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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
24 September 2015 (24.09.2015)

WIPO | PCT

(10) International Publication Number
WO 2015/142390 A1

(51) International Patent Classification:
B64G 1/64 (2006.01)

(21) International Application Number:
PCT/US2014/066553

(22) International Filing Date:
20 November 2014 (20.11.2014)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
14/221,357 21 March 2014 (21.03.2014) US

(71) Applicant: **THE BOEING COMPANY** [US/US]; 100 North Riverside Plaza, Chicago, IL 60606-2016 (US).

(72) Inventors: **GHOFRANIAN, Siamak**; 100 North Riverside Plaza, Chicago, IL 60606 (US). **CHUANG, Li-Ping, Christopher**; 100 North Riverside Plaza, Chicago, IL 60606 (US). **MOTAGHEDI, Pejmun**; 100 North Riverside Plaza, Chicago, IL 60606 (US).

(74) Agents: **WOO, Euclid** et al.; The Boeing Company, 5301 Bolsa Avenue, MC H011-B171, Huntington Beach, CA 92647 (US).

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

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report (Art. 21(3))*

(54) Title: SPACECRAFT DOCKING SYSTEM

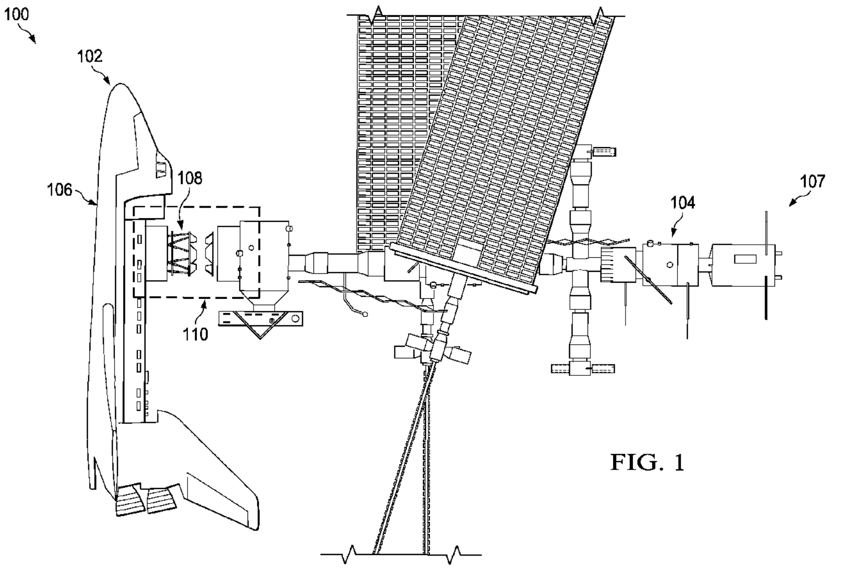


FIG. 1

(57) Abstract: A method and apparatus for docking a spacecraft. The apparatus comprises elongate members (300), movement systems (302, 504), and force management systems (304, 610). The elongate members are associated with a docking structure for a spacecraft. The movement systems are configured to move the elongate members axially such that the docking structure for the spacecraft moves. Each of the elongate members is configured to move independently. The force management systems connect the movement systems to the elongate members and are configured to limit a force applied by the each of the elongate members to a desired threshold during movement of the elongate members.

WO 2015/142390 A1

SPACECRAFT DOCKING SYSTEM

GOVERNMENT LICENSE RIGHTS

The disclosure described herein was made in the performance of work under NASA Contract No. NAS8-01099 and is subject to the provisions of Section 305 of the National Aeronautics and Space Act of 1958 (72 Stat. 435: 42 U.S.C. 2457). NASA has certain rights in this application.

BACKGROUND INFORMATION

1. Field:

The present disclosure relates generally to spacecraft and, in particular, to coupling systems for spacecraft. Still more particularly, the present disclosure relates to a method and apparatus for a spacecraft docking system.

2. Background:

Spacecraft coupling systems provide a way to mechanically connect two or more spacecraft to each other. A spacecraft, as used herein, is a vehicle, vessel, or machine configured to perform a number of operations in space. Spacecraft may be self-propelled space vehicles configured for short-term space missions, or spacecraft that are configured to remain in space for a longer period of time. In other cases, a spacecraft may be a space station, a satellite, or some other suitable structure.

Coupling two spacecraft may be desirable to transfer resources from one spacecraft to another spacecraft. For example, a space shuttle may dock at a space station to provide crew and supplies for the space station. In other examples, a space shuttle may dock with a satellite to perform maintenance and rework one or more of the components of the satellite.

In this illustrative example, the pair of spacecraft to be coupled includes an active vehicle and a target structure. The active vehicle is the spacecraft that is approaching the target structure. For instance, the active vehicle may be a spacecraft, while the target structure is a space station. The spacecraft approaches the space station for coupling. The coupling of two spacecraft may be referred to as docking or berthing.

With docking, the active vehicle maneuvers under its own propulsion to bring the two halves of the coupling system, one on the active vehicle, and one on the target structure, within the required vicinity of each other. With that requirement satisfied, the docking system is then used to couple the spacecraft together. The docking system is designed to tolerate initial misalignments between vehicles with the docking system providing the ability to still capture, align, and rigidly connect the active vehicle and target structure. In some cases, the active vehicle slows or stops its movement toward the target structure and extends the docking system outward to meet and align with the target structure.

Berthing, on the other hand, occurs when an externally attached device associated with one of the spacecraft is used to bring the active vehicle to within the required vicinity of the target structure. In some cases, this device is a robotic arm that attaches one spacecraft to the other spacecraft and guides the structures toward one another in preparation for coupling.

With the use of coupling systems for spacecraft, controllers are designed to articulate the coupling system in order for the active half of the coupling system to successfully capture the target structure, align the two, and prepare the two halves for establishment of a rigid connection. These controllers for spacecraft coupling systems, however, may be more complex than desired. For example, complex control laws may be needed to ensure that the active vehicle and the target structure engage in a desired manner. These systems also may be heavier than desired for the spacecraft.

Moreover, as the complexity of the control systems for coupling spacecraft increases, the possibility of failure of the coupling system increases due to the more numerous failure possibilities at the subsystem and component level. Therefore, it would be desirable to have a method and apparatus that take into account at least some of the issues discussed above, as well as other possible issues.

SUMMARY

In one illustrative embodiment, an apparatus comprises elongate members, movement systems, and force management systems. The elongate members are associated with a docking structure for a spacecraft. The movement systems are

configured to move the elongate members axially such that the docking structure for the spacecraft moves. Each of the elongate members moves independently. The force management systems connect the movement systems to the elongate members and are configured to limit a force applied by each of the elongate members to a desired threshold during movement of the elongate members.

In another illustrative embodiment, a method for docking a spacecraft is presented. Elongate members are moved axially such that a docking structure for the spacecraft moves. Each of the elongate members moves independently. A force is limited and applied by the each of the elongate members to a desired threshold during movement of the elongate members.

In yet another illustrative embodiment, a docking system for a spacecraft comprises a capture ring, elongate members associated with the capture ring, alignment features, motors, and force management systems connecting the motors to the elongate members. The alignment features are positioned along a mating surface of the capture ring and are configured to align the capture ring with a second structure. The motors are configured to move the elongate members axially such that the capture ring of the spacecraft moves with a number of degrees of freedom. Each of the elongate members moves independently. The force management systems are configured to limit a force applied by the each of the elongate members to a desired threshold during movement of the elongate members.

The features and functions can be achieved independently in various embodiments of the present disclosure or may be combined in yet other embodiments in which further details can be seen with reference to the following description and drawings.

Further, the disclosure comprises embodiments according to the following clauses:

Clause 1. A docking system for a spacecraft comprising:

a capture ring;

elongate members associated with the capture ring;

alignment features positioned along a mating surface of the capture ring and configured to align the capture ring with a second structure;

motors configured to move the elongate members axially such that the capture ring of the spacecraft moves with a number of degrees of freedom, wherein each of the elongate members moves independently; and

force management systems connecting the motors to the elongate members and configured to limit a force applied by the each of the elongate members to a desired threshold during movement of the elongate members.

Clause 2. The docking system of Clause 1, wherein the force management systems passively limit the force applied by the each of the elongate members in response to a load applied by the second structure, and wherein a force management system is configured to slip when the force reaches the desired threshold such that a corresponding elongate member moves from a first position to a second position.

Clause 3. The docking system of Clause 1, wherein the motors are configured to operate in a state selected from at least one of extension, attenuation, or retraction.

Clause 4. The docking system of Clause 1, wherein the force applied by the elongate members are limited based on a position of the capture ring relative to the second structure.

BRIEF DESCRIPTION OF THE DRAWINGS

The novel features believed characteristic of the illustrative embodiments are set forth in the appended claims. The illustrative embodiments, however, as well as a preferred mode of use, further objectives and features thereof, will best be understood by reference to the following detailed description of an illustrative embodiment of the present disclosure when read in conjunction with the accompanying drawings, wherein:

Figure 1 is an illustration of a docking environment for a spacecraft in accordance with an illustrative embodiment;

Figure 2 is an illustration of a block diagram of a docking environment for spacecraft in accordance with an illustrative embodiment;

Figure 3 is an illustration of a block diagram of a docking system for spacecraft in accordance with an illustrative embodiment;

Figure 4 is an illustration of a state diagram of changes between states of operation of a movement system in accordance with an illustrative embodiment;

Figure 5 is an illustration of a docking system for spacecraft in accordance with an illustrative embodiment;

Figure 6 is an illustration of an actuator assembly in accordance with an illustrative embodiment;

Figure 7 is an illustration of a docking system engaging with a second structure in accordance with an illustrative embodiment;

Figure 8 is another illustration of a docking system aligning with a second structure in accordance with an illustrative embodiment;

Figure 9 is another illustration of a docking system aligning with a second structure in accordance with an illustrative embodiment;

Figure 10 is yet another illustration of a docking system aligning with a second structure in accordance with an illustrative embodiment;

Figure 11 is still another illustration of a docking system aligning with a second structure in accordance with an illustrative embodiment;

Figure 12 is an illustration of a graph of a docking system in extension in accordance with an illustrative embodiment;

Figure 13 is an illustration of a graph of a docking system in attenuation mode in accordance with an illustrative embodiment;

Figure 14 is an illustration of a flowchart of a process for docking a spacecraft in accordance with an illustrative embodiment;

Figure 15 is another illustration of a flowchart of a process for docking a spacecraft in accordance with an illustrative embodiment;

Figure 16 is yet another illustration of a flowchart of a process for docking a spacecraft in accordance with an illustrative embodiment;

Figure 17 is an illustration of a spacecraft manufacturing and service method in the form of a block diagram in accordance with an illustrative embodiment; and

Figure 18 is an illustration of a spacecraft in the form of a block diagram in accordance with an illustrative embodiment.

DETAILED DESCRIPTION

The illustrative embodiments recognize and take into account one or more different considerations. For example, the illustrative embodiments recognize and take into account that it may be desirable to reduce the complexity of a docking system for a spacecraft. For example, some currently used docking systems for spacecraft use load sensor systems, complex control laws, and software applications to couple one spacecraft to another spacecraft. These systems are prone to complications and may not perform as desired.

The illustrative embodiments also recognize and take into account that reducing the weight of a spacecraft is desirable. For example, reducing the weight of the spacecraft allows a spacecraft to have an increased selection of launch vehicles, or can carry more payload in exchange. A reduction in weight for the spacecraft also may be desirable with respect to performing operations in space. Larger, heavier spacecraft may not maneuver as easily as desired.

The illustrative embodiments recognize and take into account, however, that using docking systems with complex controllers may involve increased hardware to support operations of the controller. This increased hardware may add more weight to the spacecraft than desired.

Thus, the illustrative embodiments provide a method and apparatus for docking a spacecraft. The illustrative embodiments provide a simplified method and docking system that is lighter than currently used docking systems for spacecraft.

In one illustrative example, the apparatus comprises elongate members, movement systems, and force management systems connecting the movement systems to the elongate members. The elongate members are associated with a docking structure for the spacecraft. The movement systems are configured to move the elongate members axially such that the docking structure for the spacecraft moves. Each of the elongate members moves independently of one another. The force management systems are configured to limit a force applied by each of the elongate members to a desired threshold during movement of the elongate members.

Referring now to the figures and, in particular, with reference to **Figure 1**, an illustration of a docking environment for spacecraft is depicted in accordance with an illustrative embodiment. In this illustrative example, docking environment **100** includes spacecraft **102** and structure **104**. Spacecraft **102** is configured to be coupled to structure **104** in this illustrative example.

As depicted, spacecraft **102** takes various forms. For example, without limitation, spacecraft **102** may be selected from one of a space vehicle, a space shuttle, a satellite, a space station, or some other suitable type of spacecraft. Structure **104** also may take the form of a space vehicle, a space shuttle, a space station, a satellite, or some other suitable structure. Structure **104** also may be a stationary structure in other illustrative examples. In this illustrative example, spacecraft **102** takes the form of space shuttle **106**, while structure **104** takes the form of space station **107**.

In this depicted example, docking system **108** is associated with spacecraft **102**. As used herein, when one component is “associated” with another component, the association is a physical connection in the depicted examples.

For example, a first component, such as docking system **108**, may be considered to be associated with a second component, such as spacecraft **102**, by being secured to the second component, bonded to the second component, mounted to the second component, welded to the second component, fastened to the second component, and/or connected to the second component in some other suitable manner. The first component also may be connected to the second component using a third component. Further, the first component may be considered to be associated with the second by being formed as part of the second component, an extension of the second component, or both.

Docking system **108** forms a mechanical assembly configured to couple two structures together. In particular, docking system **108** is configured to couple a first structure, space shuttle **106**, and a second structure, space station **107**.

In this illustrative example, docking system **108** is configured to extend from space shuttle **106** and interact with space station **107**. This interaction may be referred to as capture. Capture is the process used to initially couple space shuttle **106** to space station **107** in this illustrative example.

After capture is completed between space shuttle **106** and space station **107**, docking system **108** is commanded to align space station **107** and space shuttle **106**, followed by retraction of the active ring of docking system **108** to a desired position that supports the final, rigid connecting of docking system **108** to a docking ring in space station **107** to complete the docking process. Docking system **108** is shown in section **110** in this illustrative example.

Turning next to **Figure 2**, an illustration of a block diagram of a docking environment for spacecraft is depicted in accordance with an illustrative embodiment. Docking environment **100** in **Figure 1** is an example of one implementation for docking environment **200** shown in block form in this figure.

As depicted, docking environment **200** includes spacecraft **202** and structure **204**. Spacecraft **102** and structure **104** in **Figure 1** are examples of an implementation for spacecraft **202** and structure **204** shown in block form, respectively, in this figure.

Spacecraft **202** may take a number of different forms in this illustrative example. For instance, spacecraft **202** may take the form of a space vehicle, a space shuttle, a satellite, a space station, or some other suitable type of structure. In this depicted example, spacecraft **202** is an active vehicle. In other words, spacecraft **202** is moving in some manner in space. Spacecraft **202** may be moving relative to structure **204** in this illustrative example.

As depicted, spacecraft **202** is equipped with propulsion system **206**, landing system **208**, and docking system **210**. Propulsion system **206** is configured to accelerate spacecraft **202**. Propulsion system **206** may include at least one of rocket engines, electromagnetic propulsion elements, and other suitable types of mechanisms capable of moving spacecraft **202**.

As used herein, the phrase “at least one of,” when used with a list of items, means different combinations of one or more of the listed items may be used and only one of the items in the list may be needed. The item may be a particular object, thing, or category. In other words, “at least one of” means any combination of items or number of items may be used from the list, but not all of the items in the list may be required.

For example, “at least one of item A, item B, and item C” may mean item A; item A and item B; item B; item A, item B, and item C; or item B and item C. In some cases, “at least one of item A, item B, and item C” may mean, for example, without limitation, two of item A, one of item B, and ten of item C; four of item B and seven of item C; or some other suitable combination.

