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(54) **KINEMATICS OF A MECHANICAL END EFFECTOR FOR A HUMANOID ROBOT**

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(21) Appl. No.: **19/224,252**

(22) Filed: **May 30, 2025**

Related U.S. Application Data

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(60) Provisional application No. 63/620,633, filed on Jan. 12, 2024, provisional application No. 63/561,315, filed on Mar. 5, 2024, provisional application No. 63/573,226, filed on Apr. 2, 2024.

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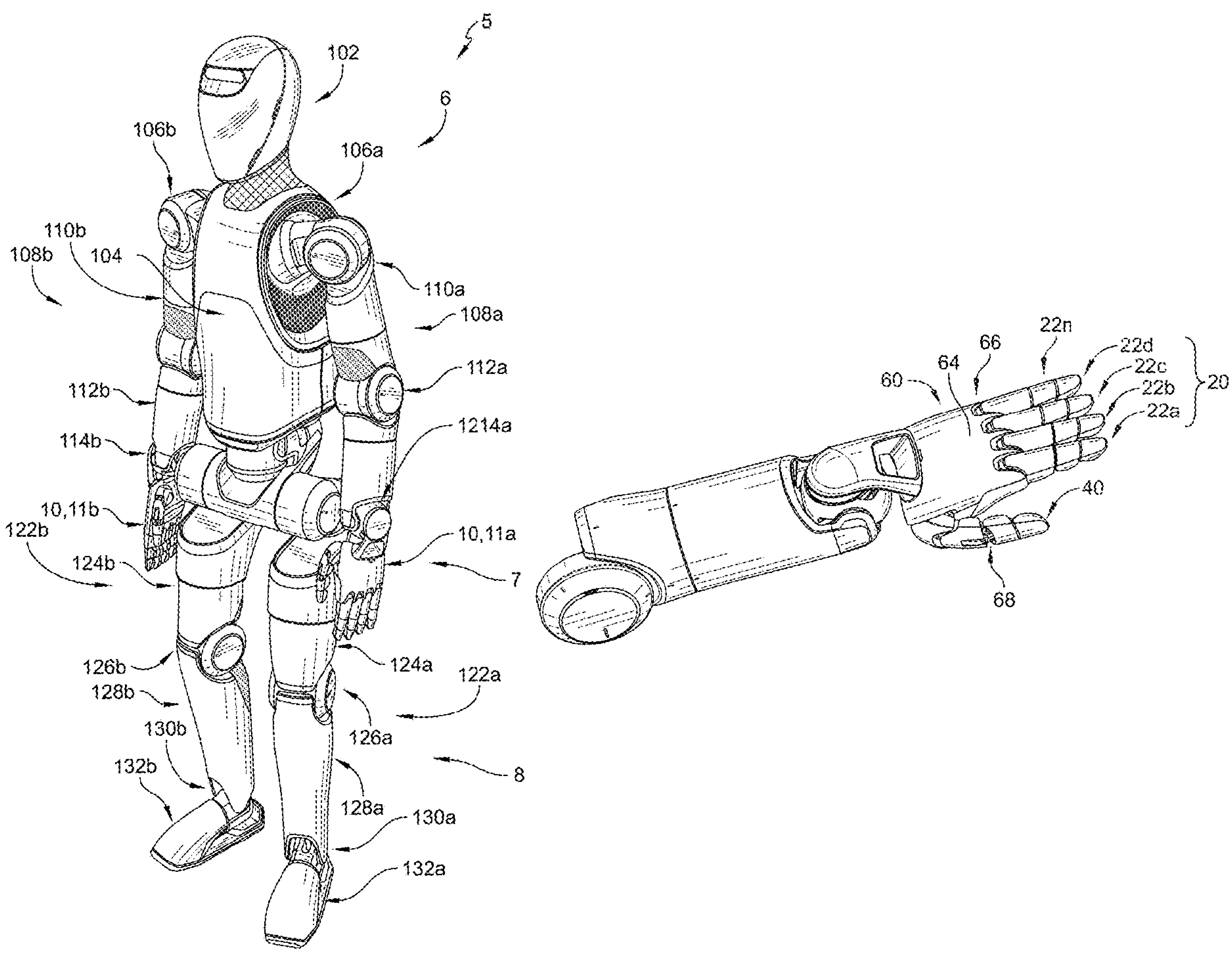
B25J 9/10	(2006.01)

(52) **U.S. Cl.**

CPC ***B25J 15/10*** (2013.01); ***B25J 9/10*** (2013.01)

(57) **ABSTRACT**

The present disclosure provides a thumb assembly for an end effector for a humanoid robot. The thumb assembly includes a digit assembly comprising a proximal assembly, a medial assembly, a distal assembly, a proximal interphalangeal joint pivotably coupling the proximal assembly to the medial assembly, and a distal interphalangeal joint pivotably coupling the distal assembly to the medial assembly. The thumb assembly also includes a motor assembly comprising a first motor and a second motor, and a gear assembly. The gear assembly includes a flexion gear configured to be driven by the first motor to cause the digit assembly to move about a second carpometacarpal joint axis, and an interposition gear configured to be driven by the second motor to cause the digit assembly to move about a first carpometacarpal joint axis.



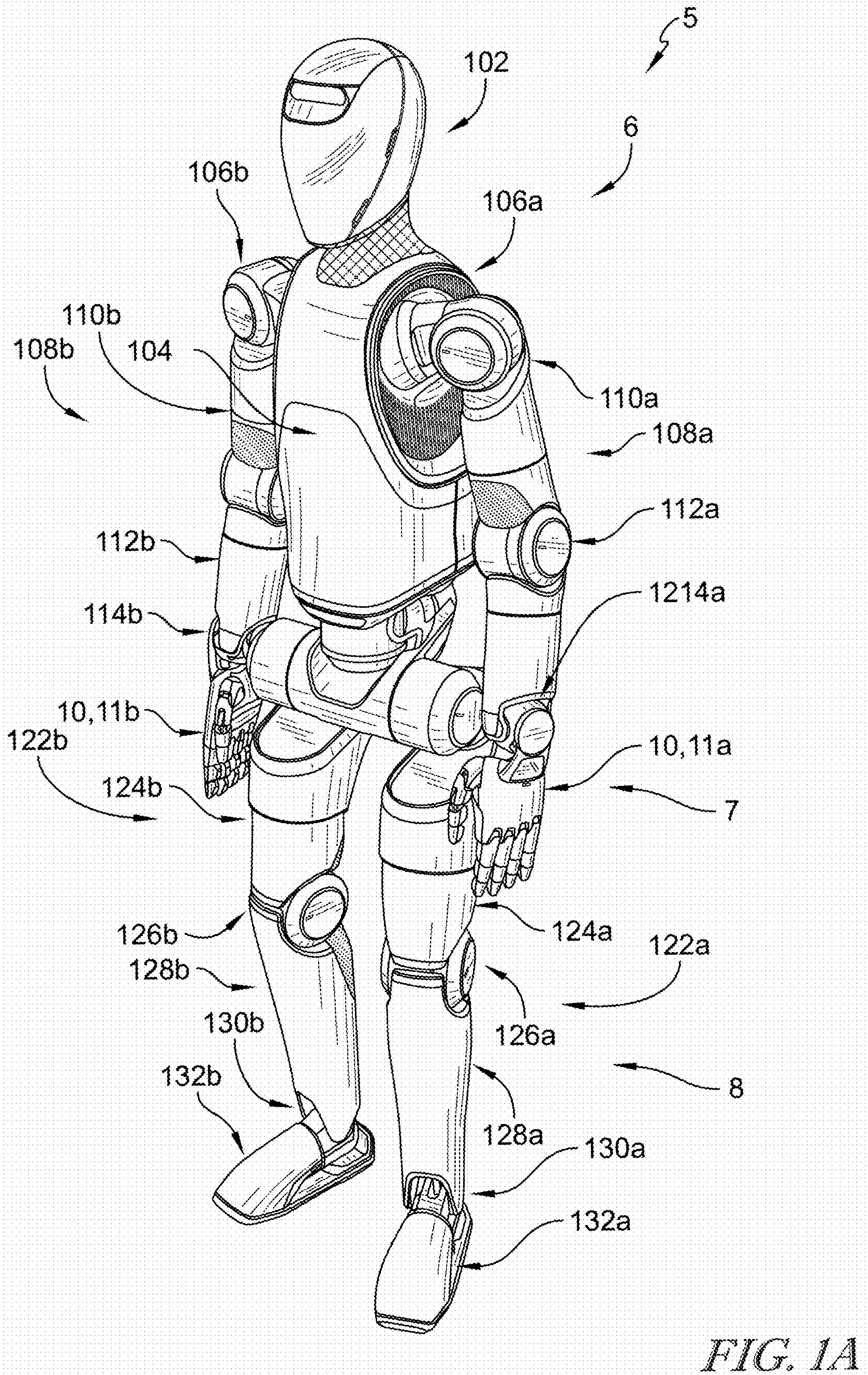

5
102
6
106b
106a
110b
108b
104
110a
108a
112a
112b
1214a
114b
10,11b
122b
10,11a
124b
7
126b
124a
122a
128b
126a
130b
8
132b
128a
130a
132a

