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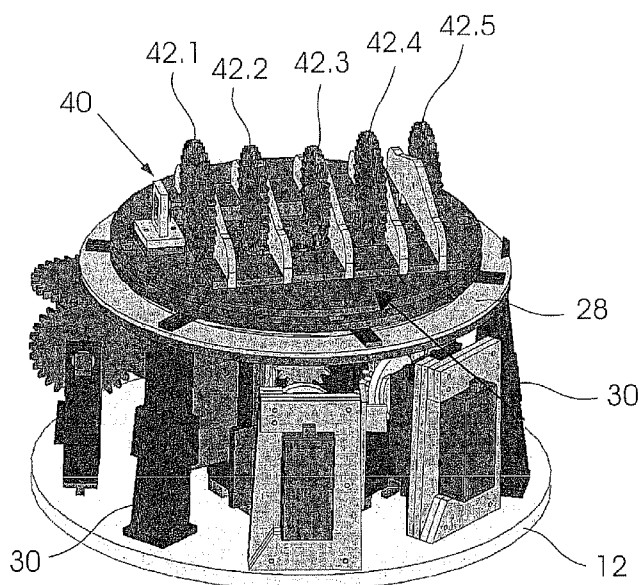


Fig. 7

(57) Abstract: This invention concerns a drive apparatus for a robotic manipulator. The drive apparatus includes a plurality of prime movers (10, 110) which are mounted on a base (12, 112). The drive apparatus further includes a concentric gear drive (18, 118) including a plurality of gears (20, 120) which are independently rotatable about a common axis (22, 122). Output gears (16, 116) of a prime movers mesh with the concentric gears (20, 120) in order to drive the concentric gears in rotation about the common axis. Drive transfer mechanisms, which have input gears driven by output gears in the concentric gear drive, are arranged to drive a driven component such as an end effector, which is preferably a 3 degrees of freedom spherical wrist.

“DRIVE APPARATUS”

BACKGROUND TO THE INVENTION

THIS invention relates to a drive apparatus. In one preferred application, the invention relates to a drive apparatus for a robotic manipulator.

Robotic manipulators of various types are widely used in modern high technology industries for operations such as component positioning and assembly, cutting, welding, spray painting and so forth.

There are two main types of robotic manipulator, namely serial mode systems and parallel mode systems. In a serial mode system, there is an open kinematics chain in which a number of actuators are arranged in series and operate to manipulate an end effector. The serial mode configuration has the advantage, particularly in applications where space is limited, of a relatively small footprint. However this configuration also has a number of disadvantages including the fact that errors in the serial components, attributable for example to gear backlash and hysteresis, tend

to be cumulative and can result in substantial inaccuracy at the end effector. Another disadvantage is the fact that drives for the various actuators are located at spaced apart, frequently elevated positions. This together with any load applied by a workpiece at the end effector requires the components of the series to be sufficiently robust to support and move the drives and workpiece. Apart from increasing the overall mass and initial and operational costs of the manipulator, there is typically an increase in inertia at different points in the system which can lead to reduced operational speed.

In a parallel mode system, the actuators and other mechanisms extend from drives on a fixed base to the end effector in closed kinematics chains. The actuators act independently of and in parallel with one another. Advantages include the fact that the manipulator can have increased levels of stability and rigidity, the fact that the parallel configuration results in individual errors being averaged rather than cumulative, the fact that inertia in each part of the manipulator can be limited and the fact that any workpiece load is transmitted through the parallel components. These factors can contribute to increased accuracy and speed of the manipulator. However a disadvantage of known parallel type manipulators, particularly in applications where there is limited space, is the fact that the fixed drives tend to occupy a substantial footprint.

SUMMARY OF THE INVENTION

According to the invention there is provided a drive apparatus comprising:

- a plurality of prime movers mounted on a base, at least some of the prime movers including an output gear,

- a concentric gear drive including a plurality of gears which are independently rotatable about a common axis, the output gears of a prime movers meshing with the concentric gears in order to drive the concentric gears in rotation about the common axis, and

a plurality of drive transfer mechanisms arranged to be driven by the concentric gear drive at one end and to drive a driven component at the other end.

The drive apparatus preferably forms part of a robotic manipulator, and the driven component may be an end effector. Preferably, the end effector is a wrist.

The robotic manipulator may include a proximal or lower arm and a distal or upper arm which may be movably connected to each other. The wrist is preferably carried by the distal arm.

The robotic manipulator may have six degrees of freedom and the end effector may be capable of performing manipulations in three degrees of freedom.

The concentric gear drive preferably comprises a plurality of independently rotatable gears arranged one inside the other. In one embodiment of drive apparatus all of the gears in the concentric gear drive except the outermost gear are spur gears. In this embodiment the outermost gear in the concentric gear drive is a worm wheel driven by an output gear of one of the prime movers in the form of a worm gear.

The spur gears may further be in the shape of ring gears, each having an input side and an output side, wherein the input and output sides of two adjacent ring gears may be axially displaced so as to avoid gear teeth interference.

Preferably, each ring gear has an annular groove located between its input and output sides, thereby allowing a concentric gear drive configuration in which the output or input side of an inner ring gear aligns with the groove in the adjacent outer ring gear in order to avoid gear teeth interference.

The concentric ring gears may also be staggered vertically to eliminate gear teeth interference.

In a second embodiment of the drive apparatus each concentric gear in the concentric gear drive has an input side and an output side. In this embodiment, an output gear of a prime mover meshes with the input side of an associated concentric gear and the output side of the concentric drive gear meshes with an input gear of an associated drive transfer mechanism. The gears in the concentric gear drive according to the second embodiment are preferably bevel gears.

In both embodiments of the drive apparatus, the concentric gears of the concentric gear drive may be supported rotatably relative to one another by bearing races. Each pair of adjacent gears preferably shares a common bearing raceway.

The drive transfer mechanisms may comprise a proximal or lower portion carrying an input gear arranged to be driven by an output gear of the concentric gear drive and a distal or upper end carrying an output gear arranged to drive the driven component.

In one embodiment, at least one of the drive transfer mechanisms comprises a slider bar linkage.

In an alternative embodiment, rotation is transferred between the proximal or lower portions and the distal or upper portions of the drive transfer mechanisms by means of output gears located on the lower portions interacting with input gears located on the upper portions.

There are preferably output gears located on the distal or upper drive transfer mechanisms drive a gear arrangement for driving the driven component in three degrees of freedom. The gear arrangement may be a concentric gear arrangement including a plurality of concentric gears independently rotatable about a common axis.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be described in more detail, by way of example only, with reference to the accompanying drawings in which:

- | | |
|-------------------------|--|
| Figure 1 | shows, in plan view, prime movers mounted on a fixed base; |
| Figure 2 | shows the prime movers and base in a perspective view; |
| Figure 3 | shows a cutaway perspective view of a concentric gear drive; |
| Figure 4 | shows a partially sectioned side view of the concentric gear drive; |
| Figure 5 | shows an exploded cutaway view of two adjacent gears of the concentric gear drive; |
| Figure 6 | shows a cutaway, exploded detail of two adjacent ball races; |
| Figure 7 | shows a perspective view of the base, prime movers, concentric gear drive and input gears of respective drive transfer mechanisms; |
| Figure 8 | shows an enlarged view of a portion of the assembly seen in Figure 7; |
| Figures 9 and 10 | diagrammatically illustrate the operation of the slider bar linkage of a drive transfer mechanism; |

- Figure 11** shows a perspective view of upper parts of the drive transfer mechanisms;
- Figures 12 and 13** illustrate lower components of the drive transfer mechanisms at an enlarged scale;
- Figures 14 to 16** illustrate an end effector drive mechanism;
- Figure 17** shows a perspective view of a fixed base including prime movers according to a second embodiment of the invention;
- Figure 18 and 19** show perspective views of a concentric gear drive of the second embodiment;
- Figure 20** shows an enlarged perspective view of a worm gear drive of the second embodiment;
- Figure 21** shows the arrangement of prime movers in perspective view;
- Figure 22** shows an exploded view of the concentric gears in the concentric gear drive;
- Figure 23** shows a perspective view on the concentric gears of the centric gear drive assembled;
- Figure 24** shows a top plan view of the concentric gear drive;
- Figure 25** shows a cutaway perspective view of the concentric gear drive and a mounting arrangement;

- Figure 26** shows a perspective view of the mounting arrangement including the gearing between the concentric gear drive and drive transfer mechanisms;
- Figure 27** shows a perspective view of the joint between a proximal or lower arm and a distal or upper arm of the drive apparatus;
- Figure 28** shows an exploded perspective view of an end effector drive mechanism; and
- Figure 29** shows a perspective view of the end effector drive mechanism assembled.

DESCRIPTION OF THE ILLUSTRATED EMBODIMENT

The accompanying drawings illustrate a drive apparatus which forms part of a robotic manipulator. Figure 1 shows six prime movers 10 mounted in fixed, spaced apart positions to a base 12. Each prime mover includes a motor and gearbox 14 including a bevel output gear 16.

Figures 3 to 6 illustrate a concentric gear drive 18 which includes six concentric bevel gears, generally indicated by the numeral 20, which are independently rotatable relative to one another about a common central axis 22.

The outer gears 20.2 to 20.6 are ring gears which are located one inside the other with the solid innermost or centre gear 20.1 located inside the first ring gear 20.2. With the exception of the outermost ring gear 20.6, each of the ring gears 20.2 to 20.5 has a beveled input side 20.2.1 to 20.5.1 and a beveled output side 20.2.2 to 20.5.2. The outermost ring gear 20.6 has only a beveled input side 20.6.1. The centre gear 20.1 has beveled input and output sides 20.1.1 and 20.1.2 respectively, as illustrated.

The concentric gear drive 18 also includes an outer ring 28 which, as shown in Figures 7 and 8, is fixed relative to the base 12 on posts 30.

Each of the concentric gears 20.1 to 20.6 is supported relative to its neighbours by double ball race bearings 32 including balls 34 mounted between races 36. The ball race bearings allow the gears to rotate freely relative to their neighbours.

Each of the six output gears 16 of the six prime movers 10 meshes at right angles with the input side of a respective one of the six concentric gears 20.1 to 20.6. In this way, with the motors of the prime movers operating independently under separate control, the concentric gears 20.1 to 20.6 can be driven independently as required through the interactions between the output gears 16 and the associated input sides of the respective concentric gears.

Each of the concentric gears 20.1 to 20.5 transfers drive from the associated prime mover 10 to an associated drive transfer mechanism, described below. The outermost concentric ring gear 20.6 supports the mass of the apparatus and is used to drive the apparatus, as a whole, in rotation about the common central axis 22, but does not transfer drive to any associated drive transfer mechanism.

Referring to Figure 7, a mounting arrangement 40 is fixedly mounted on the outermost concentric gear 20.6. The mounting arrangement supports five laterally spaced apart bevel gears 42.1 to 42.5 which are independently rotatable about a common axis. Figure 8 shows the relative positions of the gears 42.1 to 42.5 but omits the mounting arrangement 40 in the interests of clarity. Each of the gears 42.1 to 42.5 meshes at right angles with the output side 20.1.2 to 20.5.2 of one of the concentric gears 20.1 to 20.5 of the concentric gear drive, and is accordingly driven in rotation by the associated concentric gear.

The gears 42.1 to 42.5 are the input gears of drive transfer mechanisms indicated generally by the numeral 44 and consisting of individual drive transfer mechanisms 44.1 to 44.5 respectively. As shown in Figure 11 the first drive transfer mechanism 44.1 includes a proximal link member 46 which is connected to the first input gear 42.1 and to which one end of a first frame 48 is connected. The opposite end of the first frame 48 is connected to a rigid member 50 which is in turn connected through a rotary bearing to the mounting arrangement 40.

Each of the inner three drive transfer mechanisms 44.2, 44.3 and 44.4 includes a slide bar linkage. Each slide bar linkage consists of a proximal link arm 52.2, 52.3, 52.4 and a distal link arm 54.2, 54.3, 54.4.

The motion of the slide bar linkages is illustrated in Figures 9 and 10 in which respective driving and driven gears are diagrammatically indicated as pivoted links 51, 53 and 55 and proximal and distal slider bar linkages are indicated diagrammatically by the numerals 57 and 59.

A shaft 56 extends from the rigid member 46, in slidable manner through slots 58 in the proximal link arms 52.1 to 52.3, in rotatable manner through an opening in the member 50 and in slidable manner through a slot 60 in a proximal link arm 62 of the fifth drive transfer mechanism 44.5. An end of the proximal link arm 62 is connected to the input gear 42.5. Ends of the proximal link arms 52.2, 52.3 and 52.4 are connected eccentrically and in freely pivotable manner to respective ones of the input gears 42.2, 42.3 and 42.4.

Referring to Figures 12 and 13, one end of a second frame 61 is connected to the end of a distal link member 49 of the first drive transfer mechanism 44.1 which is connected pivotally to the proximal link arm 46 at a pivot 47. The opposite end of the second frame 61 is connected to the end of a distal link arm 65 which is in turn connected to the proximal link arm 62 at a sliding pivot. A shaft 67 extends within the second frame 61 between the members 49 and 65. The shaft 67 passes in slidable manner through slots

64 in the distal link arms 54.2, 54.3 and 54.4. It also passes through openings in frame members 66 and 68 fixed in the second frame 61, as shown in Figures 12 and 13. In Figure 13 a front portion of the second frame 60 has been omitted in the interests of clarity of illustration.

Ends of the distal link arms 54.2, 54.3 and 54.4 are connected eccentrically and in pivotable manner to coaxial bevel gears 70.2, 70.3 and 70.4 respectively.

This embodiment of the invention includes an end effector in the form of a wrist 71 which is movable with three degrees of freedom. The wrist includes a primary concentric gear arrangement 80 seen in Figures 14 to 16. The primary concentric gear arrangement 80 includes three concentric gears 80.2, 80.3, 80.4 (Figure 14) which mesh at right angles with respective ones of the bevel gears 70.2, 70.3 and 70.4. The primary concentric gear arrangement 80 typically includes an arrangement of supporting bearing races as described above for the concentric gear drive 18, with the centre gear 80.4 of the arrangement supporting the outer gears and itself being supported by a bracket 82 extending from the frame member 66.

The wrist also includes a secondary, in the illustrated case, upper, concentric gear arrangement 84 which has inner and outer concentric gears 84.3 and 84.4 to which drive is transmitted by the corresponding concentric gears 80.4, 80.3 of the primary concentric gear arrangement of the wrist.

In use, the illustrated drive apparatus can be used to provide for movement, with six degrees of freedom in a robotic manipulator in which the wrist forms an end effector.

With the motors of the relevant prime movers operational, rotation of the apparatus about the central axis 22 is, as described above, provided by the outermost ring gear 20.6 of the concentric gear drive 18, driven by the associated prime mover output gear 16.

Translational movement of the drive transfer mechanisms in two other degrees of freedom is provided by the concentric ring gears 20.4 and 20.5 meshing respectively with the input gears 42.1 and 42.5. Rotation of the ring gear 20.4 by its associated prime mover 10 causes rotation of the input gear 42.1 and this in turn rotates the proximal portions of the assembly of drive transfer mechanisms about a lateral axis. Rotation of the ring gear 20.5 causes rotation of the input gear and resultant translation of the distal portions of the drive transfer mechanisms relative to their coupled proximal portions

Accordingly, three degrees of translational movement, in which the position of the end effector is varied in a given space, are provided by the ring gears 20.4, 20.5 and 20.6 of the concentric gear drive 18.