In this illustrative example, landing system **208** is configured to assist spacecraft **202** during landing on a desired surface. For example, landing system **208** may be designed to assist spacecraft **202** in landing on the moon. In other examples, landing system **208** includes components configured to protect spacecraft **202** as it re-enters Earth's atmosphere. Landing system **208** includes various components such as airbags, parachutes, landing gear, and other suitable types of components.

Docking system **210** is configured to couple spacecraft **202** to structure **204**. In particular, docking system **210** is configured to couple docking structure **212** of spacecraft **202** to structure **204**. In other words, docking structure **212** connects spacecraft **202** to structure **204**. Docking system **108** in **Figure 1** is an example of one implementation for docking system **210** shown in block form in this figure.

In this illustrative example, docking structure **212** may take a number of different forms. For example, without limitation, docking structure **212** is selected from one of a capture ring, a docking base, rods, and other suitable types of structures.

In this depicted example, docking structure **212** is capture ring **216**. Capture ring **216** is a circular structural component in this illustrative example. Capture ring **216** may be comprised of various types of materials such as, for example, without limitation, a metal, a metal alloy, or some other suitable type of material that provides a desired level of stiffness.

As depicted, capture ring **216** is an active ring in this illustrative example. In other words, capture ring **216** is configured to be moved relative to structure **204**. For instance, docking system **210** moves capture ring **216** toward structure **204** such that capture ring **216** engages with structure **204** in a desired manner.

As illustrated, structure **204** also may take a number of different forms. For instance, structure **204** may be selected from a docking ring, a space station, a satellite, and a spacecraft. In this depicted example, structure **204** is space station **214**.

Space station **214** is a spacecraft designed to remain in space for an extended period of time. Space station **214** may not include propulsion systems and landing systems in this illustrative example.

Space station **214** includes passive docking ring **218**. Similar to capture ring **216**, docking ring **218** is a circular structural component. Docking ring **218** is a passive structure in this illustrative example. In other words, docking ring **218** remains stationary and does not move during docking of spacecraft **202** to structure **204**.

As illustrated, capture ring **216** in spacecraft **202** is configured to connect to docking ring **218** in space station **214** to dock spacecraft **202**. The docking may be performed to exchange resources between spacecraft **202** and space station **214**. Capture ring **216** and docking ring **218** are rings of the same size and shape.

During docking, propulsion system **206** propels spacecraft **202** toward space station **214** for docking. As spacecraft **202** gets closer to space station **214**, propulsion system **206** slows down or stops. Docking system **210** with capture ring **216** then extends from spacecraft **202** and aligns with docking ring **218** in space station **214**. Capture ring **216** is aligned with docking ring **218** when the mating surface of the capture ring **216** is arranged within a desired distance and with a desired orientation relative to docking ring **218**.

When capture ring **216** is within desired distance **215** of docking ring **218** and has desired alignment **217**, docking ring **218** and capture ring **216** may be secured to one another to dock spacecraft **202** at space station **214**. Desired distance **215** is selected such that an attachment system may be activated to attach docking ring **218** to capture ring **216**. Desired alignment **217** is selected such that docking ring **218** and capture ring **216** have an alignment that prevents free motion between docking ring **218** and capture ring **216** when the attachment system is activated.

With reference next to **Figure 3**, an illustration of a block diagram of a docking system for spacecraft is depicted in accordance with an illustrative embodiment. Examples of components that may be used to implement docking system **210** from **Figure 2** are shown in this figure.

In addition to docking structure **212**, docking system **210** includes elongate members **300**, movement systems **302**, force management systems **304**, and attachment system **306**. As illustrated, elongate members **300** are structures associated with docking structure **212**.

Elongate members **300** may take various forms and may be comprised of various types of materials. For example, elongate members **300** may be selected from at least one of actuator arms, rods, attachments for ball screws, or other suitable types of elongate members. Further, elongate members **300** may be comprised of one or more materials selected from at least one of a metal, a metal alloy, a composite, or some other suitable type of material.

In this illustrative example, elongate members **300** may have a number of different shapes. For instance, elongate members may be cylindrical, hexagonal, octagonal, or have some other shape. In this depicted example, elongate members **300** includes elongate member **308**.

As illustrated, elongate members **300** are configured to move axially such that docking structure **212** moves. In this illustrative example, axial movement is movement along an axis extending centrally through each of elongate members **300**. For example, axial movement of elongate member **308** is movement along axis **312** extending centrally through elongate member **308**. In other words, elongate member **308** moves axially through movement along axis **312**.

In this illustrative example, elongate member **308** extends and retracts along axis **312**. Elongate members **300** may extend and retract in the x-plane, the y-plane, and the z-plane with the use of joints **307** between elongate members **300** and docking structure **212**. In one illustrative example, elongate members **300** are connected in a Stewart platform arrangement to capture ring **216**.

As illustrated, elongate members **300** are arranged around capture ring **216** and connected to the lower surface of capture ring **216** at joints **307**. Capture ring **216** moves as elongate members **300** move.

Joints **307** are universal joints in this illustrative example. Joints **307** include mechanical couplings that attach docking structure **212** to elongate members **300** such that when docking structure **212** and elongate members **300** are not in line with each other, freedom of movement still occurs.

As elongate members **300** move, docking structure **212** also moves. Accordingly, elongate members **300** and docking system **210** are configured to move in the x-direction, the y-direction, and the z-direction. In particular, elongate members **300** move docking structure **212** with number of degrees of freedom **314**. A “number of” items, as used herein, means one or more items. In this illustrative example, number of degrees of freedom **314** is one or more degrees of freedom.

In this illustrative example, number of degrees of freedom **314** refers to the ability of docking structure **212** to move in three-dimensional space. In this illustrative example, docking structure **212** moves with six degrees of freedom. In other words, docking structure **212** is capable of translational motion along the x-axis, y-axis, and z-axis, and rotational motion about the x-axis, y-axis, and z-axis.

In this depicted example, movement systems **302** are configured to move elongate members **300** axially such that docking structure **212** moves with number of degrees of freedom **314**. Movement systems **302** comprise motors **316**. In this illustrative example, motors **316** are operated by at least one of electric current, hydraulic fluid pressure, pneumatic pressure, or some other suitable source of energy.

In this depicted example, each motor in motors **316** corresponds to a different elongate member in elongate members **300**. Each motor in motors **316** moves one elongate member in elongate members **300**. For example, motor **318** in motors **316** corresponds to elongate member **308** in elongate members **300**. Accordingly, motor **318** is configured to move elongate member **308** axially.

As each elongate member in elongate members **300** is moved, docking structure **212** moves. For example, docking structure **212** may tilt, rotate, move along an axis, or some combination thereof as one or more of elongate members **300** move.

In this depicted example, each of elongate members **300** moves independently of one another using motors **316**. Put differently, each of elongate members **300** may be moved in a desired manner regardless of the movement of the other elongate members **300**. As a result, docking structure **212** may move with number of degrees of freedom **314**.

In this illustrative example, movement systems **302** are configured to operate in state **315** determined by state machine **313**. State **315** is a condition of docking system **210** in which docking system **210** operates in a desired manner. State **315** may be selected from at least one of extension, attenuation, retraction, or some other suitable state. Movement systems **302** operate in a different state **315** during different stages of docking.

For example, when state **315** is extension, motors **316** move elongate members **300** and docking structure **212** toward structure **204** in **Figure 2**. When state **315** is retraction, motors **316** move elongate members **300** and docking structure **212** toward spacecraft **202**, away from structure **204**. State **315** of docking system **210** is described in greater detail in **Figure 4**.

As illustrated, each of motors **316** is configured to operate such that elongate members **300** have rate of movement **327**. Rate of movement **327** is the speed at which a motor moves its corresponding elongate member. In this illustrative example, rate of movement **327** is commanded rate **328**. For example, each of motors **316** are configured to operate such that torque generated by motors **316** is translated to axial motion of elongate members **300** at commanded rate **328**.

Commanded rate **328** is a pre-determined rate in this illustrated example. In other words, commanded rate **328** does not dynamically change based on a control system for docking system **210**. Motors **316** extend elongate members **300** at commanded rate **328**, unless resistance is present to oppose extension.

Commanded rate **328** may be the same rate or a different rate for each of elongate members **300** in this illustrative example. For instance, each of motors **316** may be commanded to extend elongate members **300** at one-inch per second. In another illustrative example, motors **316** may be commanded to extend elongate members **300** at a slower or faster rate, depending on the particular implementation.

In this illustrative example, motor **318** moves elongate member **308** at commanded rate **328**. Commanded rate **328** does not change based on a control system. Instead, motor **318** is configured to reduce rate of movement **327** of elongate member **308** based on load **338** placed on elongate member **308** by docking ring **218** in **Figure 2** as capture ring **216** touches docking ring **218**. In this manner, rate of movement **327** slows as the size of load **338** increases.

As depicted, force management systems **304** connect movement systems **302** to elongate members **300**. Force management systems **304** are mechanical devices that provide for the transmission of power from one component to another component. The power transferred by force management systems **304** is torque generated by motors **316**.

Force management systems **304** may take a number of different forms. For example, without limitation, force management systems **304** may be selected from at least one of a slip clutch, a hydraulic clutch, an electromagnetic clutch, an electromagnetic motor, software, an electronic controller, or some other suitable type of device that can limit the force transmission.

Force management systems **304** correspond to motors **316** and elongate members **300**. In other words, one of force management systems **304**, motors **316**, and elongate members **300** form an operational component of docking system **210**. In this depicted example, the operational component of docking system **210** is actuator assembly **325**. Actuator assembly **325** may be a linear actuator in this illustrative example. Actuator assembly **325** includes elongate member **308**, motor **318**, force management system **320**, and other components (not shown in this view).

In this illustrative example, force management systems **304** transfer power from movement systems **302** to elongate members **300** to move elongate members **300** as desired. In transferring power from movement systems **302** to elongate members **300**, force management systems **304** limits force **342** applied by each of elongate members **300** to desired threshold **344** during movement of each of elongate members **300**. Force **342** is based on the torque supplied by each of motors **316**. Force **342** opposes load **338** applied by docking ring **218**.

As depicted, desired threshold **344** may be a maximum force for each of elongate members **300** to exert on docking ring **218** of space station **214** from **Figure 2**. Desired threshold **344** is a pre-determined value in this illustrative example. In an illustrative example, desired threshold **344** is ten pounds of force. In other illustrative examples, desired threshold **344** may be one pound of force, three pounds of force, twenty pounds of force, or some other suitable value.

In this depicted example, force management systems **304** include force management system **320**. Force management system **320** connects motor **318** to elongate member **308** and transfers power from motor **318** to elongate member **308** such that elongate member **308** moves. Force management system **320** limits force **342** applied by elongate member **308** to desired threshold **344** in this illustrative example.

As illustrated, force management system **320** is slip clutch **322**. Slip clutch **322** is a device that limits torque transmission, or “slips,” if it reaches a higher level of torque than it is designed to transmit. Slip clutch **322** is a passive device in this illustrative example. In other words, slip clutch **322** is a mechanical component that does not change its behavior in response to a signal sent by a control system.

Slip clutch **322** controls force **342** by controlling the torque of motor **318** in this illustrative example. Slip clutch **322** is configured to slip when force **342** reaches desired threshold **344** such that elongate member **308** moves from first position **346** to second position **348** while continuing to transmit force **342** at desired threshold **344**.

In this depicted example, first position **346** is a length of elongate member **308** when force **342** reaches desired threshold **344**. Second position **348** is a length of elongate member **308** after the slipping of slip clutch **322** occurs and force **342** has dropped below desired threshold **344**.

In this illustrative example, docking structure **212** comprises mating interface **332** and alignment features **336**. Mating interface **332** is the upper surface of capture ring **216** in this illustrative example. Mating interface **332** is a portion of capture ring **216** that engages with docking ring **218** of space station **214** in **Figure 2**.

As illustrated, alignment features **336** are structural components mounted to capture ring **216**. Alignment features **336** are arranged along capture ring **216**.

In this illustrative example, alignment features **336** may be comprised of various types of materials and have a number of different shapes. For instance, alignment features **336** may be comprised of a metal, a metal alloy, or other suitable types of materials and combinations of materials. Alignment features **336** may be triangular, rectangular, or have some other suitable shape. Alignment features **336** may be referred to as “petals” in some illustrative examples.

As depicted, alignment features **336** are configured to guide and align docking system **210** of spacecraft **202** with docking ring **218** in space station **214**. As spacecraft **202** and space station **214** meet, alignment features **336** position spacecraft **202** and space station **214** relative to one another.

In this illustrative example, attachment system **306** from **Figure 3** is configured to secure docking structure **212** to structure **204**. Attachment system **306** may include various components configured to attach docking structure **212** to structure **204**. For example, without limitation, attachment system **306** may include a latch, a lock, electromagnets, or some other device to maintain a connection between capture ring **216** and docking ring **218**.

In coupling spacecraft **202** with space station **214**, motors **316** move elongate members **300** axially such that capture ring **216** for spacecraft **202** moves. This movement occurs at commanded rate **328** for each actuator assembly in docking system **210**.

As docking system **210** extends in the direction of docking ring **218** in space station **214**, mating interface **332** of capture ring **216** engages with docking ring **218** at one or more points along capture ring **216**. Elongate members **330** and capture ring **216** apply force **342** to docking ring **218**.

In response, docking ring **218** applies load **338** to capture ring **216** at the points along capture ring **216** that have interfaced with docking ring **218**. For example, capture ring **216** may interface with docking ring **218** at a point near the joint of capture ring **216** and elongate member **308**.

As docking ring **218** applies load **338** to capture ring **216** at that point, the extension of elongate member **308** slows. The other elongate members **300** continue to move at commanded rate **328** until the elongate members **300** interface with various points along docking ring **218** and slow down as load **338** is applied to capture ring **216** by docking ring **218**. In other words, load **338** applied to capture ring **216** by docking ring **218** determines force **342** applied by elongate members **300** to capture ring **216**. In this manner, actuator assembly **325** operates independently of the other actuator assemblies in docking system **210**.

In this illustrative example, alignment features **336** align capture ring **216** with respect to docking ring **218**. As docking system **210** extends toward space station **214**, state **315** is extension.

When capture ring **216** and docking ring **218** are aligned in a desired manner, attachment system **306** secures capture ring **216** to docking ring **218**. State **315** for docking system **210** is captured at this point in time.

Once attachment system **306** is activated to secure capture ring **216** to docking ring **218**, state **315** changes to attenuation. During attenuation, force **342,** applied by each of elongate members **300,** is adjusted using force management systems **304**. In particular, settings for force management systems **304** are adjusted based on load **338**. For example, when force **342,** applied by elongate member **308** to docking ring **218,** reaches desired threshold **344**, slip clutch **322** limits the transmission of torque.

Load **338** at this point in time may be greater than force **342** applied by elongate member **308**. As a result, elongate member **308** can shorten from first position **346** to second position **348** while slip clutch **322** limits transmission force by elongate member **308**. The process continues in this manner until capture ring **216** and docking ring **218** no longer move relative to one another, within selected tolerances.

In this manner, force management systems **304** passively limit force **342** applied by each of elongate members **300** in response to load **338** applied by docking ring **218** of space station **214**. In other words, the control of docking system **210** is mechanical in this illustrative example and occurs without intervention from an electronic control system, control laws, or software applications in spacecraft **202**, space station **214**, or a combination thereof. As a result, docking of spacecraft **202** with space station **214** occurs without increasing the weight or complexity of spacecraft **202** with docking system **210**. Additionally, complications with docking system **210** and its mechanical components may be less likely to occur than with some currently used software-based systems.

The illustration of docking system **210** in **Figure 2** and **Figure 3** is not meant to imply physical or architectural limitations to the manner in which an illustrative embodiment may be implemented. Other components in addition to or in place of the ones illustrated may be used. Some components may be optional. Also, the blocks are presented to illustrate some functional components. One or more of these blocks may be combined, divided, or combined and divided into different blocks when implemented in an illustrative embodiment.

