target value, battery cost of goods sold (COGS) being lower than a target value, battery cost in dollar per kilowatt hour being lower than a target value.

13. The method of claim 1 wherein the primary objective functions comprising at least internal rate of return (IRR), modified internal rate of return (MIRR), net present value (NPV) and weighted average cost of capital (WACC).

14. The method of claim 1 wherein the secondary objective functions comprising at least internal rate of return (IRR), modified internal rate of return (MIRR), net present value (NPV) and weighted average cost of capital (WACC).

15. The method of claim 1 is an iterative process comprising at least one iteration to satisfy the primary constraints and optimize the primary objective functions; the method of claim 1 is an iterative process comprising at least one iteration to satisfy the secondary constraints and optimize the secondary objective functions.

16. The method of claim 1 wherein the solid state batteries are characterized by an energy density of greater than 50 watt hour per liter.

17. A system for iteratively designing a manufacturing plant for fabricating multiple stack solid state batteries, the system comprising:

a computer readable memory device, the computer readable memory including: one or more codes directed to a plurality of battery specifications and one or more codes directed to a plurality of tool parameters corresponding respectively to a plurality of processing tools for arrangement within a predetermined spatial region of one or more manufacturing facilities;

one or more codes directed to a plurality of variables, respectively, for the plurality of processing tools and the plurality of battery specifications; one or more codes directed to a plurality of primary and secondary constraints; whereupon the plurality of variables and constraints are arranged in a tensor format; one or more codes directed to a processing tool configuration tensor; one or more codes directed to a battery specification tensor;

a tensor operation module configured to process the plurality of variables and the configuration tensor to obtain production rate, capital expenditure, and operation expenditure;

a financial modeling module to reduce a magnitude of a target financial variable associated with a set of the plurality of variables and the configuration tensor; the target financial variable comprising at least internal rate of return (IRR), modified internal rate of return (MIRR), net present value (NPV) and weighted average cost of capital (WACC); wherein these financial variables are primary objective functions; wherein these financial variables are secondary objective functions;

an optimization module configured to output an optimized configuration tensor associated with the optimal target financial variable value;

a post-processing module configured to convert the optimal configuration tensor to output the optimized set of tools and associated configuration for the set of tools; and

an evaluation module which determines whether secondary constraints meet the requirements and secondary objective functions meet the requirements and further determines if the iterative design process continues or terminates.

18. The system of claim 17 wherein the processing tool configuration tensor is a n-order tensor with n dimensions to index a plurality of specifications comprising at least the processing step, allocated locations for tools inside the processing step, processing tool type and the type of facility used inside a processing tool.

19. The system of claim 17 wherein the processing tool configuration tensor comprises elements which have binary values of zero and one.

20. The system of claim 17 wherein the tensor operation module comprises adding two tensors, multiplying two tensors, transposing first-order and second-order tensors, contracting a tensor and finding the maximum or minimum element of a tensor or a subset of the tensor along with specified dimensions.

21. The system of claim 17 wherein the optimization module comprises one or more codes directed to an integer programming optimization process applying enumerative techniques, branch-and-bound techniques or cutting planes techniques.

22. The system of claim 17 wherein the optimization module comprises one or more codes directed to genetic algorithm techniques.

23. The system of claim 17 wherein the post-processing module comprises importing the optimal configuration tensor, identifying the non-zero elements which have exactly values of one and outputting the optimal configuration information with specifications of which type of and how many processing tools are used for each processing step associated with which type of and how many processing facilities are used inside each processing tool.