The end effector or wrist can be manipulated locally in three degrees of freedom by actuation of the remaining gears 20.1, 20.2 and 20.3 of the concentric gear drive 18. For example, rotation of the central gear 20.1 causes rotation of the input gear 42.3. Through the action of the associated drive transfer mechanism and the action of the primary and secondary concentric gear arrangements and further gearing indicated by the numeral 100 in Figure 16, the wrist can be rotated about the central axis 101 of the wrist concentric gear arrangement. Rotation of the ring gear 20.2, through the action of the associated drive transfer mechanism and concentric gear arrangements, causes rotation of the end effector or wrist about an axis 103 at right angles to this central axis. Rotation of the remaining ring gear 20.3 can be used to rotate the end effector about the axis 102.

A primary advantage of the invention as exemplified above is seen to be the fact that the mass of the prime movers 10 is fixed to the base, with the concentric gear drive 18 providing a relatively compact means for transmitting drive from the respective prime movers to cause required movements in a multitude of degrees of freedom. Thus the apparatus of the invention can have a relatively small footprint, which is advantageous in

applications where there is limited space. The fixture of the prime movers to the base means that their masses do not have a disadvantageous inertial effect. The drive transfer mechanisms can be made of relatively lightweight material, thereby further limiting the necessity to overcome large inertial forces, and allowing high levels of operational speed to be attained.

Many variations are possible within the scope of the invention. For example, the concentric gear drive could make use of spur gears instead of bevel gears. Such a variation is described below with reference to a second embodiment of the invention. In another variation, the gears 42.1 and 42.5 could be replaced by worm gears in order to improve the vertical load carrying capability of the drive. Whereas in the first illustrated embodiment the proximal and distal link arms are only driven from one side, it would be possible to mirror the worm gears and associated linkages so that these link arms are driven from both sides, thereby significantly strengthening the apparatus and eliminating possibly detrimental torsional effects.

It should also be noted that it is not necessary that the vertically oriented bevel gears 70.2, 70.3 and 70.4 in the illustrated example be coaxial as illustrated, although this does simplify the design.

Figure 14 shows how the innermost gear 80.4 is held in place by a bracket 82. In other embodiments the outermost gear could be held in place by a similar arrangement.

As in the case of the concentric gear drive, spur gears could be used in the wrist 71 instead of the illustrated bevel gears. Where appropriate, other mechanisms, such as belt or chain and pulley mechanisms, could also be arranged to be driven by the links to generate rotation.

A second embodiment of the drive apparatus is illustrated in Figures 17 to 29. The second embodiment is an example of a drive apparatus including a concentric gear drive 118 which includes spur gears instead of bevel gears, thereby allowing for a more compact design.

The drive apparatus again includes six prime movers 110. Similar to the first embodiment, each prime mover includes a motor and gearbox 114. A number of the prime movers, in the illustrated embodiment all but one, has an output gear 116 which drives a corresponding gear in the concentric gear drive 118. In this embodiment five of the prime movers are mounted in fixed, spaced apart positions to a base 112. As shown in Figure 17, the five prime movers on the base are arranged in a straight line. The four outermost prime movers have output gears 116 arranged to engage corresponding gears in the concentric gear drive 118. The output shaft 117 of the innermost prime mover is aligned with the central axis of the base 112 and extends through the concentric gear drive 118 so that a gear 146.3 carried at its upper end engages a gear 148.3 in the next stage of the drive apparatus i.e. the stage after the concentric gear drive.

Figures 18 to 25 illustrate the concentric gear drive 118 which includes five concentric gears, generally indicated by the numeral 120, which are independently rotatable relative to one another about a common axis 122.

The concentric gear drive 118 has a bottom cover 124 which is mounted, in a fixed manner, directly onto the base 112 and which, in use, locate the concentric gears 120 of the concentric gear drive. The bottom cover 124 locates the gears 120 in a similar manner as in the first embodiment i.e. using raceways 136 in which ball bearings 134 run. An exploded view of the components of the concentric gear drive 118 is shown in Figure 18.

The concentric gear drive 118 includes a fixed outermost section 128 which mounts directly on the bottom cover 124 and does not move relative to the five inner movable gears 120.1 to 120.5. As can be seen in Figures 18 and 19, the sixth prime mover 110 is mounted on the outer section 128. Instead of having a spur gear as an output gear, the sixth prime mover drives a worm gear 126 which in turn drives the outermost gear 120.5 of the concentric gear drive 118. In this example the worm gear 126 is a spring-loaded compound worm gear as shown in Figure 20. The gear 120.5 is in

the form a worm wheel and is driven by the worm 126 through an opening in the sidewall of the non-movable outer section 128.

Although the design of the drive apparatus is simpler when the outermost or innermost movable sections of the concentric gear drive is used to control rotation about the vertical axis 122, it must be understood that any of the sections could be used to do this. In an alternative embodiment, rotation about the axis 122 may be controlled by the innermost section of the concentric gear drive 118 and it may have a more efficient harmonic gear drive, in terms of power transmission.

Figure 21 shows all of the six prime movers 110, but excludes the bottom cover 124 for the sake of clarity.

It must be understood that the worm wheel 126 and fixed bottom cover 124 have concentrically aligned raceways 136 so that the worm wheel is allowed to rotate relative to the outermost section 128 and, accordingly, the base 112 of the drive apparatus.

Figures 22 to 24 show the arrangement of gears 120 of the concentric gear drive 118. The four inner gears 120.1 to 120.4 are also ring gears, in the form of spur gears, which are located one inside the other. Each set of consecutive internal and external spur gears 120 share a common raceway 136 and ball bearings 134. Although it is envisaged that each of the gears 120 may have its own dedicated raceway and ball bearings, this design was omitted to keep the illustration simpler and easily understandable.

The concentric gear drive 118 is covered by a top cover 130 which mounts directly onto the worm wheel 120.5 so that it rotates when the worm wheel is rotated. The top cover 130 has openings 132 which facilitate the mounting of spur gears 140.1 to 140.4, which interacts with the gears 120 of the concentric gear drive 118. As can be seen in Figures 18 and 25, each of the spur gears 140.1 to 140.4 is carried on the end of a tubular

shaft 142 which is used to locate the gears 140 in the openings 132 in the top cover 130.

As shown in Figure 25, each of the gears 120.1 to 120.4 of the concentric gear drive 118 has an input side 120.1.1 to 120.4.1 and an output side 120.1.2 to 120.4.2. It must be understood that the input and output sides of the gears 120 are spaced apart axially seeing that the gears are spur gears. Each gear 120 has an annular groove 121 located between the input and output side of the gear. In other words, the annular groove 121 separates the input side from the output side of the gear 120. It must be understood that the grooves 121 allow for a concentric gear drive configuration in which the output or input side of an inner ring gear, for example 120.4, aligns with the groove 121 in the adjacent outer ring gear 120.3, thereby avoiding unwanted gear teeth interference. The grooves 121 are clearly visible in Figure 25. In addition to the grooves 121, the gears 120 in the concentric gear drive 118 are also staggered vertically to eliminate gear teeth interference.

Similarly to the first embodiment of the drive apparatus, a mounting arrangement 144 is provided and located on the top cover 130. As shown in Figure 25, there are five bevel gears 146.1 to 146.5 located on a surface of the mounting arrangement 144 which in use is a top surface 145. The bevel gears 146.1 to 146.4 are connected to the tubular shafts 142 of the spur gears 140.1 to 140.4 in such a manner that rotation of one of the spur gears causes the corresponding bevel gear to rotate. The central bevel gear 146.3 is connected directly to the central prime mover 120 through a tubular shaft, similar to the shaft 142, and has no need for a corresponding gear in the concentric gear drive 118.

Referring now to Figure 26 it can be seen that the mounting arrangement 144 has a shaft 147 about which five laterally spaced apart bevel gears 148.1 to 148.5 are mounted. The bevel gears 148 are independently rotatable about a common axis and, in use, transfer rotation between the output gears 146.1 to 146.4 and input gears 150.1 to 150.4 of proximal or

lower drive transfer mechanisms, indicated generally by the numeral 152 and consisting of individual drive transfer mechanisms 152.1 to 152.4 respectively. As shown in Figure 26 the top surface 145 of the mounting arrangement 144 has multiple sections which are staggered vertically to prevent gear teeth interference.

Similarly to the first embodiment of the drive apparatus, the inner bearings do not carry any vertical load, they simply facilitate the transfer of rotation and torque from the prime movers 110 to the designated transfer mechanism. The entire vertical load, which is the complete mass of the moving machine, is carried by the worm wheel 120.5 which lies on the outermost bearings. The five bevel gears 148.1 to 148.5 are used to direct torque to the remaining five axes of interest in the robotic manipulator.

The three inner drive transfer mechanisms 152.2 to 152.4 are used to transfer torque to corresponding gears in a concentric gear arrangement 160 of an end effector, which in this embodiment is a 3 DOF wrist which will orient a tool. Returning now to Figure 26, the bevel gear 148.5 is connected directly to a frame member 153.1 forming part of a proximal or lower arm 153 of the robotic manipulator to control the elevation of the arm with respect to the horizontal plane. The bevel gear 148.1 in turn drives the transfer mechanism 152.1, which controls the angle between a distal or upper arm 154 and the proximal or lower arm 153 of the robotic manipulator.

Figure 27 shows the connecting joint between the proximal and distal arms 153 and 154. As can be seen from this figure, the two arms are pivotally connected to each other about a centre axis of a shaft 155. The shaft 155 carries four spaced apart bevel gears 156.1 to 156.4 which are driven independently by bevel gears 157.1 to 157.4 located at the ends of the proximal or lower drive transfer mechanisms 152.1 to 152.4. The first bevel gear 156.1 is connected directly to a frame member 154.1 of the distal arm 154 so that rotation of the bevel gear 156.1 causes the distal arm to pivot relative to the proximal arm. The three remaining bevel gears 156.2 to

156.4 are double bevel gears and used to transfer rotation of the proximal or lower drive transfer mechanisms 152.2 to 152.4 to distal or upper drive transfer mechanisms 158.1 to 158.3 which is used to drive the gear arrangement 160 of the wrist.

The gear arrangement 160 will now be described in greater detail with reference to Figures 28 and 29 of the accompanying drawings. From the description below it will be clear that the wrist has three degrees of freedom with all wrist axes intersecting at a point, thereby making it a spherical wrist. Although a spherical wrist is easier to model and control, it is envisaged that a wrist other than a spherical one could be used i.e. all of the axes need not intersect at a point. The three axes of rotation of the wrist are shown in Figure 29 and indicated by the reference numerals 161, 162 and 163 respectively. The first axis of rotation, indicated by the reference numeral 161, is parallel to and, in this embodiment, coincides with the centre axis of the distal drive transfer mechanism 158.2, when both the proximal and distal arms are set to their vertical positions. The first axis 161 is always perpendicular to the arms' elbow joint axis i.e. the centre axis of shaft 155.

The gear arrangement 160 has a frame section 164 which is connected directly to the distal arm 154 and which has three openings through which the distal drive transfer mechanisms 158.1 to 158.3 pass. Each of the distal drive transfer mechanisms is used to transfer torque to a different concentric section of the gear arrangement 160.

In total the gear arrangement 160 includes an outermost section 166 in the form of an upper cover which is fixed to the distal arm 154 and accordingly not rotatable. As shown in Figures 28 and 29, the gear arrangement 160 also makes use of the double ball race bearing design of the concentric gear drive 118 so that the remaining inner concentric sections are all independently rotatable. This allows the central distal drive transfer mechanism 158.2 to cause the wrist to rotate about its first axis 161 or, in

other words, the central drive transfer mechanism controls the azimuth of the wrist.

The drive transfer mechanism 158.2 connects directly and rigidly to a tubular connecting member 185. By rotating the drive transfer mechanism 158.2 the member 185 rotates with respect to the frame section 164, thereby controlling the rotation about axis 162.

The distal drive transfer mechanism 158.1 in turn controls the elevation of an end effector link 165 with respect frame section 164 or the distal arm 154 by causing it to rotate about its second axis 162. This is achieved by driving a disc 168 by means of a spur gear 170 which is carried by the first distal drive transfer mechanism 158.1. The disc 168 has an internal ring gear 172, which meshes with the spur gear 170, and a beveled profile 174 on a surface thereof which is in use a top surface. A bevel gear 176 runs on the profile 174 and causes a shaft 178 to rotate, thereby rotating the effector link 165 about the axis 162.

The distal drive transfer mechanism 158.3 in turn controls the rotation of the end effector link 165 about its third axis 163. A spur gear 180, which is carried by the distal drive transfer mechanism 158.3, meshes with an intermediate spur gear 182 which has a beveled gear profile 184 formed on the top surface thereof. An intermediate bevel gear 186 meshes with the beveled profile 184 and is used to transfer torque to the effector link 165 through another bevel gear 188 provided on the effector link. This causes link 165 to rotate about axis 163.

It is envisaged that various devices for improving positioning accuracy of the drive apparatus of the robotic manipulator could be used. These devices attempt to eliminate inaccuracies resulting from, for example, gear backlash or play. In the drawings the possible positions where one of the devices could be located are indicated simply as a box. For example, see box 200 in Figure 26 wherein the device is mounted on the mounting arrangement 144. Another possible position for one of these devices is

shown in Figure 27 where it is mounted in the joint between the proximal and distal arms 153 and 154.

The positioning improving apparatus could for example be a harmonic drive, which is a zero backlash gear drive. A person skilled in the art of drive apparatuses for robotic manipulators will be familiar with harmonic drives and it will therefore only be described briefly. A typical harmonic drive includes an elliptical wave generator, a flexible cup (which has radial flexibility but torsional rigidity) called the flexspline, and a rigid circular spline. The wave generator fits in the flexspline which fits into the circular spline. The elliptical shape of the wave generator stretches the flexspline outwards to engage with the circular spline at two locations, unlike conventional gears which mate at one location only. It is this feature of flexibility and two contact positions that prevents any backlash. When used in the drive apparatus according to the invention the circular spline would be fixed to one link, the flexspline to another and the output of a drive mechanism to the wave generator.

Another example of a positioning improving apparatus could be a braking mechanism which can hold the relative angular position between two consecutive links, for example the proximal and distal arms 153 and 154. The braking mechanism is then used to brake the linkage when a direction change is required or an external disturbance is detected to prevent position inaccuracy, hunting and oscillation.