For example, docking ring **218** in space station **214** in **Figure 2** also may be an active structure. In this instance, both capture ring **216** and docking ring **218** may move relative to one another to align spacecraft **202** and space station **214** in a desired manner.

In other illustrative examples, docking structure **212** may take other forms other than capture ring **216**. For example, without limitation, docking structure **212** may be a rod configured to interface with a cone structure on space station **214**.

In still other illustrative examples, force management system **320** may be a program configured to control motor **318** in actuator assembly **325**. For example, torque transmitted by motor **318** may be limited by electronic circuitry instead of slip clutch **322**.

Turning now to **Figure 4**, an illustration of a state diagram of changes between states of operation of a movement system is depicted in accordance with an illustrative embodiment. In this depicted example, state machine **400** illustrates an example of one implementation of conditions for changes of state **315** of motors **316** in docking system **210** from **Figure 3**. State machine **400** is an example of an implementation of the state machine **313** in **Figure 3**.

In this illustrative example, state machine **400** has different states that may occur during the operation of motors **316**. For example, state machine **400** includes extension state **402**, attenuation state **406**, and retraction state **408**. In particular, these different states are examples of state **315** that may occur for motor **318**.

In extension state **402**, capture ring **216** starts from a ready-to-dock position, with capture ring **216** extending to align with docking ring **218**, as described with respect to **Figure 11**. Slip clutch **322** in **Figure 3** is set to a low slippage force in extension state **402**.

Alignment features **336** on capture ring **216** and alignment features on docking ring **218** align the two rings with respect to one another. Each of the actuator assemblies in docking system **210** adjusts its position independently to allow capture ring **216** to become aligned relative to docking ring **218**.

When the capture ring is aligned and within a desired distance from the docking ring, the attachment system is deployed. In this illustrative example, the desired distance may be three millimeters. The desired distance may be determined using a sensor system arranged along the docking ring, or in some other suitable manner, depending on the particular implementation.

In this illustrative example, attachment system **306** in docking system **210** engages with body latches on docking ring **218**. In some illustrative examples, attachment system **306** may include magnetic latches on capture ring **216**, docking ring **218**, or both.

In this depicted example, operation of motors **316** shift to attenuation state **406** after the attachment system engages the capture ring with the docking ring (event **412**). Slip clutch **322** switches to a higher slippage force in attenuation state **406**. In attenuation state **406**, free play exists between capture ring **216** and docking ring **218**. In this illustrative example, free play is five millimeters. Attenuation state **406** occurs automatically in response to the attachment system connecting capture ring **216** and docking ring **218**.

In attenuation state **406**, each of motors **316** behave in the manner described in **Figure 13**. As a result, forces applied by the actuator assemblies within docking system **210** cause relative motion between spacecraft **202** and space station **214** to be reduced or eliminated.

The operation of motors **316** may be changed to retraction state **408** in response to a number of conditions. For example, the operation of motors **316** is changed to retraction state **408** when it is no longer desired for the capture ring to be attached to the docking ring and attachment system disengages (event **416**).

In another illustrative example, the operation of motors **316** is changed to retraction state **408** when the docking system receives a command to begin hard docking (event **414**). In this instance, retraction state **408** is used to bring spacecraft **202** and space station **214** closer together such that a tunnel may be attached and pressurized. Thereafter, resources can be exchanged between spacecraft **202** and space station **214**. During retraction state **408**, the actuator assemblies retract towards a stowed position.

In some illustrative examples, motors **316** may operate in other states not shown in state machine **400**. For example, without limitation, motors may operate in an alignment state. In the alignment state, motors **316** are commanded to extend elongate members **300** to a common length, which could be the maximum length, or some other common length. In this state, the system is preparing for transition to retraction state **408**, which draws the two vehicles together along the axial direction, bringing them together in preparation for hard-docking, where a separate system pulls the two docking structures together firmly to create a rigid structural connection. In some examples, a pressurized connection is achieved.

The illustration of the different states in state machine **400** is not meant to limit the manner in which state machine **400** may be implemented. State machine **400** may include other states in addition to or in place of the ones depicted. For example, state machine **400** also may include a manual operation mode, extension to “ready-for-capture” mode, a position hold mode, and maybe others.

With reference next to **Figure 5**, an illustration of a docking system for spacecraft is depicted in accordance with an illustrative embodiment. In this depicted example, docking system **500** is an example of one implementation for docking system **210** shown in block form in **Figure 3**.

As depicted, docking system **500** comprises capture ring **502**, actuator assemblies **504**, and alignment features **508**. Actuator assemblies **504** are examples of implementations for actuator assembly **325** shown in block form in **Figure 3**. Actuator assemblies **504** are connected to capture ring **502** at joints **510**.

Actuator assemblies **504** are also connected to base plate **512** in this illustrative example. Base plate **512** is a stationary structure attached to a spacecraft. For example, base plate **512** may be a platform attached to spacecraft **102** to provide stability for docking system **108** in **Figure 1**. Although base plate **512** has a circular shape in this illustrative example, base plate **512** may have a different shape. In other examples, base plate **512** may be part of a skin panel of spacecraft **102**, instead of a separate platform as shown in this figure.

Actuator assemblies **504** are connected to base plate **512** at joints **514**. Joints **510** and joints **514** are universal joints in this illustrative example. As a result, capture ring **502** may move with six degrees of freedom.

In this illustrative example, alignment features **508** are positioned along mating interface **516** of capture ring **502** and configured to align capture ring **502** with a second structure, such as docking ring **218** from **Figure 2**. Alignment features **508** comprise three petals in this illustrative example. Other numbers of petals may be present in other illustrative examples.

Although not shown in this view, alignment features **508** may be arranged at an angle with respect to capture ring **502**. In other words, alignment features **508** may be angled inward in some illustrative examples. In other illustrative examples, alignment features **508** may have a different orientation, depending on the particular implementation. For example, one or more of alignment features may be tilted outward.

As depicted, actuator assemblies **504** comprise a number of housings **518**. Housings **518** are configured to protect the components within actuator assemblies **504**, including motors, clutches, gears, and other components. Housings **518** are comprised of metal in this illustrative example, but also may be comprised of a different type of material with desired structural properties for protecting the functional components of actuator assemblies **504**. Each of actuator assemblies **504** moves independently, as described above.

Turning next to **Figure 6**, an illustration of an actuator assembly is depicted in accordance with an illustrative embodiment. In this depicted example, actuator assembly **600** is one example of an implementation for actuator assembly **325** comprising elongate member **308**, motor **318**, and slip clutch **322** shown in block form in **Figure 3**. Actuator assembly **600** is also an example of a functional component used in docking system **500** shown in **Figure 5**. Actuator assembly **600** is an example of one implementation for an actuator assembly in actuator assemblies **504** in **Figure 5**.

As depicted, actuator assembly **600** includes motor **602**, brake **604**, gears **606**, ball screw **608**, slip clutch **610**, ball nut **611**, and sliding tube **613**. Actuator assembly **600** is a linear actuator in this illustrative example. In other words, actuator assembly **600** creates motion in a straight line along axis **612** that extends centrally through actuator assembly **600**. In other illustrative examples, actuator assembly **600** may be some other type of actuator, depending on the functionality involved.

In this depicted example, motor **602** is an example of one implementation for motor **318** in **Figure 3**. Motor **602** is configured to move ball nut **611** rotationally. As motor **602** applies torque, gears **606** turn to rotate ball nut **611**. Sliding tube **613** is attached to ball nut **611**. As ball nut **611** rotates about its axis, ball nut **611** moves in its axial direction since the grooves in ball screw **608** continuously provide helical form. As ball nut **611** moves axially, sliding tube **613** also moves. In other words, sliding tube **613** is configured to extend and retract based on power provided by motor **602**.

End **609** of sliding tube **613** may be attached directly to capture ring **502** from **Figure 5**. In other examples, ball screw **608** may be directly attached to capture ring **502**. In this illustrative example, brake **604** is a mechanical component configured to inhibit motion of actuator assembly **600**. The brake **604** is used to prevent motion of actuator assembly **600** when power to actuator assembly **600** is removed.

Slip clutch **610** is one example of an implementation for slip clutch **322** shown in block form in **Figure 3**. Slip clutch **610** connects motor **602** to ball screw **608** and is configured to limit a force applied by ball screw **608** to a desired threshold during movement of ball screw **608**.

Slip clutch **610** is configured to passively limit the force applied by ball screw **608** in response to a load applied by a second structure. Slip clutch **610** is configured to slip when the force reaches the desired threshold such that sliding tube **613** moves from a first position to a second position.

One or more of the components shown in actuator assembly **600** are positioned within housing **614**. Housing **614** is an example of one of housings **518** shown in docking system **500** in **Figure 5**. Housing **614** is shown in phantom in this figure. As illustrated, motor **602**, brake **604**, gears **606**, and slip clutch **610** are positioned within the interior of housing **614**.

The illustrations of docking system **500** in **Figure 5** and actuator assembly **600** in **Figure 6** are examples of a physical implementation of docking system **210** shown in block form in **Figure 2**. These illustrations are not meant to imply physical or architectural limitations to the manner in which an illustrative embodiment may be implemented. Other components in addition to or in place of the ones illustrated may be used. Some components may be optional.

The different components shown in **Figure 5** and **Figure 6** may be illustrative examples of how components shown in block form in **Figure 2** and **Figure 3** can be implemented as physical structures. Additionally, some of the components in **Figure 5** and **Figure 6** may be combined with components in **Figure 2** and **Figure 3**, used with components in **Figure 2** and **Figure 3**, or a combination of the two.

For instance, in some illustrative examples, ball screw **608** may be directly connected to capture ring **502** in **Figure 5**. In this case, sliding tube **613** is unnecessary. In other illustrative examples, ball nut **611** may apply a force directly to capture ring **502** to move capture ring **502** in a desired manner.

Referring now to **Figure 7**, an illustration of a docking system engaging with a second structure is depicted in accordance with an illustrative embodiment. In this depicted example, a more detailed illustration of section **110** from **Figure 1** is shown. Docking system **108** for space shuttle **106** is in position to engage with docking system **700** for space station **107** in this illustrative example. Docking system **700** does not move in this illustrative example. However, in other illustrative examples docking system **700** may move.

As illustrated, docking system **108** for space shuttle **106** includes capture ring **701**, base ring **703**, actuator assemblies **705**, alignment features **707**, and base plate **709**. In this illustrative example, base ring **703** is a structural component that provides a stopping point for retraction of capture ring **701**.

Docking system **700** for space station **107** includes docking ring **702**, alignment features **704**, and base plate **711**. Docking ring **702** is an example of one implementation for docking ring **218** shown in block form in **Figure 2**. Alignment features **704** guide docking ring **702** to interface with capture ring **701**. Alignment features **704** are arranged along docking ring **702** and are angled inward in this illustrative example.

In this depicted example, docking system **108** is shown in ready-to-dock position **706**. Ready-to-dock position **706** indicates that docking system **108** is extended such that alignment features **707** may engage with alignment features **704**. Docking system **108** aligns with docking system **700** using alignment features **707** and alignment features **704** as guides.

Figures 8-11 illustrate the movement of docking system **108** during various stages of docking. The process illustrated in **Figures 8-18** provides only one example of the manner in which an illustrative embodiment may be implemented.

Turning to **Figure 8**, another illustration of a docking system aligning with a second structure is depicted in accordance with an illustrative embodiment. In this illustrative example, docking system **108** is in the extension state. In other words, state **315** from **Figure 3** for docking system **108** is extension. During extension, the elongate members within actuator assemblies **705** in docking system **108** are extending toward docking ring **702**.

During extension, the elongate members extend at a commanded rate until capture ring **701** engages with docking ring **702**. Distance **800** is present between capture ring **701** and docking ring **702** in this illustrative example.

As shown in this view, capture ring **701** is not aligned with docking ring **702**. Accordingly, the position of capture ring **701** needs to be adjusted. Contact forces between components within docking system **108** and docking system **700** align capture ring **701** with docking ring **702**. In particular, alignment features **707** and alignment features **704** move capture ring **701** in line with docking ring **702**.

In **Figure 9**, another illustration of a docking system aligning with a second structure is depicted in accordance with an illustrative embodiment. In this depicted example, distance **800** is smaller than in **Figure 7**.

Alignment features **707** on capture ring **701** and alignment features **704** on docking ring **702** have further aligned the two structures in a desired manner. In this illustrative example, a portion of capture ring **701** will interface with docking ring **702** before the rest of capture ring **701**, in a clearly misaligned state. Capture ring **701** and docking ring **702** cannot properly attach if a misalignment is present. Therefore, docking system **108** will need adjustment to bring capture ring **701** into the desired aligned condition relative to docking ring **702**, for docking.

As illustrated, capture ring **701** first touches docking ring **702** at point **900**. When capture ring **701** touches docking ring **702**, a load is applied to capture ring **701** by docking ring **702**. The load causes the rate of extension of the corresponding elongate members in actuator assemblies **705** to slow.

In this illustrative example, elongate member **902** and elongate member **904** are closest to point **900**. Accordingly, the rate of extension for elongate member **902** and elongate member **904** will slow based on the resistance encountered from docking ring **702** to capture ring **701**. The other elongate members in docking system **108** continue to extend at the commanded rate until those elongate members encounter resistance.

If the resistance encountered by the elongate members is more than a specified limit, the elongate members will fail to extend further. Otherwise, the elongate members will continue to extend, but at a slower rate than the commanded rate.

With reference to **Figure 10**, yet another illustration of a docking system aligning with a second structure is depicted in accordance with an illustrative embodiment. In this illustrative example, elongate member **902** and elongate member **904** have been forced to retract based on the resistance encountered by capture ring **701** when touching docking ring **702** at point **900** in **Figure 9**.

As seen in this view, distance **800** between capture ring **701** and docking ring **702** is substantially uniform. This alignment allows capture ring **701** and docking ring **702** to interface in a desired manner such that substantially all of the mating surface of capture ring **701** is flush to the mating surface of docking ring **702**. Elongate members in actuator assemblies **705** continue to extend in order to completely remove the remaining misalignment of the two rings.

With reference to **Figure 11**, still another illustration of a docking system aligning with a second structure is depicted in accordance with an illustrative embodiment. In this depicted example, the mating surface of capture ring **701** has interfaced with the mating surface of docking ring **702**.

Capture ring **701** and docking ring **702** may now be secured to one another using an attachment system (not shown). The attachment system may be a latch system in this illustrative example. In response to the positive connection of the two rings using the attachment system, state **315** shown in block form in **Figure 3** changes to attenuation to eliminate remaining relative vehicle motion of space shuttle **106** relative to space station **107** using docking system **108**.

In **Figure 12**, an illustration of a graph of a docking system in extension is depicted in accordance with an illustrative embodiment. In this illustrative example, graph **1200** illustrates a force-velocity curve. Graph **1200** shows the behavior of an actuator assembly in docking system **108** in **Figure 7**. This behavior is present for each of the actuator assemblies in docking system **108** in **Figure 7**.

As depicted, graph **1200** has x-axis **1202** and y-axis **1203**. X-axis **1202** represents velocity of an actuator in docking system **108** in inches-per second, while y-axis **1203** represents the resistance encountered by the actuator in pounds. Velocity for each actuator assembly is pre-determined to be a commanded rate. The commanded rate is one inch-per-second in this illustrative example.

When the actuator assembly encounters zero resistance, the actuator assembly lengthens at the commanded rate, as shown at point **1204** in graph **1200**. The actuator also may have a resistance threshold in this illustrative example. The resistance threshold is the maximum amount of force the actuator assembly is permitted to apply, occurring when the actuator assembly is externally prevented from extending at all.

At point **1206** in graph **1200**, the actuator assembly is at the resistance threshold. Accordingly, velocity for the actuator assembly is zero. Line **1208** represents the behavior of the actuator assembly between point **1204** and point **1206** in graph **1200**.

