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Inventor(s)	Lu; Xiaodong et al.

Stator modules and robotic systems

Abstract

Stator modules are disclosed. Stator modules may include: a stator body; a working surface supported relative to the stator body; and a plurality of electrical conductors, each electrical conductor of the plurality of electrical conductors extending along a respective portion of the working surface and operable to generate a magnetic field to facilitate moving, relative to the working surface, a magnetized mover in the magnetic field in response to electrical current through the electrical conductor. Robotic systems including such stator modules are also disclosed.

Inventors: **Lu; Xiaodong (Vancouver, CA), Williamson; Graham (Vancouver, CA)**

Applicant: **PLANAR MOTOR INCORPORATED** (Vancouver, CA)

Family ID: **1000008765251**

Assignee: **PLANAR MOTOR INCORPORATED (N/A, CA)**

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Primary Examiner: Desai; Naishadh N

Attorney, Agent or Firm: EWING & JONES, PLLC

Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS (1) This is a continuation application which claims the benefit of, and priority to U.S. utility application Ser. No. 17/785,831 filed Jun. 15, 2022, which is itself a National Stage Entry of and claims the benefit of, and priority to, international application PCT/CA2020/051735 filed Dec. 16, 2020, which itself claims the benefit of, and priority to, U.S. provisional patent application No. 62/948,335 filed on Dec. 16, 2019, and U.S. provisional patent application No. 63/081,584 filed on Sep. 22, 2020, the entire contents of which are each incorporated by reference herein.

FIELD
(1) This disclosure relates generally to stator modules and robotic systems.

RELATED ART

(2) Robotic systems are known. However, known robotic systems may have some disadvantages.

SUMMARY

(3) According to one embodiment, there is disclosed a stator module comprising: a stator body; a working surface supported relative to the stator body and extending by a width in a first dimension between first and second exposed opposite sides of the stator module, the working surface further extending by a length in a second dimension between first and second opposite ends of the stator module, the second dimension different from the first dimension, the length greater than the width; and a plurality of electrical conductors, each electrical conductor of the plurality of electrical conductors extending along a respective portion of the working surface and operable to generate a magnetic field to facilitate moving, relative to the working surface, a magnetized mover in the magnetic field in response to electrical current through the electrical conductor; at least some electrical conductors of the plurality of electrical conductors in a first layer of electrical conductors of the plurality of electrical conductors extending in a first electrical conductor direction; and at least some electrical conductors of the plurality of electrical conductors in a second layer of electrical conductors of the plurality of electrical conductors separate from the first layer of electrical conductors extending in a second electrical conductor direction nonparallel to the first electrical conductor direction; the at least some electrical conductors of the plurality of electrical conductors in the first layer at least partially overlapping the at least some electrical conductors of the plurality of electrical conductors in the second layer in a direction orthogonal to the first and second electrical conductor directions; wherein the plurality of electrical conductors and the working surface are supported relative to the stator body such that the stator module is a unitary assembly.

(4) According to another embodiment, there is disclosed a stator module comprising: a stator body; a working surface supported relative to the stator body; and a plurality of electrical conductors, each electrical conductor of the plurality of electrical conductors extending along a respective portion of the working surface and operable to generate a magnetic field to facilitate moving, relative to the working surface, a magnetized mover in the magnetic field in response to electrical current through the electrical conductor; at least some electrical conductors of the plurality of electrical conductors in a first layer of electrical conductors of the plurality of electrical conductors extending in a first electrical conductor direction; at least some electrical conductors of the plurality of electrical conductors in the first layer of electrical conductors of the plurality of electrical conductors extending in a second electrical conductor direction nonparallel to the first electrical conductor direction; and at least some electrical conductors of the plurality of electrical conductors in a second layer of electrical conductors of the plurality of electrical conductors separate from the first layer of electrical conductors extending in a third electrical conductor direction nonparallel to the first electrical conductor direction and nonparallel to the second electrical conductor direction.

(5) According to another embodiment, there is disclosed a stator module comprising: a stator body; a working surface supported relative to the stator body; a motor sub-module comprising a plurality of electrical conductors, each electrical conductor of the plurality of electrical conductors extending along a respective portion of the working surface and operable to generate a magnetic field to facilitate moving, relative to the working surface, a magnetized mover in the magnetic field in response to electrical current through the electrical conductor; and a position-sensor sub-module comprising at least one position sensor operable to sense a position of the mover and defining a plurality of through-holes; wherein the stator body comprises a surface and a plurality of protrusions, each protrusion of the plurality of protrusions extending from the surface, towards the motor sub-module, and through a respective through-hole of the plurality of through-holes of the position-sensor sub-module and supporting the motor sub-module.

(6) Other aspects and features will become apparent to those ordinarily skilled in the art upon

review of the following description of illustrative embodiments in conjunction with the accompanying figures.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) FIG. **1** is a top view of a robotic system according to one embodiment.
(2) FIG. **2** is a cross-sectional view of the robotic system of FIG. **1**.
(3) FIG. **3** schematically illustrates a stator module according to one embodiment.
(4) FIG. **4** schematically illustrates stator modules and a control system according to one embodiment.
(5) FIG. **5** and FIG. **6** illustrate a stator module according to one embodiment.
(6) FIG. **7** illustrates a stator module according to another embodiment.
(7) FIG. **8** illustrates a stator module according to another embodiment.
(8) FIG. **9** illustrates an electromagnetic driving region of the stator module of FIG. **5** and FIG. **6**.
(9) FIG. **10** illustrates electrical conductors in a first layer of the electromagnetic driving region of FIG. **9**.
(10) FIG. **11** illustrates electrical conductors in a second layer of the electromagnetic driving region of FIG. **9**.
(11) FIG. **12** illustrates a stator module according to another embodiment.
(12) FIG. **13** illustrates additional electrical conductors of the stator module of FIG. **12** according to one embodiment.
(13) FIG. **14** illustrates a stator module and a mover according to another embodiment.
(14) FIG. **15** illustrates a product on the mover of FIG. **14**.
(15) FIG. **16** illustrates a stator module and a mover according to another embodiment.
(16) FIG. **17** illustrates a motor sub-module according to another embodiment.
(17) FIG. **18** illustrates electrical conductors in one layer of the motor sub-module of FIG. **17**.
(18) FIG. **19** illustrates electrical conductors according to another embodiment.
(19) FIG. **20** illustrates electrical conductors in another layer of the motor sub-module of FIG. **17**.
(20) FIG. **21** is a plan view of magnet arrays of a mover according to one embodiment.
(21) FIG. **22** is an elevation view of one of the magnet arrays of the mover of FIG. **21**.
(22) FIG. **23** shows two coordinate systems that may describe some embodiments.
(23) FIG. **24** shows a mover-stator interaction according to one embodiment.
(24) FIG. **25** shows a mover-stator interaction according to another embodiment.
(25) FIG. **26** shows a mover-stator interaction according to another embodiment.
(26) FIG. **27** shows a mover-stator interaction according to another embodiment.
(27) FIG. **28** is an elevation view of a robotic system according to one embodiment.
(28) FIG. **29** is a top view of the robotic system of FIG. **28**.
(29) FIG. **30** is a cross-sectional view of the robotic system of FIG. **28**, taken along the line **29-29** in FIG. **29**.
(30) FIG. **31** is a perspective view of a stator body of the robotic system of FIG. **28**.
(31) FIG. **32** is a perspective view of a position-sensor sub-module of the robotic system of FIG. **28**.
DETAILED DESCRIPTION
(32) The following references may assist the reader: U.S. Pat. Nos. 6,003,230; 6,097,114; 6,208,045; 6,441,514; 6,847,134; 6,987,335; 7,436,135; 7,948,122; United States patent publication no. 2008/0203828; W. J. Kim and D. L. Trumper, “High-precision magnetic levitation stage for photolithography”, Precision Eng. 22 2 (1998), pp. 66-77; D. L. Trumper et al., “Magnet arrays for synchronous machines”, IEEE Industry Applications Society Annual Meeting, vol. 1, pp.

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(33) Referring to FIG. **1** and to FIG. **2**, robotic system according to one embodiment includes a stator **20** and movers **100**A and **100**B. The stator **20** includes stator modules **200**A, **200**B, **200**C, **200**D, **200**E, and **200**F. The stator modules **200**A, **200**B, **200**C, **200**D, **200**E, and **200**F collectively define a working surface **30** of the stator **20**, and the movers **100**A and **100**B may move relative to the working surface **30** as described herein, for example. Of course the embodiment shown is an example only, and alternative embodiments may differ. For example, alternative embodiments may include more, fewer, or different stator modules, and alternative embodiments may include more, fewer, or different movers. For example, some embodiments may include only one stator module or more than one stator module. Further, the working surface **30** is planar, but alternative working surfaces may be curved, cylindrical, spherical, or other shapes, for example.

(34) In the embodiment shown, the robotic system may be described with reference to various axes. For example, in the embodiment shown, the stator **20** may be described with reference to Cartesian axes identified as X, Y, and Z in the drawings, and the Cartesian axes identified as X, Y, and Z may be fixed relative to the stator **20** such that the X and Y axes are perpendicular to each other, such that the working surface **30** extends in the X and Y axes, and such that the Z axis is perpendicular to the working surface **30** and to the X and Y axes. However, alternative embodiments may differ, and embodiments such as those described herein are not limited to or limited by any particular axes.