Figure 1

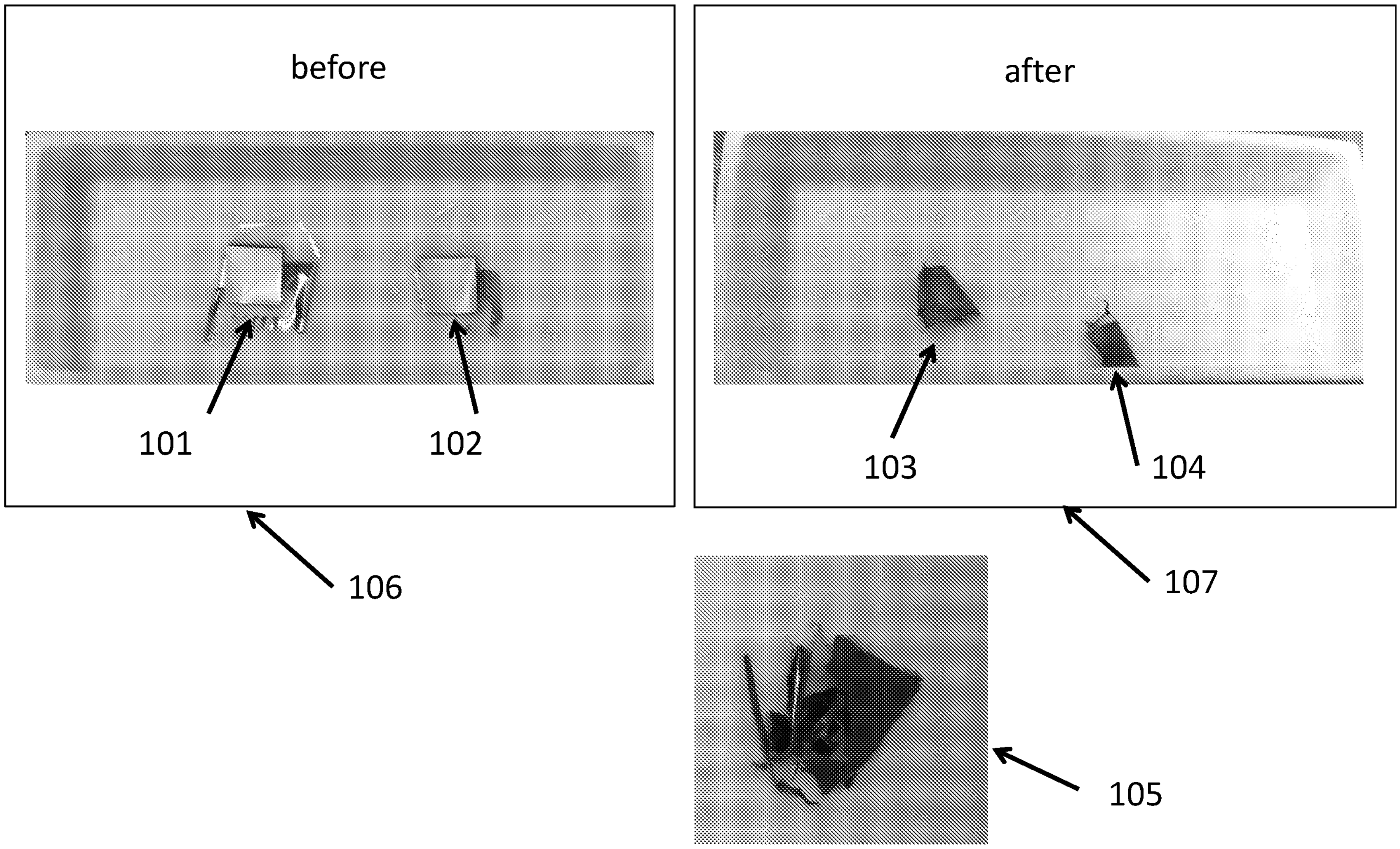


Figure 2

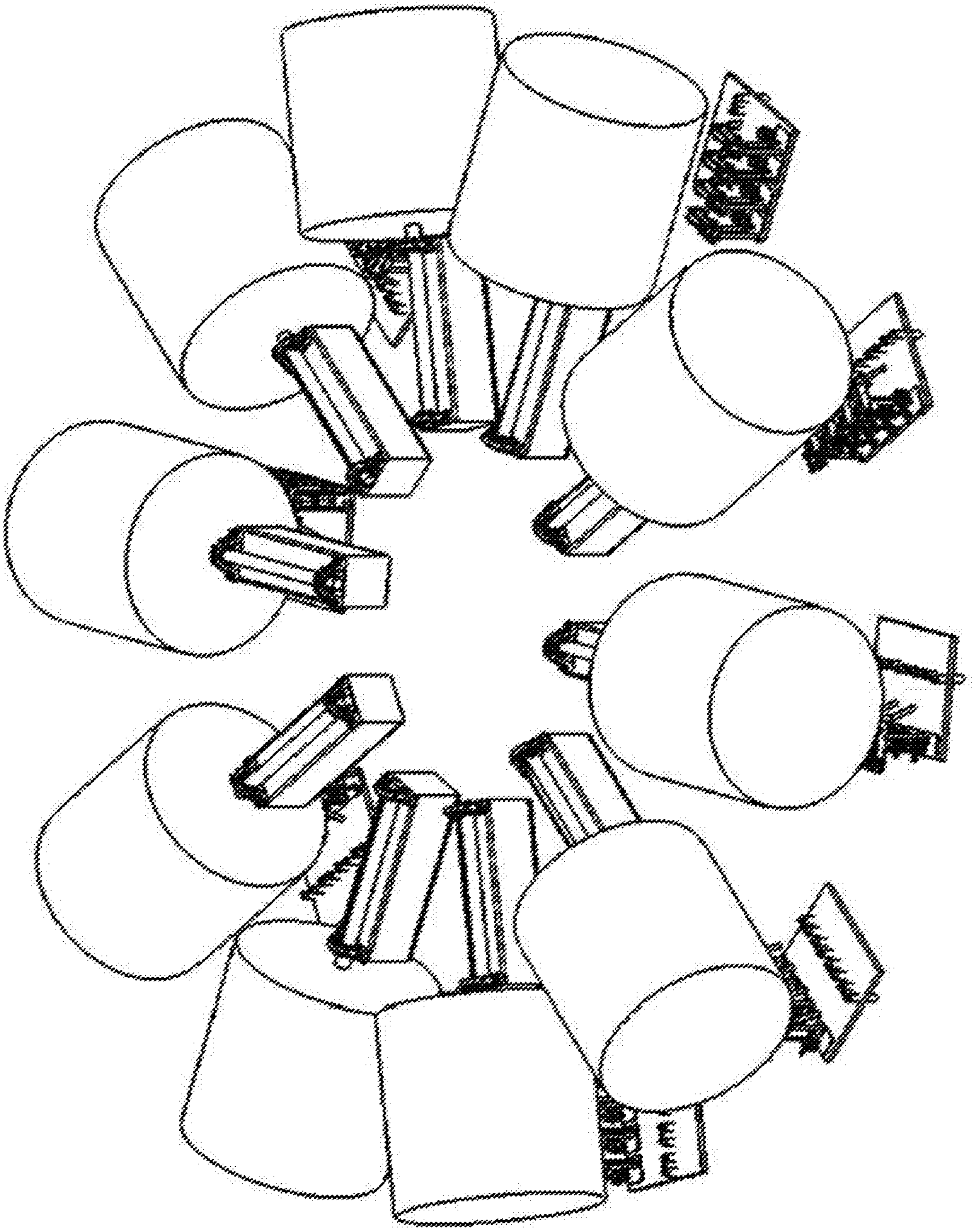


Figure 3

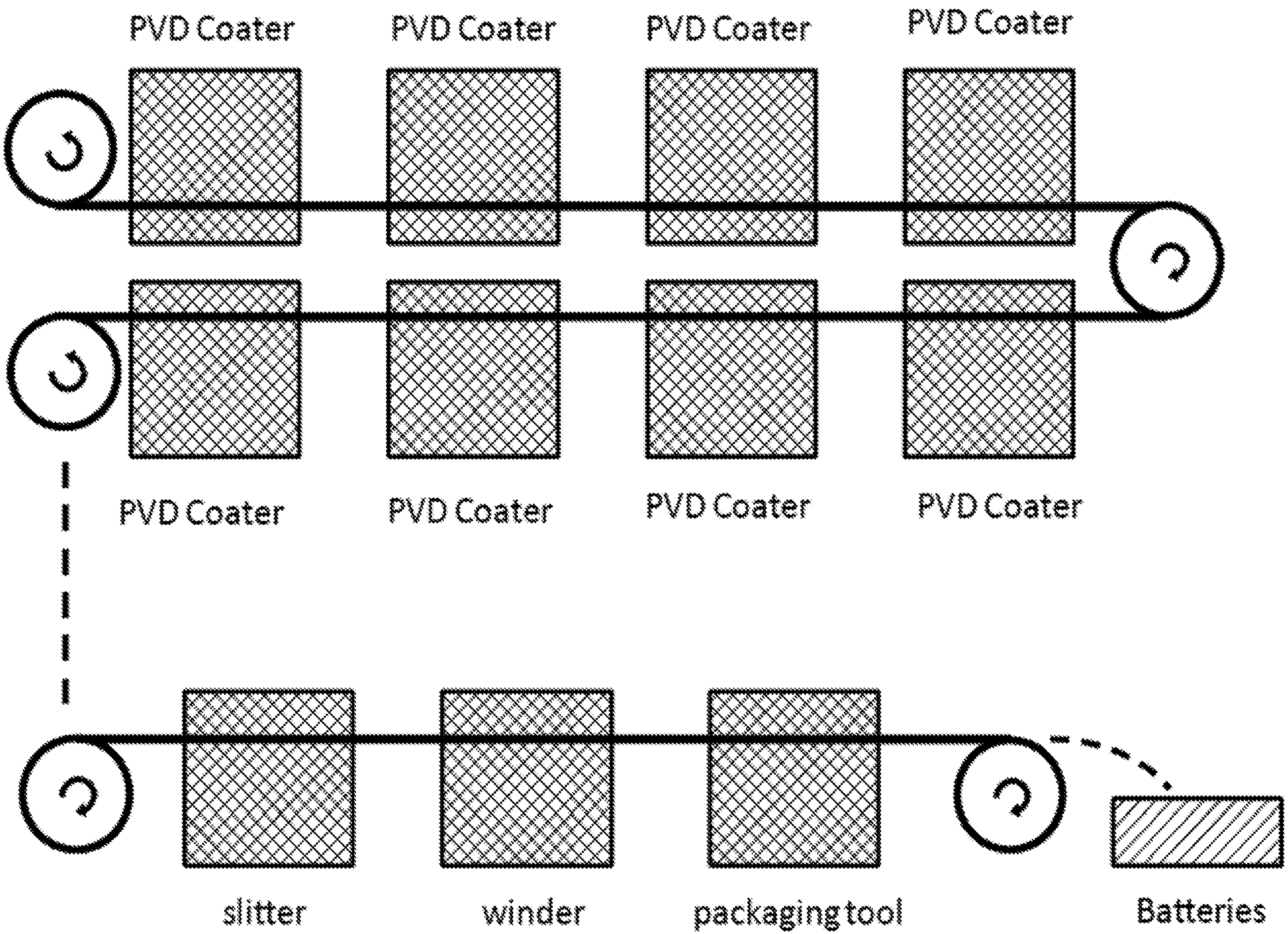

PVD Coater
PVD Coater
PVD Coater
PVD Coater
PVD Coater
PVD Coater
PVD Coater
PVD Coater
slitter
winder
packaging tool
Batteries