If the resistance applied to the actuator assembly exceeds the resistance threshold, the velocity becomes negative. In other words, the actuator assembly will retract, or shorten, based on the amount of resistance encountered by the actuator. In this manner, each actuator assembly in docking system **108** behaves passively and independently during extension of docking system **108**.

Referring next to **Figure 13**, an illustration of a graph of a docking system in attenuation mode is depicted in accordance with an illustrative embodiment. In this illustrative example, graph **1300** illustrates the relative position of the actuator assembly based on the force applied to the clutch corresponding to the actuator. Graph **1300** shows the behavior of each actuator assembly in docking system **108** in **Figure 7**.

In this depicted example, graph **1300** has x-axis **1302** and y-axis **1304**. X-axis **1302** represents the relative position of the elongate member in the actuator assembly in inches. In other words, the length of the actuator assembly is shown along x-axis **1302**.

As illustrated, y-axis **1304** represents a clutch load in pounds. A clutch load threshold is identified as Fmax **1305** in this illustrative example. The clutch load threshold, Fmax **1305**, is the maximum amount of force that the clutch will withstand without slippage. Fmax **1305** is a pre-determined value in this illustrative example. When clutch load reaches Fmax **1305**, the clutch is configured to slip.

In this illustrative example, position **1306** represents the current length of the actuator assembly. Free play **1308** is the distance that the actuator assembly can lengthen or shorten due to mechanical free play in gears and joints, also commonly referred to as “backlash.”

In this depicted example, the actuator assembly resists leaving position **1306** once past the free play **1308**. As the clutch load increases, the position of the actuator assembly changes in response to the increasing load. Line **1310** and line **1312** are stiffness curves that show that there is a proportional displacement of an actuator assembly as a function of the compression or tension load applied. When the load reaches the slippage load, the actuator assembly will not resist with increasing load, but slip with a constant resistance.

When clutch load reaches Fmax **1305**, the clutch slips, while continuing to resist at a load of Fmax **1305,** and slippage occurs until the actuator no longer faces resistance by docking ring **702**. In this case, slippage is indicated by arrow **1307** in graph **1300**. As a result, clutch load decreases. Line **1314** represents one example of a decreasing clutch load. Position **1316** is a new position for the actuator assembly, representing the new lengthened state of the actuator assembly after slippage occurs. The actuator assembly now resists movement from position **1316** in the same manner as described above.

A similar result occurs in the opposite direction. When the clutch load reaches Fmin **1317**, slippage occurs until the clutch load magnitude is decreased. In this case, slippage is indicated by arrow **1309** in graph **1300**. Line **1318** represents one example of a decreasing clutch load magnitude. Position **1320** is a new position for the actuator assembly, representing the new shortened length of the actuator assembly after slippage occurs. The actuator assembly now resists movement from position **1320**.

The attenuation process, as described in this figure, will occur one or more times during the attenuation state until the clutch load no longer reaches either Fmax **1305** or Fmin **1317** and therefore, no slippage occurs. In this manner, docking system **108** is configured to attenuate forces and absorb remaining relative vehicle energy between space shuttle **106** and space station **107**. Each actuator assembly moves independently using the attenuation process described in this figure.

With reference now to **Figure 14**, an illustration of a flowchart of a process for docking a spacecraft is depicted in accordance with an illustrative embodiment. As depicted, the process described in **Figure 14** may be an example of a process implemented in docking environment **200** using docking system **210** in **Figure 2**. In particular, the process described in **Figure 14** is an example of the operations that may be performed during extension state **402** shown in state machine **400** in **Figure 4**.

The process begins by moving elongate members axially such that a docking structure for the spacecraft moves (operation **1400**). Next, the process determines whether the docking structure has contacted with a docking ring of a second structure at a point along the docking structure (operation **1402**). If the docking structure has contacted with the docking ring, the contact slows rate of the movement of the elongate members closest to the point along the docking structure in response to a load applied to the docking structure by the docking ring (operation **1404**). If the docking structure has not connected with the docking ring, the process returns to operation **1400**.

During operation **1400** and operation **1402**, each of elongate members **300** operate independently. In other words, while the rate of movement slows for some of elongate members **300**, others continue to move at commanded rate **328**.

Thereafter, the process aligns the docking structure with a docking ring using a group of alignment features (operation **1406**). A determination is then made as to whether the docking structure is within a desired distance of the docking ring (operation **1408**).

If the docking structure is within the desired distance of the docking ring, a determination is made as to whether the docking structure has a desired alignment with the docking ring (operation **1410**). If so, the process attaches the docking structure and the docking ring (operation **1412**) with the process terminating thereafter.

Returning to operation **1408**, if the docking structure is not within the desired distance of the docking ring, the process returns to operation **1400**, as described above. In a similar fashion with respect to operation **1410**, if the docking structure does not have a desired alignment with the docking ring, the process returns to operation **1400**.

Referring next to **Figure 15**, another illustration of a flowchart of a process for docking a spacecraft is depicted in accordance with an illustrative embodiment. As depicted, the process described in **Figure 15** may be an example of a process implemented in docking environment **200** using docking system **210** in **Figure 2**. In particular, the process described in **Figure 15** is an example of operations that may be performed during operation **1412** in **Figure 14**.

The process begins by receiving a command to deploy an attachment system (operation **1500**). Next, the process deploys the attachment system (operation **1502**). The process then connects the docking structure to the docking ring (operation **1504**). After the docking structure is connected to the docking ring, the process then enters the attenuation state (operation **1506**) with the process terminating thereafter.

Turning next to **Figure 16**, yet another illustration of a flowchart of a process for docking a spacecraft is depicted in accordance with an illustrative embodiment. As depicted, the process described in **Figure 16** may be an example of a process implemented in docking environment **200** using docking system **210** in **Figure 2**. In particular, the process described in **Figure 16** is an example of operations that may be performed during attenuation state **406** shown in state machine **400** in **Figure 4**.

The process begins by applying a force using the elongate members (operation **1600**). Each of elongate members **300** may apply force **342** independent of the other elongate members **300**.

Next, a determination is made as to whether the force has reached a desired threshold (operation **1602**). For example, a determination is made as to whether force **342** for each of elongate members **300** has reached desired threshold **344**.

If the force has reached a desired threshold, the process limits the force applied by each of the elongate members (operation **1604**). Limiting the force applied by each of elongate members **300** may be achieved using a slip clutch, as described above. If the force has not reached the desired threshold, the process returns to operation **1600**.

Thereafter, the process moves the elongate members from a first position to a second position (operation **1606**) with the process returning to operation **1600**. Attenuation state **406** will continue until docking structure **212** and docking ring **218** do not move relative to one another beyond selected tolerances. These selected tolerances may be free play **1308** as described in **Figure 13**.

After docking is complete, retraction state **408** of docking structure **212** may occur. Retraction state **408** of docking structure **212** may occur in response to a command to disengage attachment system **306**, or to bring space station **214** closer to spacecraft **202** such that a pressurized tunnel may be deployed to connect spacecraft **202** to space station **214**.

The flowcharts and block diagrams in the different depicted embodiments illustrate the architecture, functionality, and operation of some possible implementations of apparatuses and methods in an illustrative embodiment. In this regard, each block in the flowcharts or block diagrams may represent a module, a segment, a function, and/or a portion of an operation or step.

In some alternative implementations of an illustrative embodiment, the function or functions noted in the blocks may occur out of the order noted in the figures. For example, in some cases, two blocks shown in succession may be executed substantially concurrently, or the blocks may sometimes be performed in the reverse order, depending upon the functionality involved. Also, other blocks may be added in addition to the illustrated blocks in a flowchart or block diagram.

Illustrative embodiments of the disclosure may be described in the context of the spacecraft manufacturing and service method **1700** as shown in **Figure 17** and spacecraft **1800** as shown in **Figure 18**. Turning first to **Figure 17**, an illustration of a spacecraft manufacturing and service method is depicted in the form of a block diagram in accordance with an illustrative embodiment. Docking system **210** and components within docking system **210** may be fabricated and installed during various stages of spacecraft manufacturing and service method **1700**. These modifications may be made on the ground or, in some cases, in space.

During pre-production, spacecraft manufacturing and service method **1700** may include specification and design **1702** of spacecraft **1800** in **Figure 18** and material procurement **1704**. During production, component and subassembly manufacturing **1706** and system integration **1708** of spacecraft **1800** in **Figure 18** takes place.

Thereafter, spacecraft **1800** in **Figure 18** may go through certification **1710** in order to be placed in service **1712**. Certification **1710** may include meeting customer requirements, industry requirements, governmental requirements, or some combination thereof. While in service by a customer, spacecraft **1800** in **Figure 18** is scheduled for routine maintenance and service **1714,** which may include modification, reconfiguration, refurbishment, and other maintenance or service.

Each of the processes of spacecraft manufacturing and service method **1700** may be performed or carried out by a system integrator, a third party, and/or an operator. In these examples, the operator may be a customer. For the purposes of this description, a system integrator may include, without limitation, any number of spacecraft manufacturers and major-system subcontractors; a third party may include, without limitation, any number of vendors, subcontractors, and suppliers; and an operator may be company, a military entity, a service organization, and so on.

With reference now to **Figure 18**, an illustration of a spacecraft is depicted in the form of a block diagram in which an illustrative embodiment may be implemented. In this illustrative example, spacecraft **1800** is produced by spacecraft manufacturing and service method **1700** in **Figure 17**. Spacecraft **1800** may include frame **1802** with a plurality of systems **1804** and interior **1806**.

Examples of plurality of systems **1804** include one or more of propulsion system **1808**, electrical system **1810**, hydraulic system **1812**, environmental system **1814**, and thermal protection system **1816**. Although an aerospace example is shown, different illustrative embodiments may be applied to other industries, such as the aircraft industry, the automotive industry, the ship industry, and/or other suitable industries.

Apparatus and methods embodied herein may be employed during at least one of the stages of spacecraft manufacturing and service method **1700** in **Figure 17**. In particular, docking system **210** from **Figure 2** may be installed during any one of the stages of spacecraft manufacturing and service method **1700.** For example, without limitation, docking system **210** from **Figure 2** may be installed in spacecraft **1800** during at least one of component and subassembly manufacturing **1706,** system integration **1708,** routine maintenance and service **1714**, or some other stage of spacecraft manufacturing and service method **1700**.

In one illustrative example, components or subassemblies produced in component and subassembly manufacturing **1706** in **Figure 17** may be fabricated or manufactured in a manner similar to components or subassemblies produced while spacecraft **1800** is in service **1712** in **Figure 17**.

As yet another example, a number of apparatus embodiments, method embodiments, or a combination thereof may be utilized during production stages, such as component and subassembly manufacturing **1706** and system integration **1708** in **Figure 17.**

A number of apparatus embodiments, method embodiments, or a combination thereof may be utilized while spacecraft **1800** is in service **1712** and/or during maintenance and service **1714** in **Figure 17**. The use of a number of the different illustrative embodiments may substantially expedite the assembly of and/or reduce the cost of spacecraft **1800**.

Thus, the illustrative embodiments provide a method and apparatus for docking spacecraft **202**. The apparatus comprises elongate members **300**, movement systems **302**, and force management systems **304** connecting movement systems **302** to elongate members **300**. Elongate members **300** are associated with docking structure **212** for spacecraft **202**. Movement systems **302** are configured to move elongate members **300** axially such that docking structure **212** for spacecraft **202** moves. Each of elongate members **300** moves independently of one another. Force management systems **304** are configured to limit force **342** applied by each of elongate members **300** to desired threshold **344** during movement of elongate members **300**.

With the use of docking system **210**, complex control laws, load sensors, or software are not needed dock spacecraft **202** to a second structure. Instead, docking system **210** simplifies the process, as the attenuation of forces occurs in a passive manner, without a closed-loop control system. As a result, less hardware is needed for docking system **210** and therefore, docking system **210** is lighter and less complex than some currently used docking systems.

In addition, docking system **210** operates using a simplified system with mechanical components, which have less probability of undesired results in space. Accordingly, docking system **210** may be more reliable than other docking systems.

The description of the different illustrative embodiments has been presented for purposes of illustration and description, and is not intended to be exhaustive or limited to the embodiments in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art. Further, different illustrative embodiments may provide different features as compared to other desirable embodiments. The embodiment or embodiments selected are chosen and described in order to best explain the principles of the embodiments, the practical application, and to enable others of ordinary skill in the art to understand the disclosure for various embodiments with various modifications as are suited to the particular use contemplated.

CLAIMS:

What is claimed is:

1. An apparatus comprising:
elongate members associated with a docking structure for a spacecraft;
movement systems configured to move the elongate members axially such that the docking structure for the spacecraft moves, wherein each of the elongate members moves independently; and
force management systems connecting the movement systems to the elongate members and configured to limit a force applied by the each of the elongate members to a desired threshold during movement of the elongate members.

2. The apparatus of claim 1, wherein the docking structure connects the spacecraft to a second structure selected from one of a docking ring, a space station, a satellite, and a spacecraft.

3. The apparatus of claim 2, wherein the force management systems passively limit the force applied by the each of the elongate members in response to a load applied by the second structure.

4. The apparatus of claims 2-3 further comprising:
an attachment system configured to secure the docking structure to the second structure.

5. The apparatus of any preceding claim, wherein the docking structure is selected from one of a capture ring and a rod.

6. The apparatus of any preceding claim, wherein the elongate members move the docking structure with a number of degrees of freedom.

7. The apparatus of any preceding claim, wherein the movement systems are configured to operate in a state selected from at least one of extension, attenuation, or retraction.

8. The apparatus of any preceding claim, wherein the docking structure comprises a mating interface and a group of alignment features.

9. The apparatus of any preceding claim, wherein the force management systems each comprise at least one of a slip clutch, a hydraulic clutch, an electromagnetic clutch, an electromagnetic motor, software, or an electronic controller.

10. The apparatus of any preceding claim, wherein the movement systems each comprise a motor configured to move a corresponding elongate member at a commanded rate.

11. The apparatus of claim 10, wherein the motor is configured to reduce a rate of movement of the corresponding elongate member based on a load placed on the corresponding elongate member.

12. The apparatus of claims 10-11, wherein a force management system in the force management systems comprises a slip clutch configured to slip when the force reaches the desired threshold such that the corresponding elongate member moves from a first position to a second position.

13. A method for docking a spacecraft, the method comprising:

moving elongate members axially such that a docking structure for the spacecraft moves, wherein each of the elongate members moves independently; and

limiting a force applied by the each of the elongate members to a desired threshold during movement of the elongate members.

14. The method of claim 13 further comprising:

connecting the docking structure to a second structure using an attachment system.

15. The method of claims 13-14, wherein limiting the force comprises:
passively limiting the force applied by the each of the elongate members in response to a load applied by a second structure.

16. The method of claims 13-15 further comprising:
reducing a rate of movement of a motor based on a load placed on a corresponding elongate member.