It is also envisaged that self locking gears, for example worm and worm wheel sets or spur gear sets, could be used as a positioning improving apparatus. In self locking gears the pinion can drive the gear but the gear cannot back drive the pinion. Self locking gears are essential in applications when power is lost and it is critical to halt motion, such as when heavy loads are being lifted. These self locking gears can be used as the last set of gears in a gear train or gear chain to limit the effects of backlash to the last set of gears. As a result, relative play between consecutive links will be limited to 1 gear set. A person skilled in the art will realise that this effect

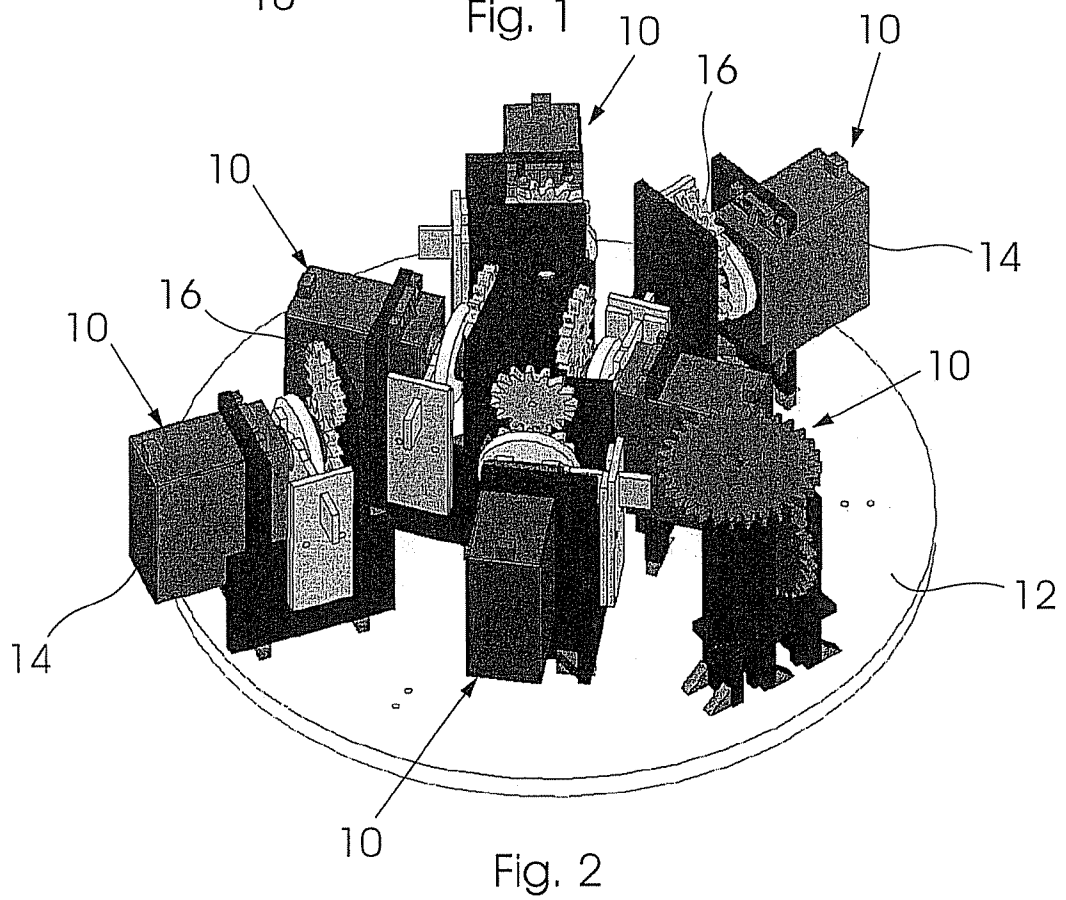
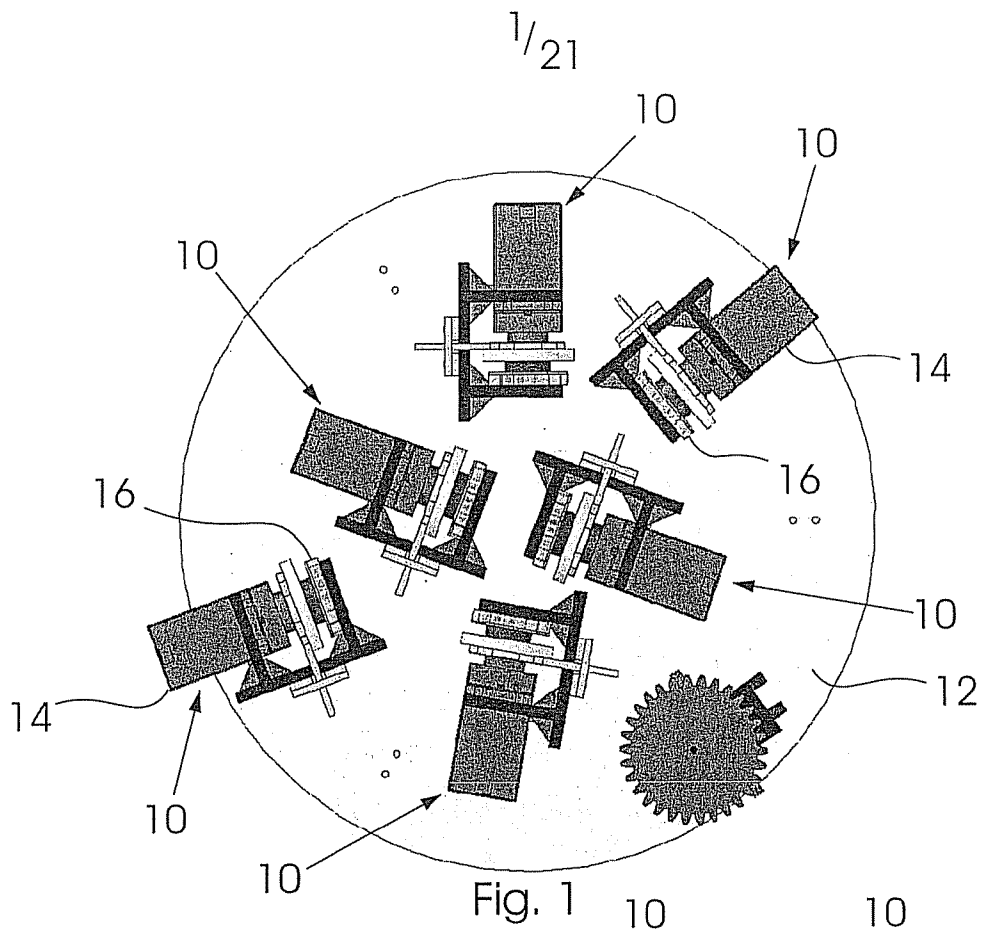
will be additive for a six degrees of freedom robotic manipulator and thus it will feel the effect of backlash for six gear pairs in total and not the multitude of gear pairs for each gear train/chain linkage for each axis. This backlash be eliminated by using spring loaded gearing in the self locking gear sets. The spring loaded compound gear would comprise two identical self-locking gears having a spring between them which forces them apart and to engage with a third self locking gear at two points, similar to the harmonic drive mentioned above. It will be understood that the spring has to be designed for a particular load, and if the load is exceeded the spring compresses and positioning inaccuracy caused by backlash returns.

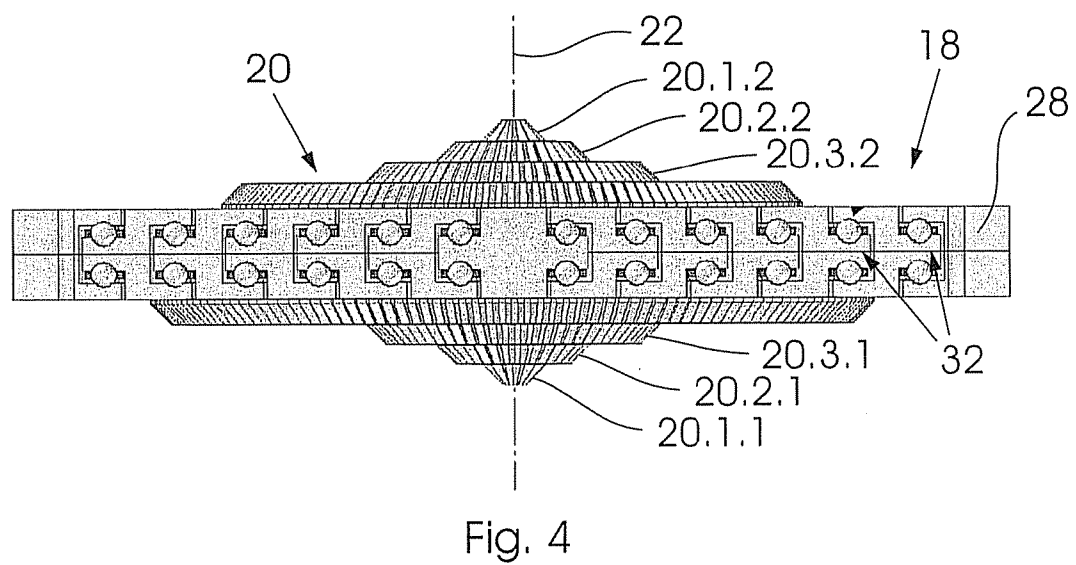
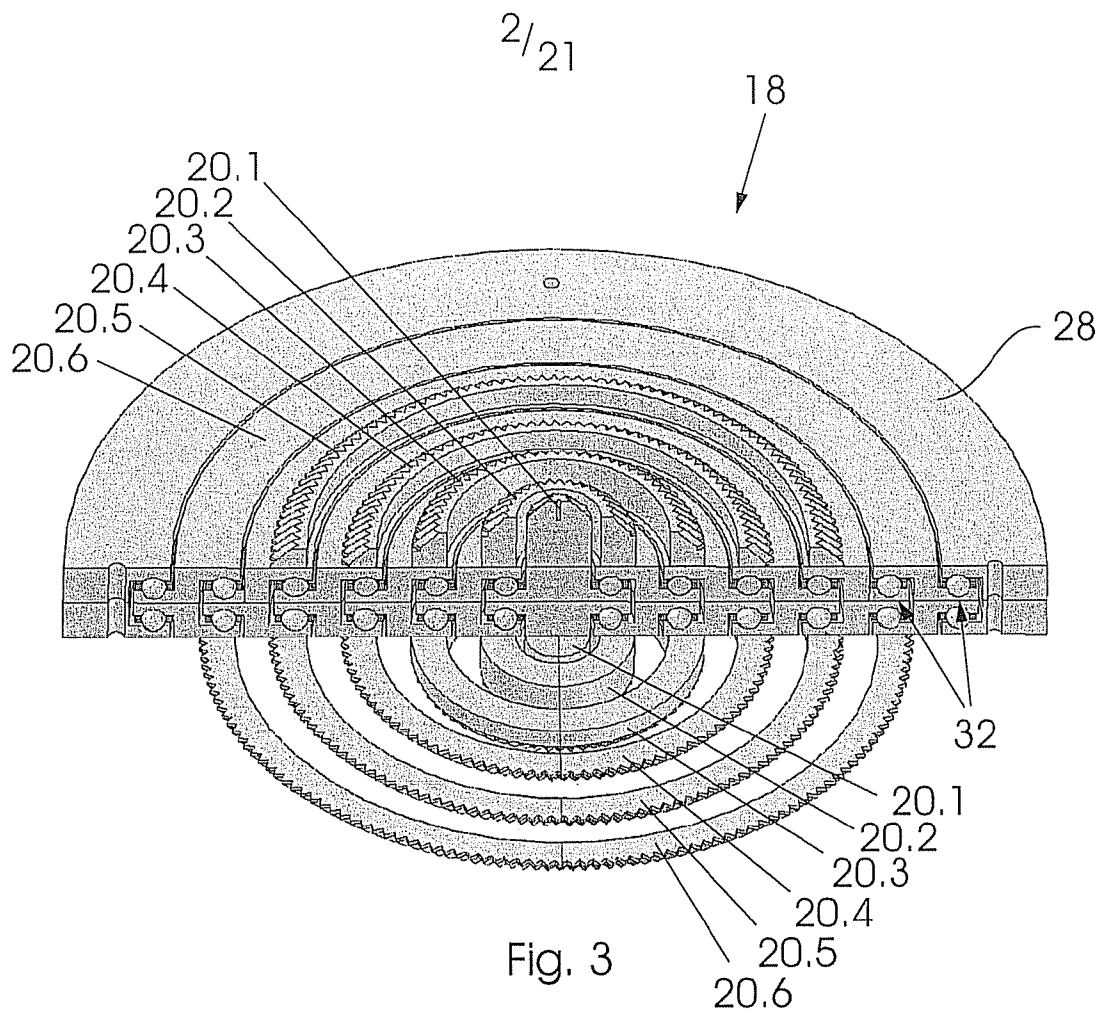
CLAIMS

1. A drive apparatus comprising:
 - a plurality of prime movers mounted on a base, at least some of the prime movers including an output gear,
 - a concentric gear drive including a plurality of gears which are independently rotatable about a common axis, the output gears of a prime movers meshing with the concentric gears in order to drive the concentric gears in rotation about the common axis, and
 - a plurality of drive transfer mechanisms arranged to be driven by the concentric gear drive at one end and to drive a driven component at the other end.
2. A drive apparatus according to claim 1, wherein the drive apparatus forms part of a robotic manipulator, and wherein the driven component is an end effector.
3. A drive apparatus according to claim 2, wherein the end effector is a wrist.
4. A drive apparatus according to claim 3, wherein the robotic manipulator includes a proximal or lower arm and a distal or upper arm which are movably connected to each other, and wherein the wrist is carried by the distal arm.
5. A drive apparatus according to any one of claims 2 to 4, wherein the robotic manipulator has six degrees of freedom and the end effector is capable of performing manipulations in three degrees of freedom.
6. A drive apparatus according to any one of claims 1 to 5, wherein the concentric gear drive comprises a plurality of independently rotatable gears arranged one inside the other.

7. A drive apparatus according to claim 6, wherein all of the gears in the concentric gear drive except the outermost gear are spur gears.
8. A drive apparatus according to claim 7, wherein the outermost gear in the concentric gear drive is a worm wheel driven by an output gear of one of the prime movers in the form of a worm gear.
9. A drive apparatus according to either claim 7 or 8, wherein the spur gears are in the shape of ring gears, each having an input side and an output side, wherein the input and output sides of two adjacent ring gears are axially displaced so as to avoid gear teeth interference.
10. A drive apparatus according to claim 9, wherein each ring gear has an annular groove located between the its input and output sides, thereby allowing a concentric gear drive configuration in which the output or input side of an inner ring gear aligns with the groove in the adjacent outer ring gear in order to avoid gear teeth interference.
11. A drive apparatus according to any one of claims 7 to 10, wherein the concentric ring gears are staggered vertically to eliminate gear teeth interference.
12. A drive apparatus according to claim 6, wherein each concentric gear has an input side and an output side.
13. A drive apparatus according to claim 12, wherein an output gear of a prime mover meshes with the input side of an associated concentric gear and the output side of the concentric drive gear meshes with an input gear of an associated drive transfer mechanism.
14. A drive apparatus according to claim 13, wherein the gears in the concentric gear drive are bevel gears.

15. A drive apparatus according to any one of claims 6 to 14, wherein the concentric gears of the concentric gear drive are supported rotatably relative to one another by bearing races.
16. A drive apparatus according to claim 15, wherein each pair of adjacent gears shares a common bearing raceway.
17. A drive apparatus according to any one of claims 1 to 16, wherein the drive transfer mechanisms comprise a proximal or lower portion carrying an input gear arranged to be driven by an output gear of the concentric gear drive and a distal or upper end carrying an output gear arranged to drive the driven component.
18. A drive apparatus according to claim 17, wherein at least one of the drive transfer mechanisms comprises a slider bar linkage.
19. A drive apparatus according to claim 17, wherein rotation is transferred between the proximal or lower portions and the distal or upper portions of the drive transfer mechanisms by means of output gears located on the lower portions interacting with input gears located on the upper portions.
20. A drive apparatus according to any one of claims 17 to 19, wherein the output gears on the distal or upper drive transfer mechanisms drive a gear arrangement for driving the driven component in three degrees of freedom.
21. A drive apparatus according to claim 20, wherein the gear arrangement is a concentric gear arrangement including a plurality of concentric gears independently rotatable about a common axis.