Figure 4

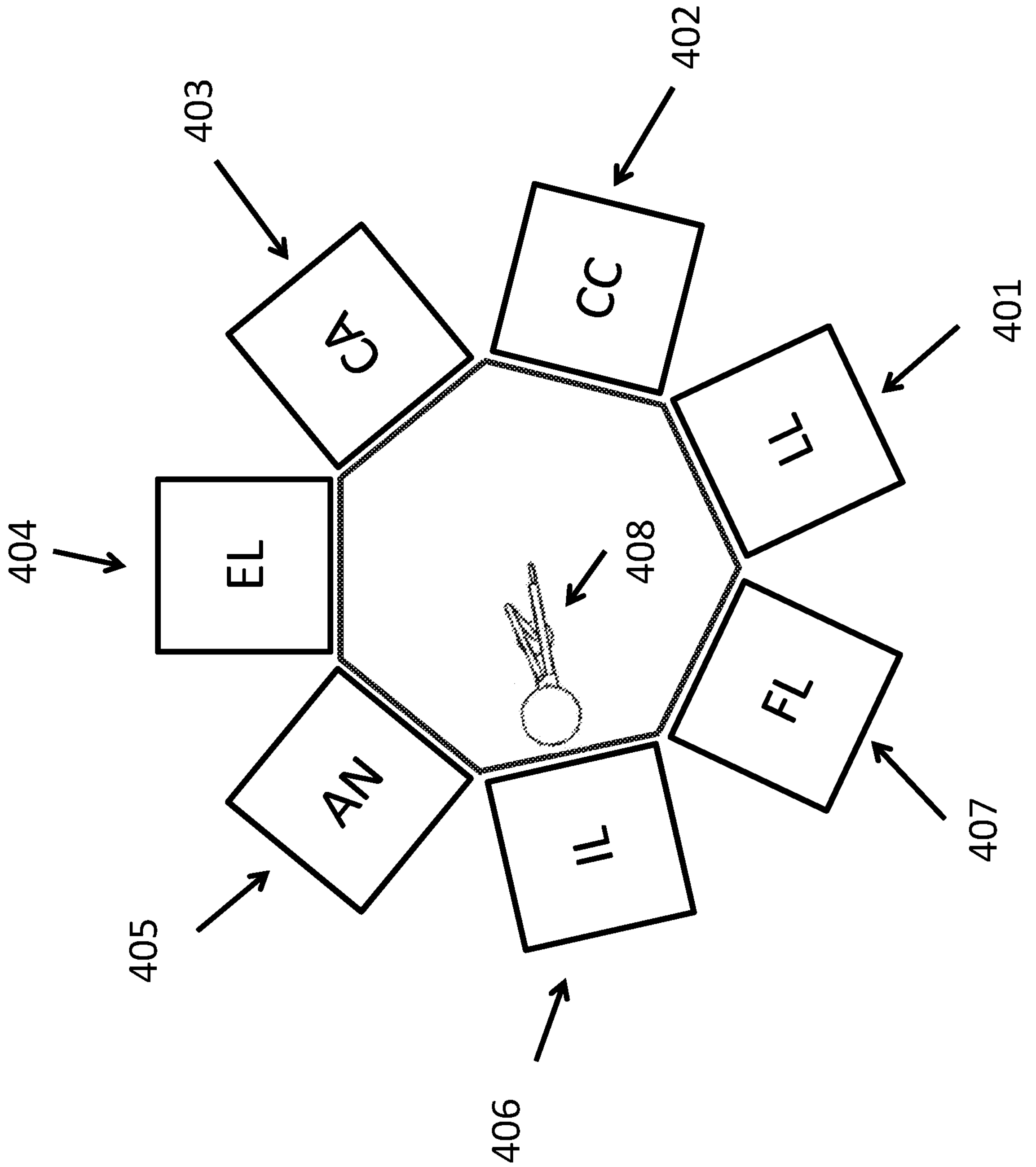


Figure 5

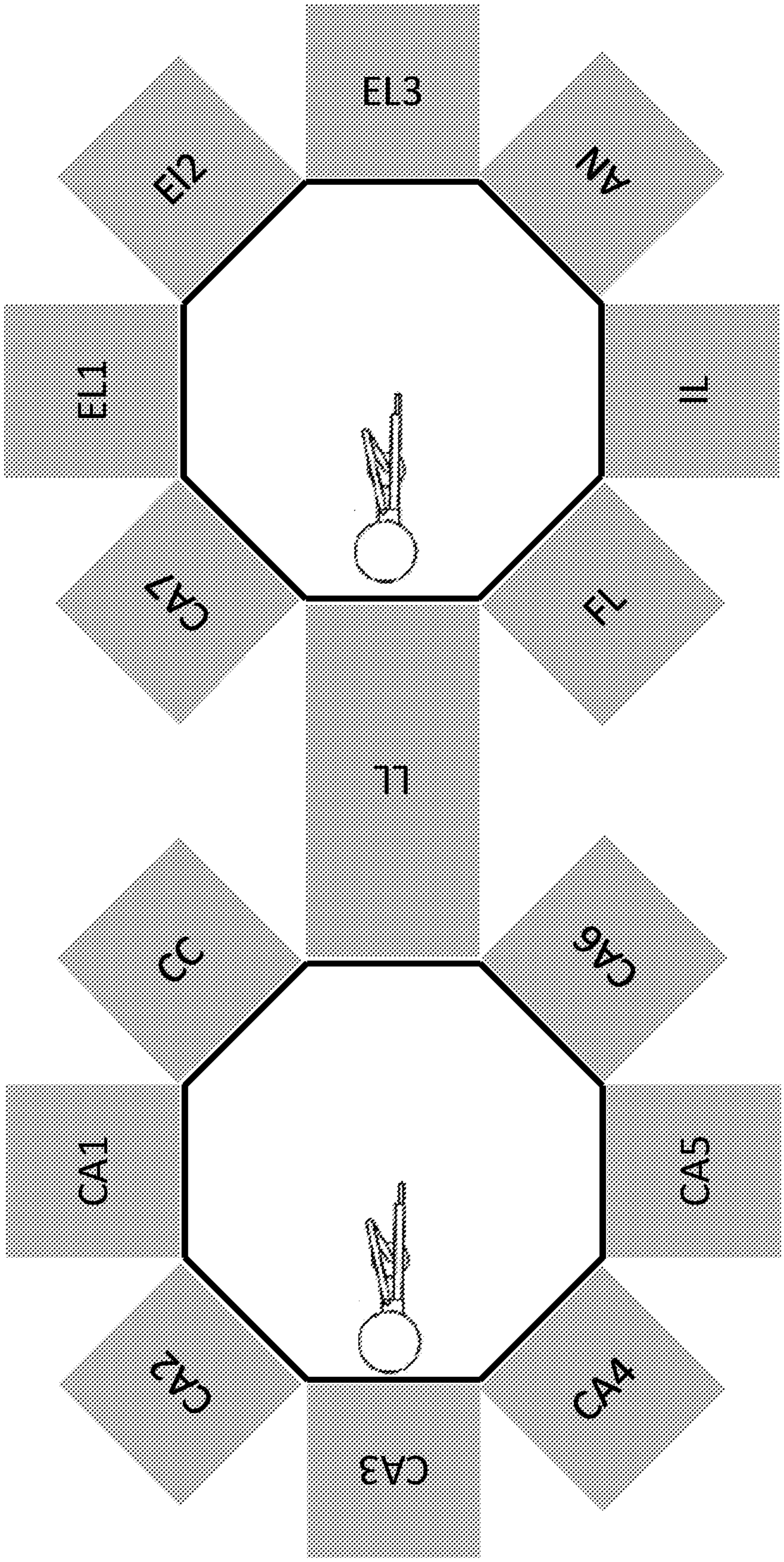


Figure 6

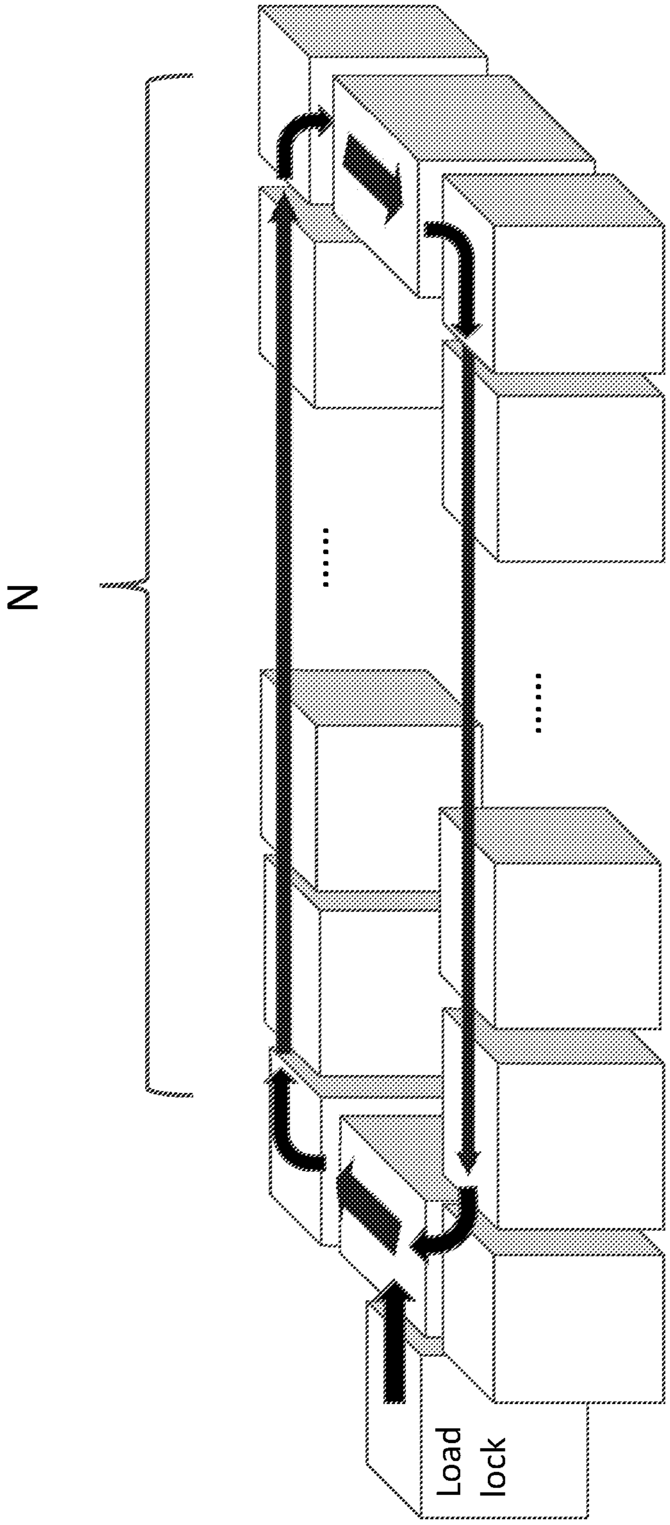


Figure 7

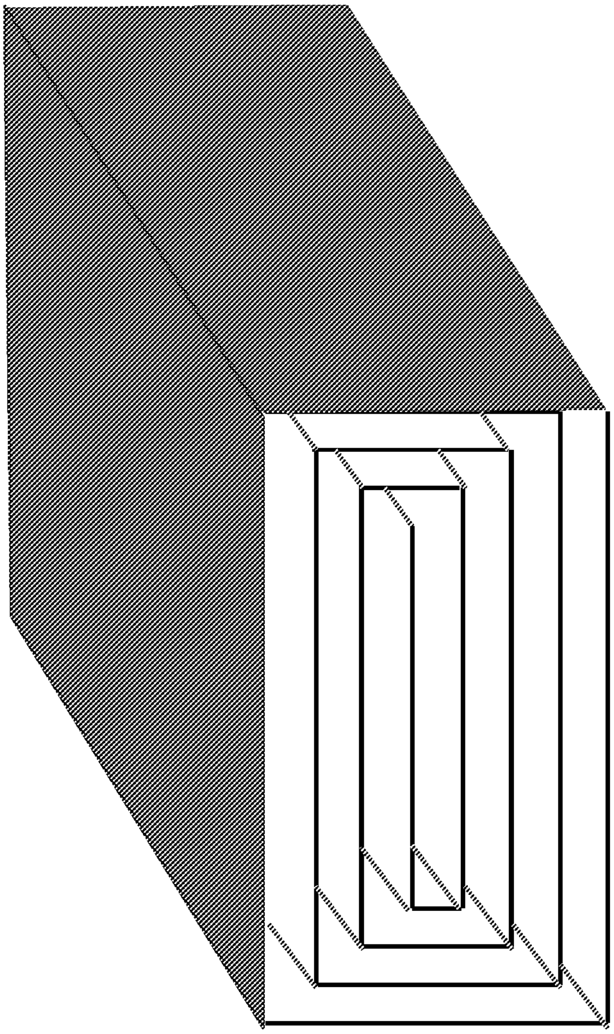


Figure 8

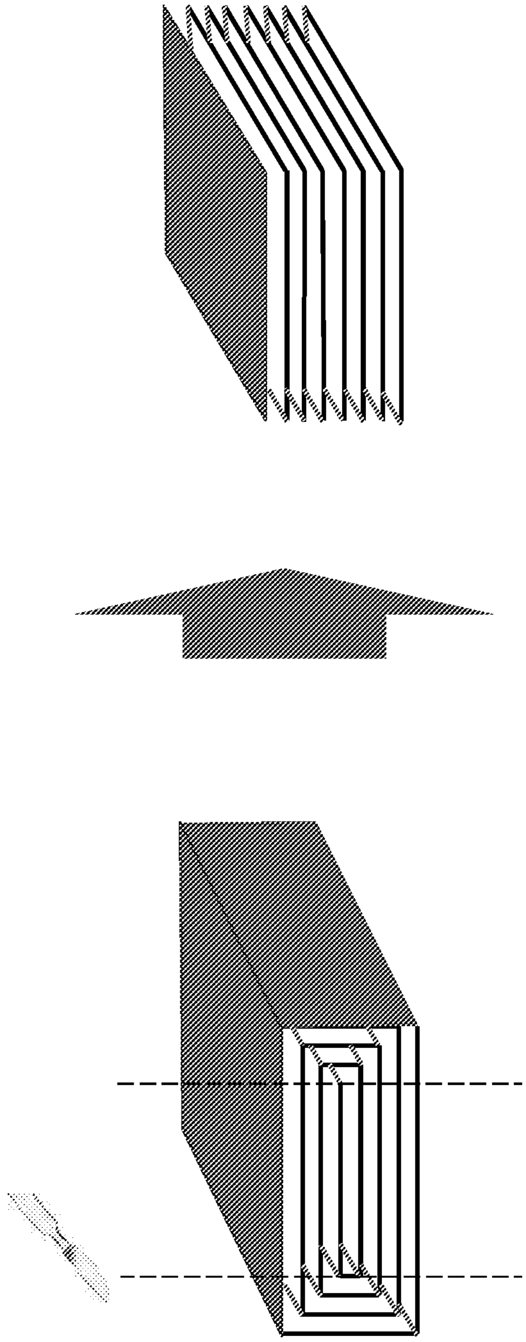