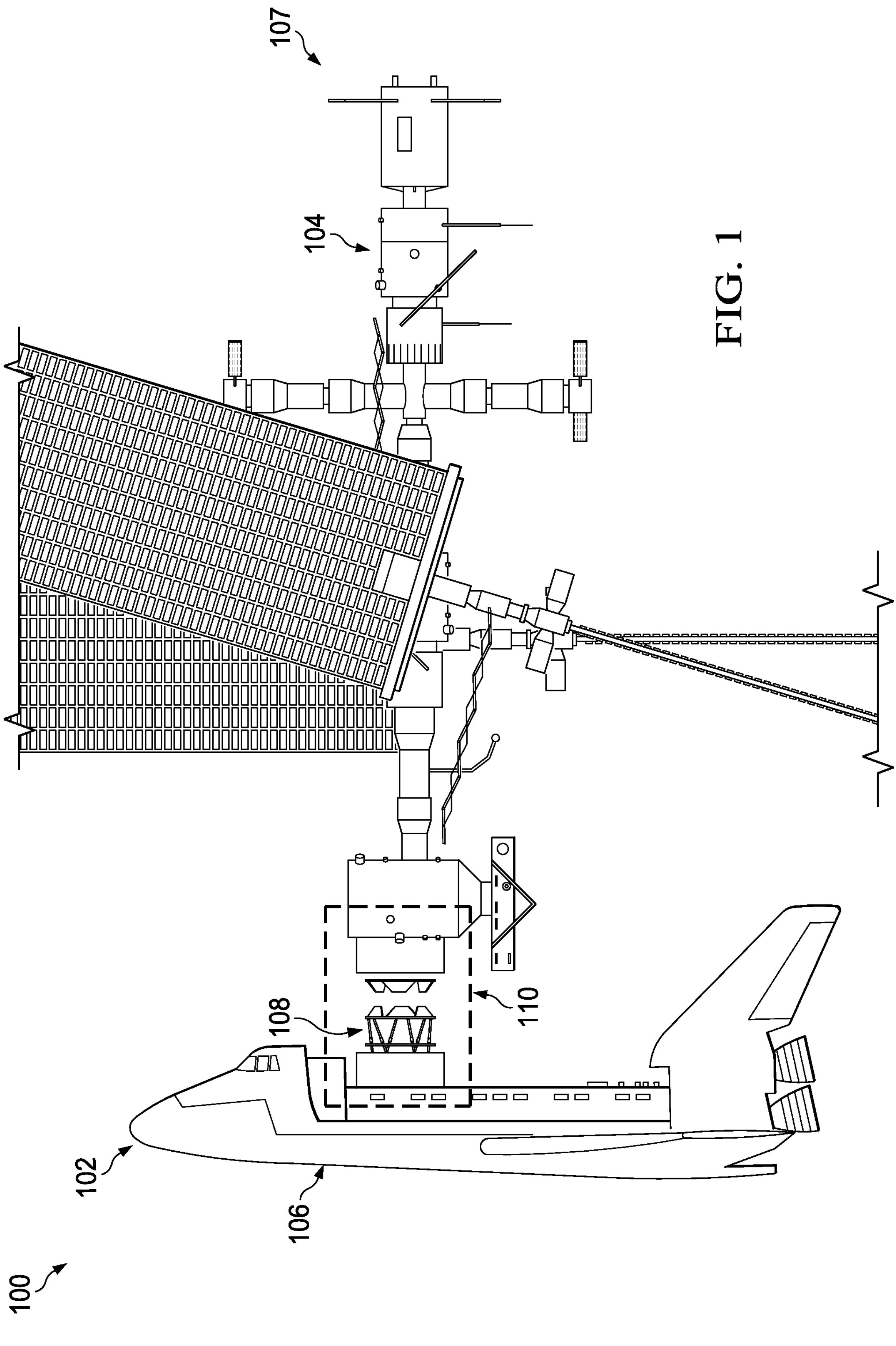


FIG. 1

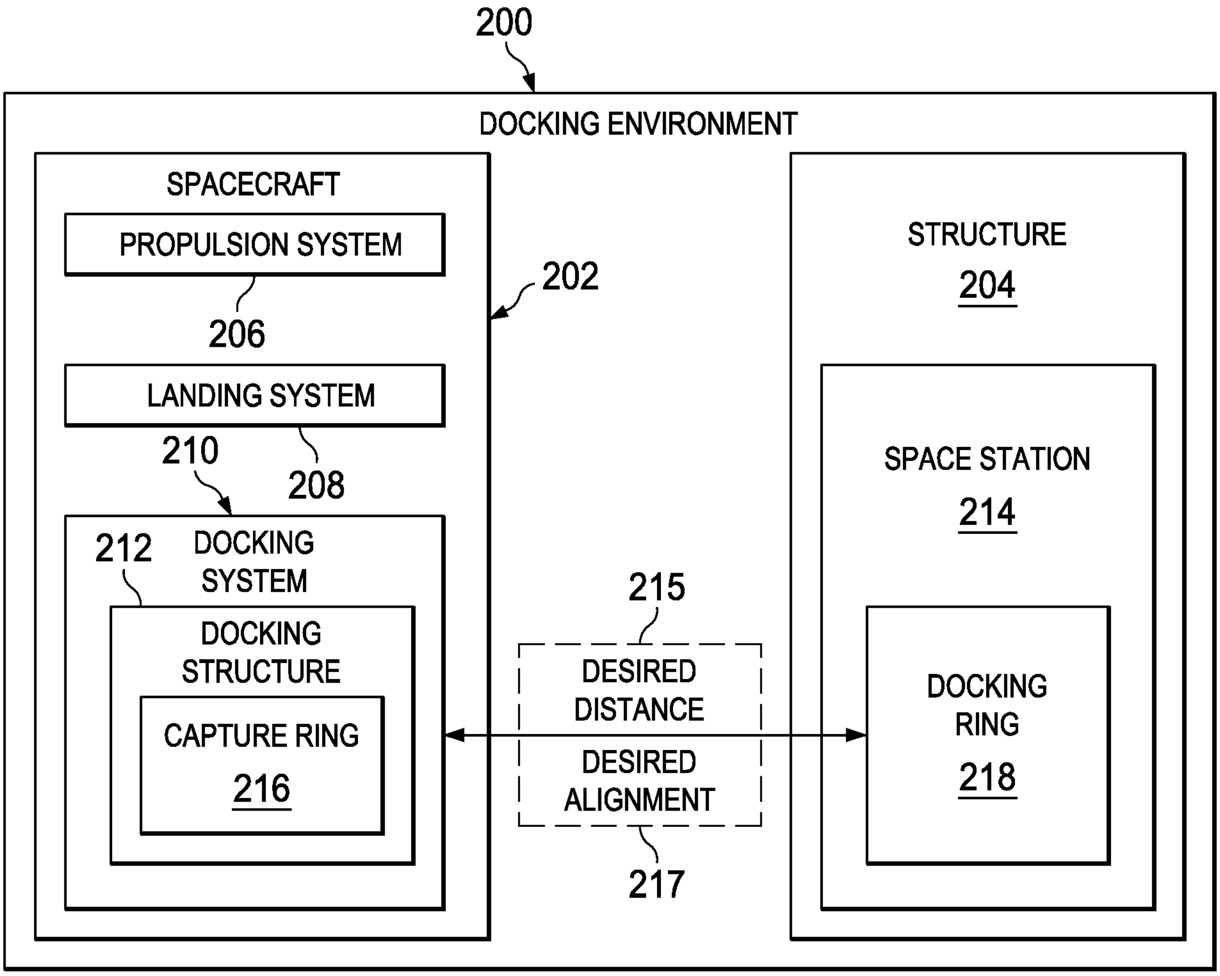
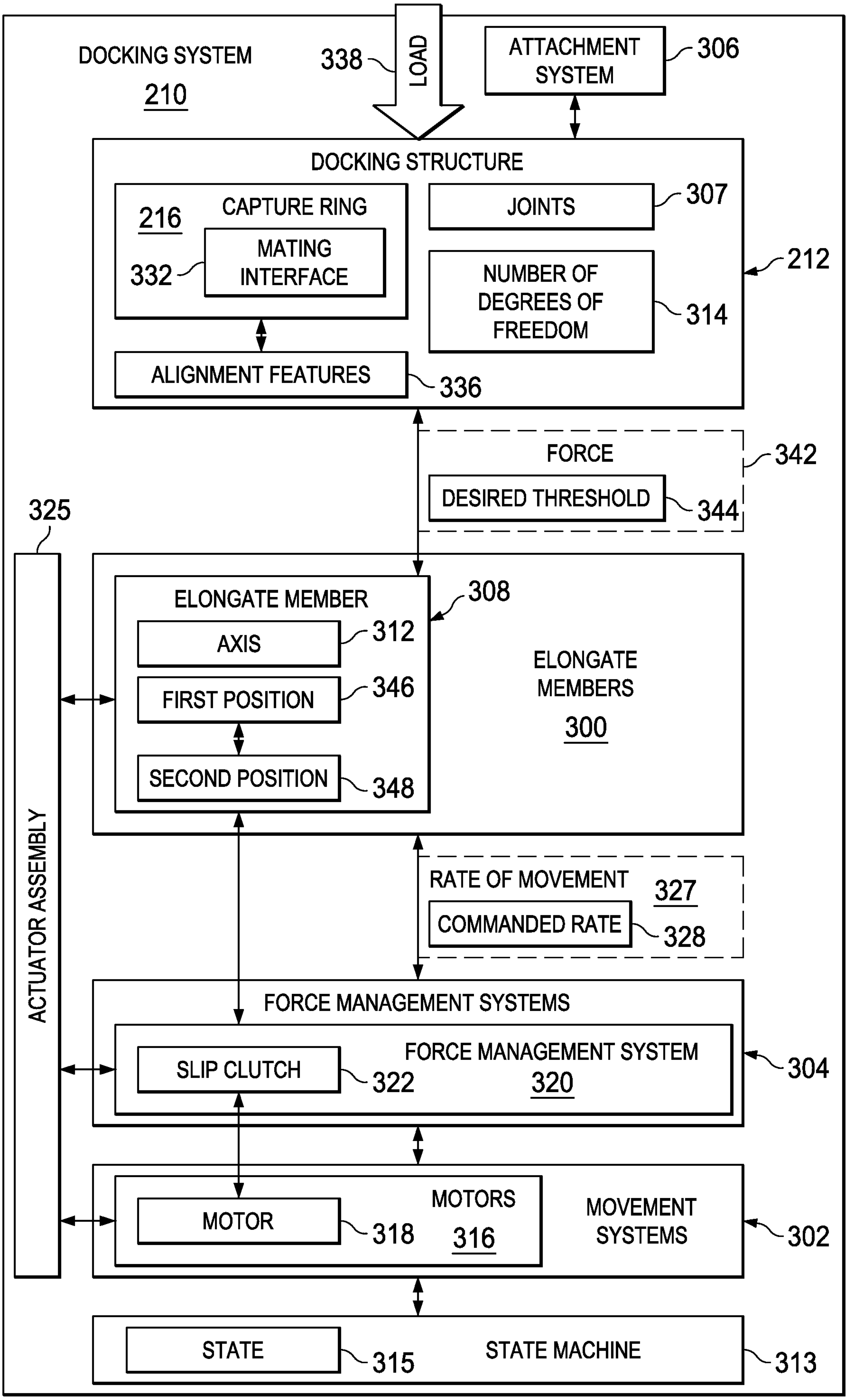

200
DOCKING ENVIRONMENT
SPACECRAFT
PROPULSION SYSTEM
202
206
LANDING SYSTEM
210
208
212
DOCKING SYSTEM
DOCKING STRUCTURE
CAPTURE RING
216
STRUCTURE
204
SPACE STATION
214
215
DESIRED DISTANCE
DESIRED ALIGNMENT
217
DOCKING RING
218

FIG. 2

FIG. 3


DOCKING SYSTEM
210
338
LOAD
ATTACHMENT SYSTEM
306
DOCKING STRUCTURE
216
CAPTURE RING
MATING INTERFACE
332
JOINTS
307
NUMBER OF DEGREES OF FREEDOM
314
212
ALIGNMENT FEATURES
336
FORCE
DESIRED THRESHOLD
342
344
325
ELONGATE MEMBER
308
AXIS
312
FIRST POSITION
346
SECOND POSITION
348
ELONGATE MEMBERS
300
ACTUATOR ASSEMBLY
RATE OF MOVEMENT
327
COMMANDED RATE
328
FORCE MANAGEMENT SYSTEMS
SLIP CLUTCH
322
FORCE MANAGEMENT SYSTEM
320
304
MOTOR
318
MOTORS
316
MOVEMENT SYSTEMS
302
STATE
315
STATE MACHINE
313

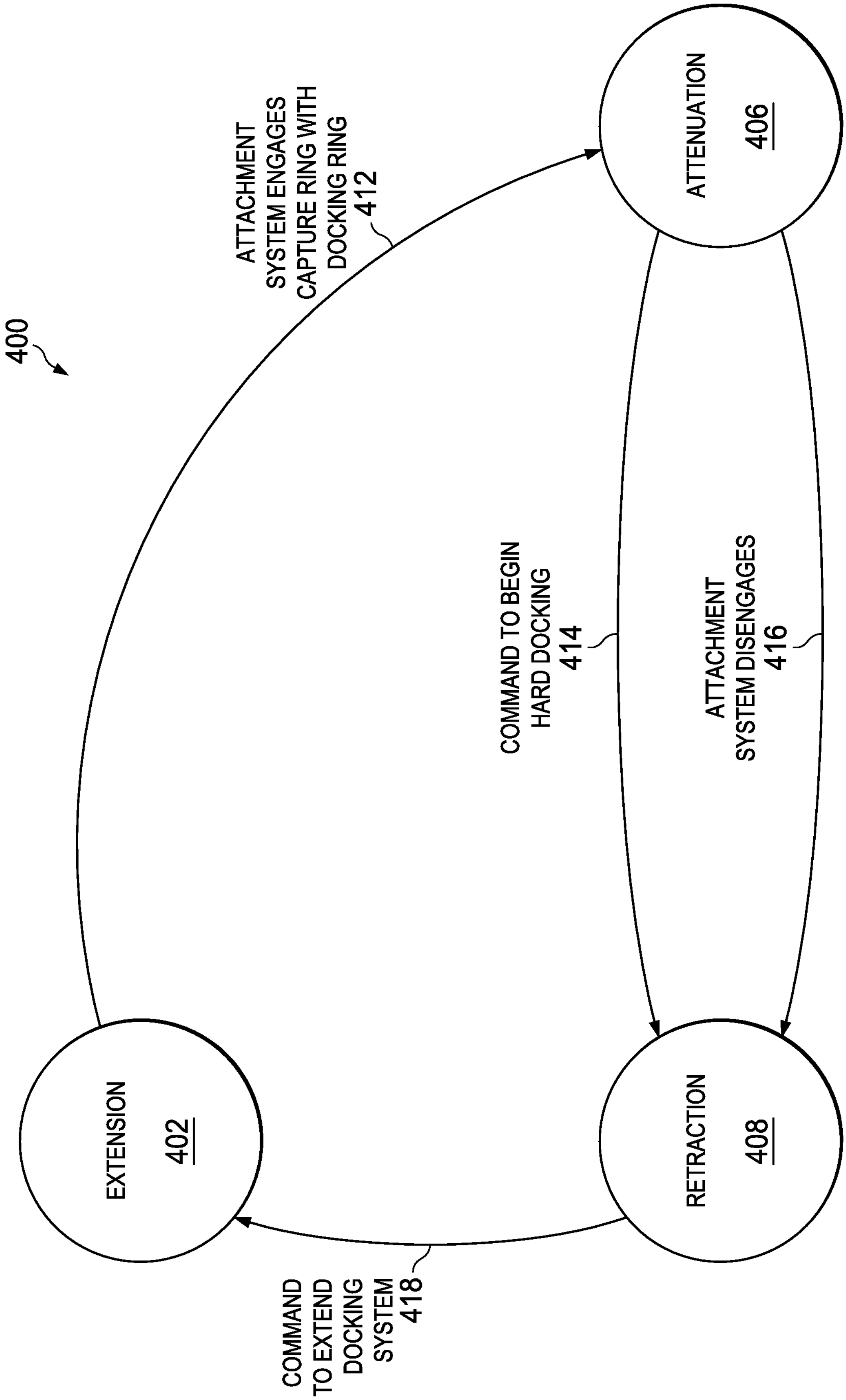

400
EXTENSION
402
ATTACHMENT SYSTEM ENGAGES CAPTURE RING WITH DOCKING RING
412
ATTENUATION
406
COMMAND TO BEGIN HARD DOCKING
414
ATTACHMENT SYSTEM DISENGAGES
416
RETRACTION
408
COMMAND TO EXTEND DOCKING SYSTEM
418