(35) As shown in FIG. **1** for example, embodiments such as those described herein may include stators including differently shaped stator modules. As also shown in FIG. **1** for example, embodiments such as those described herein may include stators including stator modules having working surfaces that form respective portions of at least some of an overall working surface of a stator, and the respective working surfaces of the stator modules may have different shapes.

(36) For example, in the embodiment of FIG. **1**, each of the stator modules **200**A, **200**B, **200**C, **200**D, **200**E, and **200**F has a respective working surface, and as examples, FIG. **1** illustrates a working surface **30**A of the stator module **200**A, a working surface **30**B of the stator module **200**B, and a working surface **30**C of the stator module **200**C. In the embodiment of FIG. **1**, the respective working surfaces of the stator modules **200**A, **200**B, **200**C, **200**D, **200**E, and **200**F form respective portions of at least some of the working surface **30**, and the respective working surfaces of the stator modules **200**A, **200**B, **200**C, **200**D, **200**E, and **200**F have different shapes. For example, in the embodiment shown, the working surfaces **30**B and **30**C of the stator modules **200**B and **200**C are square-shaped and the respective working surfaces of the stator modules **200**A, **200**D, **200**E, and **200**F are rectangular, but of course alternative embodiments may differ.

(37) In other words, in the embodiment shown, for example, the stator module **200**A and the working surface **30**A of the stator module **200**A have a length **201** in a dimension (along the X axis in this embodiment) between opposite ends **202** and **203** of the stator module **200**A and of the working surface **30**A of the stator module **200**A, the stator module **200**A and the working surface **30**A of the stator module **200**A have a width **204** in a different dimension (along the Y axis in this embodiment) between exposed opposite sides **205** and **206** of the stator module **200**A and of the working surface **30**A of the stator module **200**A, and the length **201** is greater than the width **204**. The sides **205** and **206** may be referred to as “exposed” because the sides **205** and **206** are exposed to an environment of the stator **30** without other structure of the stator **30** or without any other structure on the sides **205** and **206**.

(38) As shown in FIG. **1** for example, a stator module having one shape (or having a working surface having one shape) may be positioned against, adjacent, or abutting a stator module having a different shape (or having a working surface having a different shape), and a stator module having

one orientation (or having a working surface having one orientation) may be positioned against, adjacent, or abutting a stator module having a different orientation (or having a working surface having a different orientation).

(39) For example, in the embodiment of FIG. **1**, the stator module **200**A is rectangular, the working surface **30**A of the stator module **200**A is rectangular, and the stator module **200**A is positioned against, adjacent, or abutting a side **207** of the stator module **200**B with the respective working surfaces of the stator modules **200**A and **200**B adjacent or abutting each other, and the stator module **200**B and the working surface of the stator module **200**B are square-shaped. The side **207** has a width (or, more generally, an extent) **208** greater than the width **204**.

(40) Also, in the embodiment of FIG. **1**, the stator module **200**D is positioned against, adjacent, or abutting the stator module **200**E with the respective working surfaces of the stator modules **200**D and **200**E adjacent or abutting each other, the stator modules **200**D and **200**E are rectangular, and the respective working surfaces of the stator modules **200**D and **200**E are rectangular, but the stator module **200**D and the working surface of the stator modules **200**D extend along the Y axis and the stator module **200**E and the working surface of the stator modules **200**E extend along the X axis. In other words, in the embodiment shown, the stator module **200**D and the working surface of the stator modules **200**D have one orientation (along the Y axis) and may be positioned against, adjacent, or abutting another stator module (the stator module **200**E in the embodiment shown), and the other stator module and the working surface of the other stator module have a different orientation (along the X axis). Of course alternative embodiments may differ.

(41) In general, such combinations of stator modules having such different shapes may allow for greater flexibility for designing or assembling different stators for different applications when compared to stator modules having the same shapes (such as only square shapes, for example). Further, such combinations of stator modules having such different shapes may allow for stators to be assembled at lower costs when compared to stators that are assembled from stator modules having the same shapes (such as only square shapes, for example) because, for example, rectangular stator modules such as the stator modules **200**A, **200**D, **200**E, and **200**F may extend a longer distance for a lower cost than square-shaped stator modules, for example.

(42) FIG. **3** schematically illustrates a stator module **200**, which may be illustrative of the stator modules **200**A, **200**D, **200**E, and **200**F or of other stator modules such as those described herein, for example. The stator module **200** includes a motor sub-module **220**, a position-sensor sub-module **230**, an amplifier sub-module **238**, and a stator body **250** as mechanical structure supporting the sub-modules and the working surfaces. The motor sub-module **220** may include electrical conductors that may be operable to generate a magnetic field to facilitate moving, relative to a working surface of the stator module **200**, a magnetized mover (such as the mover **100**A or **100**B) in the magnetic field along (or otherwise relative to) the working surface in response to electrical currents through the electrical conductors. The position-sensor sub-module **230** may include at least one position sensor operable to sense a position of such a mover. The amplifier sub-module **238** may be operable to amplify control signals received from a system controller or a module controller to control at least some of the electrical conductors of the motor sub-module **220**. In some embodiments, the amplifier sub-module **238** may be operable to amplify control signals received from a system controller or a module controller to control each electrical conductor of the motor sub-module **220**.

(43) In this particular non-limiting embodiment, the order of components from top to bottom is motor sub-module **220**, then the position-sensor sub-module **230**, followed by the amplifier sub-module **238**. That particular arrangement from top to bottom is not required, and alternative embodiments may differ. However, in some embodiments, the motor sub-module should be as close to the working surface as possible to maximize the generated magnetic field experienced by a mover (such as the mover **100**A or **100**B) above the working surface. In alternative embodiments, the arrangement of sub-modules may differ, or alternative embodiments may include more, fewer,

or different sub-modules.

(44) FIG. **4** schematically illustrates the stator modules **200**A, **200**B, and **200**C and a control system (or a system controller or a control circuit) **400** operable to control the stator modules **200**A, **200**B, and **200**C (and possibly more or fewer stator modules). The stator module **200**A includes a motor sub-module **220**A, a position-sensor sub-module **230**A, an amplifier sub-module **238**A, and a module controller **500**A. The stator module **200**B includes a motor sub-module **220**B, a position-sensor sub-module **230**B, an amplifier sub-module **238**B, and a module controller **500**B. The stator module **200**C includes a motor sub-module **220**C, a position-sensor sub-module **230**C, an amplifier sub-module **238**C, and module controller **500**C. Each stator module may also include a stator body (such as the stator body **250** described above, for example) as mechanical structure supporting the sub-modules and the working surfaces of the stator module. The motor sub-modules **220**A, **220**B, and **220**C may each include electrical conductors that may be operable to generate a magnetic field to facilitate moving, relative to a working surface of the stator module **200**, a magnetized mover (such as the mover **100**A or **100**B) in the magnetic field along (or otherwise relative to) the working surface in response to electrical currents through the electrical conductors. The position-sensor sub-modules **230**A, **230**B, and **230**C may each include at least one position sensor operable to sense a position of such a mover. The amplifier sub-module **238**A may include circuitry operable to amplify control signals received from the module controller **500**A to control the electrical conductors of the motor sub-modules **220**A, the amplifier sub-module **238**B may include circuitry operable to amplify control signals received from the module controller **500**B to control the electrical conductors of the motor sub-modules **220**B, and the amplifier sub-module **238**C may include circuitry operable to amplify control signals received from the module controller **500**C to control the electrical conductors of the motor sub-modules **220**C.

(45) In the embodiment of FIG. **4**, the control system **400** communicates with the module controller **500**A using a data cable **700**A, the module controller **500**A communicates with the module controller **500**B using a data cable **700**B, and the module controller **500**B communicates with the module controller **500**C using a data cable **700**C. Such communication may involve transmitting or receiving one or more signals to control the amplifier sub-module of the stator modules or transmitting or receiving one or more signals representing measurements by the position-sensor sub-modules of the stator modules, for example. In some embodiments, the control system **400** may transmit one or more control signals representing one or more set points (or desired values) of electrical currents flowing through some of the electrical conductors as described above, and such electrical current set points may transmitted to one or more module controllers (such as the module controllers **500**A, **500**B, and **500**C), which may further generate one or more signals to one or more amplifier sub-modules (such as the amplifier sub-modules **238**A, **238**B, and **238**C) so that the amplifier sub-modules may cause electrical currents to flow through electrical conductors as described above according to the electrical current set points. In some embodiments, the control system **400** may transmit one or more control signals representing one or more set points (or desired values) of mover positions to one or more module controllers (such as the module controllers **500**A, **500**B, and **500**C), which may further use the position set points and position sensor information to determine electrical current set points for electrical currents flowing through some of the electrical conductors as described above. For example, to control an amplifier sub-module (such as the amplifier sub-module **238**A, **238**B, or **238**C), a module controller (such as the module controller **500**A, **500**B, and **500**C) may transmit, to the amplifier sub-module, one or more control signals (such as one or more pulse-width modulation (PWM) or analog control signals, for example) according to the electrical current set points. The data cables **700**B and **700**C are external to the stator modules **200**A, **200**B, and **200**C, and in general, stator modules such as those described herein may communicate with each other using data cables external to the stator modules. Of course alternative embodiments may differ, and may include wireless communication or other alternatives to the embodiment of FIG. **4**.