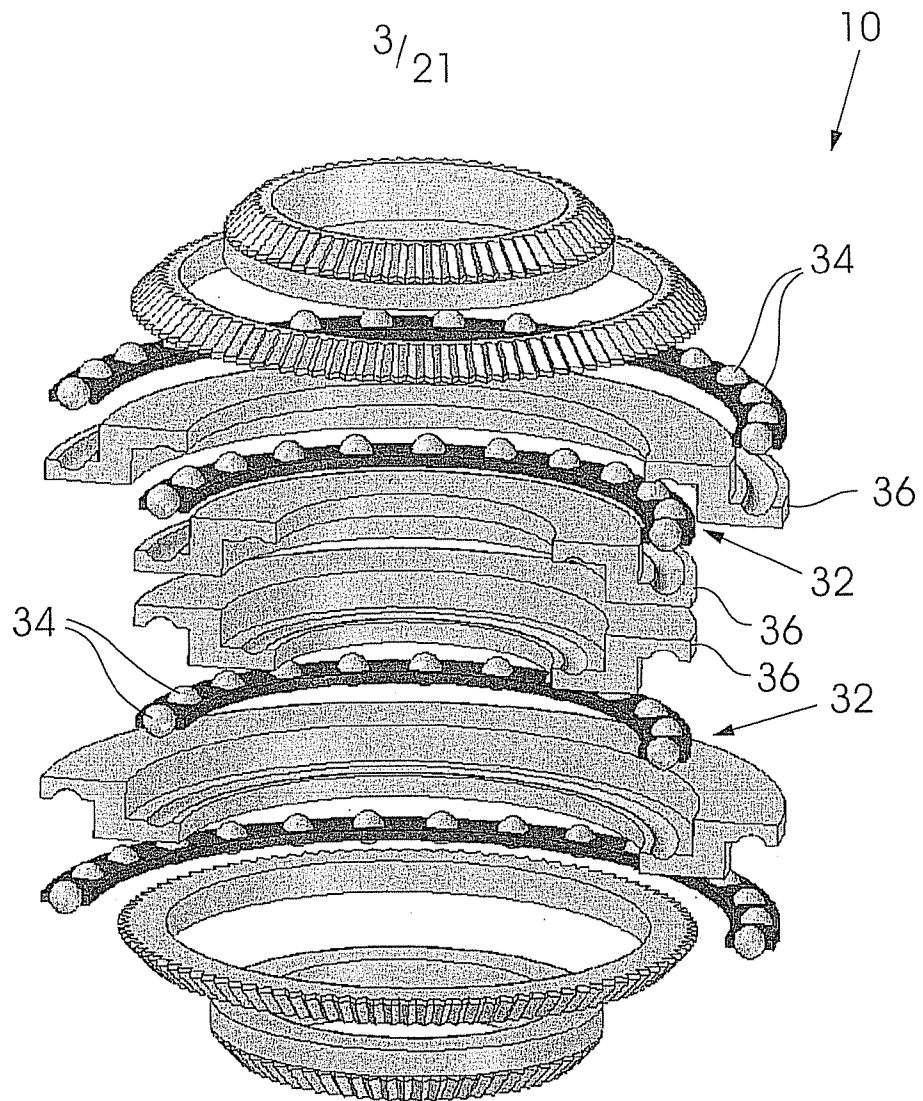


Fig. 5

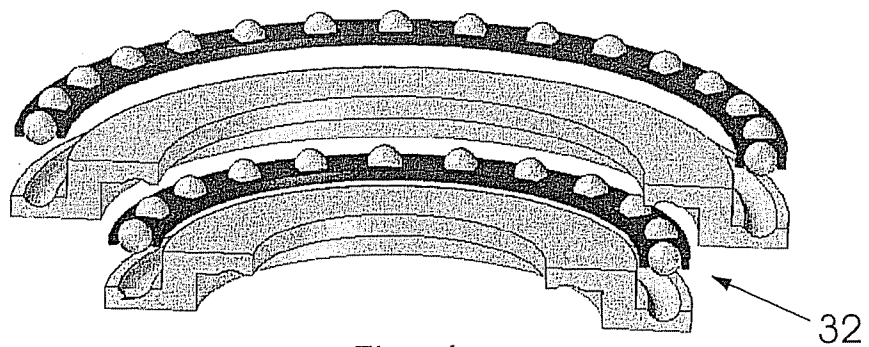


Fig. 6

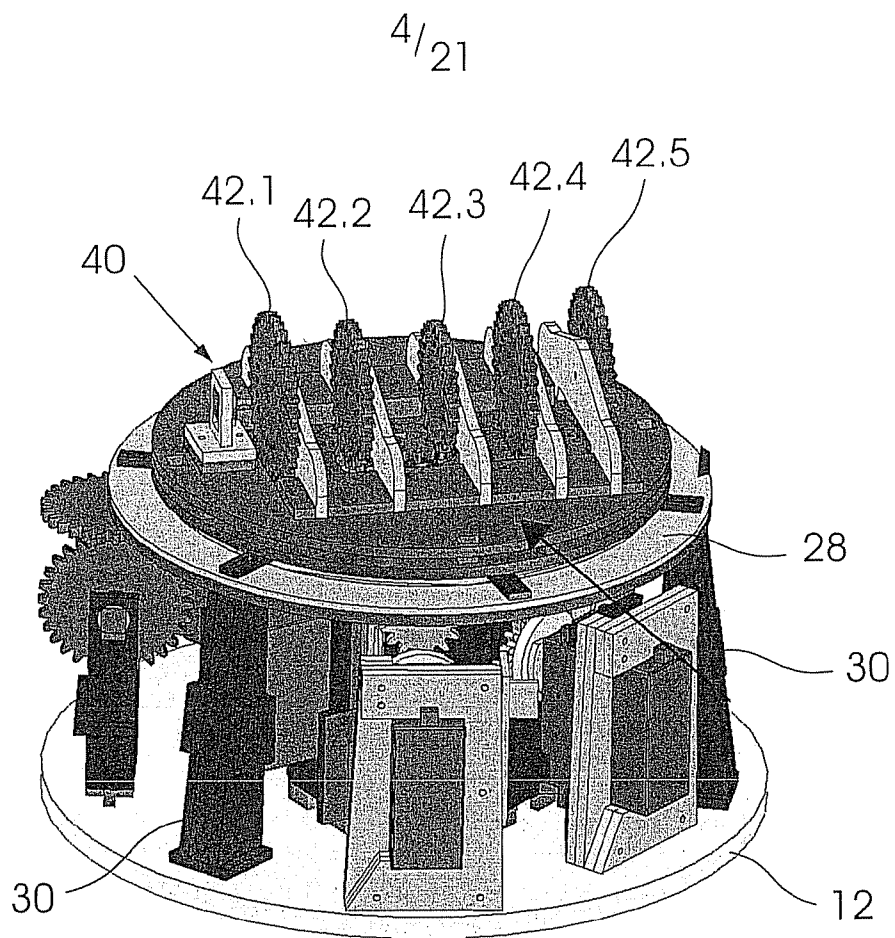


Fig. 7

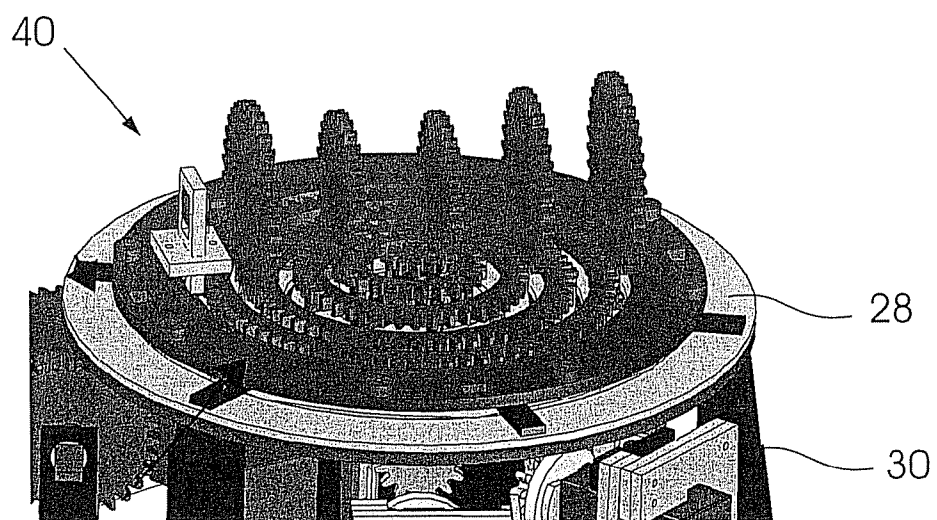


Fig. 8

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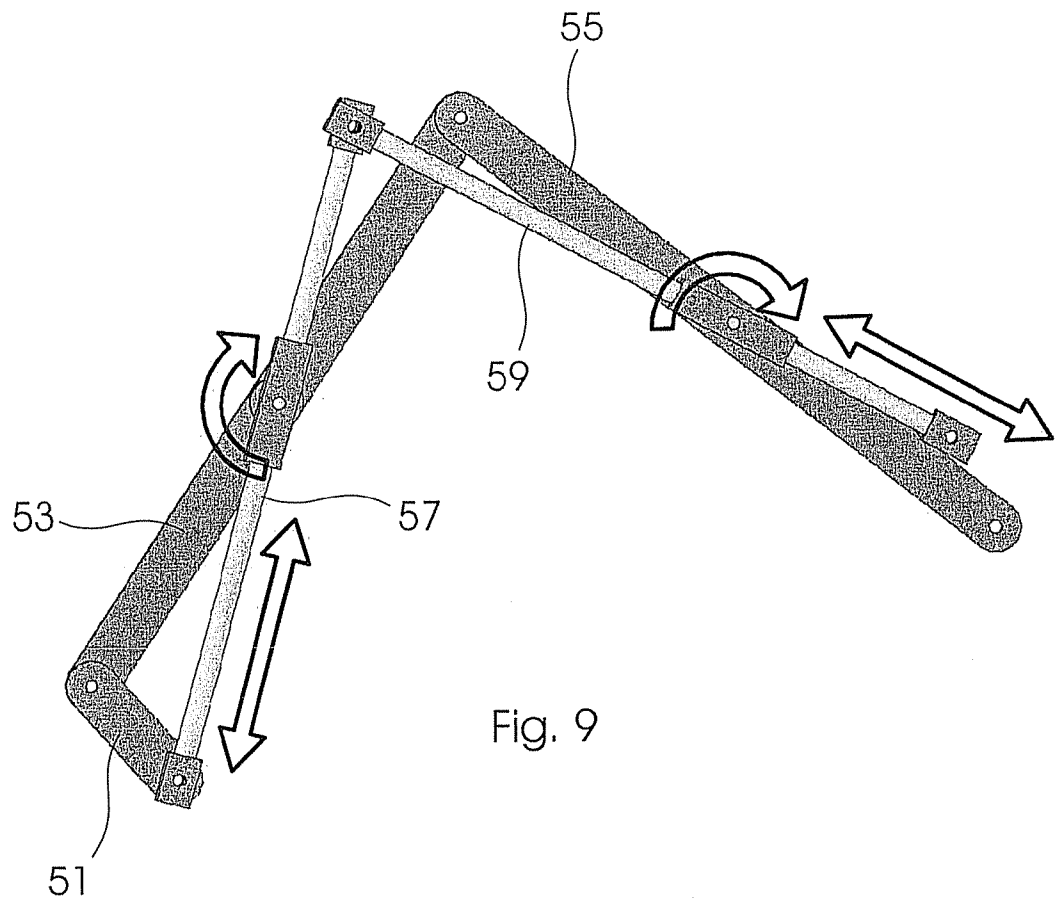