FIG. 1A

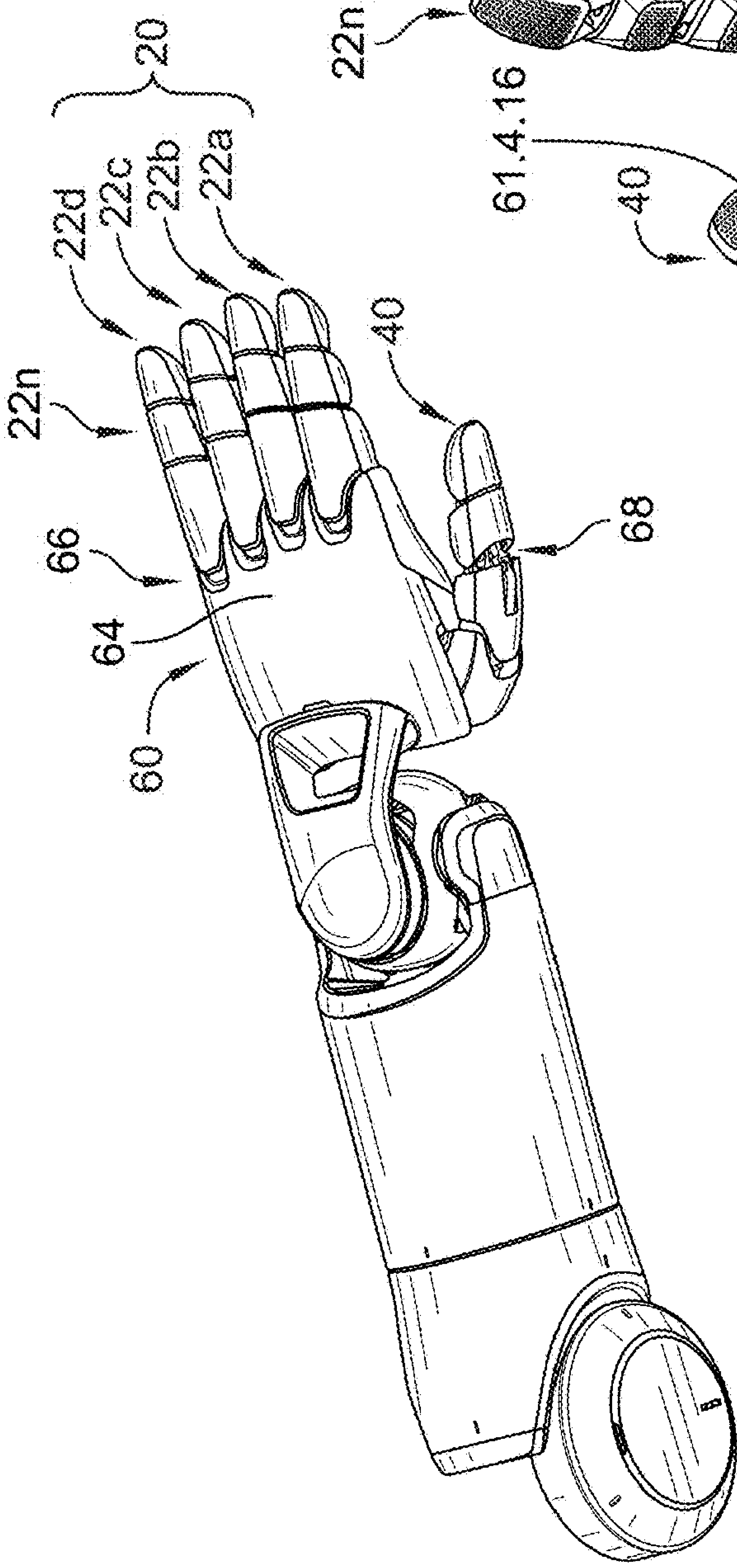

20
22d
22c
22b
22a
22n
40
66
68
64
60

FIG. 1B

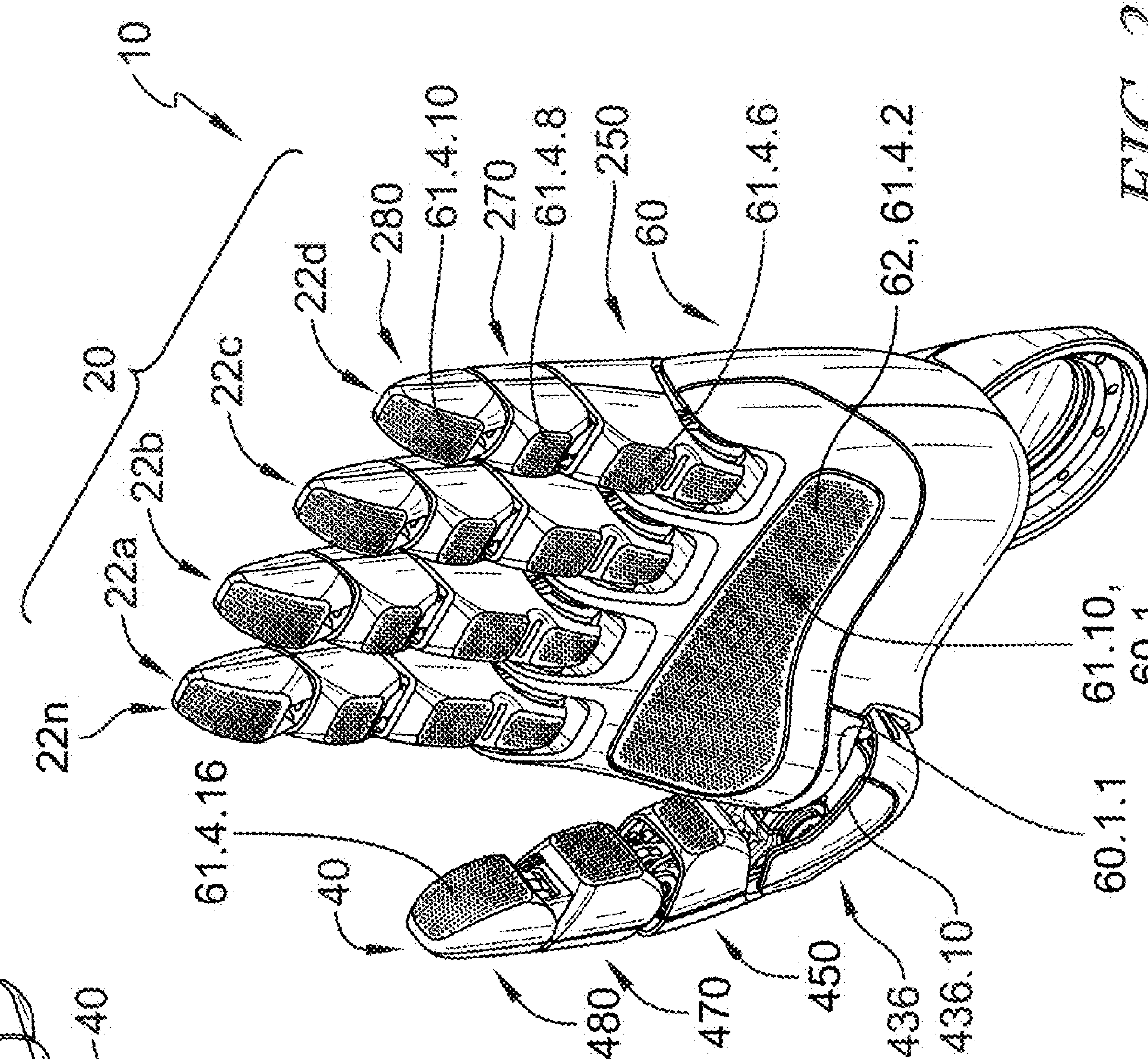

10
20
22n
22a
22a
22b
22c
22d
280
61.4.10
270
61.4.8
250
60
61.4.6
62, 61.4.2
61.10,
60.1
60.1.1
61.4.16
40
480
470
450
436
436.10