(46) In general, the stator modules described above may be unitary. For example, stator bodies (such as the stator body **250**) may support motor sub-modules, electrical conductors of the motor sub-modules, working surfaces, or other sub-modules such as those described herein, or two or more thereof such that the stator modules described above may be unitary assemblies. Such unitary assemblies may be connected to each other using external data cables (such as the data cables **700**B and **700**C external to the stator modules **200**A, **200**B, and **200**C, for example) or other connections external to the stator modules. Further, stator modules as described herein may be units of a stator such that the stator may be formed from the stator modules such that the stator modules are the smallest units of the stator that include some or all of the sub-modules described above and that can function individually or collectively as stators.
(47) FIG. **5** and FIG. **6** illustrate a stator module **200**G according to one embodiment. The stator module **200**G includes a stator body **250**G, a motor sub-module **220**G, and a working surface **30**G. The motor sub-module **220**G includes two electromagnetic driving regions **221**A and **221**B in a single row and covered by the working surface **30**G.
(48) Alternative embodiments may include only one electromagnetic driving region or more than two electromagnetic driving regions. For example, FIG. **7** illustrates a stator module **200**H according to one embodiment and including three electromagnetic driving regions **221**C, **221**D, and **221**E in a single row. As another example, FIG. **8** illustrates a stator module **200**I according to one embodiment and including four electromagnetic driving regions **221**F, **221**G, **221**H, and **221**I in a single row. In such embodiments, Y-oriented edges (or, more generally, transverse edges) of the electromagnetic driving regions may be generally coincidental to such edges of one or more adjacent electromagnetic driving regions. The stator module **200**H and **200**I may otherwise be similar to the stator module **200**G.
(49) Referring back to FIG. **5** and FIG. **6**, in the embodiment shown, the stator body **250**G has outer side surfaces with a first outer side surface **511** (with a normal direction in −Y), a second outer side surface **516** (with a normal direction in −X), a third outer side surface **512** (with a normal direction in +Y), and a fourth outer side surface **517** (with a normal direction in +X). The projection of the surfaces **511**, **512**, **516**, and **517** on the X-Y plane forms, respectively, a first projected surface edge **211**, a second projected surface edge **216**, a third projected surface edge **212**, and a fourth projected surface edge **217**.
(50) In the embodiment shown, the first electromagnetic driving region **221**A has a first edge **231**A, a second edge **236**A, a third edge **232**A, and a fourth edge **237**A. Although only four edges are shown, additional edges may be adopted in some embodiments. The second electromagnetic driving region **221**B has a fifth edge **231**B, a sixth edge **236**B, a seventh edge **232**B, and an eighth edge **237**B. Again, although only four edges are shown, additional edges may be adopted in some embodiments. In this embodiment, the first projected surface edge **211** coincides with the first edge **231**A, the third projected surface edge **212** coincides with the third edge **232**A, the second projected surface edge **216** coincides with the second edge **236**A, the fourth edge **237**A coincides with the sixth edge **236**B, the first projected surface edge **211** coincides with the fifth edge **231**B, and the third projected surface edge **212** coincides with the seventh edge **232**B.
(51) Therefore, in the embodiment shown, the stator module **200**G, the stator body **250**G, and the working surface **30**G have a width **233** between exposed opposite sides of the stator module **200**G at the first projected surface edge **211** and at the third projected surface edge **212**, and a length **234** between opposite ends of the stator module **200**G at the second projected surface edge **216** and at the fourth projected surface edge **217**. The length **234** is greater than the width **233**, and the stator module **200**G may therefore be included in a stator similarly to the stator module **200**A as shown in FIG. **1**, for example.
(52) Referring to FIG. **9**, FIG. **10**, and FIG. **11**, the electromagnetic driving region **221**A (also shown in FIG. **5** and FIG. **6**) includes electrical conductors **224**X (which may be referred to a subset of the electrical conductors of the stator module **200**G) in a first layer **223**X of the

electromagnetic driving region **221**A. The electrical conductors **224**X extend longitudinally relative to the working surface **30**G, although alternative embodiments may include electrical conductors that extend in one or more different longitudinal directions, such as one or more curvilinear longitudinal directions or one or more directions that may not necessarily be along the X axis as shown. In general, a line, direction, or dimension as described herein may include a straight or curvilinear line, a linear or curved direction, or a linear or curved dimension.

(53) In the embodiment shown, the electrical conductors **224**X are evenly spaced apart from each other along the Y axis and extend between the edges **231**A and **232**A, but alternative embodiments may differ. Also, in the embodiment shown, a distance between the edge **231**A and the electrical conductor **224**X closest to the edge **231**A is no more than five or ten times a width of the electrical conductor **224**X, and a distance between the edge **232**A and the electrical conductor **224**X closest to the edge **232**A is no more than five or ten times a width of the electrical conductor **224**X, but alternative embodiments may differ. Each of the electrical conductors **224**X also extends between the edges **236**A and **237**A, which may mean that a distance from the electrical conductors **224**X to the edge **236**A and a distance from the electrical conductors **224**X to the edge **237**A is no more than five or ten times a width of each electrical conductor **224**X.

(54) In general, herein, an electrical conductor may extend between two edges, meaning that a distance from the electrical conductor to each of the edges is no more than five or ten times a width of the electrical conductor.

(55) Each of the electrical conductors **224**X extends along a respective portion of the working surface **30**G. When an electrical current passes through an electrical conductor **224**X, a magnetic field around the electrical conductor **224**X is generated. Therefore, each of the electrical conductors **224**X may be operable to generate a magnetic field to facilitate moving, relative to the working surface **30**G, a magnetized mover (such as the mover **100**A or **100**B) in the magnetic field along (or otherwise relative to) the working surface **30**G in response to electrical currents **240**X through the electrical conductors. Although the currents **240**X are shown in the positive X direction, the actual current flowing direction can be either positive or negative, depending on the values of the current. The labeled current directions in this document are merely illustrative reference directions rather than restrictive or actual flowing directions.

(56) The electromagnetic driving region **221**A also includes electrical conductors **224**Y (which may be referred to a subset of the electrical conductors of the stator module **200**G) in a second layer **223**Y of the electromagnetic driving region **221**A separate from the first layer **223**X in the Z direction (or, more generally, in a direction nonparallel or orthogonal to directions of the electrical conductors **224**X and **224**Y). The electrical conductors **224**Y extend transversely relative to the working surface **30**G, and may be orthogonal to the electrical conductors **224**X, although alternative embodiments may include electrical conductors that extend in one or more different transverse directions, such as one or more curvilinear transverse directions or one or more directions that may not necessarily be along the Y axis as shown.

(57) In the embodiment shown, the electrical conductors **224**Y are evenly spaced apart from each other along the X axis and extend between the edges **236**A and **237**A, but alternative embodiments may differ. Also, in the embodiment shown, a distance between the edge **236**A and the electrical conductor **224**Y closest to the edge **236**A is no more than five or ten times a width of the electrical conductor **224**Y, and a distance between the edge **237**A and the electrical conductor **224**Y closest to the edge **237**A is no more than five or ten times a width of the electrical conductor **224**Y, but alternative embodiments may differ. Each of the electrical conductors **224**Y also extends between the edges **231**A and **232**A, which may mean that a distance from the electrical conductors **224**Y to the edge **231**A and a distance from the electrical conductors **224**Y to the edge **232**A is no more than five or ten times a width of each electrical conductor **224**Y.

(58) Each of the electrical conductors **224**Y extends along a respective portion of the working surface **30**G. When an electrical current passes through an electrical conductor **224**Y, a magnetic

field around the electrical conductor **224**Y is generated. Therefore, each of the electrical conductors **224**Y may be operable to generate a magnetic field to facilitate moving, relative to the working surface **30**G, a magnetized mover (such as the mover **100**A or **100**B) in the magnetic field along (or otherwise relative to) the working surface **30**G in response to electrical currents **240**Y through the electrical conductors.

(59) Further, the electrical conductors **224**Y extend entirely across a portion **235** of the width **233** of the working surface **30**G, and all of the electrical conductors of the stator module **200**G that extend transversely relative to the working surface **30**G are within at least a portion of the portion **235** of the width **233** of the working surface **30**G.

(60) As shown in FIG. **9**, the first layer **223**X and the second layer **223**Y at least partially overlap in the Z direction (or, more generally, in a direction nonparallel or orthogonal to directions of the electrical conductors **224**X and **224**Y). Further, although two layers are shown in FIG. **9**, some embodiments may include only the first layer **223**X or only the second layer **223**Y, or some embodiments may include more than two layers. For example, some embodiments may include two or more layers similar to the first layer **223**X, two or more layers similar to the second layer **223**Y, or both. Of course other embodiments may include other alternatives.

(61) Other electromagnetic driving regions, such as the electromagnetic driving regions **221**B, **221**C, **221**D, **221**E, **221**F, **221**G, **221**H, and **221**I for example, may be similar to the electromagnetic driving region **221**A. Therefore, in the stator module **200**G shown in FIG. **5** and FIG. **6**, the electromagnetic driving region **221**A includes longitudinal electrical conductors (such as the electrical conductors **224**X, for example), and the electromagnetic driving region **221**B also includes longitudinal electrical conductors (similar to the electrical conductors **224**X, for example) but distinct from the longitudinal electrical conductors of the electromagnetic driving region **221**A. In general, electromagnetic driving regions may include electrical conductors that may be distinct from some or all of the electrical conductors of some or all other electromagnetic driving regions of a stator module.