Fig. 9

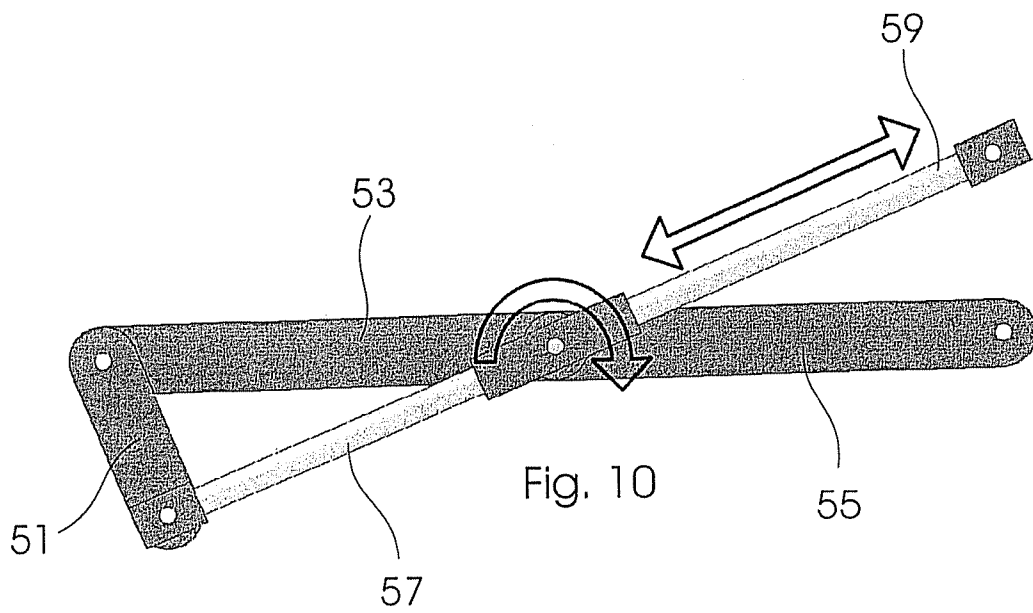


Fig. 10

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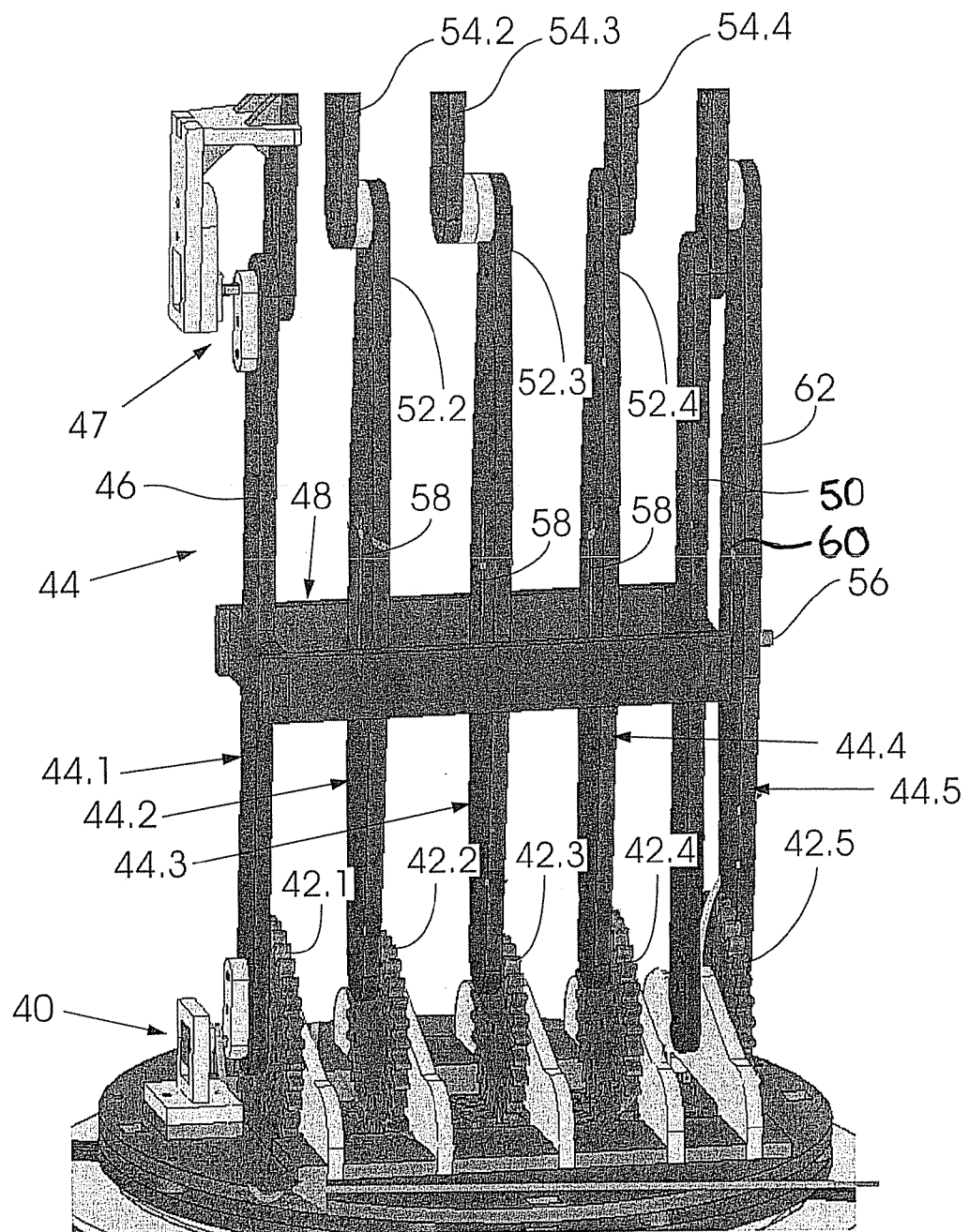
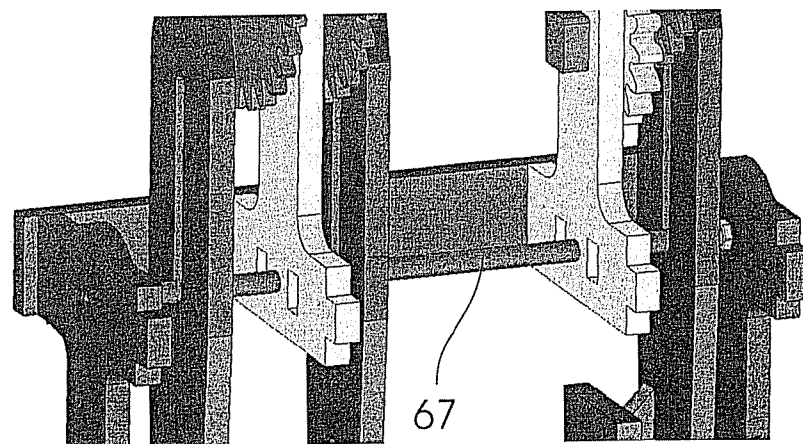
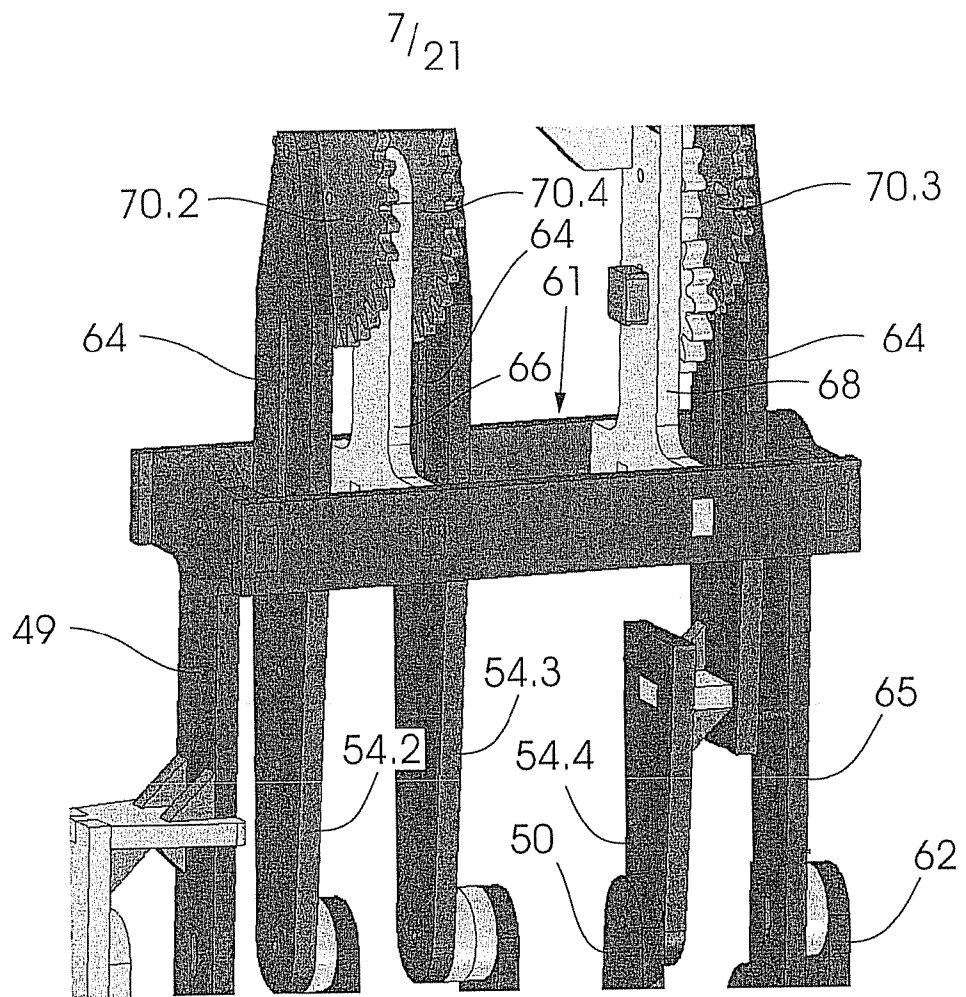
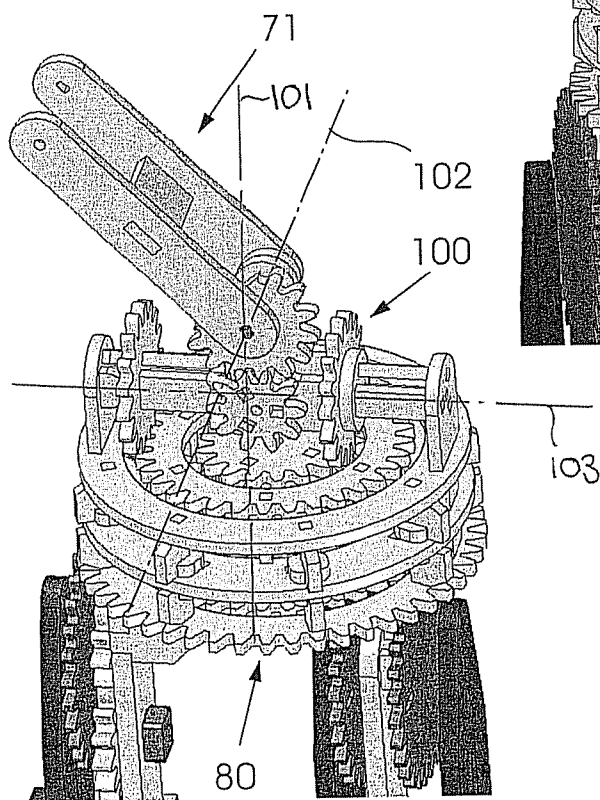
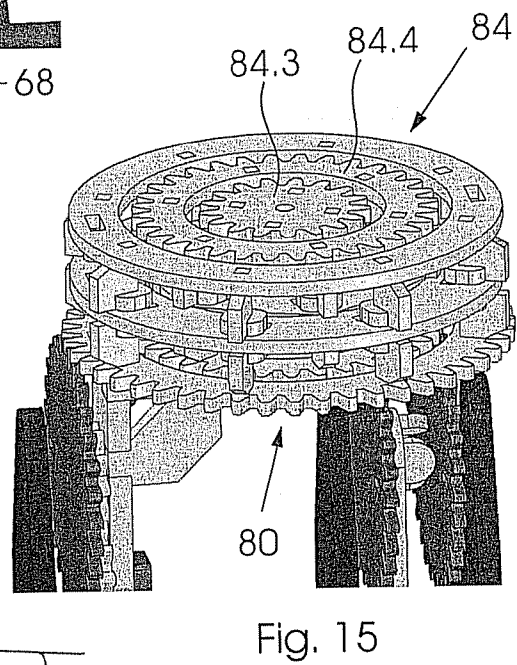
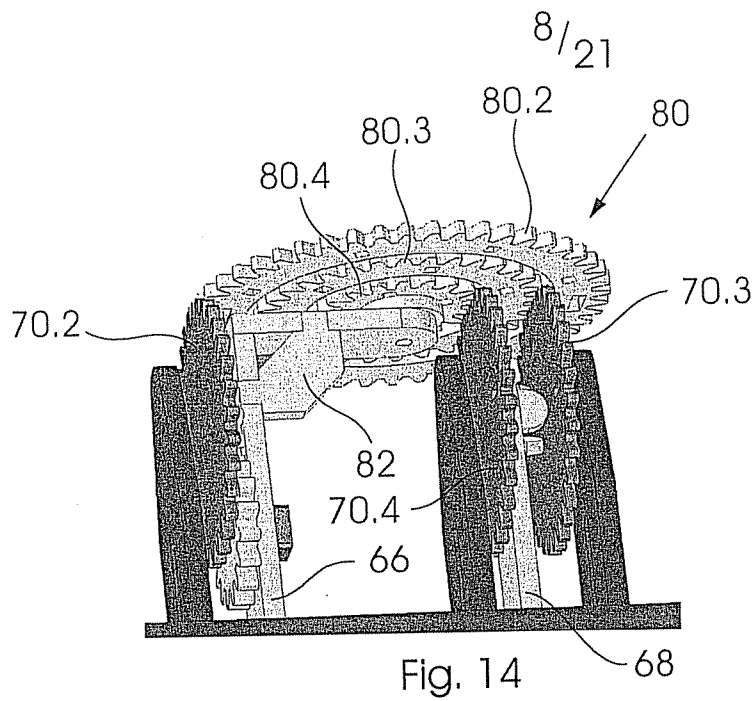


Fig. 11





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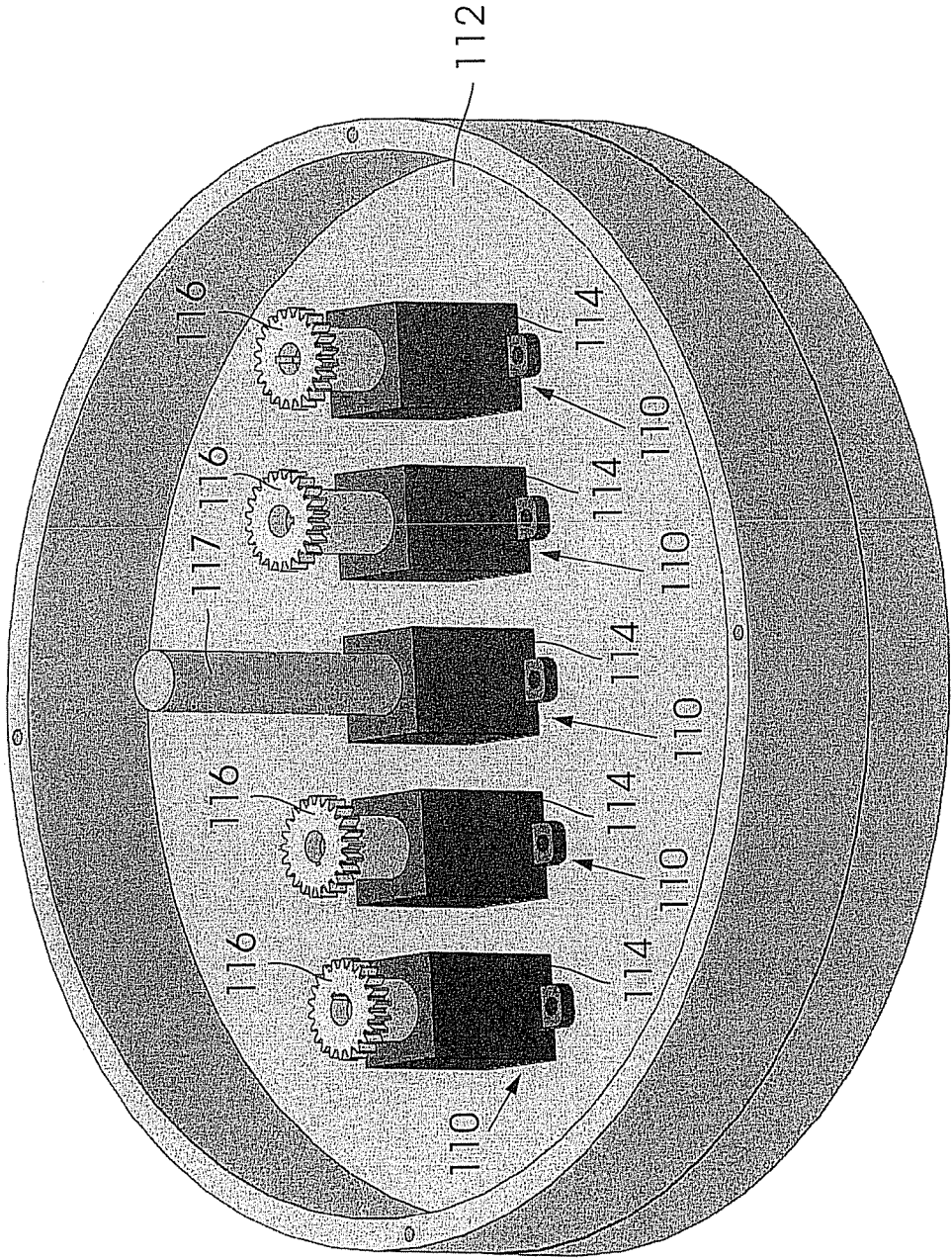