FIG. 2

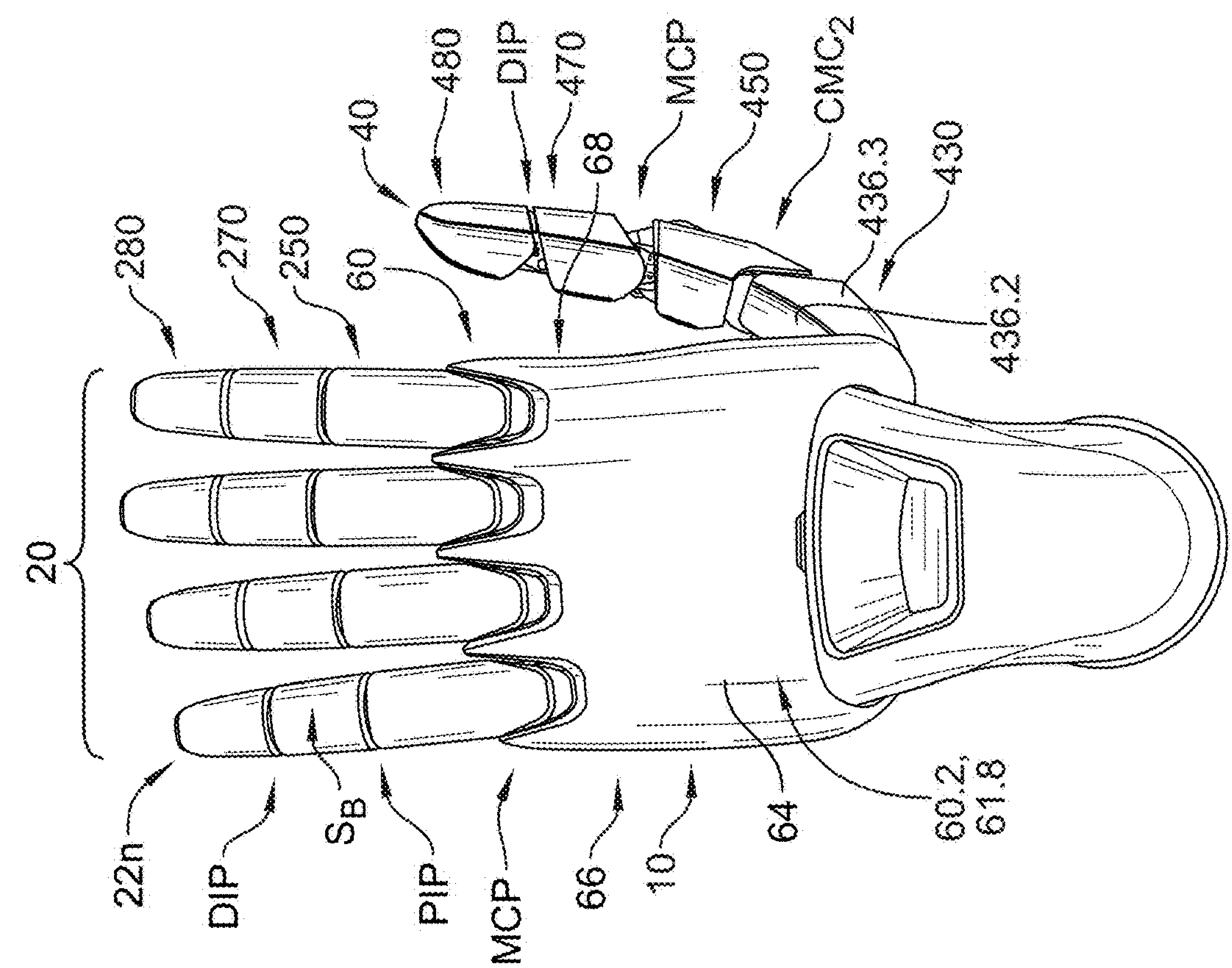

20
280
270
250
60
40
480
DIP
470
68
MCP
450
CMC$_2$
436.3
430
436.2
22n
DIP
S_B
PIP
MCP
66
10
64
60.2,
61.8

FIG. 4

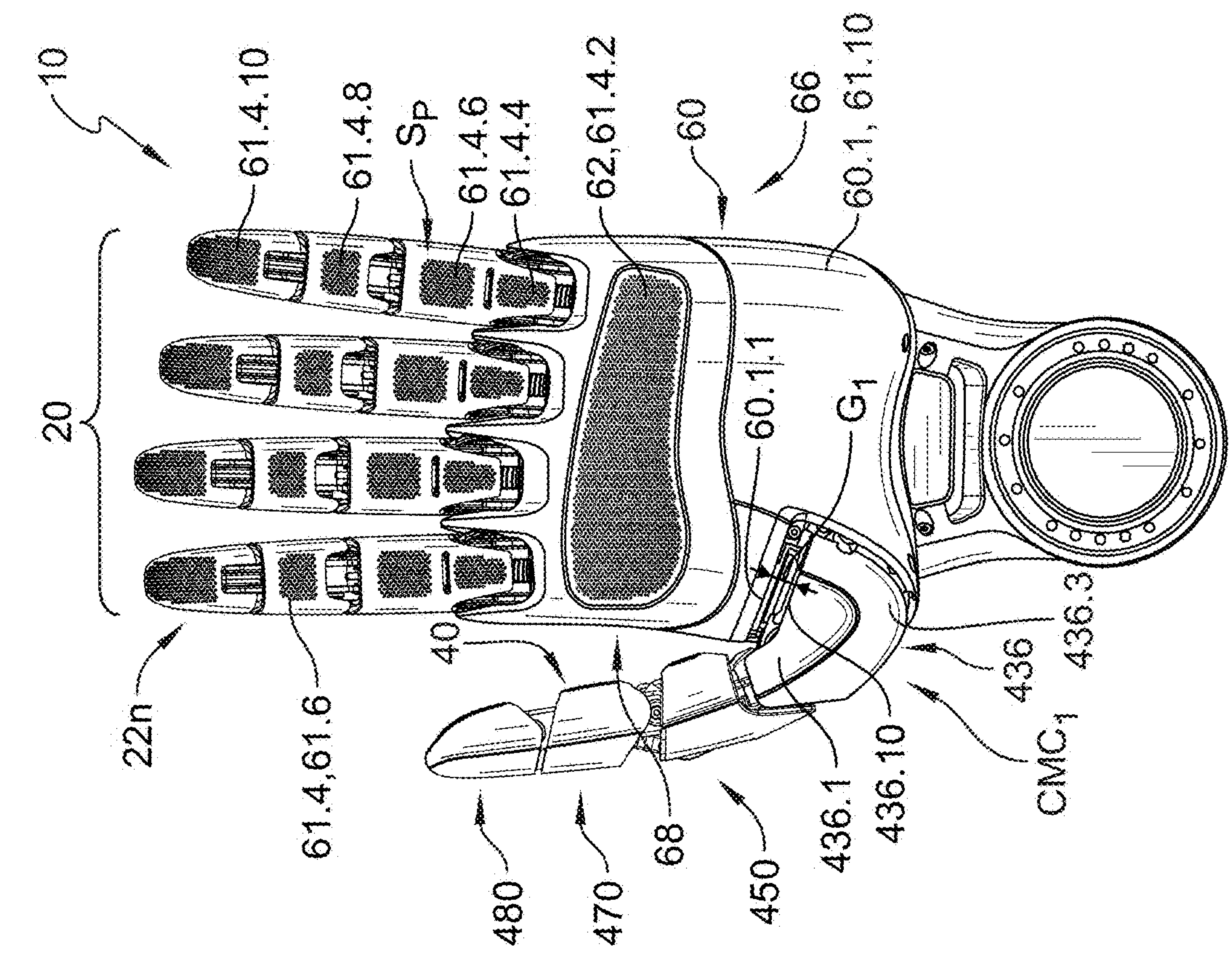

10
20
22n
61.4.10
61.4.8
S_P
61.4.6
61.4.4
62,61.4.2
60
66
60.1, 61.10
60.1.1
G_1
40
61.4,61.6
480
470
68
450
436.1
436.10
CMC$_1$
436
436.3