(62) The working surface **30**G is substantially rectangular, but alternative embodiments may differ. For example, FIG. **12** illustrates a stator module **200**J having a working surface **30**J. The stator module **200**J and the working surface **30**J have a curved length **209** in a dimension (a curved dimension in this embodiment) between opposite ends **210** and **213** of the stator module **200**J and of the working surface **30**J, the stator module **200**J and the working surface **30**J have a width **214** in a different dimension (a radial dimension in this embodiment) between exposed opposite curved sides **215** and **218** of the stator module **200**J and of the working surface **30**J, and the length **209** is greater than the width **214**. The stator module **200**J includes radially extending electrical conductors **224**R that may be similar to electrical conductors as described above, or the stator module **200**J may include other electrical conductors that may be similar to electrical conductors as described above and that may at least partially overlap in the Z direction (or, more generally, in a direction nonparallel or orthogonal to directions of the electrical conductors). For example, in some embodiments, electrical conductors of the stator module **200**J may be curved, and may be orthogonal to the radially extending electrical conductors **224**R, such as curved electrical conductors **224**C as shown in FIG. **13**, for example.

(63) In general, each electrical conductor may have different electrical current set point (or desired value) based on suitable commutation laws, such as but not being limited to three-phase sinusoidal commutation, for example. Multiple electrical conductors may be connected in serial at their ends, for example.

(64) In general, the electrical currents through electrical conductors as described above may be determined to move a magnetized mover (such as the mover **100**A or **100**B) in one, two, three, four, five, or six degrees of freedom along a working surface of one stator module or along or relative to a working surface (such as the working surface **30** shown in FIG. **1** and FIG. **2**) of a stator including more than one stator module. For example, the electrical currents through electrical

conductors as described above may be determined to move a magnetized mover from the working surface of one stator module to the working surface of another stator module of such as stator.

(65) For example, FIG. **14** illustrates a mover **100** (with one or more bearing units **140** each having bearing surfaces **141**) and a stator **200** (with one or more bearing units **240**, which may be rails, each having bearing surfaces **241**) according to one embodiment. During operation, the mover **100** may operate in a levitated state where the mover **100** is controlled by the stator **200** to maintain a sufficient working gap clearance **40** to ensure there is no contact between the mover bearing surfaces **141** and the stator bearing surfaces **241** such that the bearing support gap is a positive value. While operating in a levitated state, the Y direction motion of the mover may be limited in this particular embodiment by the stator bearing units **240**, which may protrude above the stator work surface **30**. During operation with this particular stator embodiment, the mover **100** may operate in a landed or engaged state in which the working gap **40** is decreased until the mover bearing surfaces **141** contact the stator bearing surfaces **241** (such that the bearing support gap **50** is generally zero). While operating in this state, motion of the mover **100** is constrained in five degrees of freedom, limiting motion of the mover **100** to be along the X direction. In such embodiments, electrical conductors of the stator **200** may all extend transversely (such as the electrical conductors **224**Y, for example) relative to the stator work surface **30**, although such electrical conductors may be shorter in length than the electrical conductors **224**Y.

(66) As indicated above, rectangular stator modules such as the stator modules **200**A, **200**D, **200**E, **200**F, and **200**G may extend a longer distance for a lower cost than square-shaped stator modules, for example. Further, rectangular stator modules may more easily allow a product to extend wider than the stator modules. For example, FIG. **15** illustrates a product **150** is mounted on the mover **100** of FIG. **14** according to one embodiment. The product **150** has two ends **170**A and **170**B, which extend wider than the stator **100**. In some embodiments, a high-force or energy-processing station (such as stamping, welding, or laser machining, for example) can be configured to process the product **150** on the two ends **170**A and **170**B of the product **150**.

(67) FIG. **16** illustrates an alternative to the mover **100** and stator **200** of FIG. **14**. In general, the bearing surfaces **141** and **241** of the mover and stator bearing units **140** and **240** may be in the shape of curves, flat geometry, triangle, cylindrical, spherical, or some combination sufficient to guide mover motion and/or support the weight of the mover **100** (along the Z direction) while operating in a landed state. It may be desirable to maintain certain contact areas between the two mating bearing units to minimize wear during operation. The respective bearing units of the mover **100** and stator **200** may be matched together to achieve a desired behavior or performance. The bearings may utilize sliding or rolling contact during operation. In some embodiments, the two mating surfaces may not touch each other directly and a fluid film may exist in between, such as air or fluid during high speed motion. Such aero-dynamic bearing may help significantly reduce wear on bearing surfaces without requiring much electrical energy as needed in magnetic levitation. The mating bearing units may be made of materials such as but not being limited to ceramics, glass, plastics, metals with surface properly processed, or other suitable materials with smooth surfaces.

(68) FIG. **17** illustrates a motor sub-module according to another embodiment. The motor sub-module of FIG. **17** includes electrical conductors in a first layer **223**X as described above and shown in FIG. **10**, electrical conductors in a second layer **223**Y (separate from the first layer **223**X in the Z direction, or, more generally, in a direction nonparallel or orthogonal to directions of the electrical conductors in the first layer **223**X and in the second first layer **223**Y) as described above and shown in FIG. **11**, electrical conductors in a third layer **223***a* (separate from the first and second layers **223**X and **223**Y in the Z direction, or, more generally, in a direction nonparallel or orthogonal to directions of the electrical conductors in the first layer **223**X, in the second first layer **223**Y, and in the third layer **223**α), and electrical conductors in a third first layer **223***p* separate from the first, second, and third layers **223**X, **223**Y, and **223**α. As shown in FIG. **17**, the first, second, third, and fourth layers **223**X, **223**Y, **223**α, and **223**β at least partially overlap in the Z

direction (or, more generally, in a direction nonparallel or orthogonal to directions of the electrical conductors of the first, second, third, and fourth layers **223**X, **223**Y, **223**α, and **223**β).

(69) FIG. **18** illustrates electrical conductors **224**α**1** in a sub-sector **225**α**1**, electrical conductors **224**α**2** in a sub-sector **225**α**2**, electrical conductors **224**α**3** in a sub-sector **225**α**3**, and electrical conductors **224**α**4** in a sub-sector **225**α**4** of the third layer **223**α. The electrical conductors **224**α**1** extend at an angle α**1** around the Z axis from the X axis, the electrical conductors **224**α**2** extend at an angle α**2** around the Z axis from the X axis, the electrical conductors **224**α**3** extend at an angle α**3** around the Z axis from the X axis, and the electrical conductors **224**α**4** extend at an angle α**4** around the Z axis from the X axis. The electrical conductors in FIG. **18** are linear but may be curvilinear or include one or more curved segments in other embodiments. Further, although FIG. **18** illustrates four sub-sectors, alternative embodiments may include more or fewer sub-sectors, such as two or more sub-sectors, for example. In general, electrical conductors of one such sub-sector may be nonparallel to electrical conductors of another such sub-sector, and the electrical conductors of such sub-sectors may be in a common layer. Further, the electrical conductors of such sub-sectors may be nonparallel to the electrical conductors of another layer, such as the electrical conductors of the first layer **223**X, of the second layer **223**Y, or of both, for example. Electrical currents **240**α**1**, **240**α**2**, **240**α**3**, **240**α**4** in the electrical conductors **224**α**1**, **224**α**2**, **224**α**3**, **224**α**4** respectively may be controlled as described above, for example. In the embodiment shown, α**2**=α**1**+90°, α**3**=α**1**, α**4**=α**2**, and α**1** is between 15° and 45°, for example 30°, although alternative embodiments may differ and, for example, α**1** may differ from α**3** and α**2** may differ from α**4**. In each sub-sector **225**α**1**, **225**α**2**, **225**α**3**, and **225**α**4** in FIG. **18**, current set points for each electrical conductor can be determined by positions of magnet arrays of a mover relative to the electrical conductors according to suitable commutation laws, such as but not being limited to three-phase sinusoidal commutation. The spacing of electrical conductors in the transverse direction (or pitch) can be designed based on a spatial period of a magnet array of a mover, and on a number of electrical conductor phases within one magnet array spatial period. For example, for a three-phase design, the pitch can be about the spatial period of the magnet array divided by 3n, where n is an integer number. If the magnet array spatial period is 60 millimeters (mm), for example, then the conductor pitch can be close to 5 mm, 10 mm, or 20 mm, for example.

(70) In the embodiment shown in FIG. **18**, the electrical conductors **224**α**1** and the electrical conductors **224**α**3** overlap partially along their lengths in a plane including directions in which the electrical conductors **224**α**1** and **224**α**3** extend, but are spaced apart from each other in such a plane in a direction transverse to their lengths. Also in the embodiment shown in FIG. **18**, the electrical conductors **224**α**2** and the electrical conductors **224**α**4** overlap partially along their lengths in a plane including directions in which the electrical conductors **224**α**2** and **224**α**4** extend, but are spaced apart from each other in such a plane in a direction transverse to their lengths. Of course alternative embodiments may differ.