Figure 9

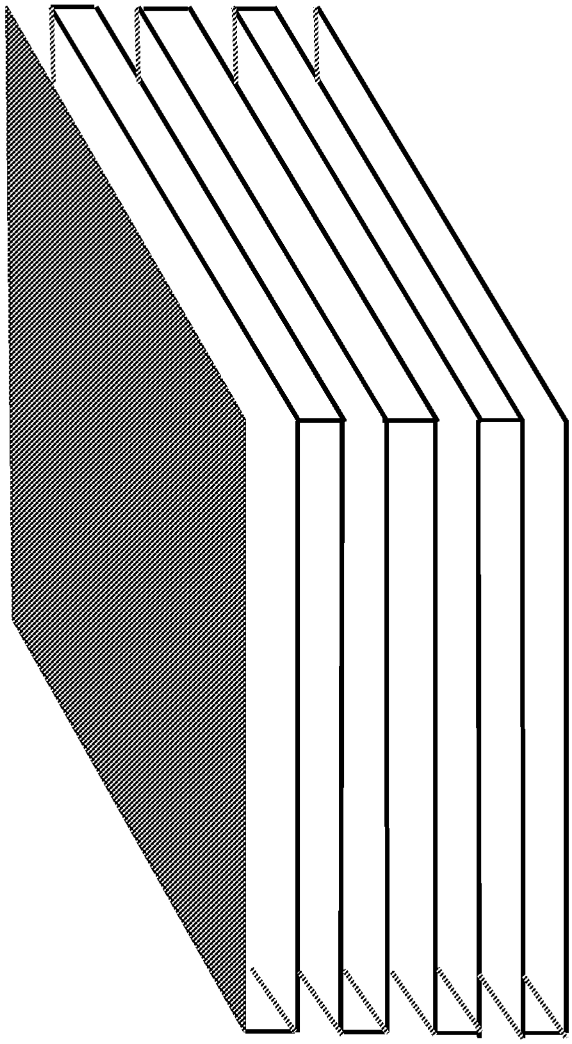


Figure 10

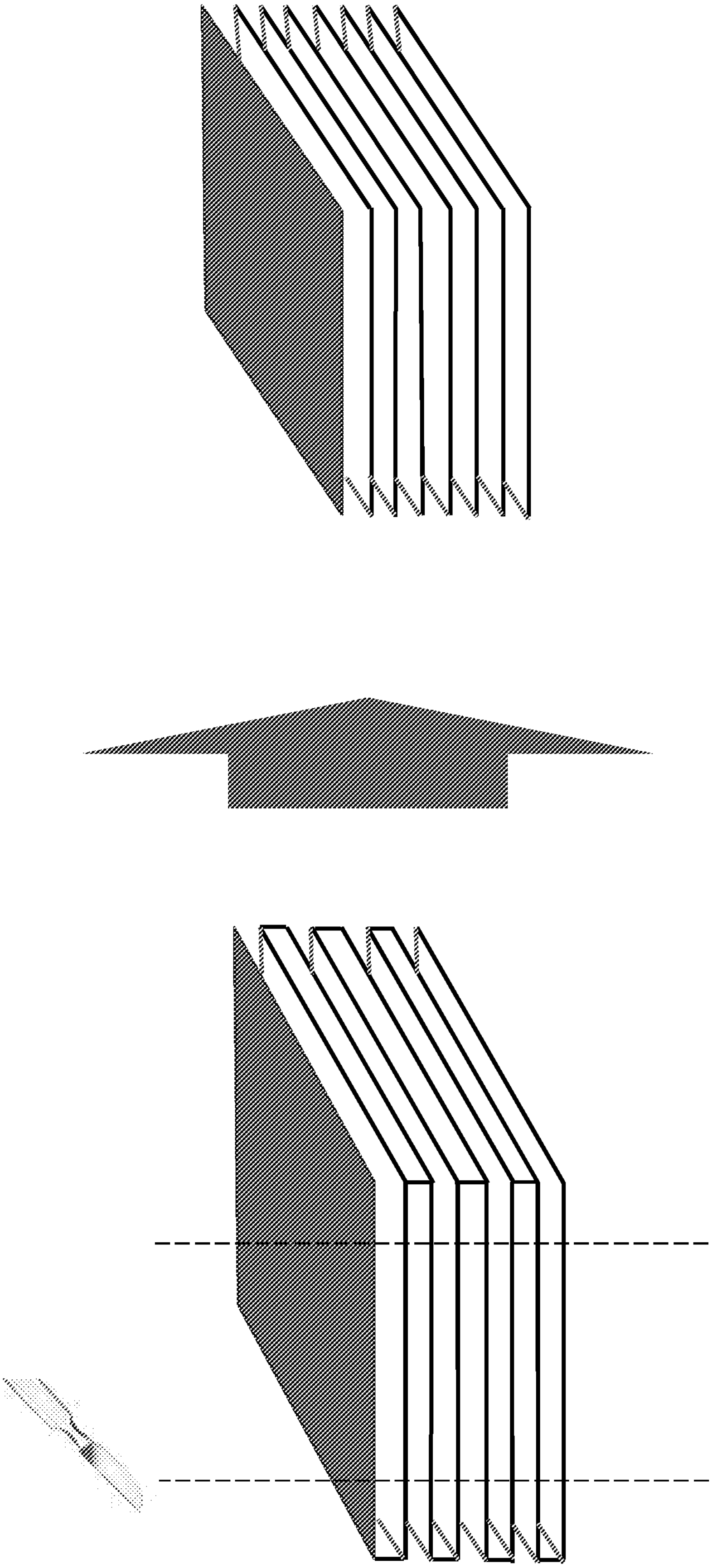


Figure 11

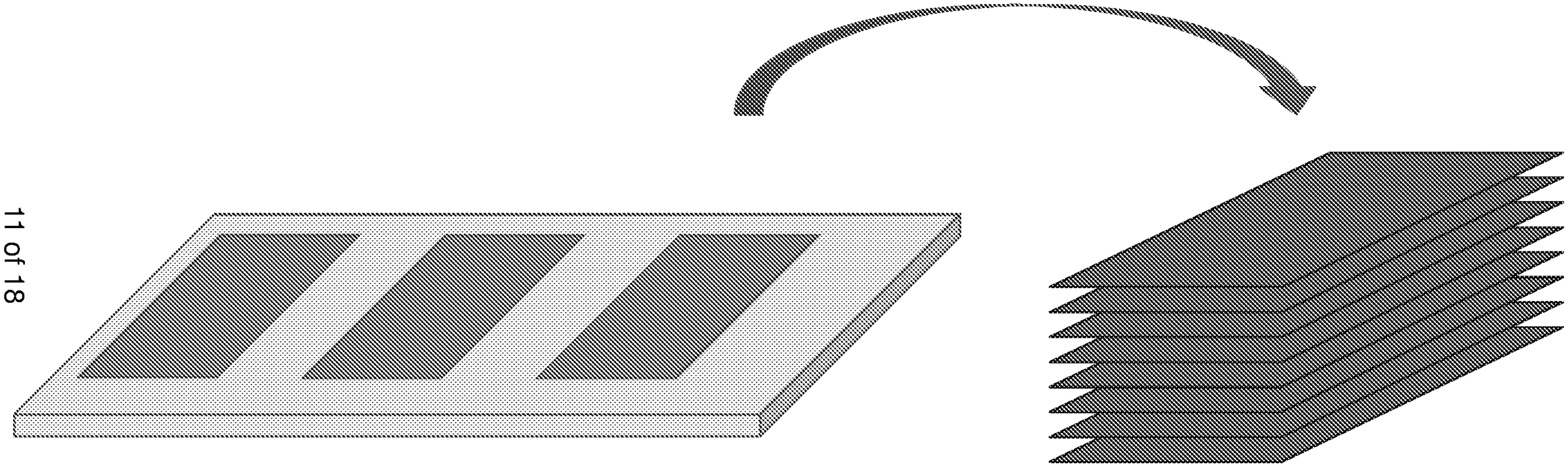


Figure 12

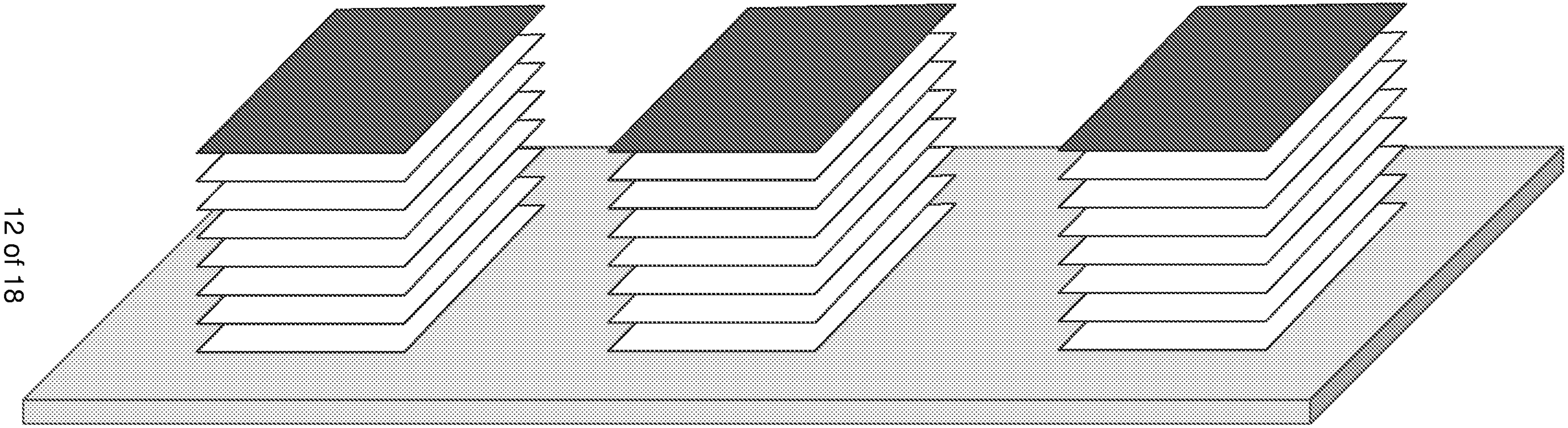


Figure 13

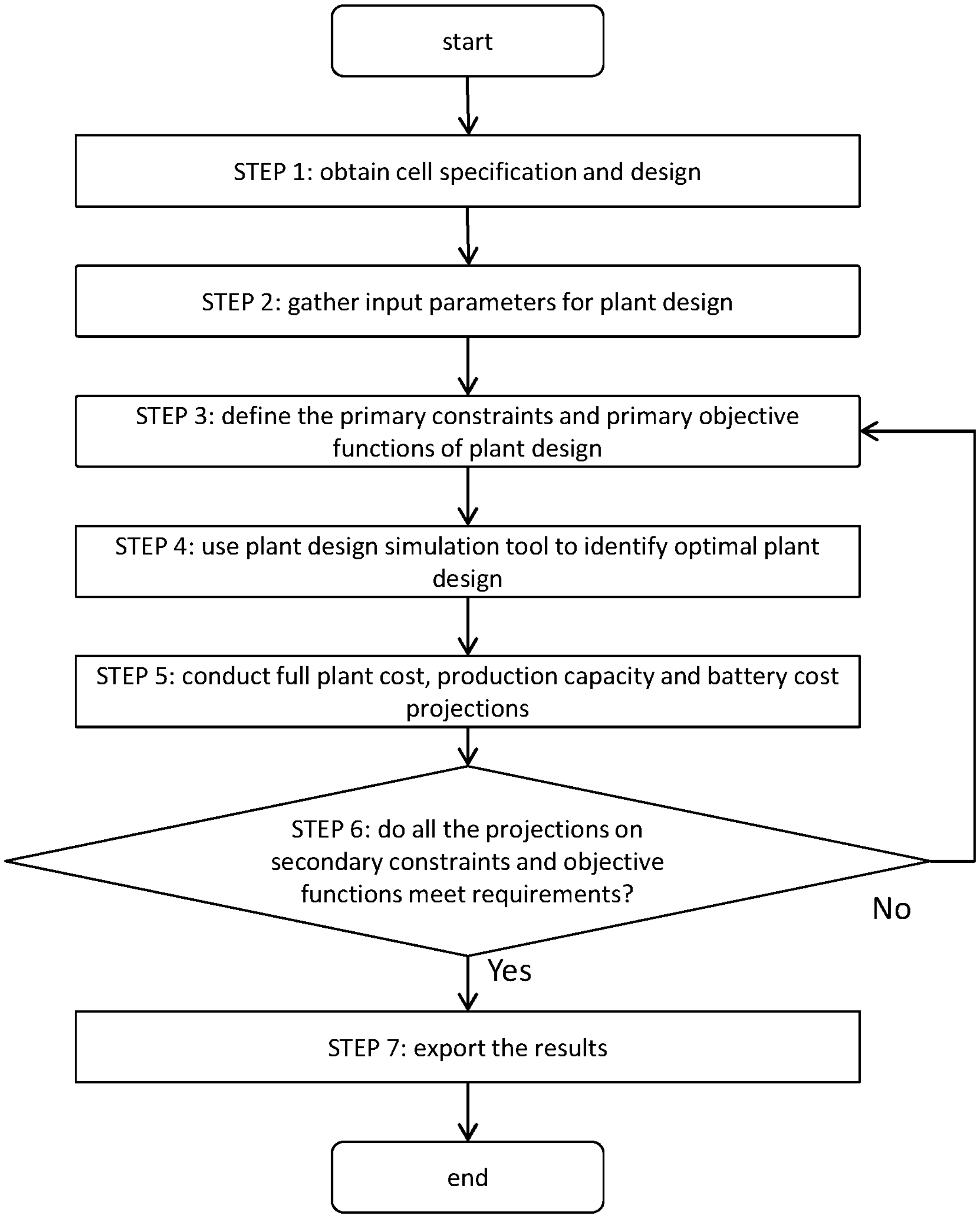