FIG. 3

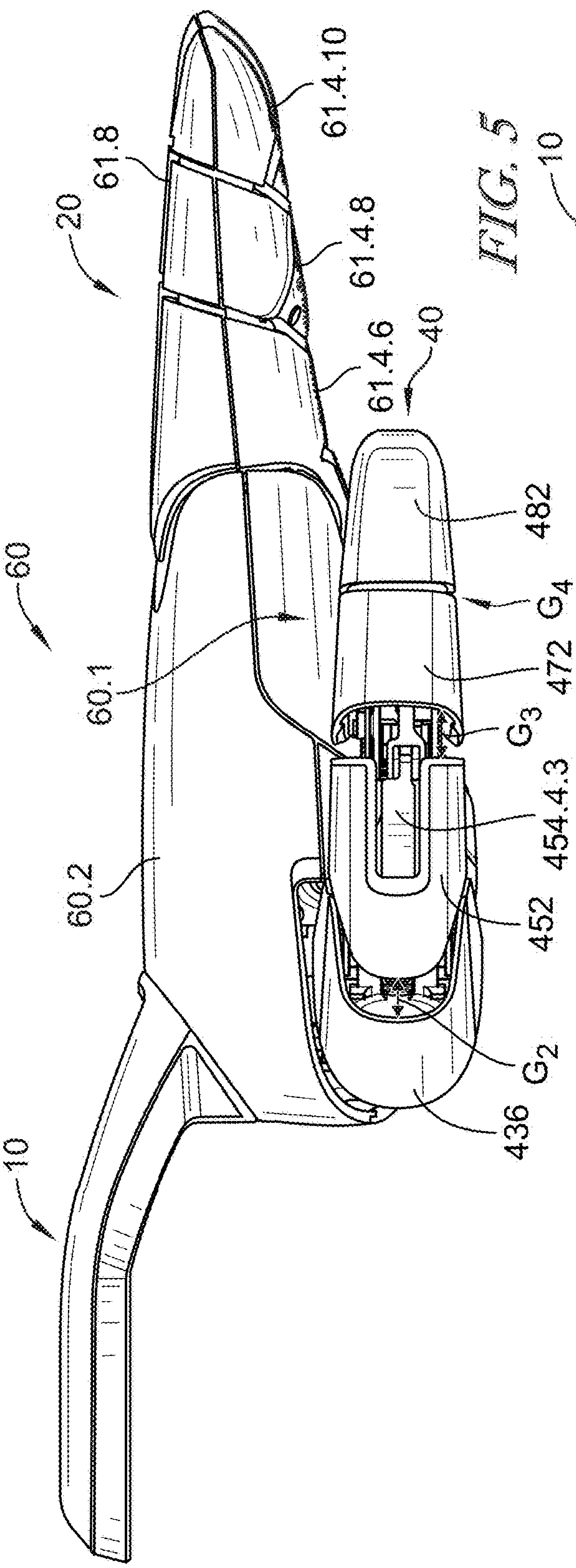

10
20
60
60.1
60.2
61.8
61.4.10
61.4.8
61.4.6
40
482
G_4
472
G_3
454.4.3
452
G_2
436

FIG. 5

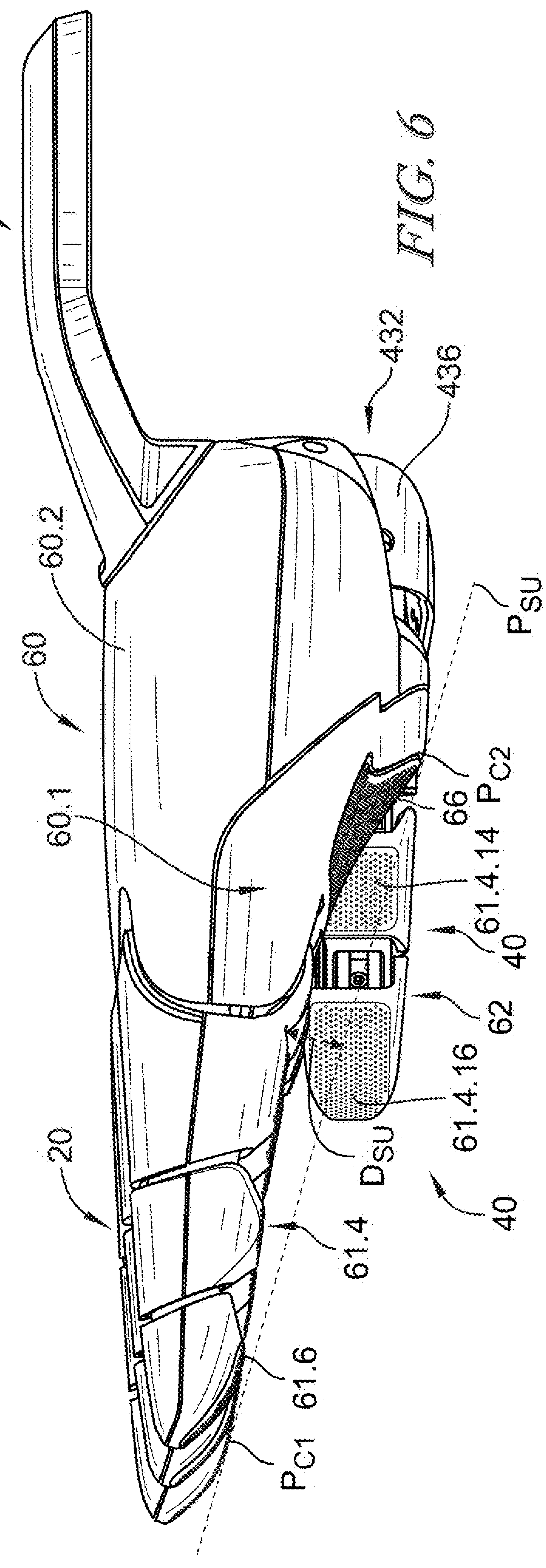

10
432
436
60.2
60
P_{SU}
60.1
P_{C2}
66
61.4.14
40
62
61.4.16
D_{SU}
20
61.4
40
61.6
P_{C1}

FIG. 6

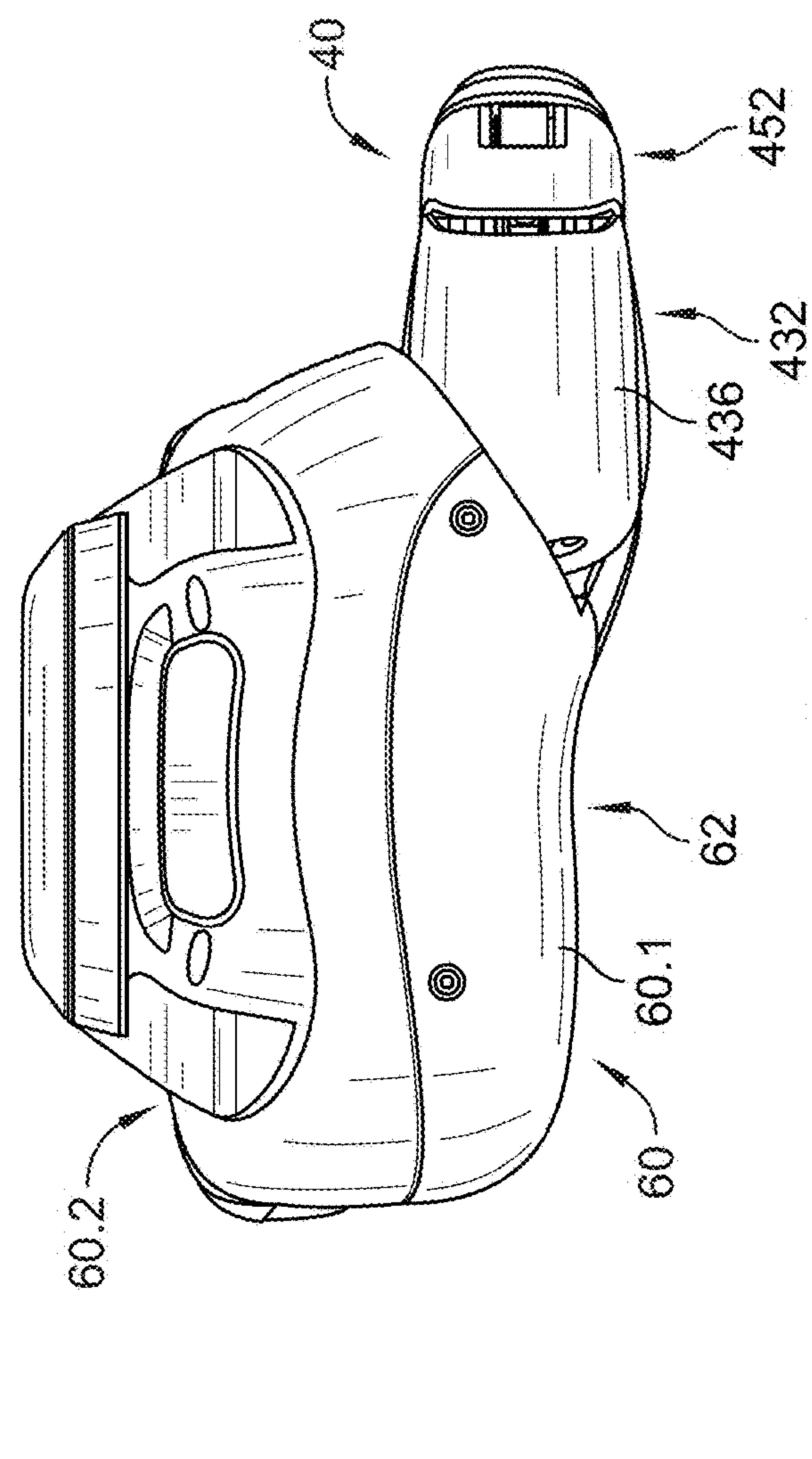

10
40
452
432
436
62
60.1
60
60.2

FIG. 7

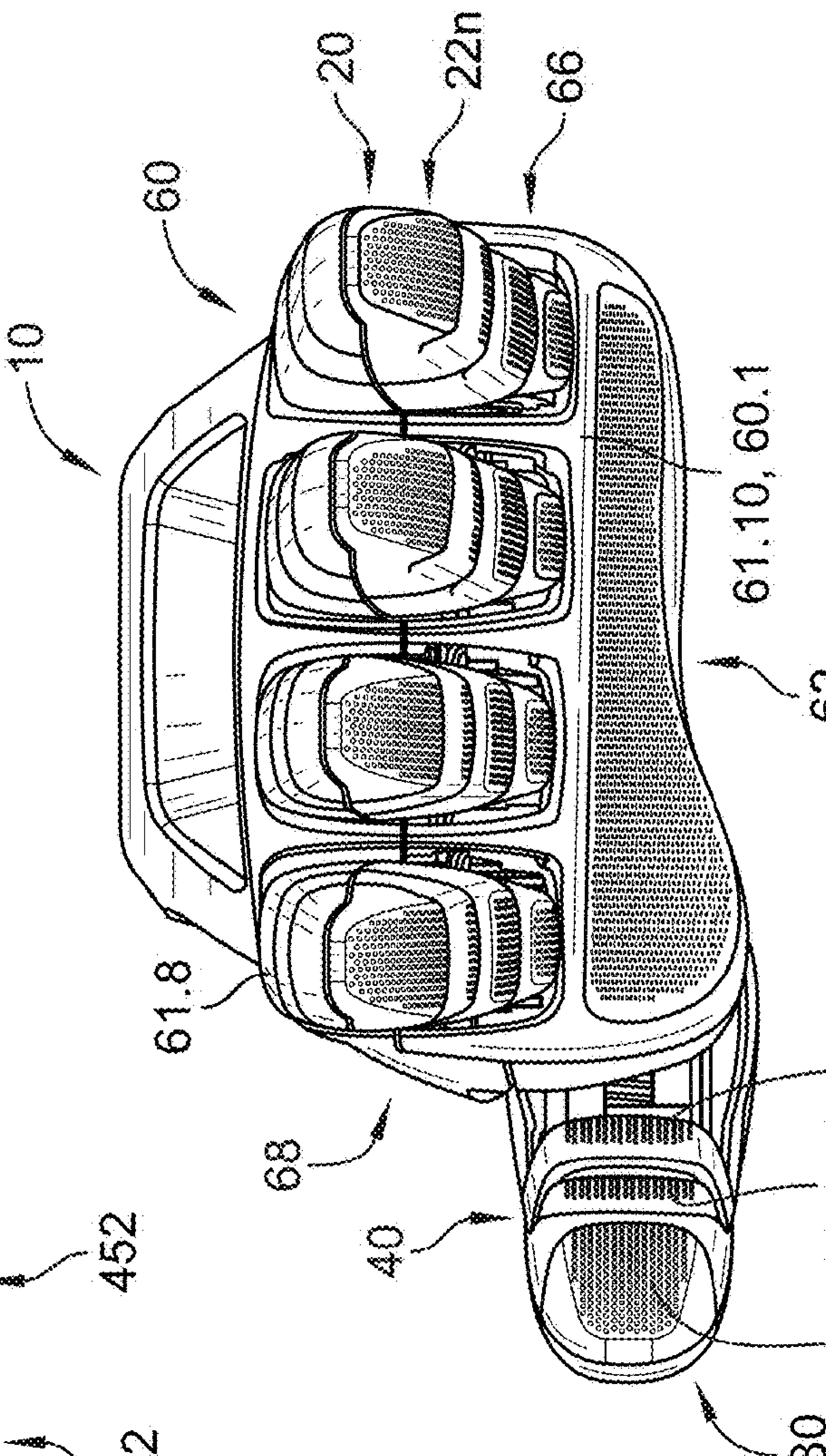

10
60
20
22n
66
61.10, 60.1
62
61.8
68
40
61.4.12
61.4.14
61.4.16
480

FIG. 8

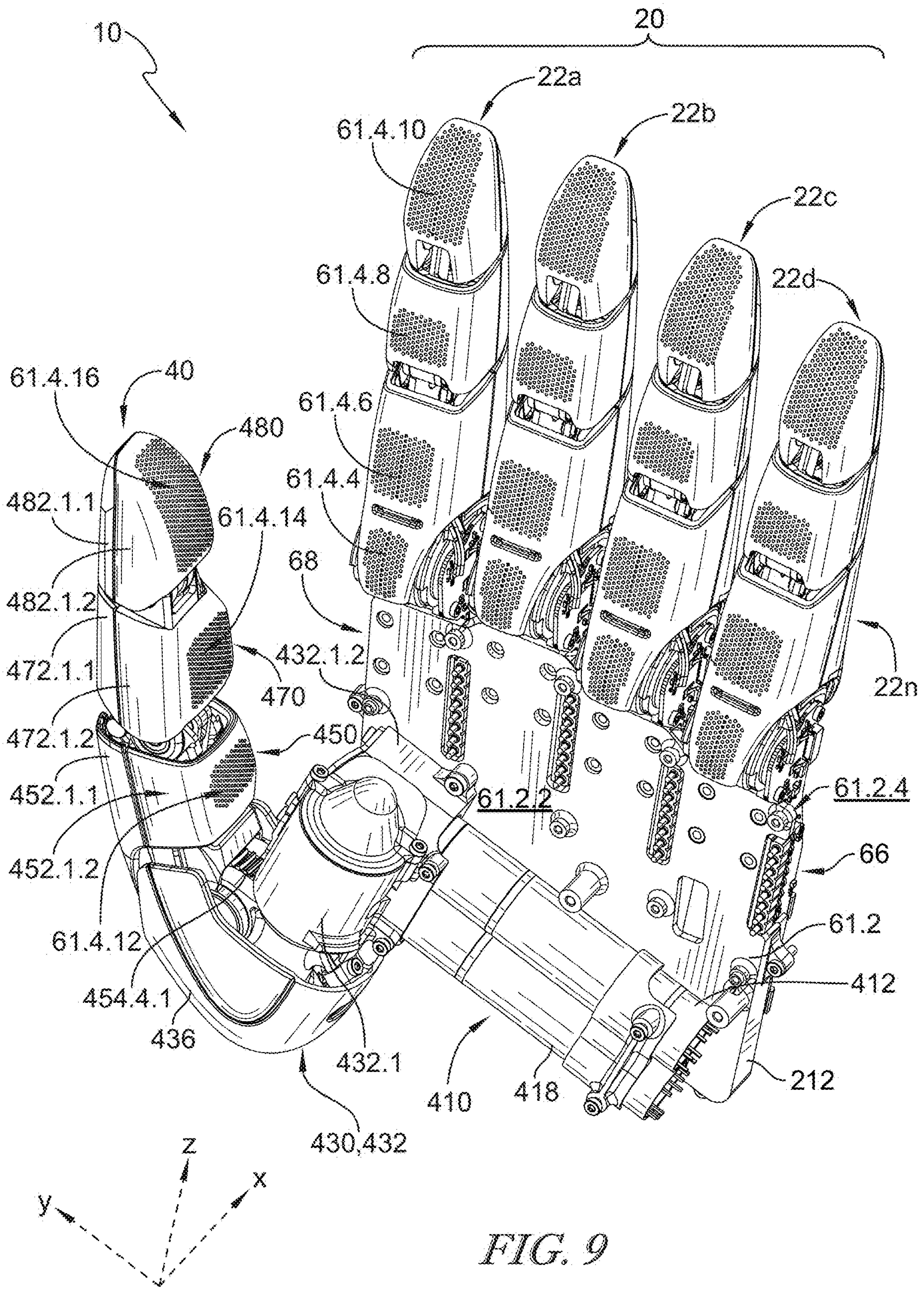

10
20
22a
22b
22c
22d
22n
61.4.10
61.4.8
61.4.6
61.4.4
61.4.16
40
480
482.1.1
61.4.14
482.1.2
472.1.1
470
472.1.2
450
452.1.1
452.1.2
61.4.12
454.4.1
436
432.1
430,432
410
418
212
412
61.2
66
61.2.4
61.2.2
432.1.2
68
z
x
y