(71) As indicated above, the electrical conductors in FIG. **18** are linear but may be curvilinear or include one or more curved segments in other embodiments, as shown in FIG. **19**, for example. In the embodiment of FIG. **19**, the first sub-sector **225**α**1** comprises a first plurality of curvilinear electrical conductors **224**α**1** elongated along a first curvilinear direction. The second sub-sector **225**α**2** comprises a second plurality of curvilinear electrical conductors **224**α**2** elongated along a second curvilinear direction. The third sub-sector **225**α**3** comprises a third plurality of electrical conductors **224**α**3** elongated along a third curvilinear direction. The fourth sub-sector **225**α**4** comprises a fourth plurality of electrical conductors **224**α**4** elongated along a fourth curvilinear direction. The electrical conductors **224***a***1**, **224**α**2**, **224**α**3**, and **224**α**4** may be driven by an amplifier sub-module with current **240***a***1**, **240**α**2**, **240**α**3**, and **240**α**4** respectively with suitable amount. The curve of a curvilinear direction may be generally gradual with an angle between a start and an end tangent typically being less than 45°. Although FIG. **18** illustrates four sub-sectors, alternative embodiments may include more or fewer sub-sectors, such as two or more sub-sectors,

for example. In the embodiment shown, the curvilinear directions could be approximated to follow corresponding linear directions, where α**2**=α**1**+90°, α**3**=α**1**, α**4**=α**2**, and α**1** is between 15° and 45°, for example 30°, although alternative embodiments may differ and, for example, α**1** may differ from α**3** and α**2** may differ from α**4**.
(72) In the embodiment shown in FIG. **19**, the electrical conductors **224**α**1** and the electrical conductors **224**α**3** overlap partially along their lengths in a plane including directions in which the electrical conductors **224**α**1** and **224**α**3** extend, but are spaced apart from each other in such a plane in a direction transverse to their lengths. Also in the embodiment shown in FIG. **19**, the electrical conductors **224**α**2** and the electrical conductors **224**α**4** overlap partially along their lengths in a plane including directions in which the electrical conductors **224**α**2** and **224**α**4** extend, but are spaced apart from each other in such a plane in a direction transverse to their lengths. Of course alternative embodiments may differ.
(73) FIG. **20** illustrates electrical conductors **224**β**1** in a sub-sector **225***p***1**, electrical conductors **224**β**2** in a sub-sector **225**β**2**, electrical conductors **224**β**3** in a sub-sector **225**β**3**, and electrical conductors **224**β**4** in a sub-sector **225**β**4** of the third layer **2230**. The electrical conductors **224**β**1** extend at an angle β**1** around the Z axis from the X axis, the electrical conductors **224**β**2** extend at an angle β**2** around the Z axis from the X axis, the electrical conductors **224**β**3** extend at an angle β**3** around the Z axis from the X axis, and the electrical conductors **224**β**4** extend at an angle β**4** around the Z axis from the X axis. The electrical conductors in FIG. **20** are linear but may be curvilinear or include one or more curved segments in other embodiments. Further, although FIG. **20** illustrates four sub-sectors, alternative embodiments may include more or fewer sub-sectors, such as two or more sub-sectors, for example. In general, electrical conductors of one such sub-sector may be nonparallel to electrical conductors of another such sub-sector, and the electrical conductors of such sub-sectors may be in a common layer. Further, the electrical conductors of such sub-sectors may be nonparallel to the electrical conductors of another layer, such as the electrical conductors of the first layer **223**X, of the second layer **223**Y, of the third layer **223**α, or of two or more thereof, for example. Electrical currents **240**β**1**, **240**β**2**, **240**β**3**, **240**β**4** in the electrical conductors **224**β**1**, **224**β**2**, **224**β**3**, **224**β**4** respectively may be controlled as described above, for example. In the embodiment shown, β**2**=β**1**+90°, β**3**=β**1**, β**4**=β**2**, and β**1** is between 45° and 75°, for example 60°, although alternative embodiments may differ and, for example, β**1** may differ from β**3** and β**2** may differ from β**4**.
(74) In the embodiment shown in FIG. **20**, the electrical conductors **224**β**1** and the electrical conductors **224**β**3** overlap partially along their lengths in a plane including directions in which the electrical conductors **224**β**1** and **224**β**3** extend, but are spaced apart from each other in such a plane in a direction transverse to their lengths. Also in the embodiment shown in FIG. **18**, the electrical conductors **224**β**2** and the electrical conductors **224**β**4** overlap partially along their lengths in a plane including directions in which the electrical conductors **224**β**2** and **224**β**4** extend, but are spaced apart from each other in such a plane in a direction transverse to their lengths. Of course alternative embodiments may differ.
(75) Further, in the Z direction (or, more generally, in a direction nonparallel or orthogonal to directions of the electrical conductors of the first, second, third, and fourth layers **223**X, **223**Y, **223**α, and **223**β), the sub-sector **225**β**1** may at least partially overlap the sub-sectors **225**α**1** and **225**α**2**, the sub-sector **225**β**2** may at least partially overlap the sub-sectors **225**α**2** and **225**α**3**, the sub-sector **225**β**3** may at least partially overlap the sub-sectors **225**α**3** and **225**α**4**, and the sub-sector **225**β**4** may at least partially overlap the sub-sectors **225**α**4** and **225**α**1**.
(76) In general, embodiments such as the motor sub-module of FIG. **17** include electrical conductors that extend along portions of a working surface within 15° of each other, or along at least four different directions, and that at least partially overlap in a direction nonparallel or orthogonal to directions of the electrical conductors.
(77) As shown from FIG. **21** to FIG. **27**, the motor sub-module of FIG. **17** may significantly extend

controllable rotary motion range around the Z axis.
(78) FIG. **21** shows a particular embodiment of a mover **100**. The mover **100** includes a magnet assembly including four magnet arrays **110**A, **110**B, **110**C, and **110**D. Each of the magnet arrays **110**A, **110**B, **110**C, and **110**D includes a plurality of linearly elongated magnetization segments (such as permanent magnets, for example), each having a magnetization direction that may be orthogonal to its elongation direction. For example, the magnet array **110**A includes magnetization segments **120**A**1**, **120**A**2**, **120**A**3**, and **120**A**4** as shown in FIG. **21** and in FIG. **22**. As shown in FIG. **22**, the magnetization segments **120**A**1**, **120**A**2**, **120**A**3**, and **120**A**4** may have magnetization directions **121**A**1**, **121**A**2**, **121**A**3**, and **121**A**4**. Each such magnetization segment may include a plurality of magnet pieces, which may be oriented in a particular pattern to generate a strong magnetic force on the bottom side of the mover. In this particular non-limiting embodiment, each magnet array includes four magnets, but alternative embodiments may include more, fewer, or different magnets.
(79) FIG. **23** shows two coordinate systems that may describe some embodiments. As indicated above, Cartesian axes identified as X, Y, and Z may be fixed relative to a stator, and Cartesian axes identified as Xm, Ym, and Zm may be fixed relative to a mover such as the mover **100**. However, alternative embodiments may differ, and embodiments such as those described herein are not limited to or limited by any particular axes. A relative angle between the stator and mover axes X and Xm when projected onto the XY plane of the stator work surface may be defined as θm. This angle θm may be utilized in other embodiments to describe the relative orientation between the two coordinate systems.
(80) FIG. **24** shows a mover-stator interaction according to one embodiment in which the magnet arrays **110**A and **110**C interact with the electrical conductors **224**X and the magnet arrays **110**B and **110**D interact with the electrical conductors **224**Y. In such an embodiment, the electrical conductors **224**X and the electrical conductors **224**Y may cause rotation of the mover **100** around the Z axis by about 15° in either direction around the Z axis such that
(81) -15° < *m* < 15°.
(82) FIG. **25** shows a mover-stator interaction according to another embodiment in which the magnet array **110**A interacts with the electrical conductors **224**α**1**, the magnet array **110**B interacts with the electrical conductors **224**α**2**, the magnet array **110**C interacts with the electrical conductors **224**α**3**, and the magnet array **110**D interacts with the electrical conductors **224**α**4**. Again, in such an embodiment, the electrical conductors **224**α**1**, **224**α**2**, **224**α**3**, and **224**α**4** may cause rotation of the mover **100** around the Z axis by about 15° in either direction around the Z axis such that α**1**−15°<θm<α**1**+15°.
(83) Therefore, the magnet arrays **110**A and **110**C may interact with the electrical conductors **224**X and the magnet arrays **110**B and **110**D may interact with the electrical conductors **224**Y to rotate the mover **100** from the orientation shown in FIG. **24** towards the orientation shown in FIG. **25**, and then the magnet arrays **110**A, **110**B, **110**C, and **110**D may interact with the electrical conductors **224**α**1**, **224**α**2**, **224**α**3**, and **224**α**4** to rotate the mover **100** towards the orientation shown in FIG. **25**, so that the electrical conductors **224**X, **224**Y, **224***al*, **224**α**2**, **224**α**3**, and **224**α**4** may be controlled to cause the mover **100** to rotate from the orientation shown in FIG. **24** to the orientation shown in FIG. **25**.
(84) FIG. **26** shows a mover-stator interaction according to another embodiment in which the magnet array **110**A interacts with the electrical conductors **224**β**1**, the magnet array **110**B interacts with the electrical conductors **224**β**2**, the magnet array **110**C interacts with the electrical conductors **224**β**3**, and the magnet array **110**D interacts with the electrical conductors **224**β**4**. Again, in such an embodiment, the electrical conductors **224**β**1**, **224**β**2**, **224**β**3**, and **224**β**4** may cause rotation of the mover **100** around the Z axis by about 15° in either direction around the Z axis such that β**1**−15°<θm<β**1**+15°.
(85) Therefore, the magnet arrays **110**A, **110**B, **110**C, and **110**D may interact with the electrical