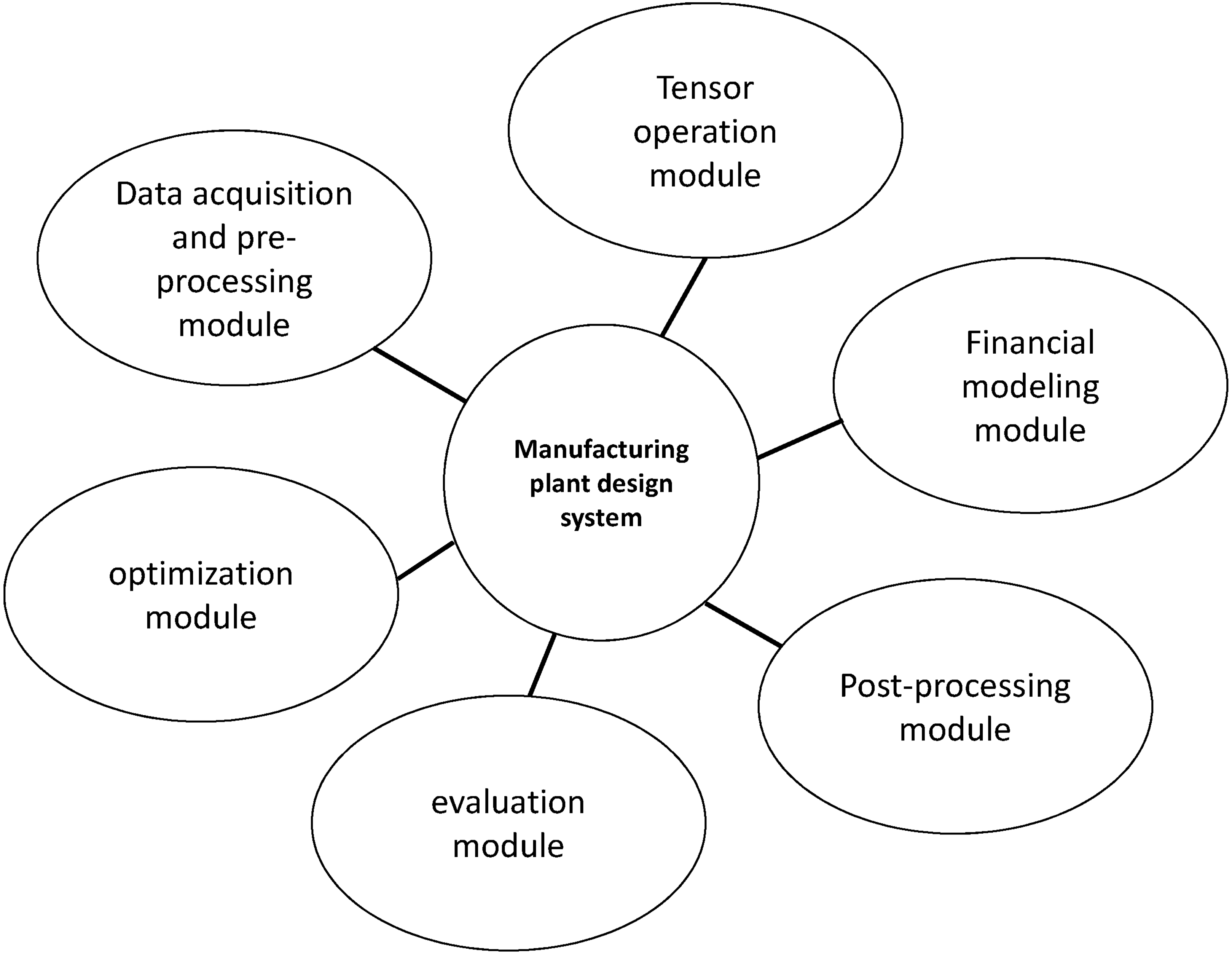

start
STEP 1: obtain cell specification and design
STEP 2: gather input parameters for plant design
STEP 3: define the primary constraints and primary objective functions of plant design
STEP 4: use plant design simulation tool to identify optimal plant design
STEP 5: conduct full plant cost, production capacity and battery cost projections
STEP 6: do all the projections on secondary constraints and objective functions meet requirements?
No
Yes
STEP 7: export the results
end