FIG. 9

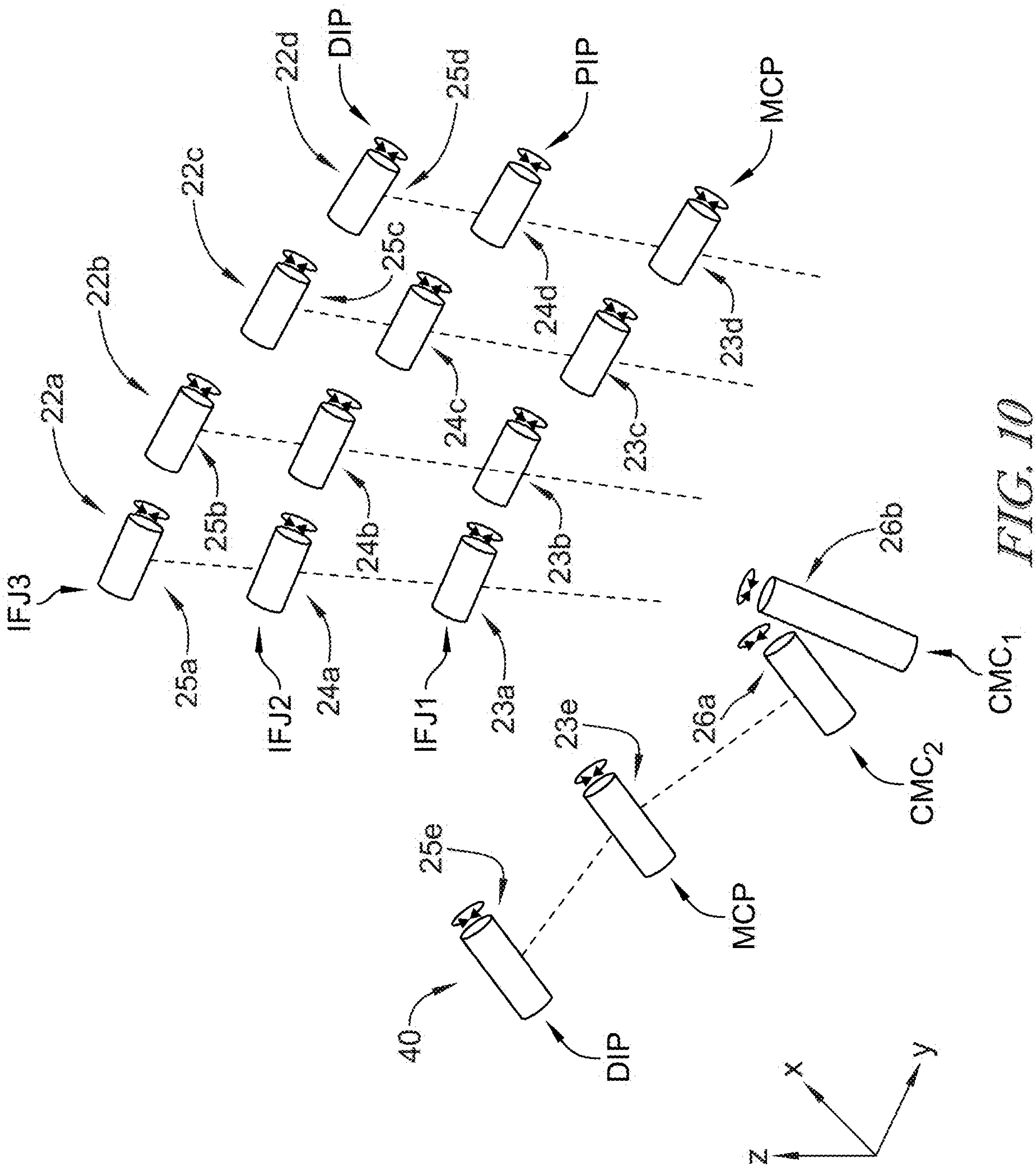
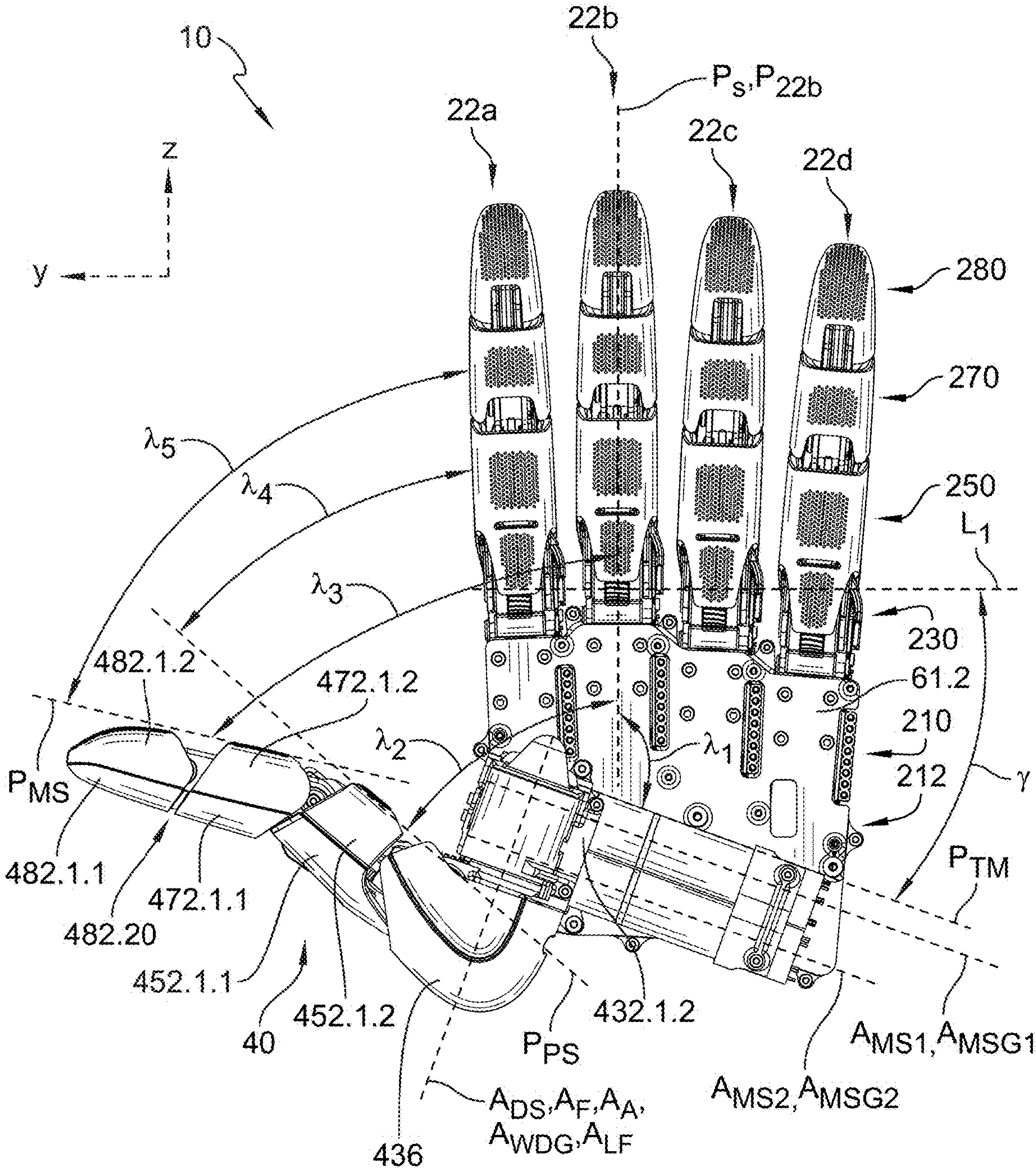

22d
DIP
25d
PIP
MCP
22c
25c
24d
23d
22b
24c
23c
22a
25b
24b
23b
IFJ3
25a
IFJ2
24a
IFJ1
23a
26b
CMC1
26a
CMC2
23e
MCP
25e
40
DIP
x
y
z

FIG. 10



10
22b
Ps,P22b
22a
22c
22d
z
y
280
270
λ5
λ4
250
L1
λ3
230
482.1.2
472.1.2
61.2
210
λ2
λ1
PMS
212
γ
482.1.1
PTM
472.1.1
482.20
452.1.1
452.1.2
432.1.2
AMS1,AMSG1
40
PPS
ADS,AF,AA,
AWDG,ALF
AMS2,AMSG2
436