conductors **224***al*, **224**α**2**, **224**α**3**, and **224**α**4** to rotate the mover **100** from the orientation shown in FIG. **25** towards the orientation shown in FIG. **26**, and then the magnet arrays **110**A, **110**B, **110**C, and **110**D may interact with the electrical conductors **224**β**1**, **224**β**2**, **224**β**3**, and **224**β**4** to rotate the mover **100** towards the orientation shown in FIG. **26**, so that the electrical conductors **224**α**1**, **224**α**2**, **224**α**3**, **224**α**4**, **224**β**1**, **224**β**2**, **224**β**3**, and **224**β**4** may be controlled to cause the mover **100** to rotate from the orientation shown in FIG. **25** to the orientation shown in FIG. **26**.
(86) FIG. **27** shows a mover-stator interaction according to one embodiment in which the magnet arrays **110**A and **110**C interact with the electrical conductors **224**Y and the magnet arrays **110**B and **110**D interact with the electrical conductors **224**X. In such an embodiment, the electrical conductors **224**X and the electrical conductors **224**Y may cause rotation of the mover **100** around the Z axis by about 15° in either direction around the Z axis such that
(87) $75° < \quad m < 105°$.
(88) Therefore, the magnet arrays **110**A, **110**B, **110**C, and **110**D may interact with the electrical conductors **224**β**1**, **224**β**2**, **224**β**3**, and **224**β**4** to rotate the mover **100** from the orientation shown in FIG. **26** towards the orientation shown in FIG. **27**, and then the magnet arrays **110**A and **110**C may interact with the electrical conductors **224**Y and the magnet arrays **110**B and **110**D may interact with the electrical conductors **224**X to rotate the mover **100** towards the orientation shown in FIG. **27**, so that the electrical conductors **224**β**1**, **224**β**2**, **224**β**3**, **224**β**4**, **224**X, and **224**Y may be controlled to cause the mover **100** to rotate from the orientation shown in FIG. **26** to the orientation shown in FIG. **27**.
(89) As shown in the examples from FIG. **24** to FIG. **27**, the motor sub-module of FIG. **17** may rotate the mover **100** 90° around the Z axis (or around an axis orthogonal or nonparallel to the working surface of a stator module including the motor sub-module of FIG. **17**). More generally, the motor sub-module of FIG. **17** may rotate the mover **100** to any rotational position around the Z axis (or around an axis orthogonal or nonparallel to the working surface of a stator module including the motor sub-module of FIG. **17**) by repeating variations of the examples from FIG. **24** to FIG. **27**.
(90) Of course the embodiments described above are examples only, and alternative embodiments may include other electrical conductors in one or more other of the same or different layers.
(91) FIG. **28**, FIG. **29**, and FIG. **30** illustrate a robotic system according to another embodiment and including a stator module **200** and a mover **100**. The stator module **200** includes a working surface **30** and motor sub-module **220**, which may be similar to the motor sub-modules described above and may include a plurality of electrical conductors in one or more layers as described above. The stator module **200** also includes a stator body **250** supporting the sub-modules and the working surfaces of the stator module.
(92) As shown in FIG. **30** and FIG. **31**, protrusions **251** (also shown as protrusions **251**A, **251**B, **251**C, and **251**D) protrude from a surface **252** of the stator body **250** and towards the motor sub-module **220**. The protrusions **251** may be attached to the motor sub-module **220** directly or indirectly (by an attachment such as, without limitation, bonding, potting, welding, or soldering) to support the motor sub-module **220** relative to the stator body **250**. Although the protrusions **251** are shown to be round, alternative embodiments may include other shapes such as square, rectangle, triangle, octagon, or hexagon, for example.
(93) As shown in FIG. **30** and FIG. **32**, the stator module **200** includes a position-sensor sub-module **230**, which includes a planar position-sensor body **239** defining through-holes **232** positioned to receive respective ones of the protrusions **251** when the position-sensor sub-module **230** is positioned between the surface **252** (from which the protrusions **251** protrude) and the motor sub-module **220**. The position-sensor sub-module **230** at least one position sensor **231** on the position-sensor body **239**. In general, one or more position sensors **231** may facilitate sensing a position of the mover **100** based on one or more physics principles such as, but not limited to, optical, capacitive, eddy current, inductive, magnetic, resistive, or a combination of two or more

thereof.

(94) In general, the protrusions **251** may transfer forces from the motor sub-module **220** to a portion of the stator body **250** on an opposite side of the position-sensor sub-module **230** from the motor sub-module **220**. The portion of the stator body **250** on the opposite side of the position-sensor sub-module **230** from the motor sub-module **220** may be relatively large, the protrusions **251** may allow the motor sub-module **220** to be supported by a relatively large portion of the stator body **250** while allowing the position-sensor sub-module **230** to be relatively close to the motor sub-module **220**. Further, any forces applied on the motor sub-module **220** by the mover **100** may be directly transferred to the portion of the stator body **250** on the opposite side of the position-sensor sub-module **230** from the motor sub-module **220** without being transferred to the position-sensor sub-module **230**. In other words, the protrusions **251** may create load paths between the motor sub-module **220** and the portion of the stator body **250** on the opposite side of the position-sensor sub-module **230** from the motor sub-module **220** that may not necessarily transmit loads to the position-sensor sub-module **230**, which may protect the position-sensor sub-module **230** from receiving potentially damaging load forces such that mechanical stress on the position-sensor sub-module **230** may be reduced, which may avoid damage to the position-sensor sub-module **230**.

(95) In general, embodiments such as those described herein may move one or more parts, such as but not limited to one or more biological samples, one or more devices, one or more drugs (which may be in suitable containers), one or more products being assembled, one or more raw parts, one or more materials, or a combination of two or more thereof, for example. Therefore, embodiments such as those described herein may be a magnetic movement apparatus or a moveable robot system that may include one or more moveable robotic devices. Embodiments such as those described herein may be used in the automation of various processes including packaging where workpieces need to be transported, sorted, weighed, or packaged, for example. Therefore, robotic systems such as those described herein for example may function as assembly systems or as other systems for packaging, transferring, printing, inspecting, analyzing, or filling, for example.

(96) This disclosure includes the following other examples as further illustrations of embodiments of the disclosure, which are not intended to limit the scope of the disclosure.

(97) 1. A stator module comprising: a stator body; a working surface extending by a width in a first dimension between first and second exposed opposite sides of the stator module, the working surface further extending by a length in a second dimension between first and second opposite ends of the stator module, the second dimension different from the first dimension, the length greater than the width; and a plurality of electrical conductors, each electrical conductor of the plurality of electrical conductors extending along a respective portion of the working surface and operable to generate a magnetic field to facilitate moving, relative to the working surface, a magnetized mover in the magnetic field in response to electrical current through the electrical conductor; at least some electrical conductors of the plurality of electrical conductors in a first layer of electrical conductors of the plurality of electrical conductors extending in a first electrical conductor direction; and at least some electrical conductors of the plurality of electrical conductors in a second layer of electrical conductors of the plurality of electrical conductors separate from the first layer of electrical conductors extending in a second electrical conductor direction nonparallel to the first electrical conductor direction; the at least some electrical conductors of the plurality of electrical conductors in the first layer at least partially overlapping the at least some electrical conductors of the plurality of electrical conductors in the second layer in a direction orthogonal to the first and second electrical conductor directions; wherein the plurality of electrical conductors and the working surface are supported relative to the stator body such that the stator module is a unitary assembly.

(98) 2. The stator module of example 1 wherein at least some electrical conductors of the plurality of electrical conductors extend transversely relative to the working surface and entirely across at least a portion of the width of the working surface.

(99) 3. The stator module of example 2 wherein all of the electrical conductors of the stator module that extend along respective portions of the working surface and transversely relative to the working surface are within the at least a portion of the width of the working surface.
(100) 4. The stator module of example 2 wherein all of the electrical conductors of the stator module that extend along respective portions of the working surface and transversely relative to the working surface extend entirely across the at least a portion of the width of the working surface.
(101) 5. The stator module of example 2, 3, or 4 wherein the working surface covers a single row of electromagnetic driving regions, each electromagnetic driving region of the single row of electromagnetic driving regions comprising a respective subset of the plurality of electrical conductors that extend entirely across the at least a portion of the width of the working surface.
(102) 6. The stator module of example 5 wherein each electrical conductor of the respective subset of the plurality of electrical conductors of each electromagnetic driving region of the single row of electromagnetic driving regions extends substantially across the electromagnetic driving region.
(103) 7. The stator module of example 5 or 6 wherein the single row of electromagnetic driving regions comprises two electromagnetic driving regions.
(104) 8. The stator module of example 5, 6, or 7 wherein the single row of electromagnetic driving regions comprises four electromagnetic driving regions.
(105) 9. The stator module of example 5, 6, or 7 wherein each electromagnetic driving region of the single row of electromagnetic driving regions comprises: a respective subset of the at least some electrical conductors of the plurality of electrical conductors in the first layer of electrical conductors; and a respective subset of the at least some electrical conductors of the plurality of electrical conductors in the second layer of electrical conductors.
(106) 10. The stator module of any one of examples 2 to 9 wherein at least some electrical conductors of the plurality of electrical conductors extend longitudinally relative to the working surface.
(107) 11. The stator module of example 10 wherein the at least some electrical conductors of the plurality of electrical conductors extend transversely relative to the working surface are orthogonal to the at least some electrical conductors of the plurality of electrical conductors that extend longitudinally relative to the working surface.
(108) 12. The stator module of example 10 or 11, when directly or indirectly dependent from example 5, wherein each electromagnetic driving region of the single row of electromagnetic driving regions comprises a respective subset of the plurality of electrical conductors that extend longitudinally relative to the working surface.
(109) 13. The stator module of example 12 wherein the respective subset of the plurality of electrical conductors that extend longitudinally relative to the working surface of each electromagnetic driving region of the single row of electromagnetic driving regions is distinct from each respective subset of the plurality of electrical conductors that extend longitudinally relative to the working surface of each other electromagnetic driving region of the single row of electromagnetic driving regions.
(110) 14. The stator module of any one of examples 1 to 13 wherein each electromagnetic driving region of the plurality of electromagnetic driving regions abuts an adjacent at least one of the plurality of electromagnetic driving regions.
(111) 15. The stator module of any one of examples 1 to 14 wherein the stator module is substantially rectangular.
(112) 16. The stator module of any one of examples 1 to 15 wherein the working surface is substantially rectangular.
(113) 17. The stator module of any one of examples 1 to 14 wherein: the working surface is in a plane; the working surface is at least partially curved in the plane; the width is a width between at-least-partially-curved sides of the working surface; and the length comprises at least one curve length.