Fig. 17

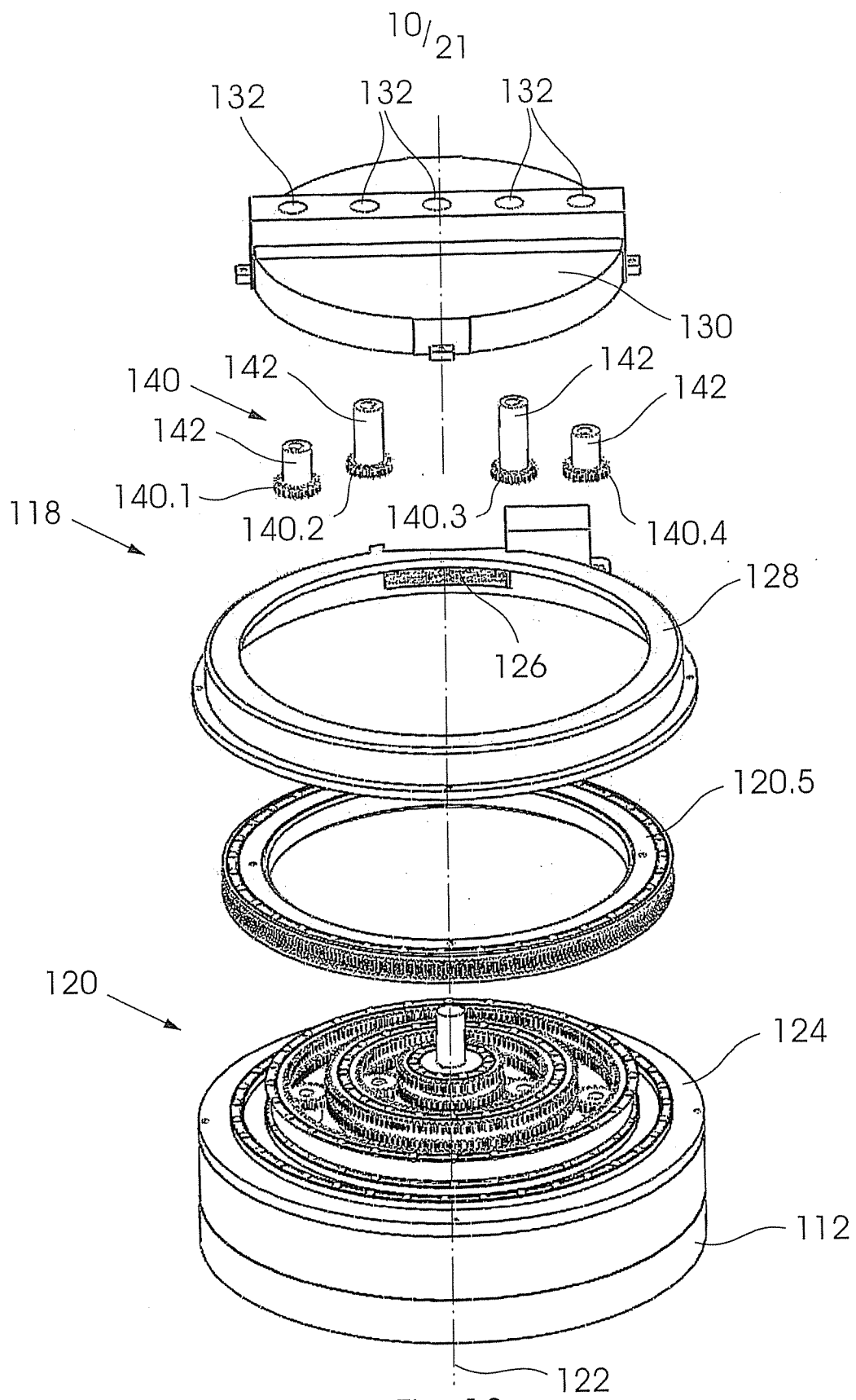


Fig. 18

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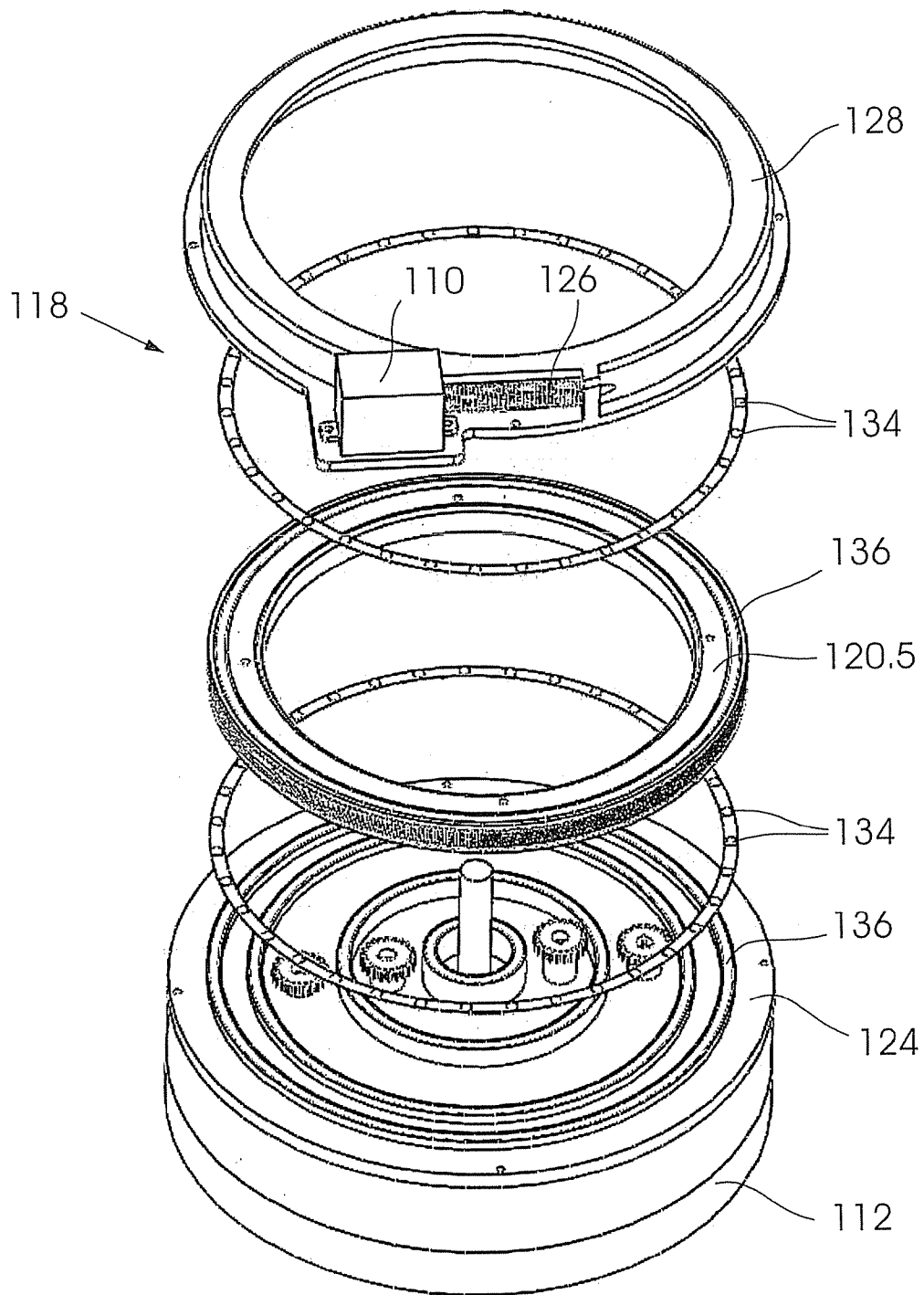


Fig. 19

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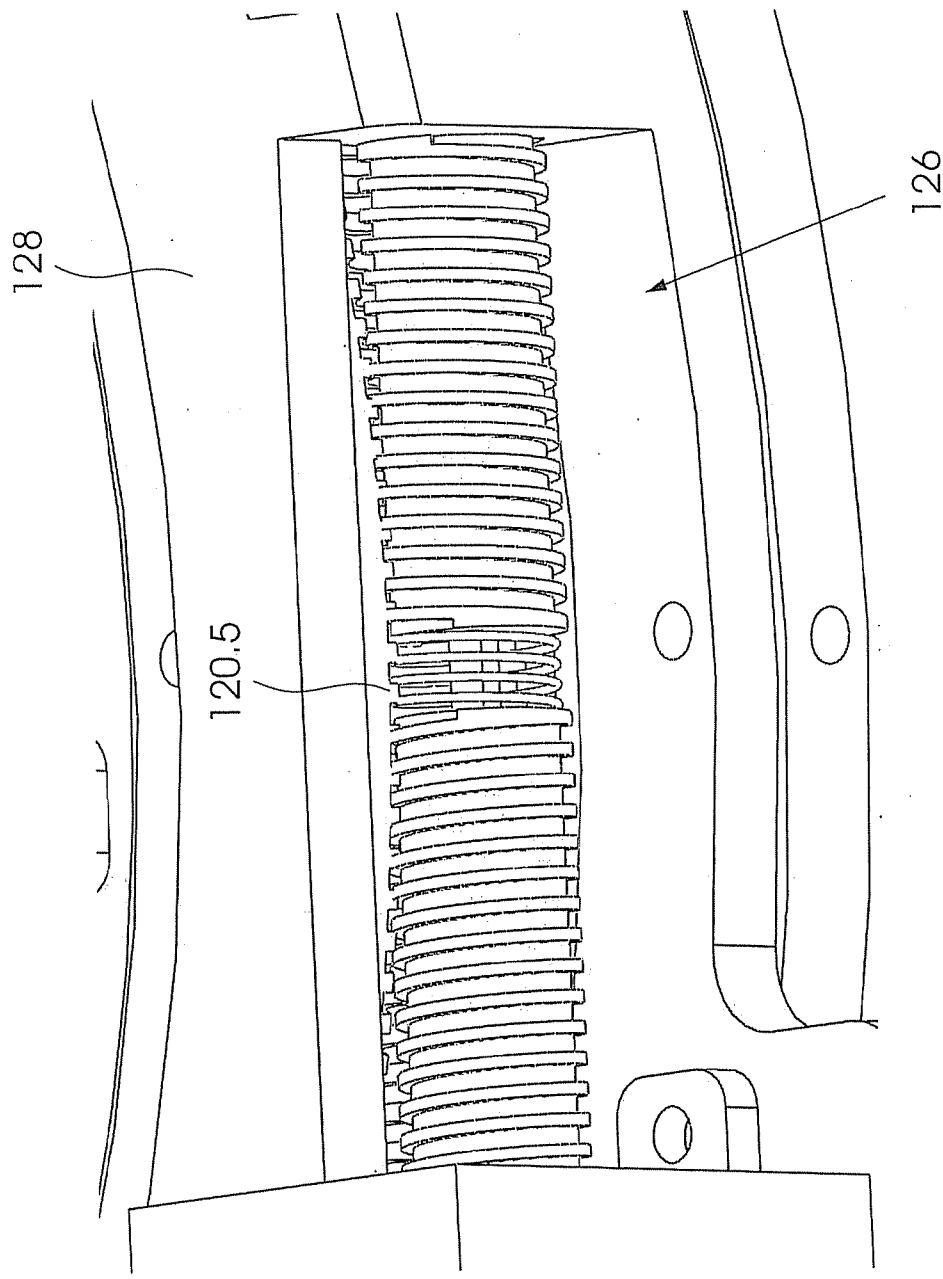