FIG. 11

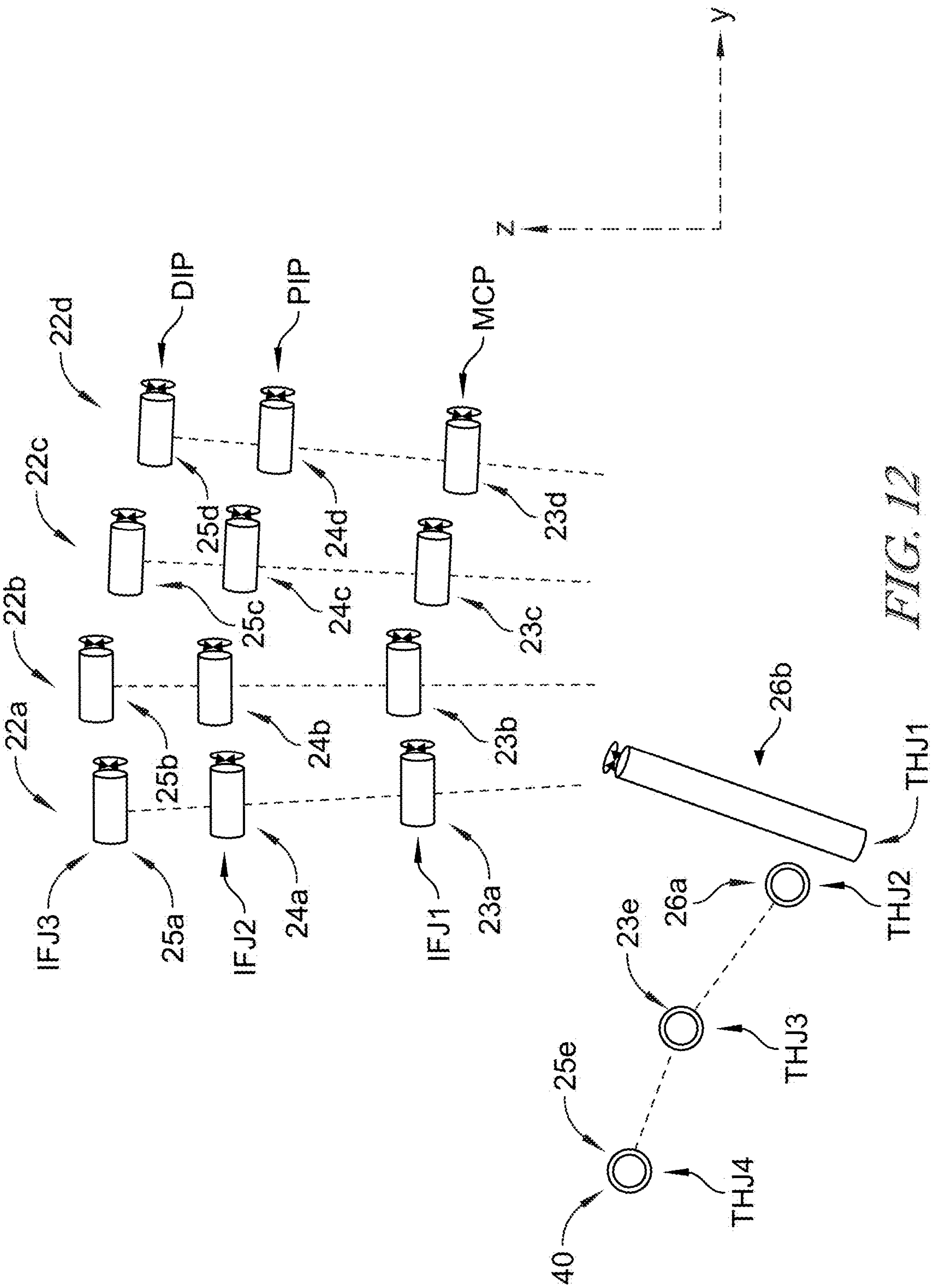

y
z
22a
22b
22c
22d
DIP
PIP
MCP
25d
24d
23d
25c
24c
23c
25b
24b
23b
IFJ3
25a
IFJ2
24a
IFJ1
23a
26b
THJ1
26a
THJ2
23e
THJ3
25e
THJ4
40

FIG. 12

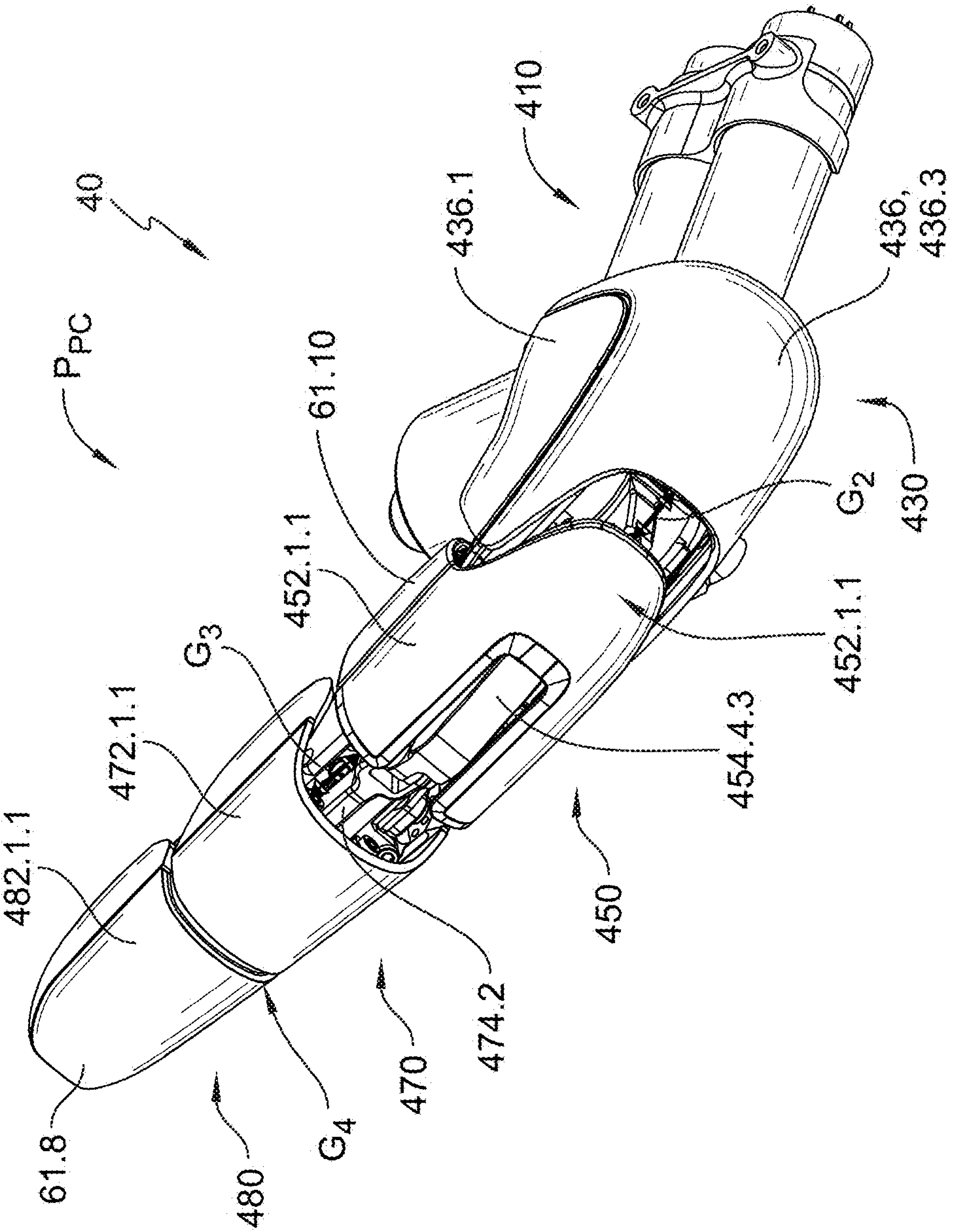

40
P_{PC}
410
436.1
436,
436.3
430
G_2
61.10
452.1.1
452.1.1
454.4.3
450
G_3
472.1.1
474.2
470
482.1.1
G_4
61.8
480

FIG. 13

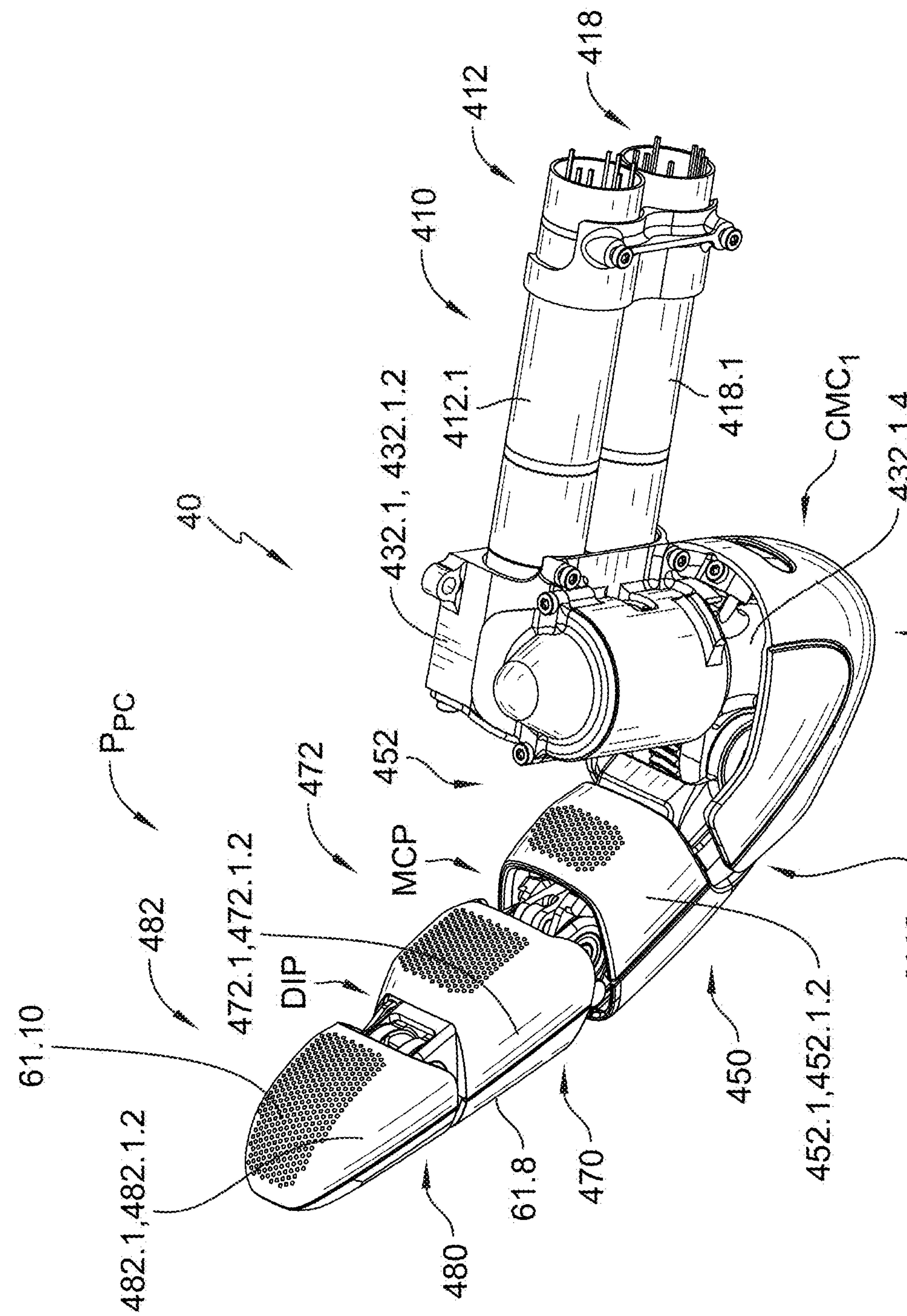

40
410
412
418
412.1
418.1
432.1, 432.1.2
432.1.4
CMC_1
430
452
472
P_{PC}
MCP
472.1,472.1.2
482
DIP
61.10
482.1,482.1.2
480
61.8
470
450
452.1,452.1.2
CMC_2