(114) 18. The stator module of any one of examples 1 to 17 wherein the stator module further comprises at least one guide positioned to guide movement of the mover relative to the stator module along the length of the working surface.
(115) 19. The stator module of example 18 wherein the at least one guide comprises at least one rail.
(116) 20. A stator module comprising: a stator body; a working surface supported relative to the stator body; and a plurality of electrical conductors, each electrical conductor of the plurality of electrical conductors extending along a respective portion of the working surface and operable to generate a magnetic field to facilitate moving, relative to the working surface, a magnetized mover in the magnetic field in response to electrical current through the electrical conductor; at least some electrical conductors of the plurality of electrical conductors in a first layer of electrical conductors of the plurality of electrical conductors extending in a first electrical conductor direction; at least some electrical conductors of the plurality of electrical conductors in the first layer of electrical conductors of the plurality of electrical conductors extending in a second electrical conductor direction nonparallel to the first electrical conductor direction; and at least some electrical conductors of the plurality of electrical conductors in a second layer of electrical conductors of the plurality of electrical conductors separate from the first layer of electrical conductors extending in a third electrical conductor direction nonparallel to the first electrical conductor direction and nonparallel to the second electrical conductor direction.
(117) 21. The stator module of example 20 wherein the first electrical conductor direction is orthogonal to the second electrical conductor direction.
(118) 22. The stator module of example 20 or 21 wherein the first electrical conductor direction is linear.
(119) 23. The stator module of example 20, 21, or 22 wherein the second electrical conductor direction is linear.
(120) 24. The stator module of example 20, 21, 22, or 23 wherein the third electrical conductor direction is curvilinear.
(121) 25. The stator module of any one of examples 20 to 24 wherein the at least some electrical conductors extending in the first electrical conductor direction at least partially overlap, in a direction orthogonal to the first and second electrical conductor directions, with the at least some electrical conductors extending in the third electrical conductor direction.
(122) 26. The stator module of any one of examples 20 to 25 wherein the at least some electrical conductors extending in the second electrical conductor direction at least partially overlap, in a direction orthogonal to the second and third electrical conductor directions, with the at least some electrical conductors extending in the third electrical conductor direction.
(123) 27. The stator module of any one of examples 20 to 26 wherein at least some electrical conductors of the plurality of electrical conductors are in a third layer of electrical conductors of the plurality of electrical conductors separate from the first and second layers of electrical conductors and extend in a fourth electrical conductor direction nonparallel to the first electrical conductor direction, nonparallel to the second electrical conductor direction, and nonparallel to the third electrical conductor direction.
(124) 28. The stator module of example 27 wherein the third electrical conductor direction is orthogonal to the fourth electrical conductor direction.
(125) 29. The stator module of example 27 or 28 wherein the fourth electrical conductor direction is curvilinear.
(126) 30. The stator module of example 27, 28, or 29 wherein the at least some electrical conductors extending in the first electrical conductor direction at least partially overlap, in a direction orthogonal to the first and fourth electrical conductor directions, with the at least some electrical conductors extending in the fourth electrical conductor direction.
(127) 31. The stator module of example 27, 28, 29, or 30 wherein the at least some electrical

conductors extending in the second electrical conductor direction at least partially overlap, in a direction orthogonal to the second and fourth electrical conductor directions, with the at least some electrical conductors extending in the fourth electrical conductor direction.
(128) 32. A stator module comprising: a stator body; a working surface supported relative to the stator body; a motor sub-module comprising a plurality of electrical conductors, each electrical conductor of the plurality of electrical conductors extending along a respective portion of the working surface and operable to generate a magnetic field to facilitate moving, relative to the working surface, a magnetized mover in the magnetic field in response to electrical current through the electrical conductor; and a position-sensor sub-module comprising at least one position sensor operable to sense a position of the mover and defining a plurality of through-holes; wherein the stator body comprises a surface and a plurality of protrusions, each protrusion of the plurality of protrusions extending from the surface, towards the motor sub-module, and through a respective through-hole of the plurality of through-holes of the position-sensor sub-module and supporting the motor sub-module.
(129) 33. The stator module of example 32 wherein the position-sensor sub-module comprises a position-sensor body defining the plurality of through-holes and supporting the at least one position sensor.
(130) 34. The stator module of example 33 wherein the position-sensor body is planar.
(131) 35. The stator module of example 32, 33, or 34 wherein the plurality of protrusions are spaced apart from each other in at least two dimensions.
(132) 36. The stator module of example 32, 33, or 34 wherein the plurality of protrusions are arranged in at least two rows and in at least two columns.
(133) 37. A robotic system comprising at least one stator module comprising a first stator module according to any one of examples 32 to 36.
(134) 38. A robotic system comprising at least one stator module comprising a first stator module according to any one of examples 20 to 31.
(135) 39. A robotic system comprising at least one stator module comprising a first stator module according to any one of examples 1 to 19.
(136) 40. The robotic system of example 39 wherein the at least one stator module further comprises a second stator module comprising: a stator body; a working surface supported relative to the stator body and having a side adjacent the first stator module, the side of the working surface of the second stator module having a greater extent than the width of the working surface of the first stator module; and a plurality of electrical conductors, each electrical conductor of the plurality of electrical conductors extending along a respective portion of the working surface and operable to generate a magnetic field to facilitate moving, relative to the working surface, the magnetized mover in the magnetic field in response to electrical current through the electrical conductor; wherein the robotic system is operable to move the magnetized mover between the working surface of the first stator module and the working surface of the second stator module in response to electrical current through at least one electrical conductor of the pluralities of electrical conductors of the first and second stator modules.
(137) 41. The robotic system of example 40 wherein the side of the working surface of the second stator module is adjacent the first end of the first stator module.
(138) 42. The robotic system of example 40 or 41 wherein the side of the working surface of the second stator module abuts the first end of the first stator module.
(139) 43. The robotic system of example 40, 41, or 42 wherein the first stator module abuts the second stator module.
(140) 44. The robotic system of example 40, 41, 42, or 43 wherein the second stator module comprises a plurality of electromagnetic driving regions, each electromagnetic driving region of the second stator module comprising a respective subset of the plurality of electrical conductors of the second stator module.

(141) 45. The robotic system of example 44 wherein the plurality of electromagnetic driving regions of the second stator module are in respective ones of a plurality of rows and respective ones of a plurality of columns of the plurality of electromagnetic driving regions of the second stator module.
(142) 46. The robotic system of example 44 wherein the plurality of electromagnetic driving regions of the second stator module are in a single row.
(143) 47. The robotic system of any one of examples 40 to 46 wherein the working surface of the second stator module has a width and a length equal to the width.
(144) 48. The robotic system of any one of examples 40 to 46 wherein the working surface of the second stator module has a width and a length greater than the width.
(145) 49. The robotic system of example 48 wherein the side of the working surface of the second stator module extends along the width of the working surface of the second stator module.
(146) 50. The robotic system of example 48 wherein the side of the working surface of the second stator module extends along the length of the working surface of the second stator module.
(147) 51. The robotic system of any one of examples 40 to 50 wherein, in the second stator module: at least some electrical conductors of the plurality of electrical conductors are in a first layer of electrical conductors of the plurality of electrical conductors extending in a first electrical conductor direction; at least some electrical conductors of the plurality of electrical conductors are in a second layer of electrical conductors of the plurality of electrical conductors separate from the first layer of electrical conductors extending in a second electrical conductor direction nonparallel to the first electrical conductor direction; and the at least some electrical conductors of the plurality of electrical conductors in the first layer at least partially overlap the at least some electrical conductors of the plurality of electrical conductors in the second layer in a direction orthogonal to the first and second electrical conductor directions.
(148) 52. The stator module of example 51, when directly or indirectly dependent from example 44, wherein, in the second stator module, each electromagnetic driving region of the plurality of electromagnetic driving regions comprises: a respective subset of the at least some electrical conductors of the plurality of electrical conductors in the first layer of electrical conductors; and a respective subset of the at least some electrical conductors of the plurality of electrical conductors in the second layer of electrical conductors.
(149) 53. The robotic system of any one of examples 38 to 52 wherein each stator module of the at least one stator module further comprises a respective position-sensor sub-module operable to sense a position of the mover.
(150) 54. The robotic system of any one of examples 33 to 53 further comprising the mover.
(151) 55. The robotic system of example 54 wherein the mover comprises a plurality of permanent magnets.
(152) 56. The robotic system of example 55 wherein: at least some of the plurality of permanent magnets are magnetized in a first magnetization direction; and at least some of the plurality of permanent magnets are magnetized in a second magnetization direction nonparallel to the first magnetization direction.
(153) 57. The robotic system of example 54, 55, or 56, when indirectly dependent from example 19, wherein the mover comprises at least one roller operable to roll on the at least one rail such that the at least one roller rolling on the at least one rail guides movement of the mover relative to the stator module along the length of the working surface.
(154) 58. The robotic system of example 54, 55, or 56, when indirectly dependent from example 19, wherein the mover comprises at least one slider operable to slide on the at least one rail such that the at least one roller rolling on the at least one rail guides movement of the mover relative to the stator module along the length of the working surface.
(155) 59. The robotic system of example 54, 55, or 56, when indirectly dependent from example 19, wherein the mover comprises at least one contact surface roller operable to contact the at least