Fig. 20

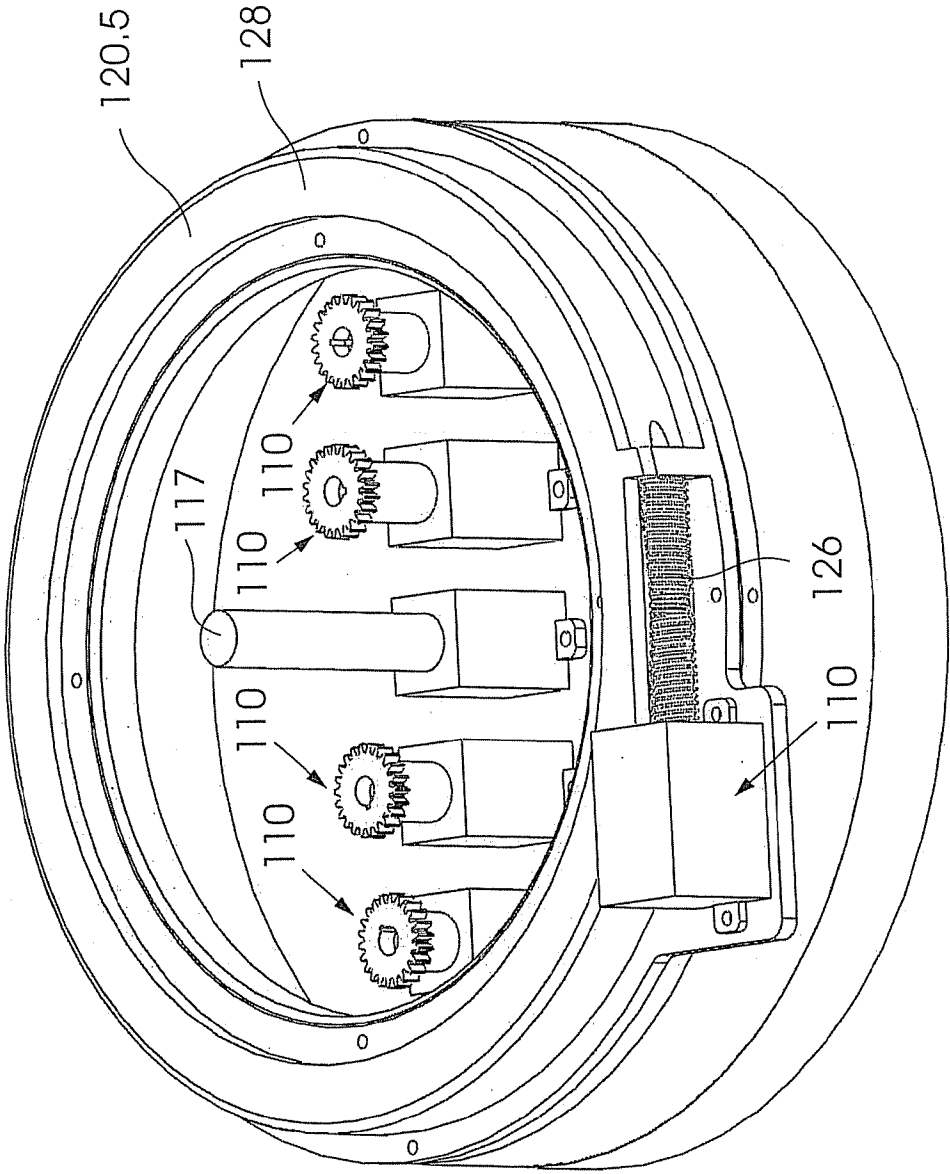


Fig. 21

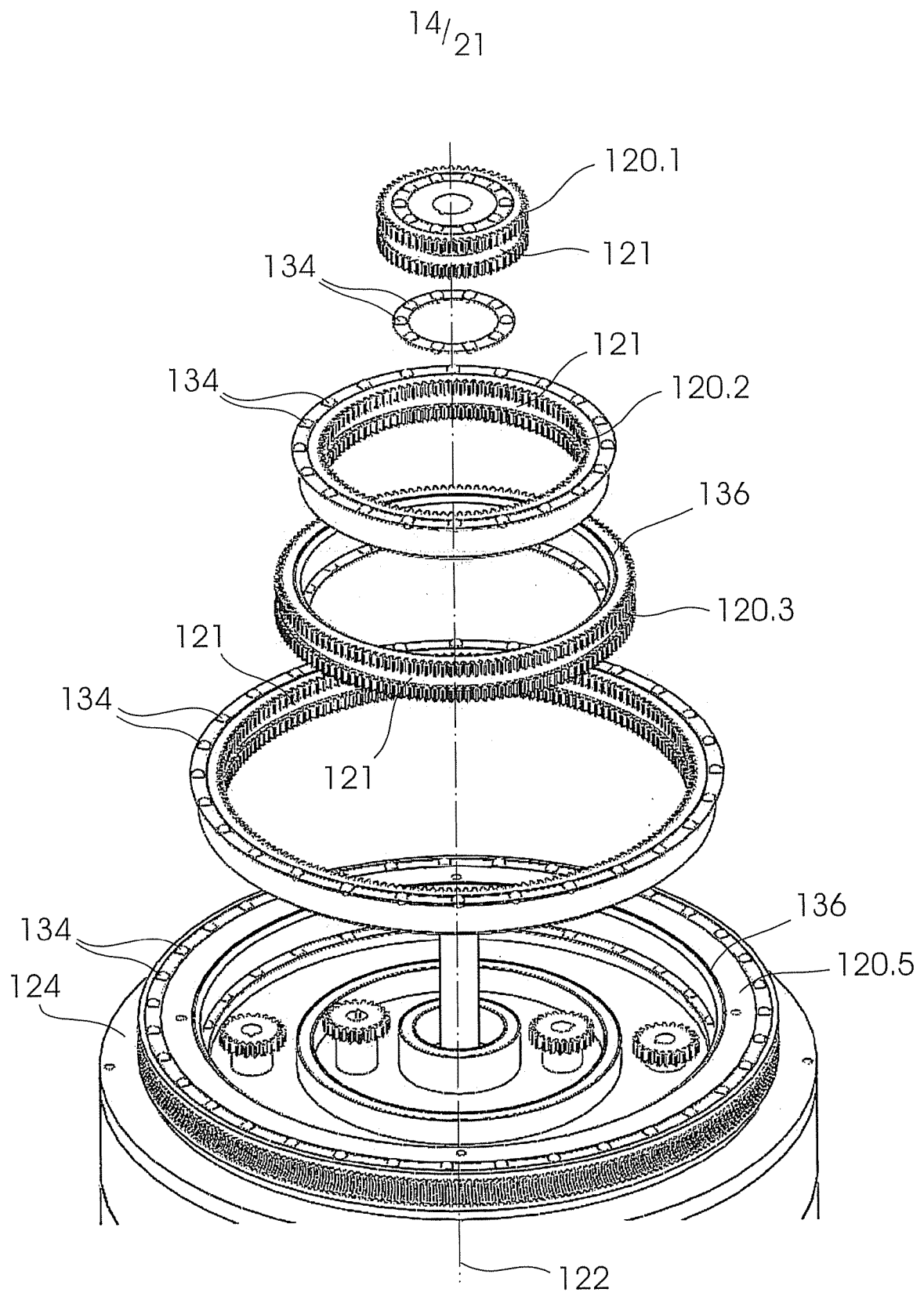


Fig. 18

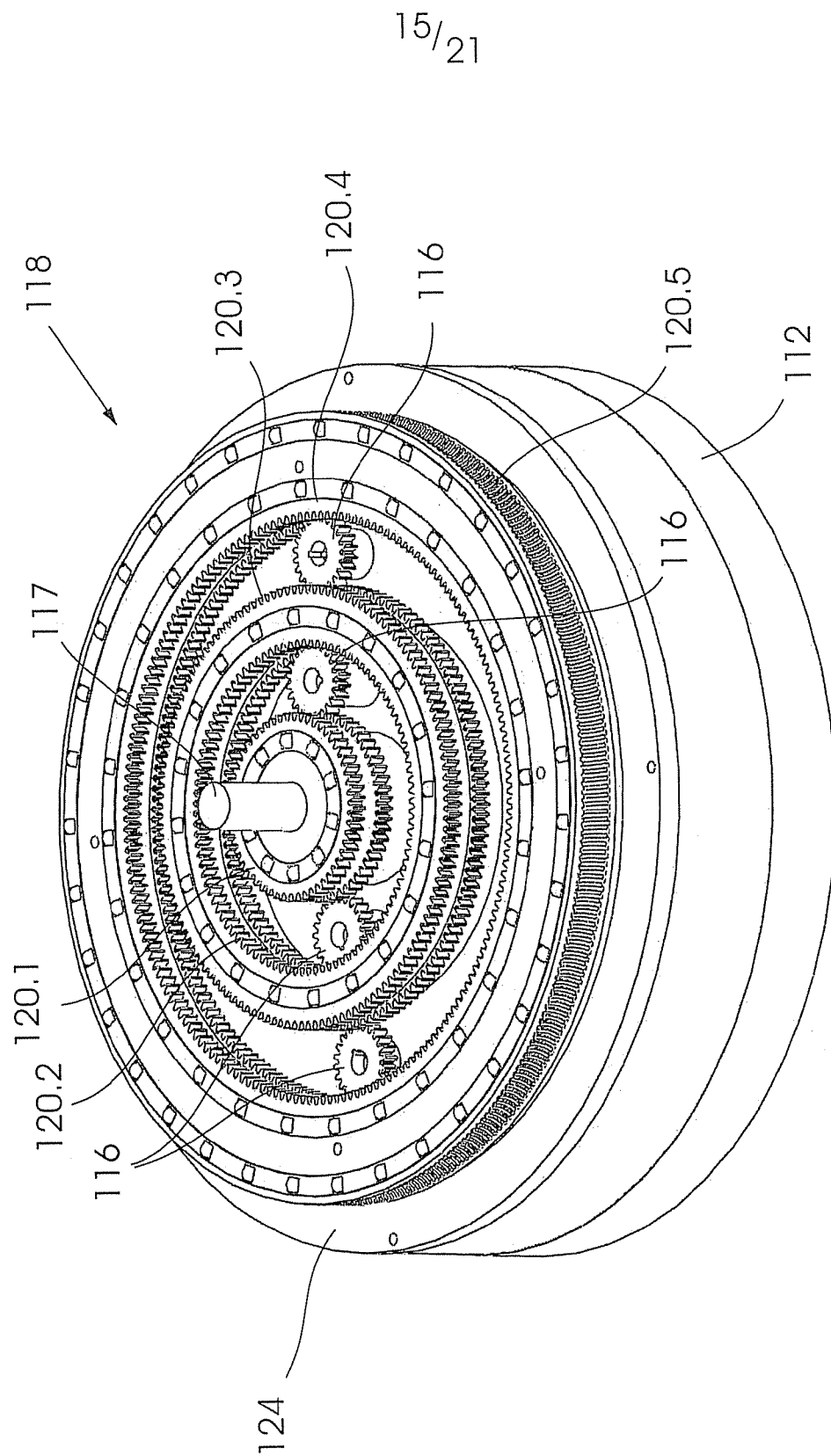


Fig. 23

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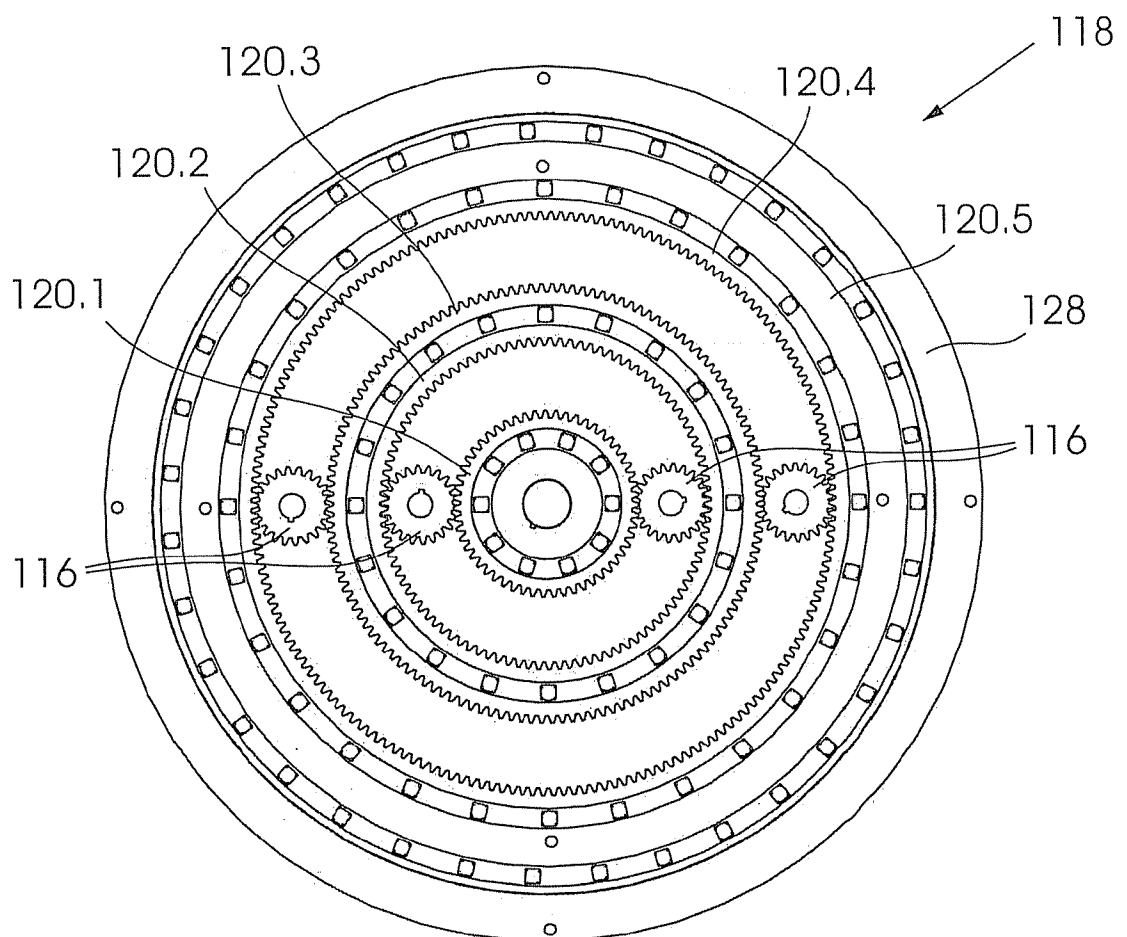