FIG. 14

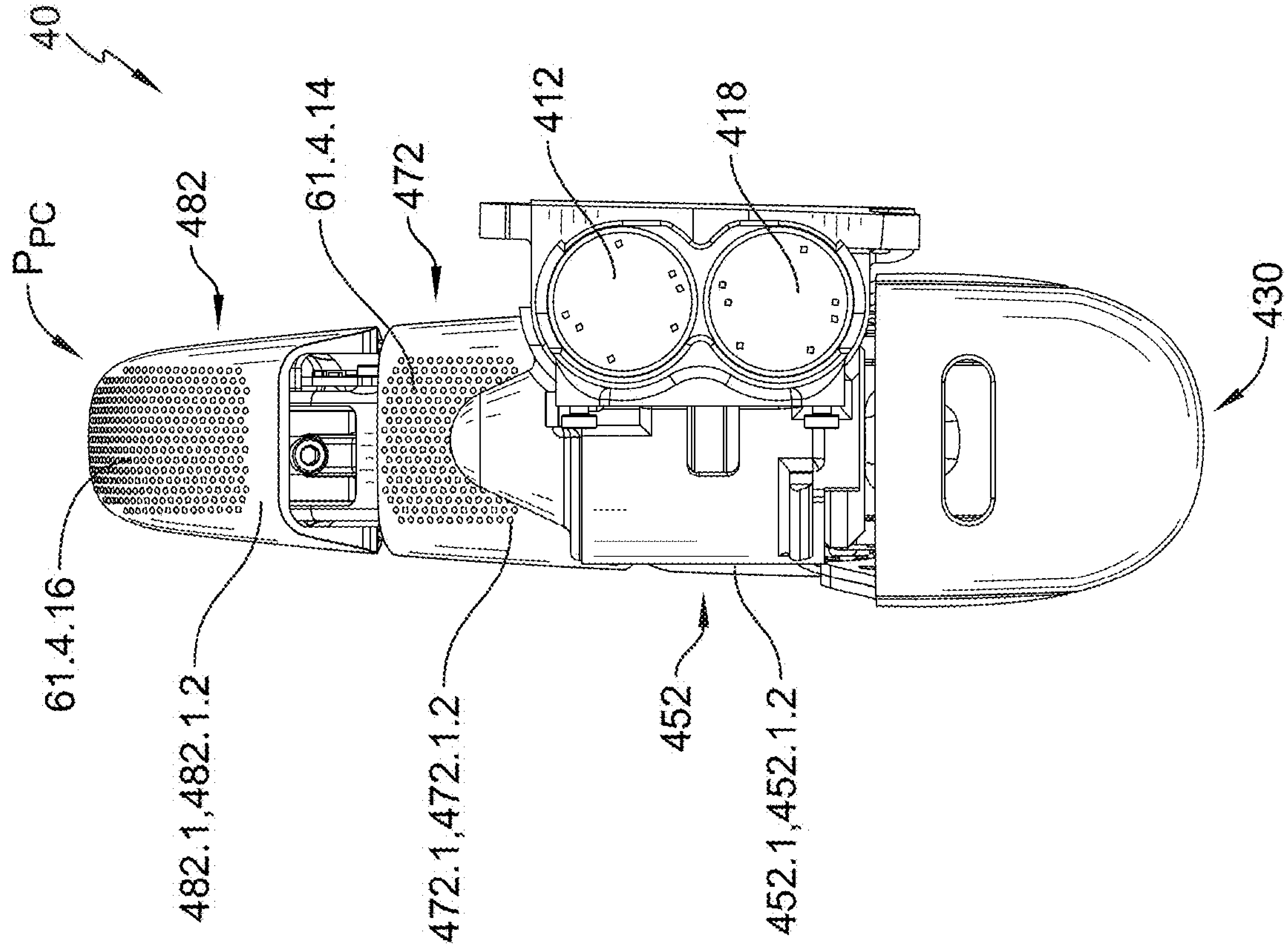

40
P_{PC}
482
61.4.14
472
412
418
430
61.4.16
482.1,482.1.2
472.1,472.1.2
452
452.1,452.1.2

FIG. 16

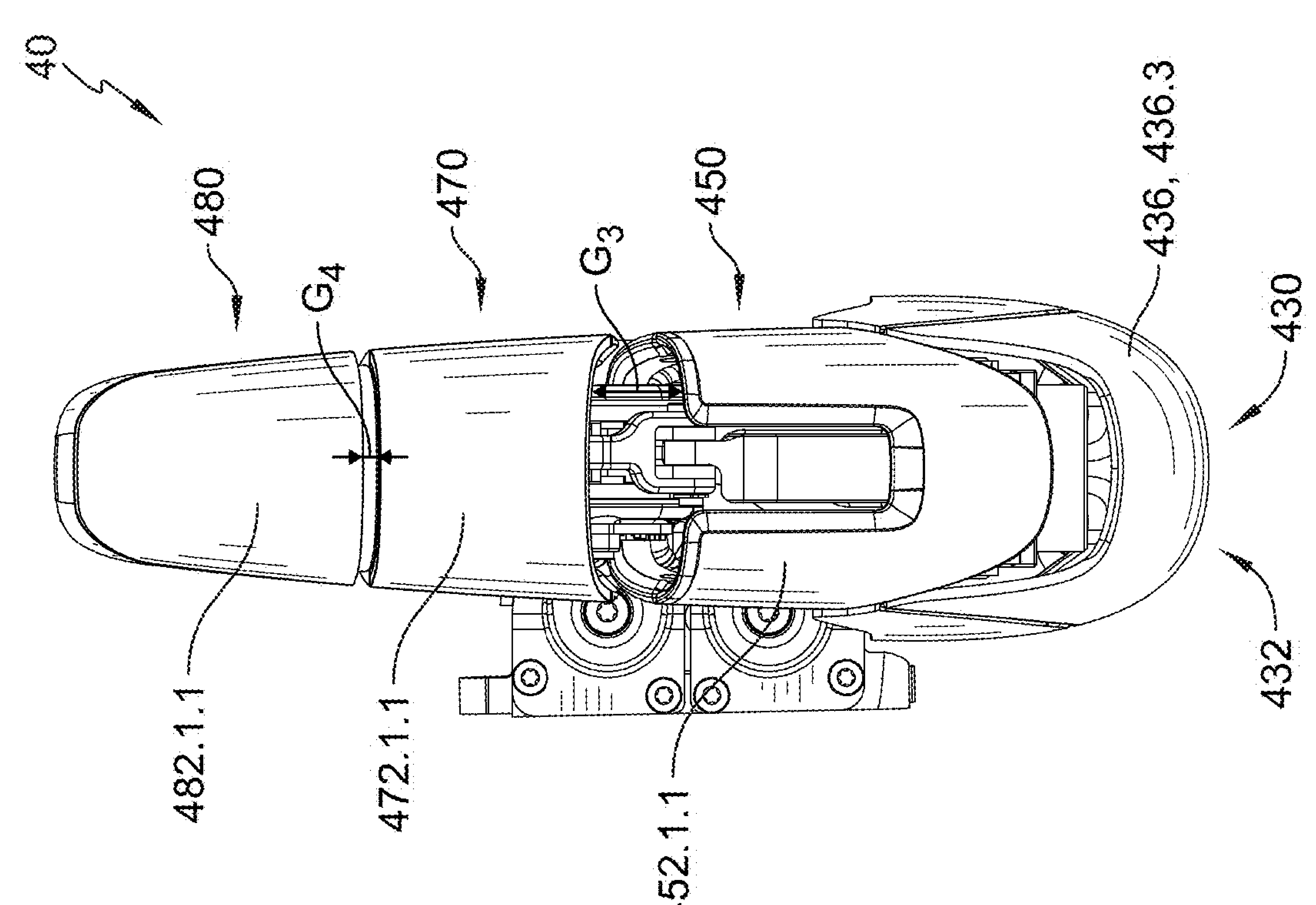

40
480
470
450
G_4
G_3
436, 436.3
430
432
482.1.1
472.1.1
452.1.1

FIG. 15

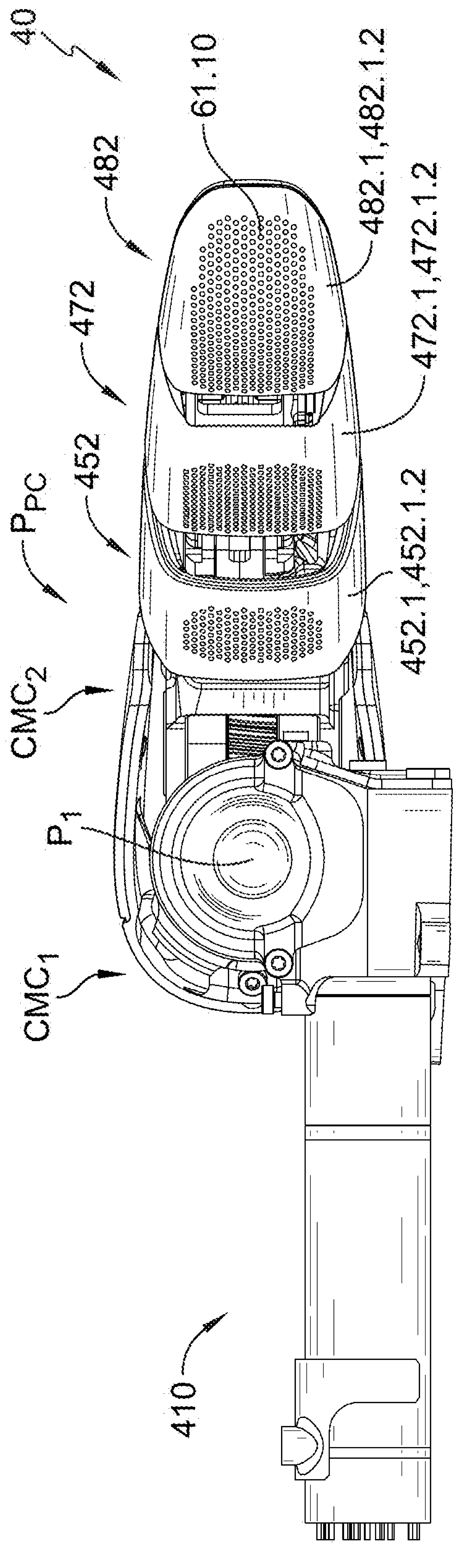

40
61.10
482
482.1,482.1.2
472
472.1,472.1.2
452
P_{PC}
452.1,452.1.2
CMC_2
P_1
CMC_1
410

FIG. 17