FIG. 4

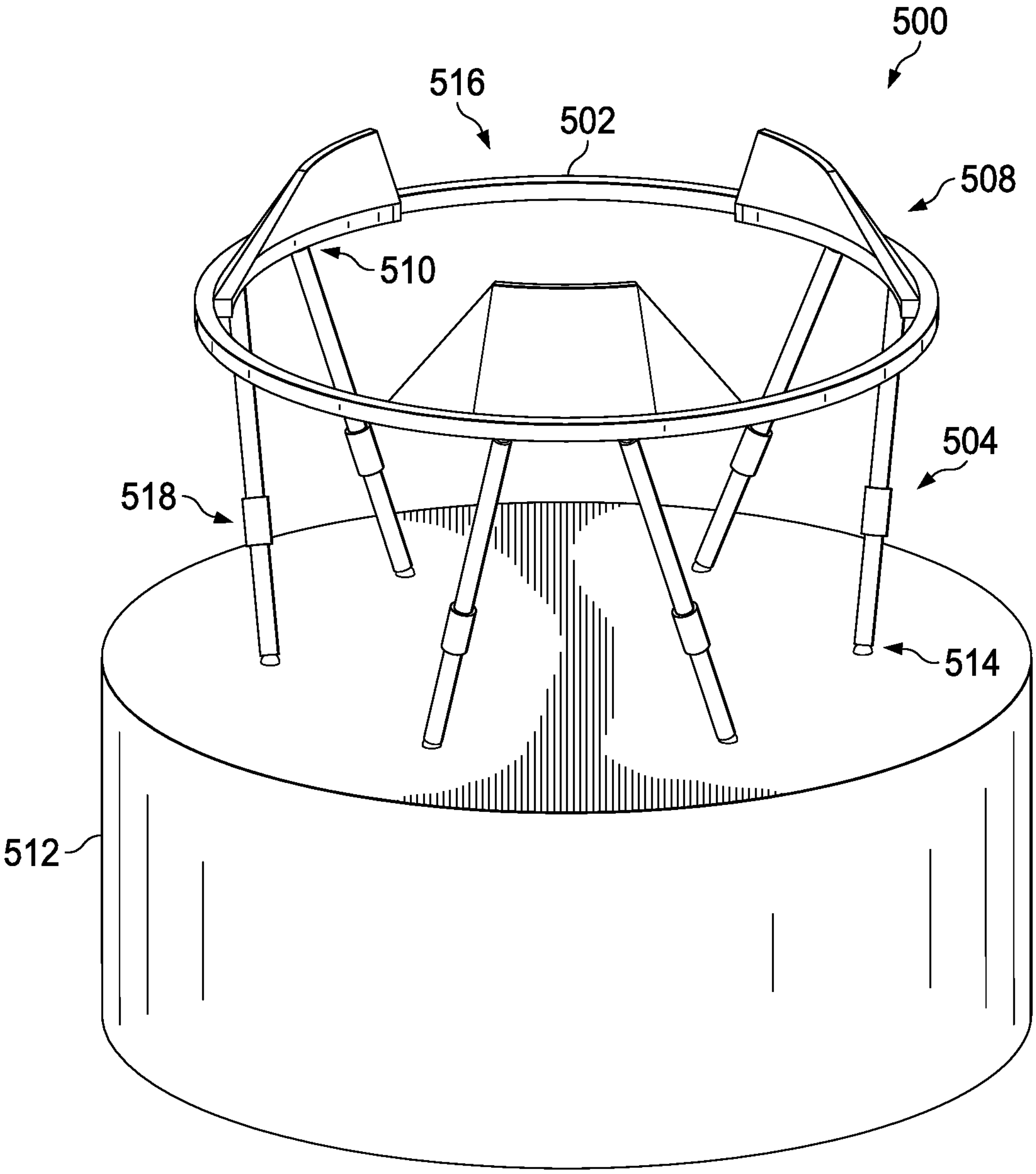


FIG. 5

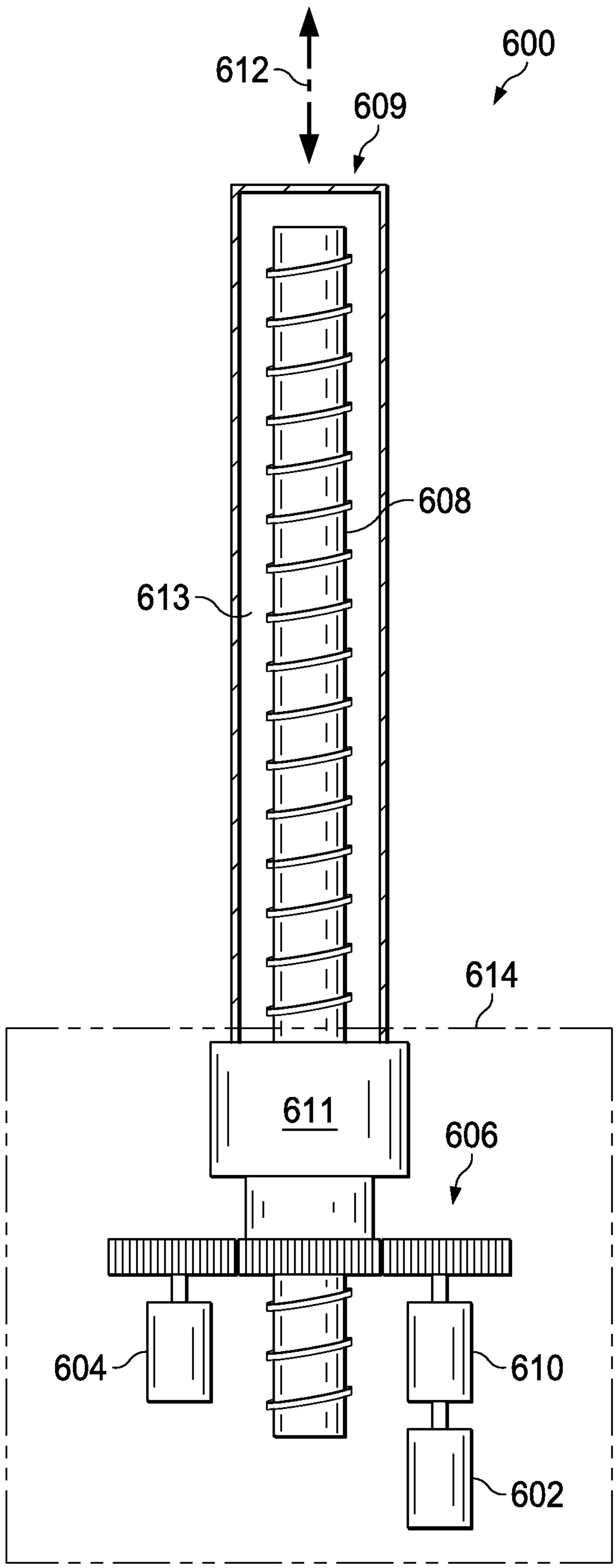


FIG. 6

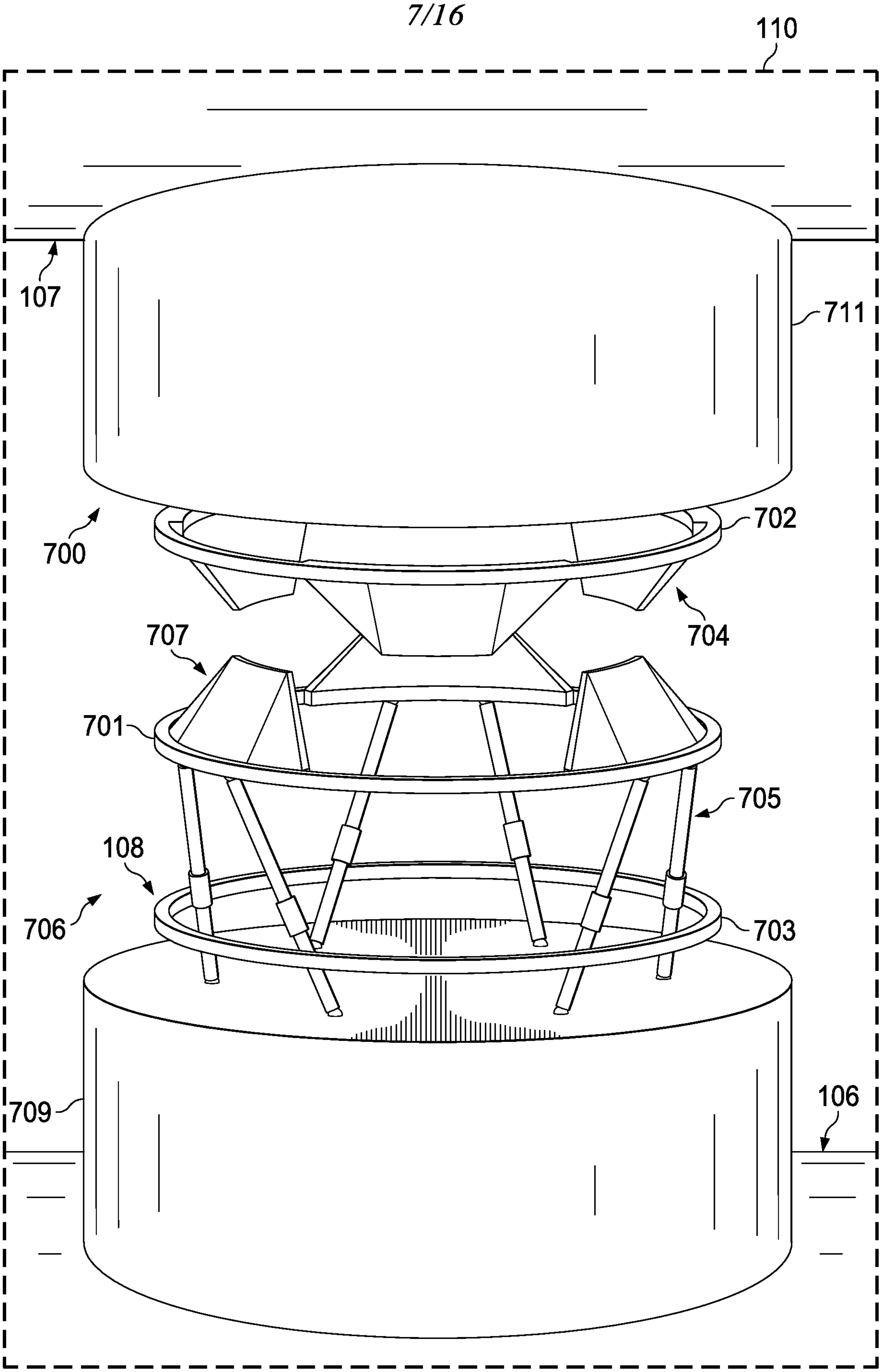


FIG. 7

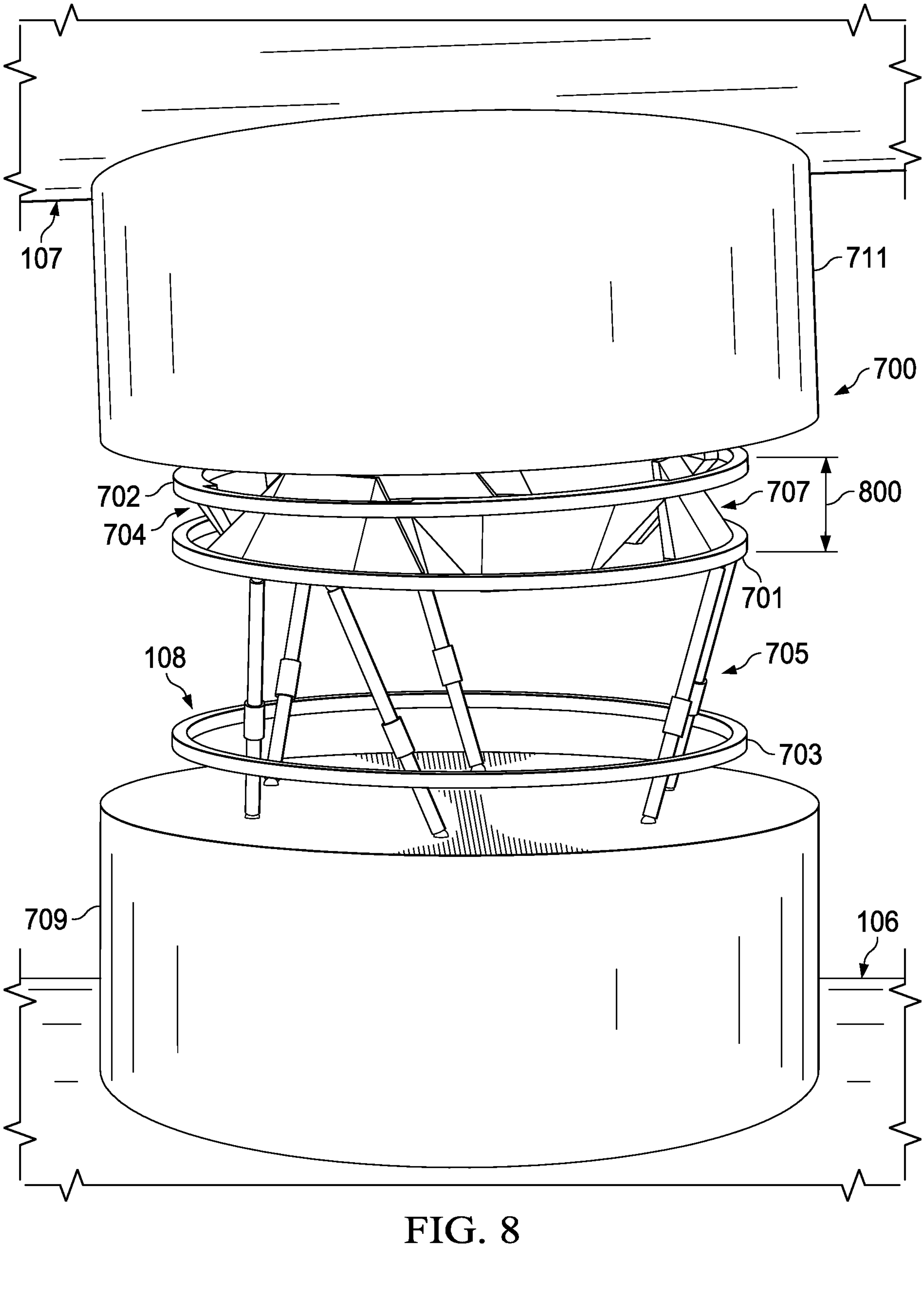


FIG. 8