Fig. 24

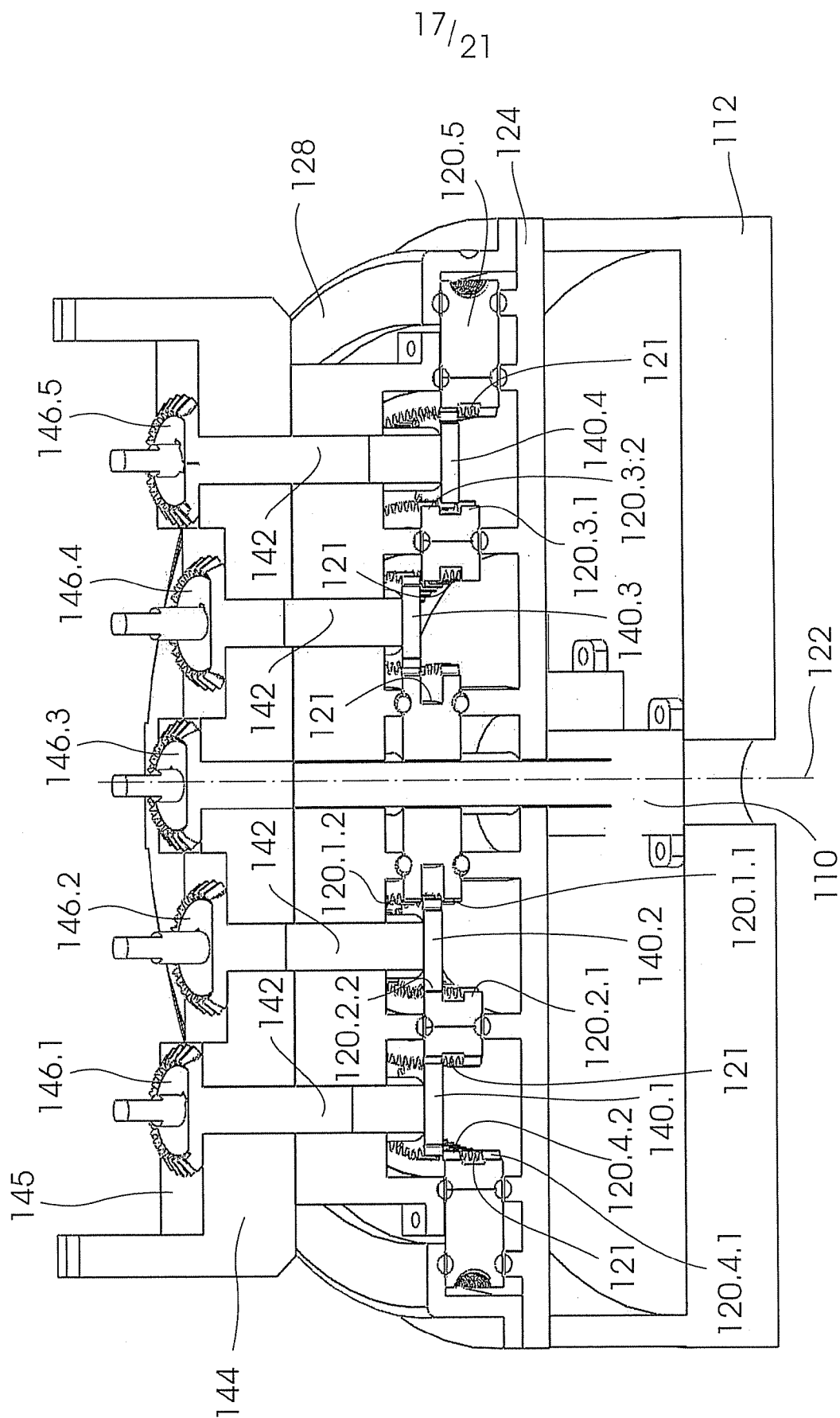


Fig. 25

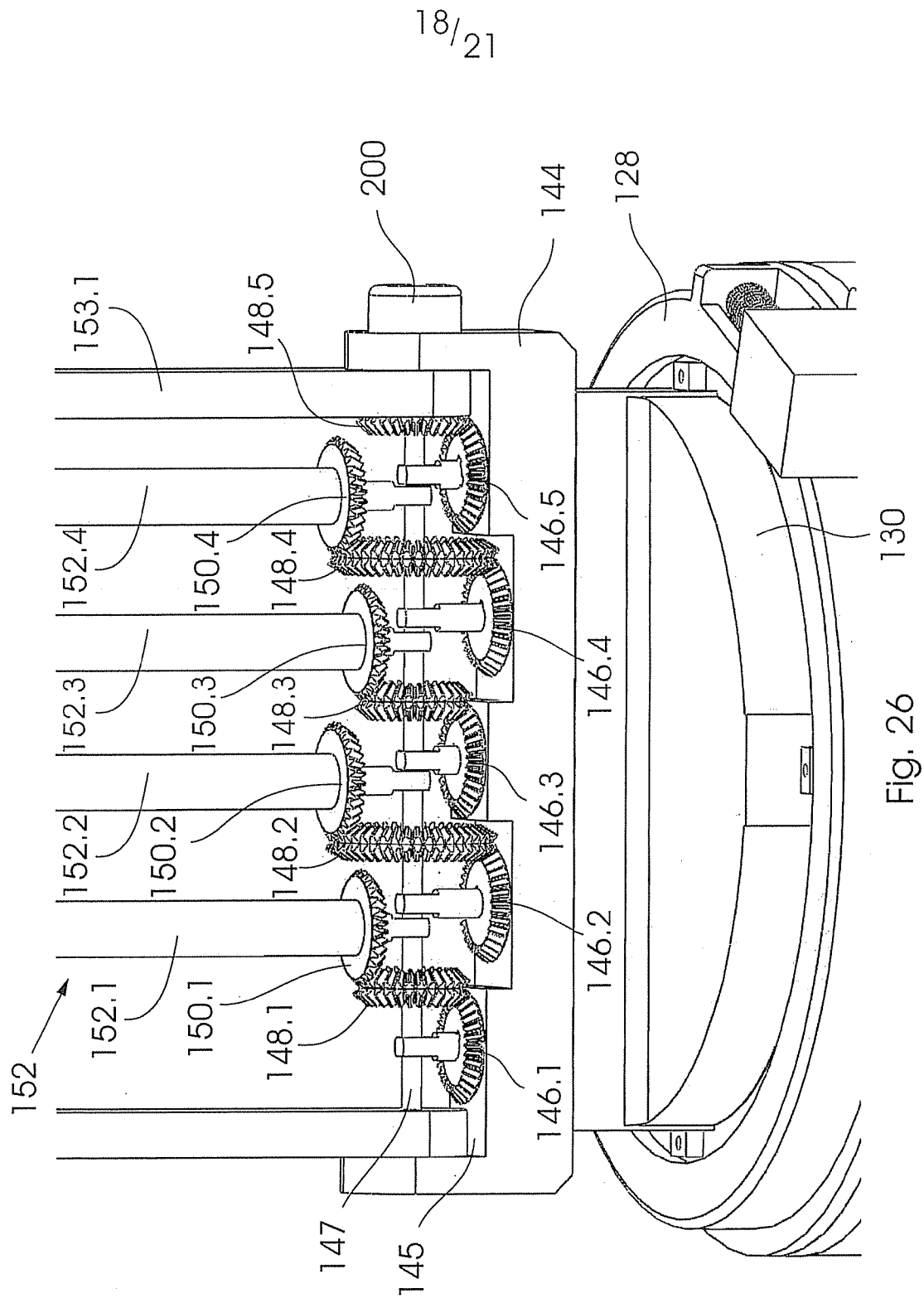


Fig. 26

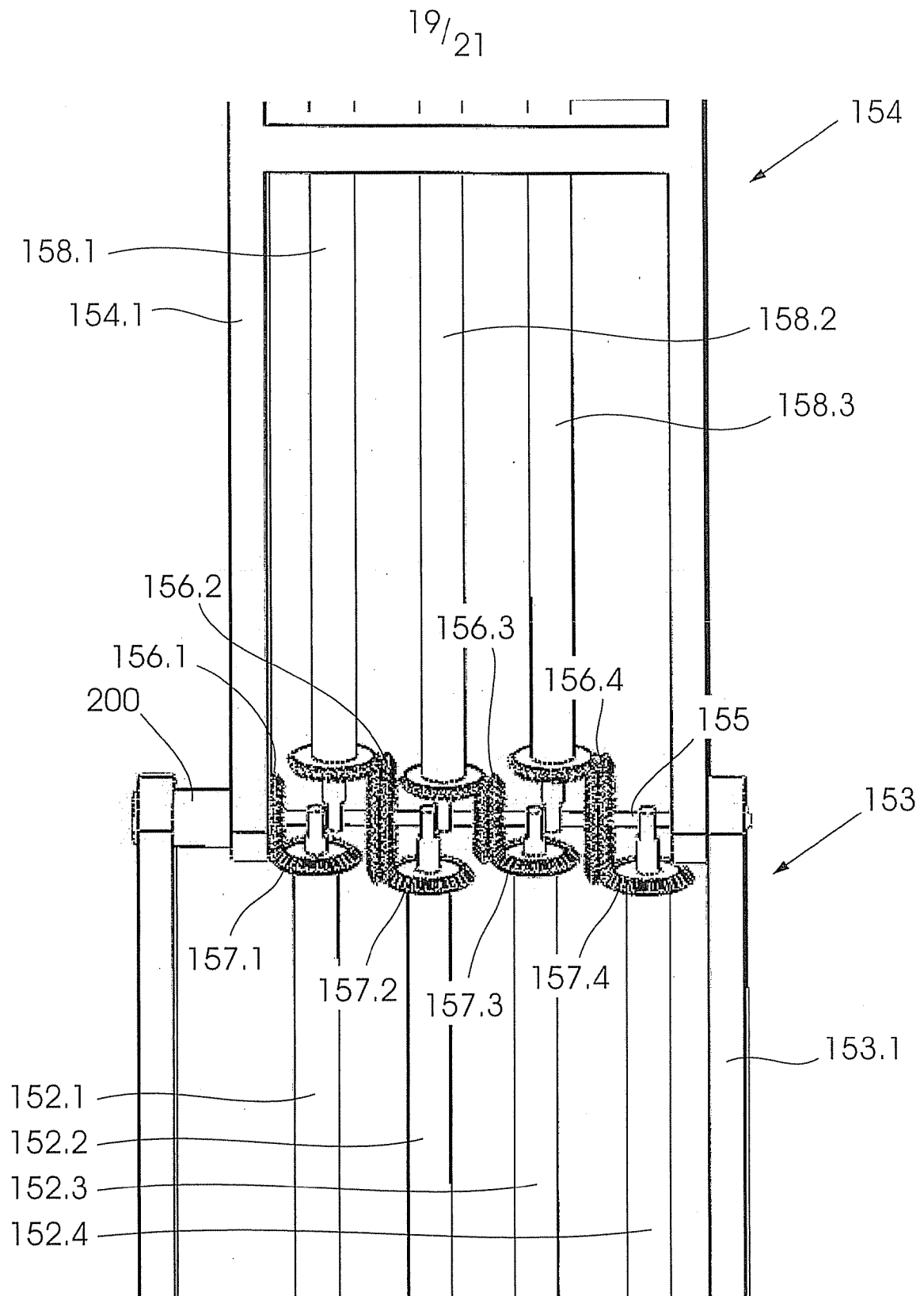


Fig. 27

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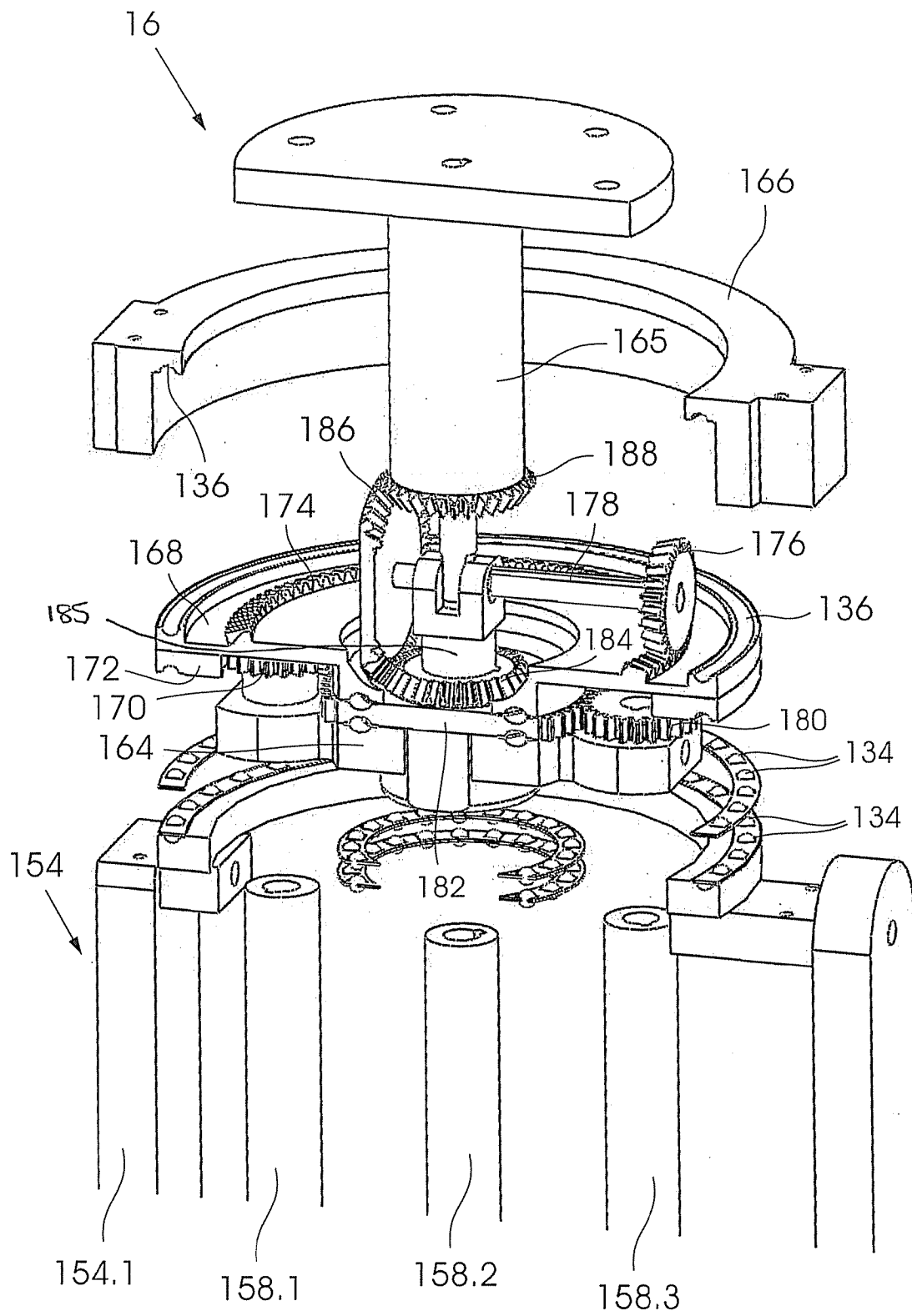


Fig. 28

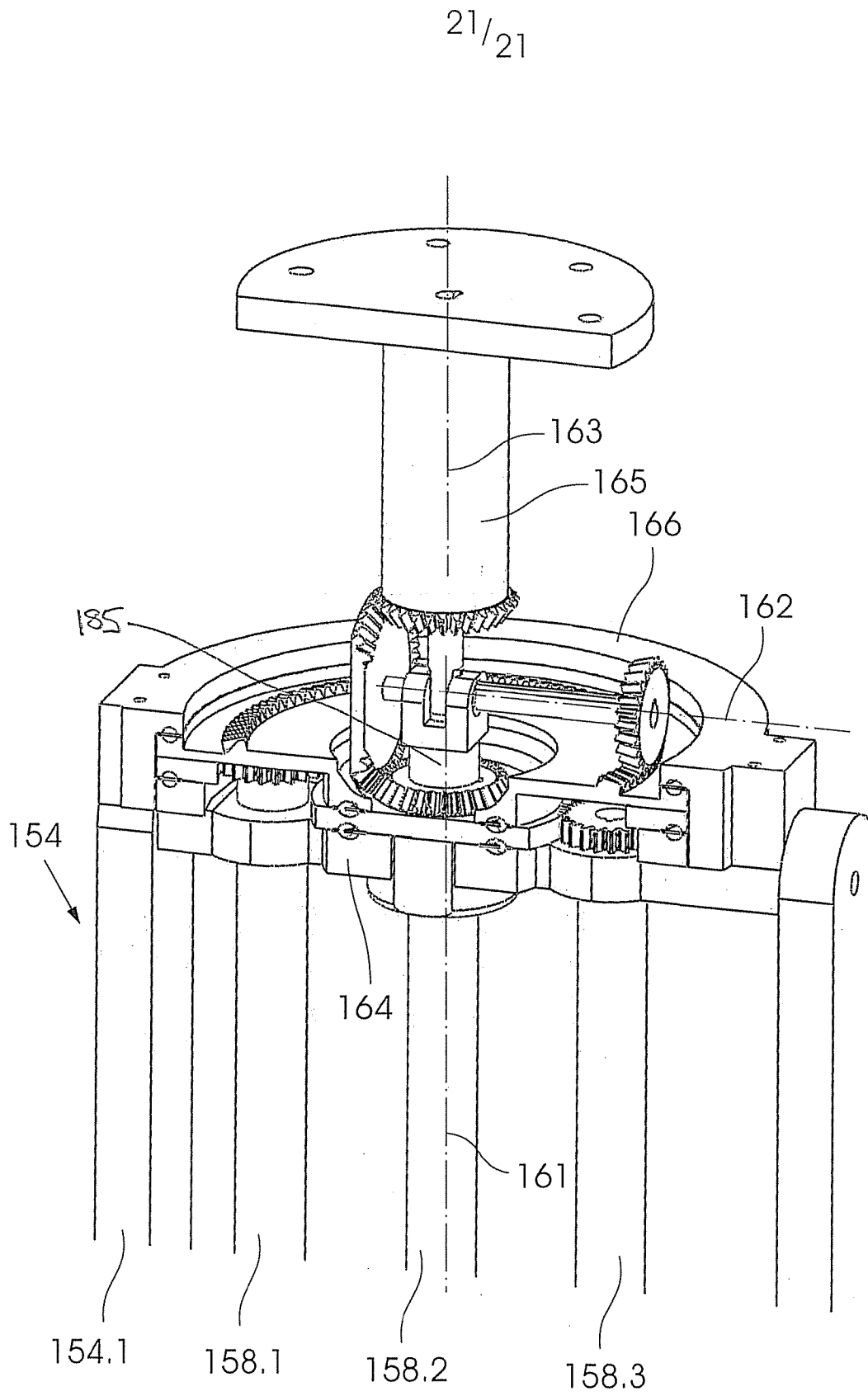


Fig. 29

INTERNATIONAL SEARCH REPORT

International application No

PCT/IB2012/050445

A. CLASSIFICATION OF SUBJECT MATTER

INV. B25J9/10

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)

B25J

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 practical, 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 A	DE 37 34 179 A1 (BUDERUS SELL [DE]) 27 April 1989 (1989-04-27) column 2, line 37 - column 4, line 35 figures 1-5	1-9, 11-21 10
X	----- EP 0 299 551 A1 (BISIACH BRUNO) 18 January 1989 (1989-01-18) column 3, line 32 - column 4, line 8 figure 1	1
X	----- US 6 593 718 B1 (YAMAZOE KATSUHIRO [JP]) 15 July 2003 (2003-07-15) column 3, line 28 - column 4, line 52 figure 2	1



Further documents are listed in the continuation of Box C.



See patent family annex.

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Date of the actual completion of the international search

12 April 2012

Date of mailing of the international search report

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Grenier, Alain

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/IB2012/050445

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