Figure 14


Tensor operation module
Data acquisition and pre-processing module
Financial modeling module
Manufacturing plant design system
optimization module
Post-processing module
evaluation module

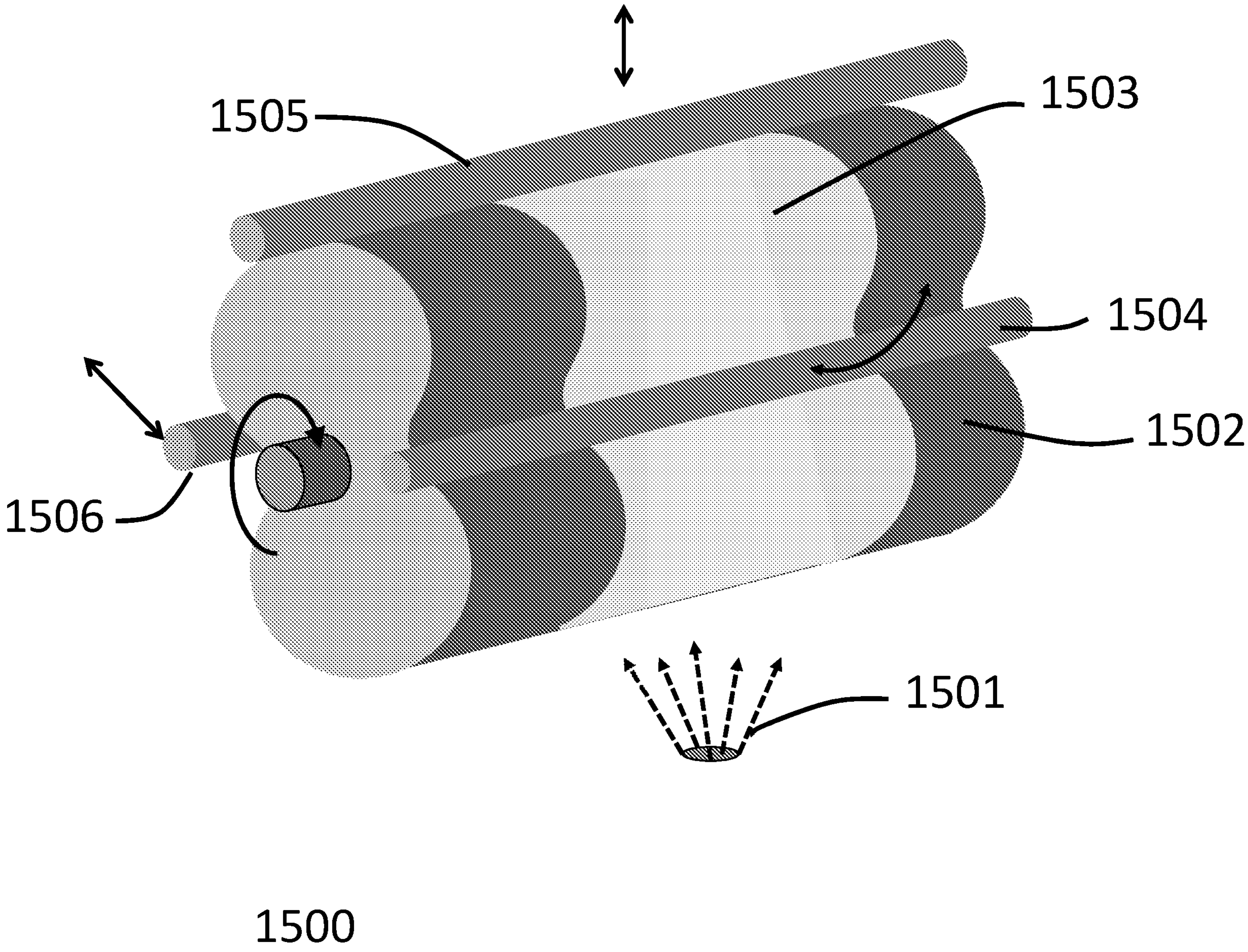


FIGURE 15

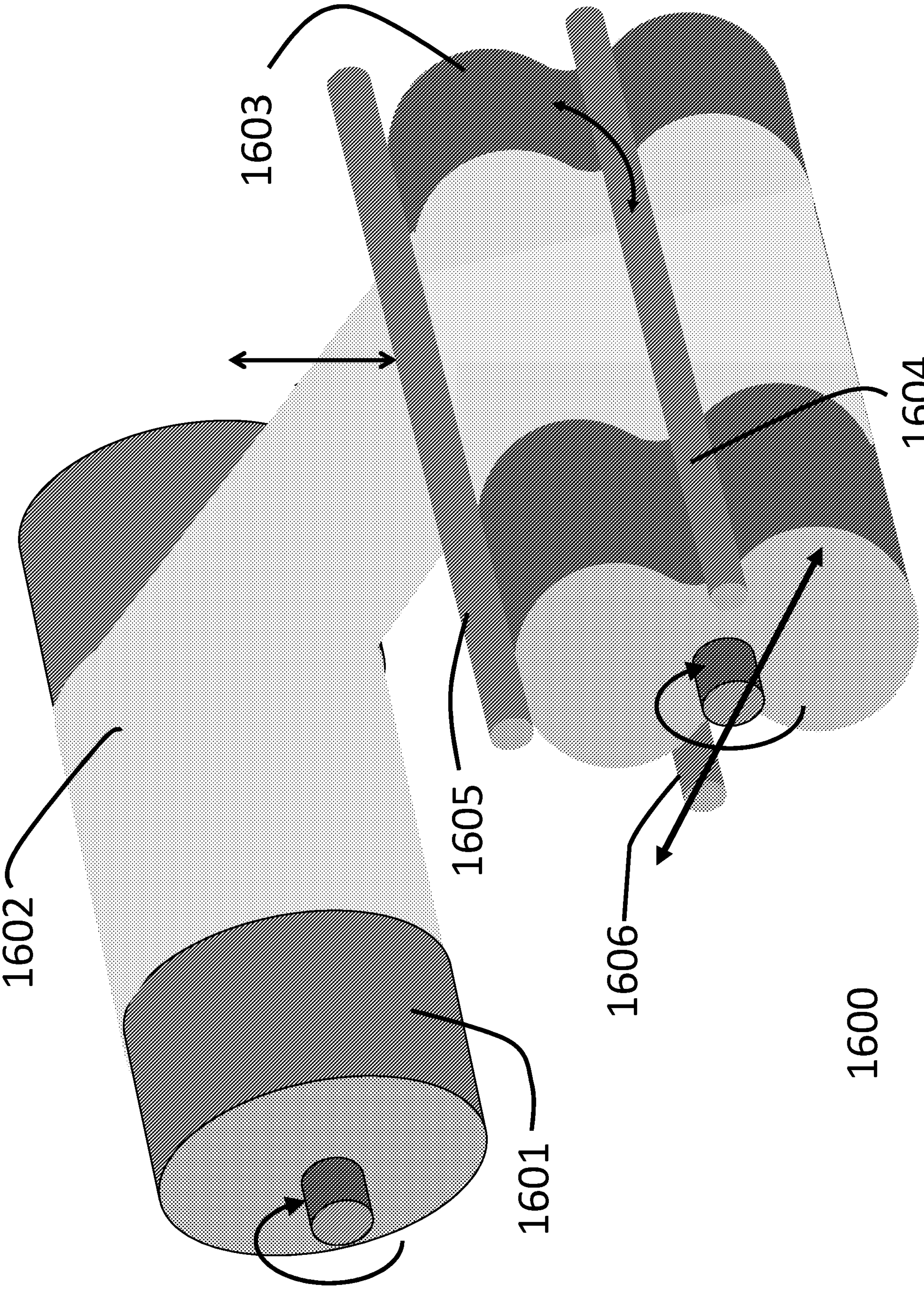


FIGURE 16

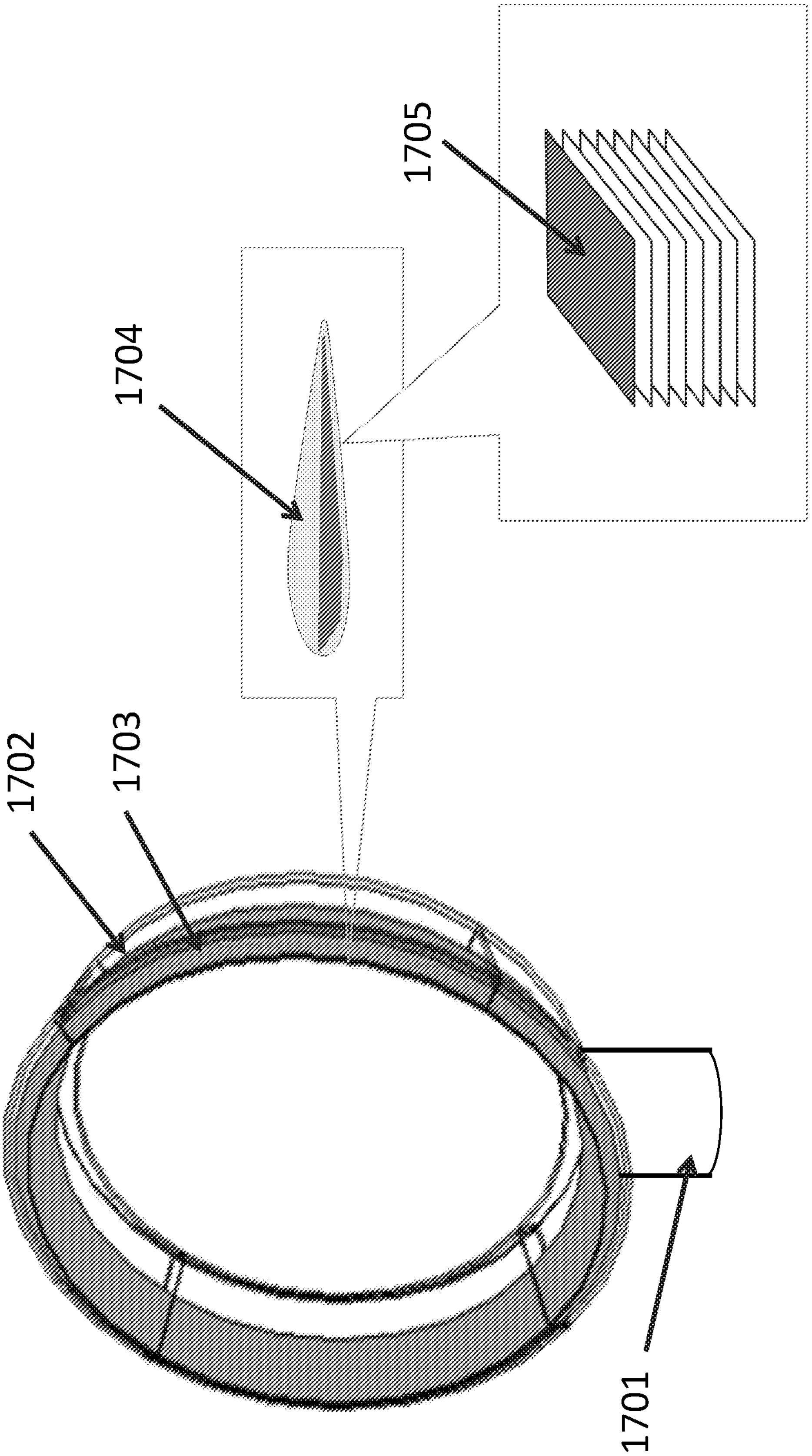


FIGURE 17A

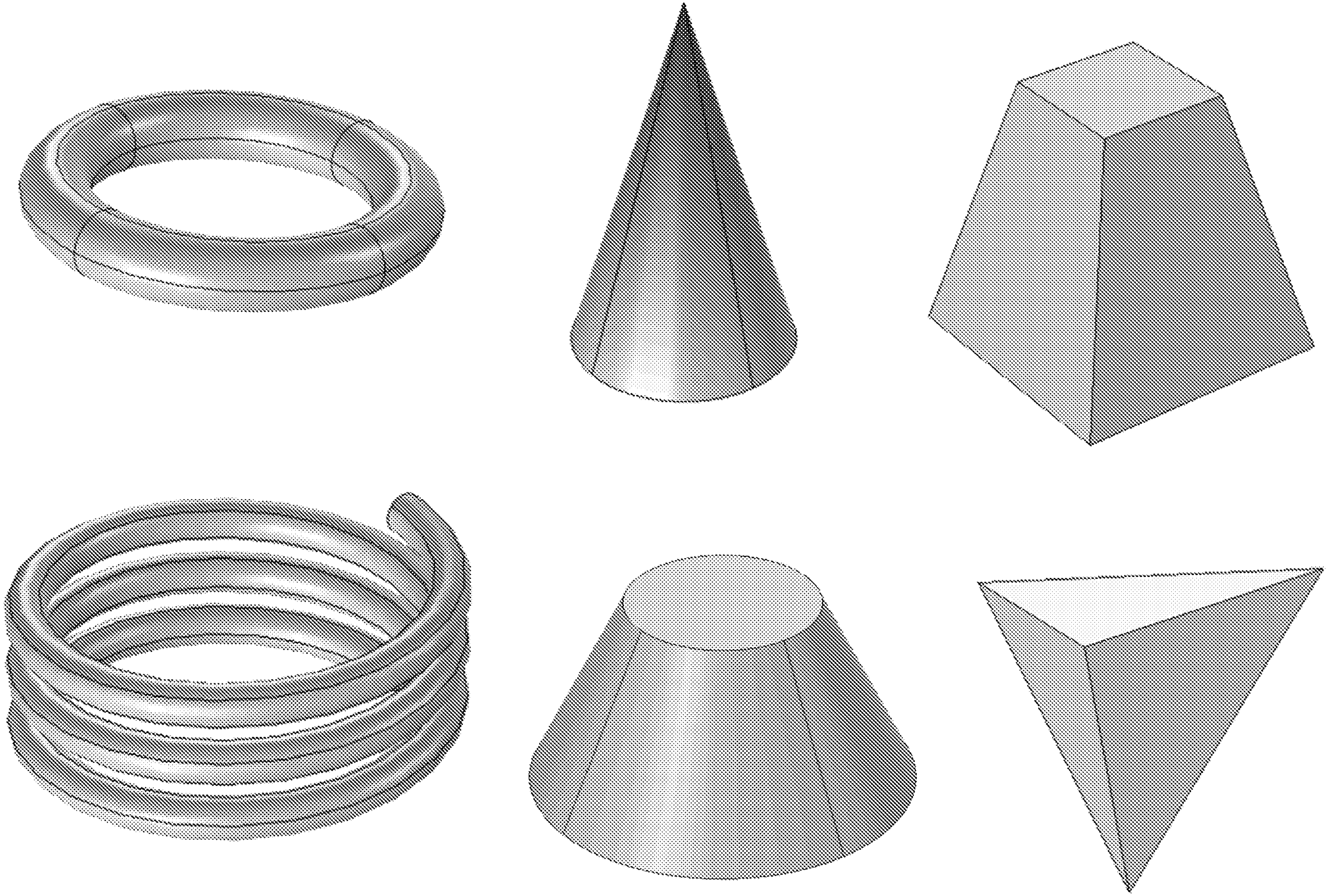


FIGURE 17B