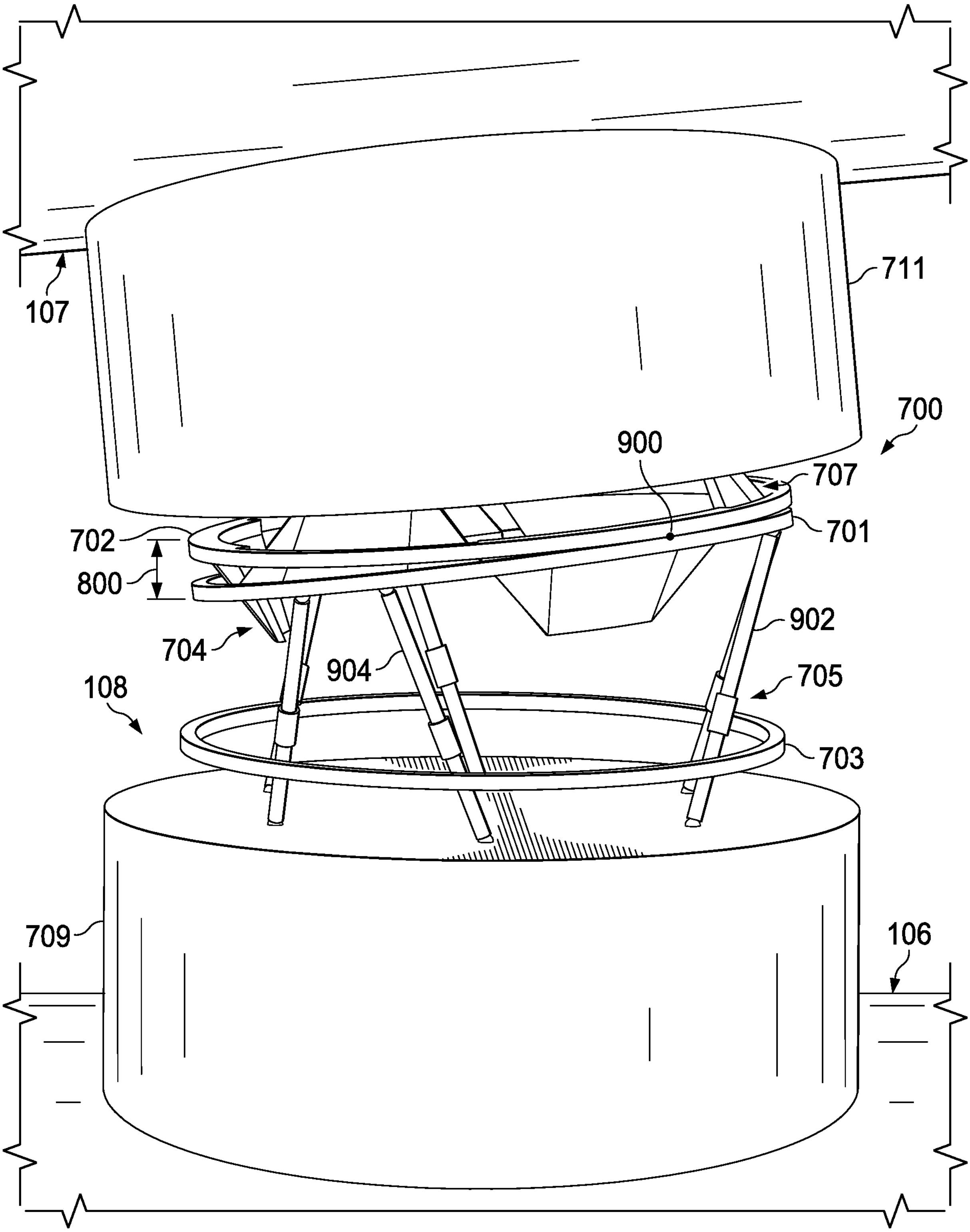


FIG. 9

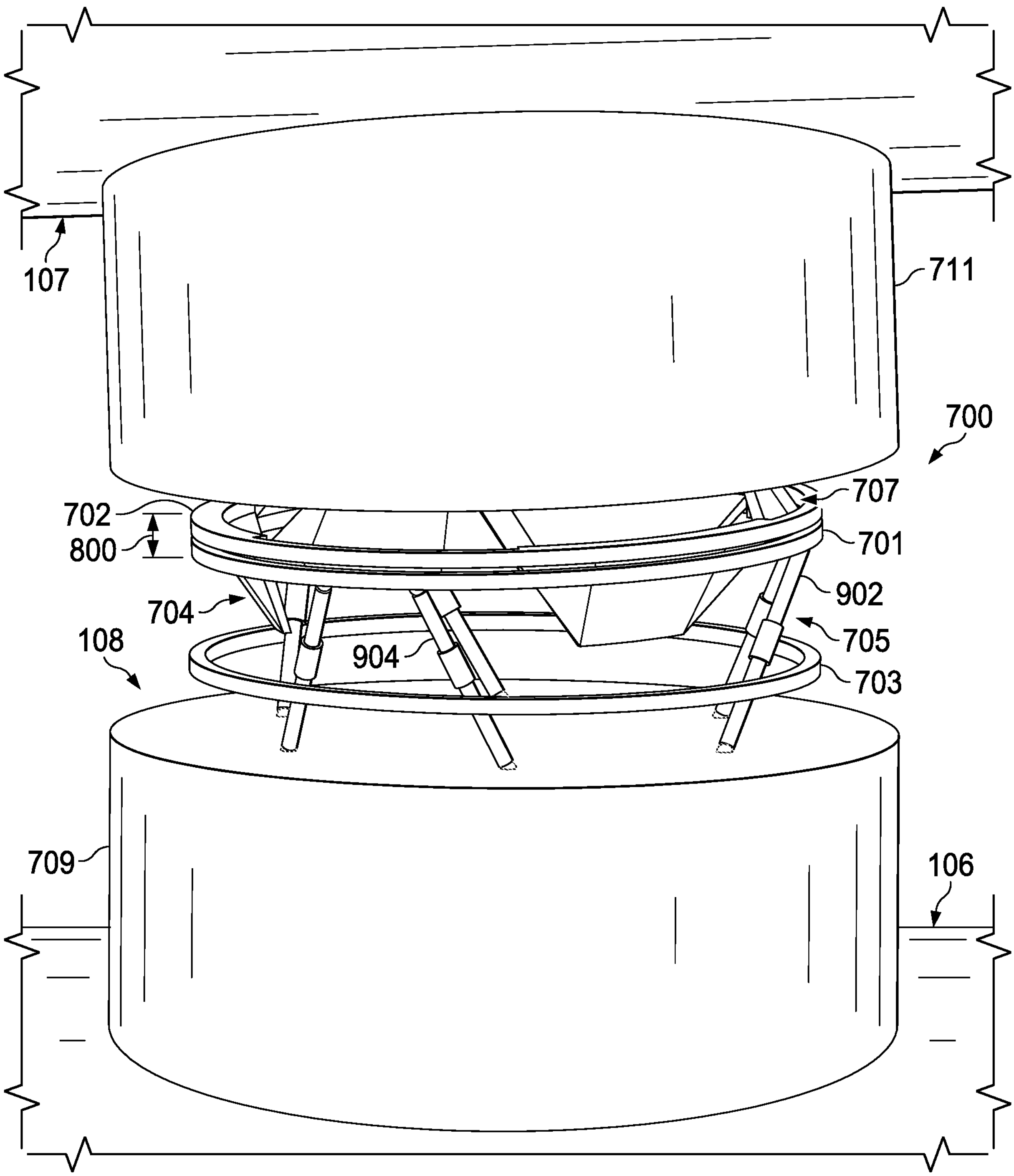


FIG. 10

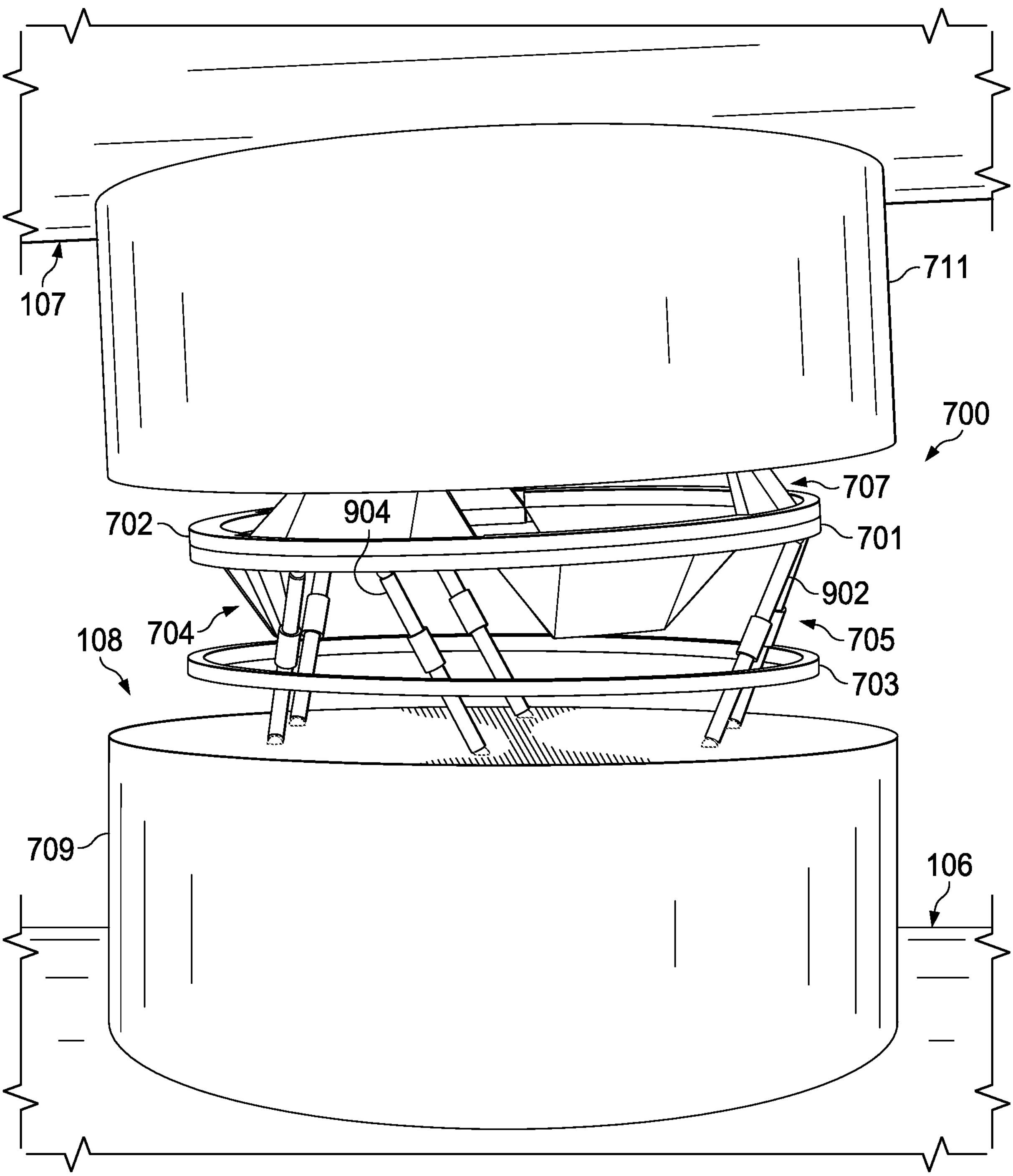


FIG. 11

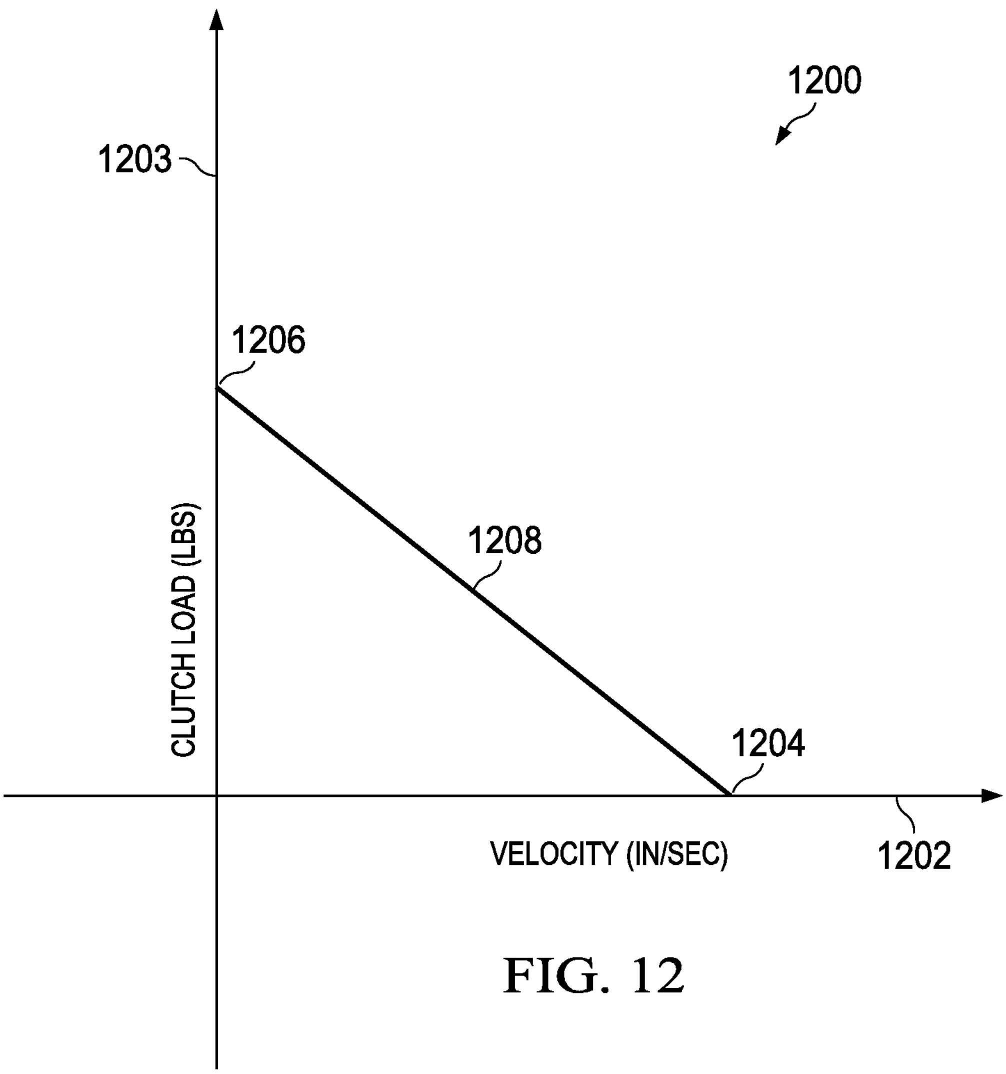
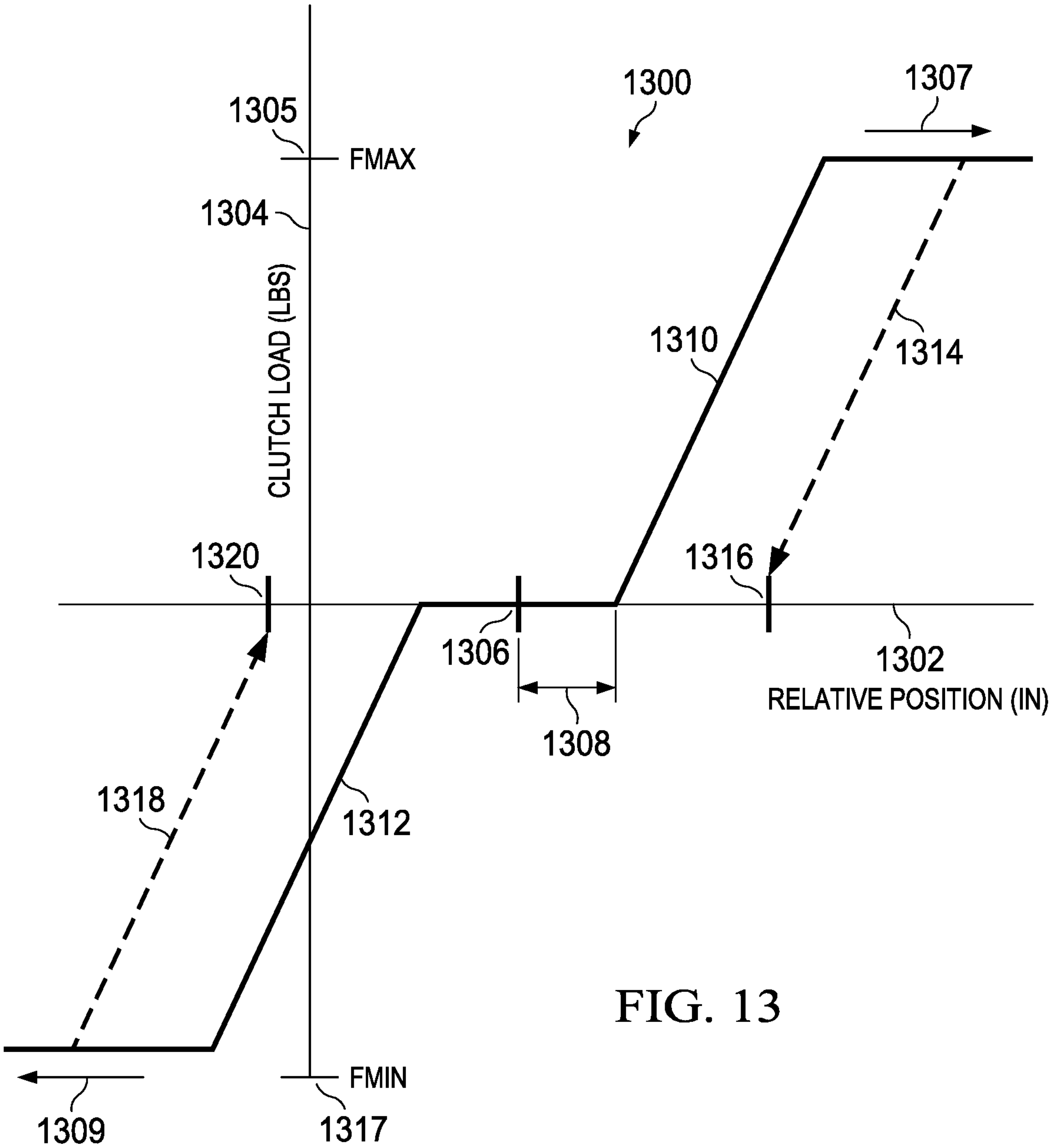