one rail such that the at least one contact surface contacting the at least one rail guides movement of the mover relative to the stator module along the length of the working surface.
(156) 60. The robotic system of any one of examples 33 to 59 further comprising a control system operable to, at least, directly or indirectly control electrical current through each electrical conductor of the plurality of electrical conductors of each stator module of the at least one stator module to cause the mover to move relative to the at least one stator module.
(157) 61. The robotic system of example 60 wherein the control system is a control circuit.
(158) 62. The robotic system of example 60 or 61 wherein the control system is operable to, at least, directly or indirectly control electrical current through at least some electrical conductors of the plurality of electrical conductors of the first stator module to cause the mover to move in a longitudinal direction relative to the first stator module between the first and second ends of the first stator module.
(159) 63. The robotic system of example 60, 61, or 62 wherein each stator module of the at least one stator module further comprises at least one amplifier operable to amplify control signals generated at least partially based on at least one signal received from the control system to control each electrical conductor of the plurality of electrical conductors of each stator module of the at least one stator module to cause the mover to move relative to the at least one stator module.
(160) 64. The robotic system of any one of examples 33 to 63 wherein the stator body of each stator module of the at least one stator module is a unitary body supporting the plurality of electrical conductors of the stator module.
(161) 65. The robotic system of any one of examples 33 to 64 wherein each stator module of the at least one stator module comprises electrical circuitry common to the plurality of electrical conductors of the stator module and operable to control electrical current through each electrical conductor of the plurality of electrical conductors of the stator module.
(162) 66. The robotic system of example 65 wherein, in each stator module of the at least one stator module, the electrical circuitry is housed within the stator body.
(163) 67. The robotic system of any one of examples 33 to 66 wherein each stator module of the at least one stator module comprises a communication device operable to communicate data between the stator module and one or more other stator modules.
(164) 68. The robotic system of example 67 wherein, in each stator module of the at least one stator module, the communication device is housed within the stator body.
(165) Although specific embodiments have been described and illustrated, such embodiments should be considered illustrative only and not as limiting the invention as construed according to the accompanying claims.

Claims

1. A stator module comprising: a stator body; a working surface supported relative to the stator body; a motor sub-module comprising a plurality of electrical conductors, each electrical conductor of the plurality of electrical conductors extending along a respective portion of the working surface and operable to generate a magnetic field to facilitate moving, relative to the working surface, a magnetized mover in the magnetic field in response to electrical current through the electrical conductor; and a position-sensor sub-module comprising at least one position sensor operable to sense a position of the mover and defining a plurality of through-holes; wherein the stator body comprises a plurality of protrusions, each protrusion of the plurality of protrusions extending towards the motor sub-module and through a respective through-hole of the plurality of through-holes of the position-sensor sub-module and supporting the motor sub-module such that the protrusions transfer forces from the motor sub-module to a portion of the stator body on an opposite side of the position-sensor sub-module from the motor sub-module.
2. The stator module of claim 1 wherein the position-sensor sub-module comprises a position-

sensor body defining the plurality of through-holes and supporting the at least one position sensor.
3. The stator module of claim 2 wherein the position-sensor body is planar.
4. The stator module of claim 1 wherein the plurality of protrusions are spaced apart from each other in at least two dimensions.
5. The stator module of claim 1 wherein the plurality of protrusions are arranged in at least two rows.
6. The stator module of claim 1 wherein the plurality of protrusions are arranged in at least two columns.
7. The stator module of claim 1 wherein the plurality of protrusions are arranged in at least two rows and in at least two columns.
8. The stator module of claim 1 wherein the stator body comprises a surface, each protrusion of the plurality of protrusions extending from the surface towards the motor sub-module and through the respective through-hole of the plurality of through-holes of the position-sensor sub-module such that the protrusions transfer forces from the motor sub-module to the portion of the stator body on the opposite side of the position-sensor sub-module from the motor sub-module.
9. The stator module of claim 1 wherein the at least one position sensor comprises one or more position sensors on the opposite side of the position-sensor sub-module from the motor sub-module.
10. The stator module of claim 1 further comprising at least one guide positioned to guide movement of the mover relative to the stator module along the length of the working surface.
11. The stator module of claim 10 wherein: at least some electrical conductors of the plurality of electrical conductors are in a first layer of electrical conductors of the plurality of electrical conductors extending in a first electrical conductor direction; at least some electrical conductors of the plurality of electrical conductors are in a second layer of electrical conductors of the plurality of electrical conductors separate from the first layer of electrical conductors and extending in a second electrical conductor direction nonparallel to the first electrical conductor direction; the at least some electrical conductors of the plurality of electrical conductors in the first layer at least partially overlap the at least some electrical conductors of the plurality of electrical conductors in the second layer in a direction orthogonal to the first and second electrical conductor directions.
12. The stator module of claim 11 wherein at least a portion of the at least some electrical conductors of the plurality of electrical conductors in the first layer and at least a portion of the at least some electrical conductors of the plurality of electrical conductors in the second layer are non-overlapping in the direction orthogonal to the first and second electrical conductor directions.
13. The stator module of claim 11 wherein the at least one guide comprises at least two rails positioned to guide movement of the mover relative to the stator module along the length of the working surface.
14. A robotic system comprising: a first stator module according to claim 11; and a second stator module comprising: a stator body; a working surface supported relative to the stator body of the second stator module; and a plurality of electrical conductors, each electrical conductor of the plurality of electrical conductors of the second stator module extending along a respective portion of the working surface of the second stator module and operable to generate a magnetic field to facilitate moving, relative to the working surface of the second stator module, the magnetized mover in the magnetic field in response to electrical current through the electrical conductor; wherein the plurality of electrical conductors of the second stator module extend only in one electrical conductor direction.
15. A stator module comprising: a stator body; a working surface supported relative to the stator body; a plurality of electrical conductors, each electrical conductor of the plurality of electrical conductors extending along a respective portion of the working surface and operable to generate a magnetic field to facilitate moving, relative to the working surface, a magnetized mover in the magnetic field in response to electrical current through the electrical conductor; and at least one

guide positioned to guide movement of the mover relative to the stator module along the length of the working surface; at least some electrical conductors of the plurality of electrical conductors in a first layer of electrical conductors of the plurality of electrical conductors extending in a first electrical conductor direction; at least some electrical conductors of the plurality of electrical conductors in a second layer of electrical conductors of the plurality of electrical conductors separate from the first layer of electrical conductors and extending in a second electrical conductor direction nonparallel to the first electrical conductor direction; and the at least some electrical conductors of the plurality of electrical conductors in the first layer at least partially overlapping the at least some electrical conductors of the plurality of electrical conductors in the second layer in a direction orthogonal to the first and second electrical conductor directions.
16. The stator module of claim 15 wherein at least a portion of the at least some electrical conductors of the plurality of electrical conductors in the first layer and at least a portion of the at least some electrical conductors of the plurality of electrical conductors in the second layer are non-overlapping in the direction orthogonal to the first and second electrical conductor directions.
17. The stator module of claim 15 wherein the at least one guide comprises at least two rails positioned to guide movement of the mover relative to the stator module along the length of the working surface.
18. A robotic system comprising: the stator module of claim 17; and the mover; wherein the mover comprises at least one roller operable to roll on the at least one rail such that the at least one roller rolling on the at least one rail guides movement of the mover relative to the stator module along the length of the working surface.
19. A robotic system comprising: the stator module of claim 17; and the mover; wherein the mover comprises at least one slider operable to slide on the at least one rail such that the at least one roller rolling on the at least one rail guides movement of the mover relative to the stator module along the length of the working surface.
20. A robotic system comprising: the stator module of claim 17; and the mover; wherein the mover comprises at least one contact surface roller operable to contact the at least one rail such that the at least one contact surface contacting the at least one rail guides movement of the mover relative to the stator module along the length of the working surface.
21. A robotic system comprising: a first stator module according to claim 17; and a second stator module comprising: a stator body; a working surface supported relative to the stator body of the second stator module; and a plurality of electrical conductors, each electrical conductor of the plurality of electrical conductors of the second stator module extending along a respective portion of the working surface of the second stator module and operable to generate a magnetic field to facilitate moving, relative to the working surface of the second stator module, the magnetized mover in the magnetic field in response to electrical current through the electrical conductor; wherein the plurality of electrical conductors of the second stator module extend only in one electrical conductor direction.
22. A robotic system comprising: the stator module of claim 15; and a controller configured to control the plurality of electrical conductors to cause the mover to move relative to the working surface in at least three degrees of freedom.
23. The robotic system of claim 21 further comprising a controller configured to control, at least: the plurality of electrical conductors of the first stator to cause the mover to move relative to the working surface in at least three degrees of freedom; and the plurality of electrical conductors of the second stator to cause the mover to move relative to the working surface in no more than two degrees of freedom.