1200
1203
1206
CLUTCH LOAD (LBS)
1208
1204
VELOCITY (IN/SEC)
1202

FIG. 12



1300
1305
FMAX
1304
CLUTCH LOAD (LBS)
1307
1310
1314
1320
1316
1306
1302
RELATIVE POSITION (IN)
1308
1318
1312
1309
FMIN
1317

FIG. 13

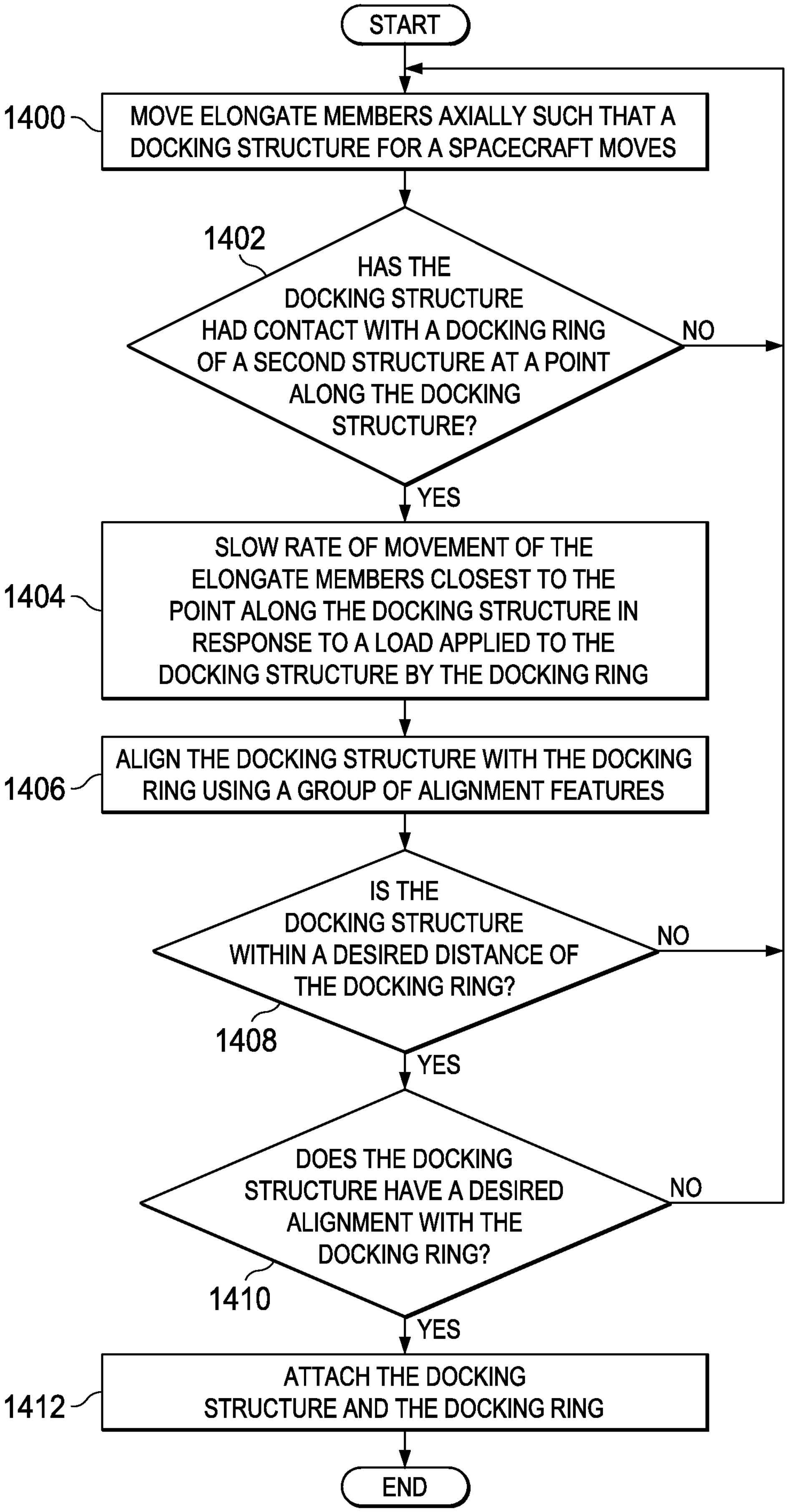

START
1400
MOVE ELONGATE MEMBERS AXIALLY SUCH THAT A DOCKING STRUCTURE FOR A SPACECRAFT MOVES
1402
HAS THE DOCKING STRUCTURE HAD CONTACT WITH A DOCKING RING OF A SECOND STRUCTURE AT A POINT ALONG THE DOCKING STRUCTURE?
NO
YES
1404
SLOW RATE OF MOVEMENT OF THE ELONGATE MEMBERS CLOSEST TO THE POINT ALONG THE DOCKING STRUCTURE IN RESPONSE TO A LOAD APPLIED TO THE DOCKING STRUCTURE BY THE DOCKING RING
1406
ALIGN THE DOCKING STRUCTURE WITH THE DOCKING RING USING A GROUP OF ALIGNMENT FEATURES
IS THE DOCKING STRUCTURE WITHIN A DESIRED DISTANCE OF THE DOCKING RING?
1408
NO
YES
DOES THE DOCKING STRUCTURE HAVE A DESIRED ALIGNMENT WITH THE DOCKING RING?
1410
NO
YES
1412
ATTACH THE DOCKING STRUCTURE AND THE DOCKING RING
END

FIG. 14

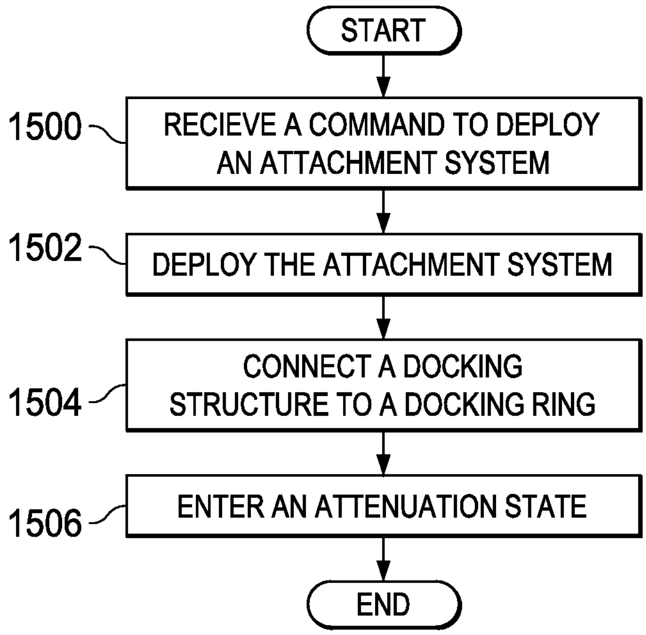

START
1500
RECIEVE A COMMAND TO DEPLOY AN ATTACHMENT SYSTEM
1502
DEPLOY THE ATTACHMENT SYSTEM
1504
CONNECT A DOCKING STRUCTURE TO A DOCKING RING
1506
ENTER AN ATTENUATION STATE
END

FIG. 15

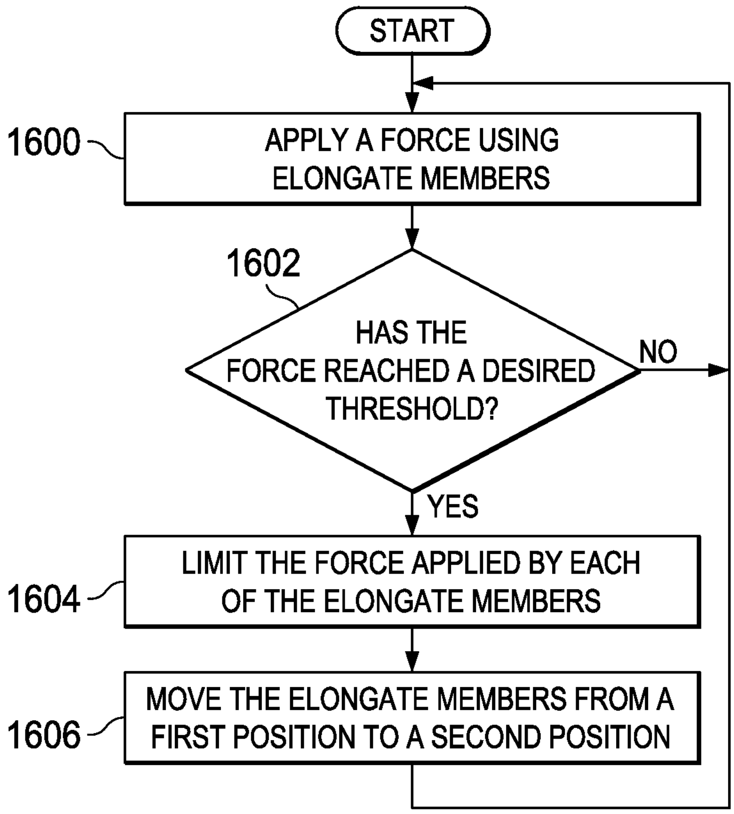

START
1600
APPLY A FORCE USING ELONGATE MEMBERS
1602
HAS THE FORCE REACHED A DESIRED THRESHOLD?
NO
YES
1604
LIMIT THE FORCE APPLIED BY EACH OF THE ELONGATE MEMBERS
1606
MOVE THE ELONGATE MEMBERS FROM A FIRST POSITION TO A SECOND POSITION

FIG. 16

FIG. 17

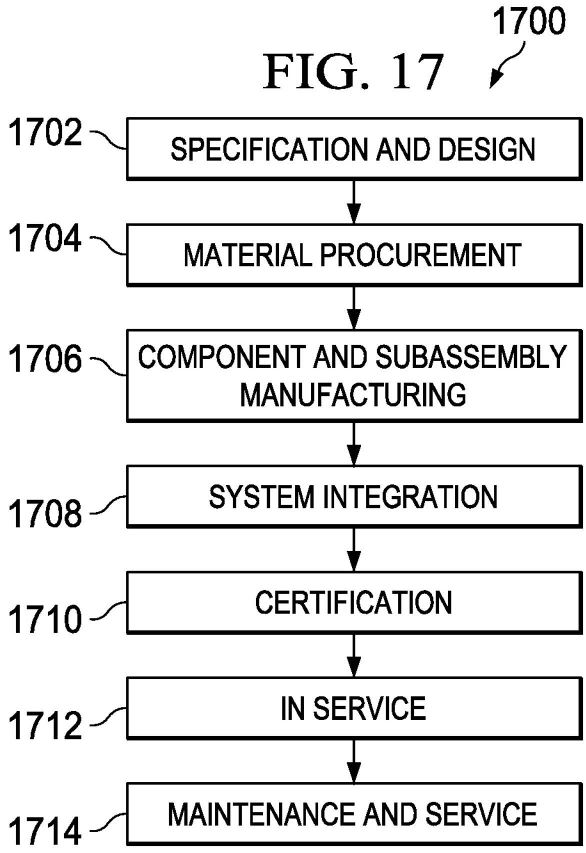
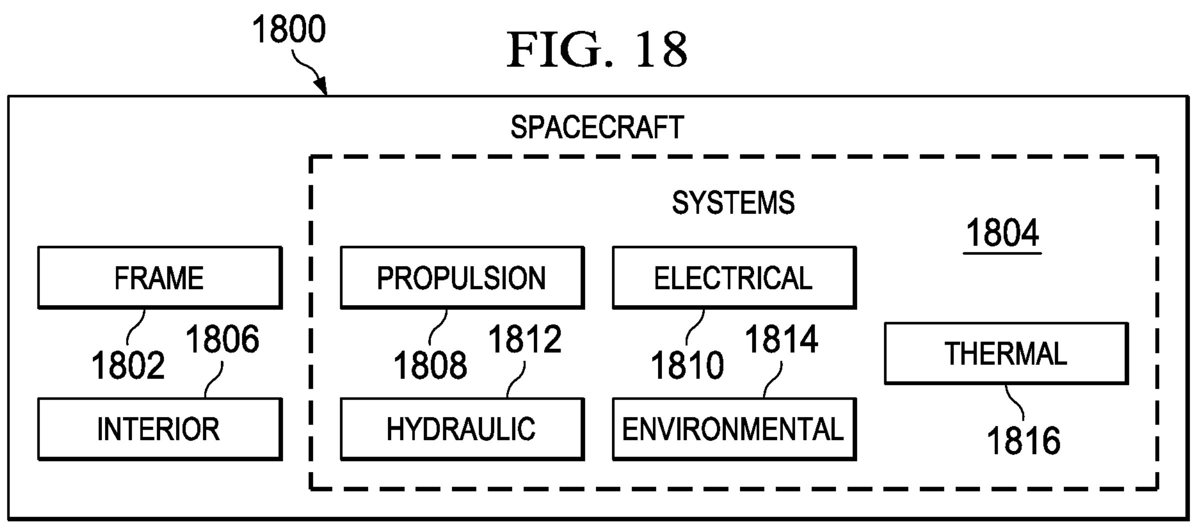

1700
1702
SPECIFICATION AND DESIGN
1704
MATERIAL PROCUREMENT
1706
COMPONENT AND SUBASSEMBLY MANUFACTURING
1708
SYSTEM INTEGRATION
1710
CERTIFICATION
1712
IN SERVICE
1714
MAINTENANCE AND SERVICE

FIG. 18


1800
SPACECRAFT
SYSTEMS
1804
FRAME
1802
1806
INTERIOR
PROPULSION
1808
1812
HYDRAULIC
ELECTRICAL
1810
1814
ENVIRONMENTAL
THERMAL
1816

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2014/066553

A. CLASSIFICATION OF SUBJECT MATTER
INV. B64G1/64
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B64G

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4 860 975 A (SCHLIESING JOHN A [US] ET AL) 29 August 1989 (1989-08-29) column 1, lines 19-28 column 3, lines 28-65 column 4, line 57 - column 5, line 45 column 6, lines 19-24 figures -----	1-7, 9-11, 13-16
X	US 7 543 779 B1 (LEWIS JAMES L [US] ET AL) 9 June 2009 (2009-06-09) column 1, lines 14-34 column 5, line 10 - column 6, line 20 column 6, lines 35-60 column 9, line 47 - column 10, line 30 column 12, line 39 - column 13, line 34 column 18, line 46 - column 20, line 10 figures -----	1-11, 13-16
	-/--	

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
17 April 2015	29/04/2015

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Weber, Carlos

1

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6 354 540 B1 (LEWIS JAMES L [US] ET AL) 12 March 2002 (2002-03-12) column 1, lines 12-22 column 4, line 39 - column 6, line 12 column 9, lines 6-31 column 11, lines 47-55 column 17, lines 49-58 column 19, lines 36-57 figures -----	1-11, 13-16

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2014/066553

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
US 4860975	A	29-08-1989	NONE	
US 7543779	B1	09-06-2009	NONE	
US 6354540	B1	12-03-2002	NONE	