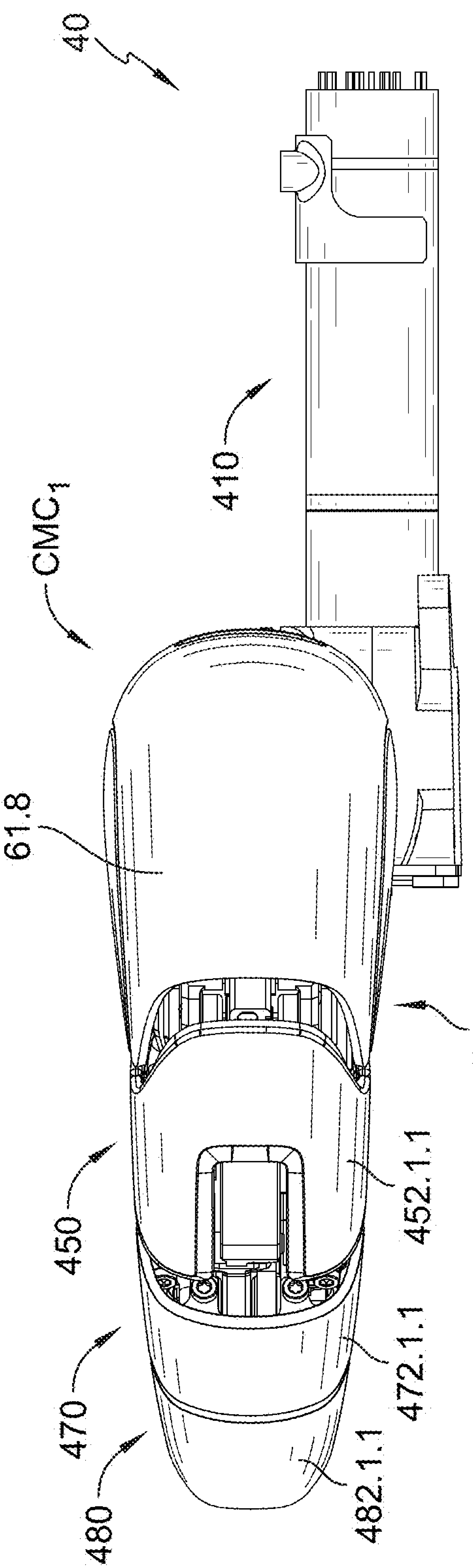

40
410
CMC_1
61.8
CMC_2
450
452.1.1
470
472.1.1
480
482.1.1

FIG. 18

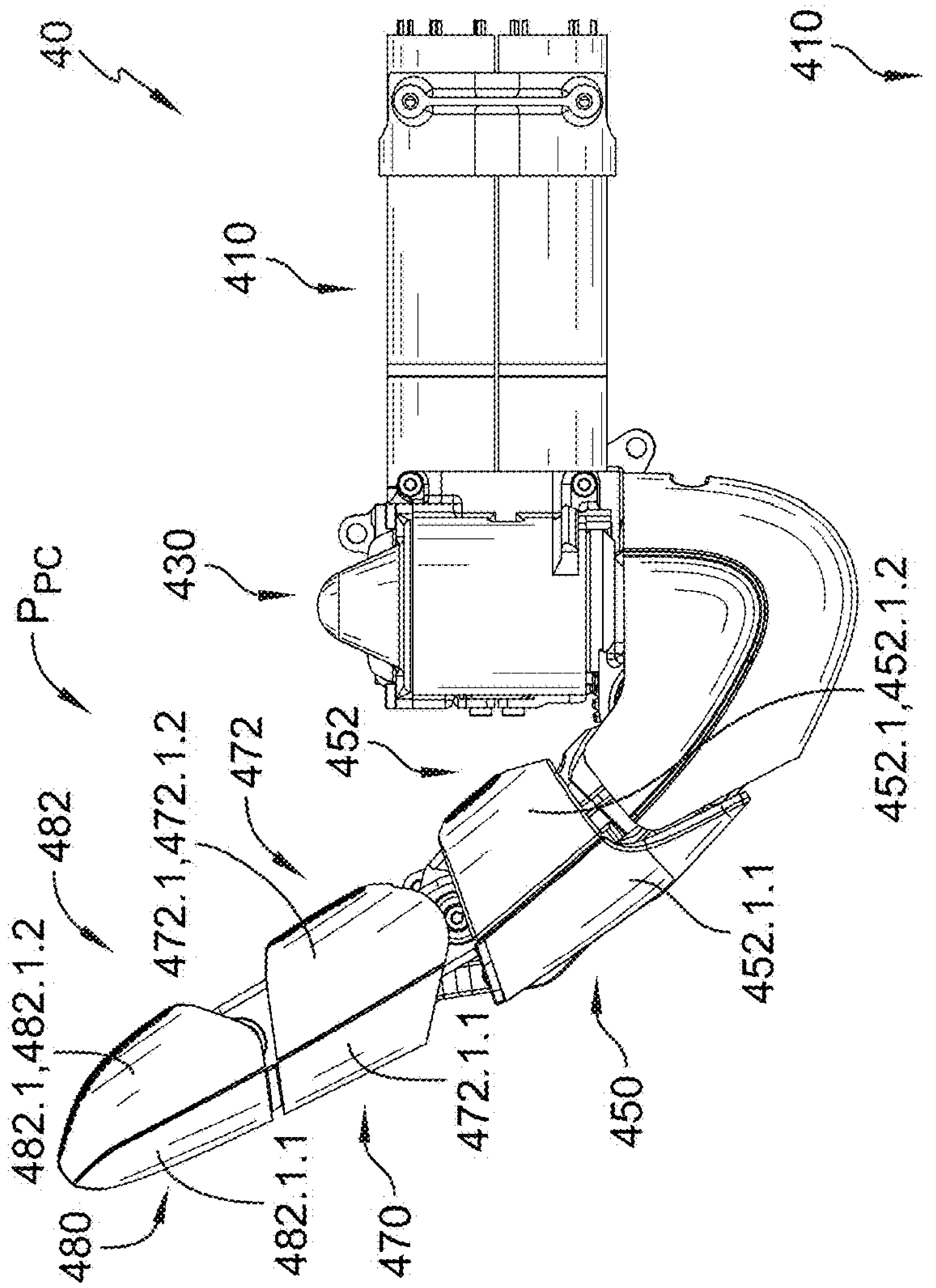

40
410
430
P_{PC}
452
472
482
482.1,482.1.2
472.1,472.1.2
452.1,452.1.2
452.1.1
472.1.1
450
482.1.1
470
480

FIG. 19

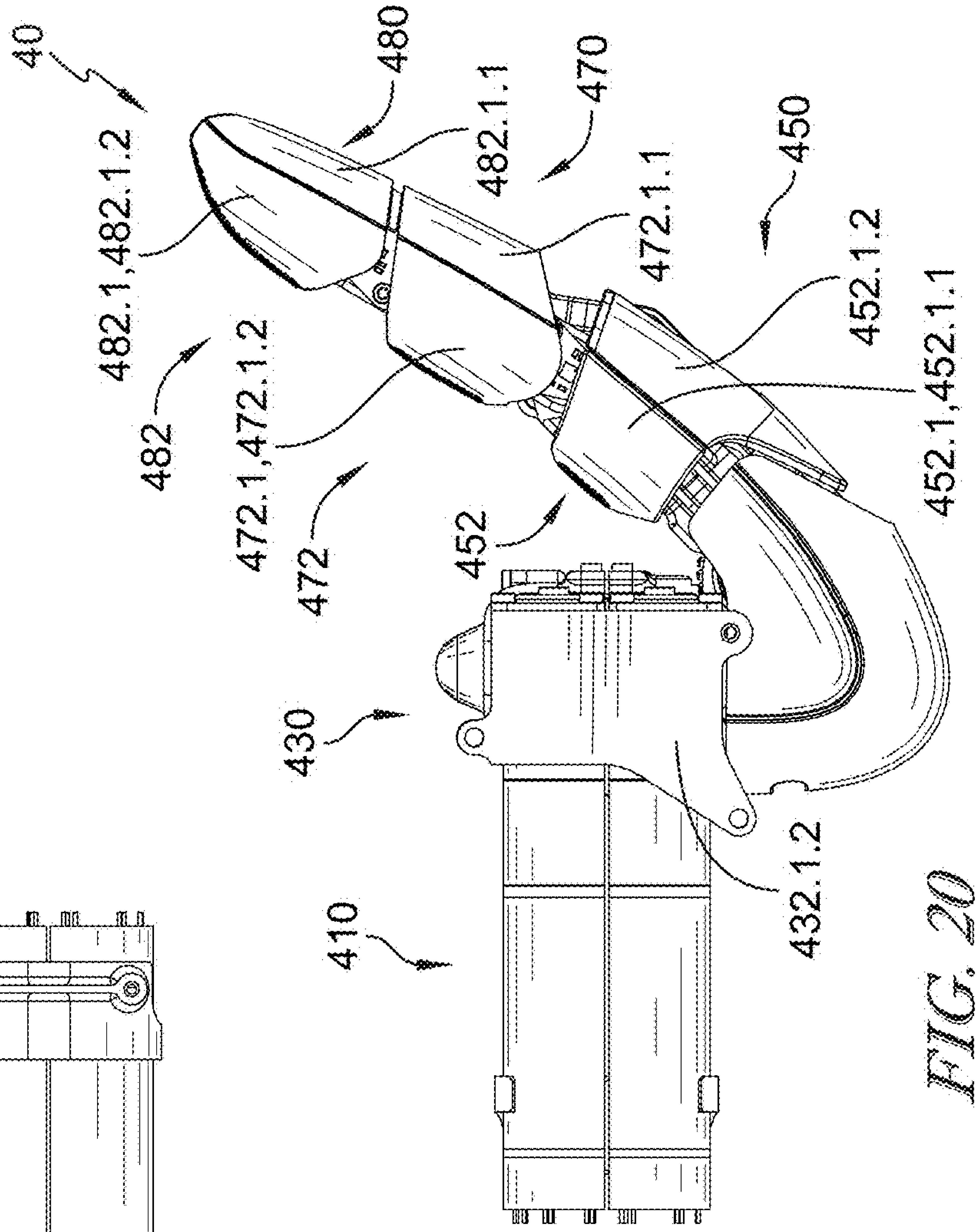

40
480
482.1.1
470
450
482.1,482.1.2
472.1.1
452.1.2
482
472.1,472.1.2
452.1,452.1.1
472
452
430
432.1.2
410

FIG. 20

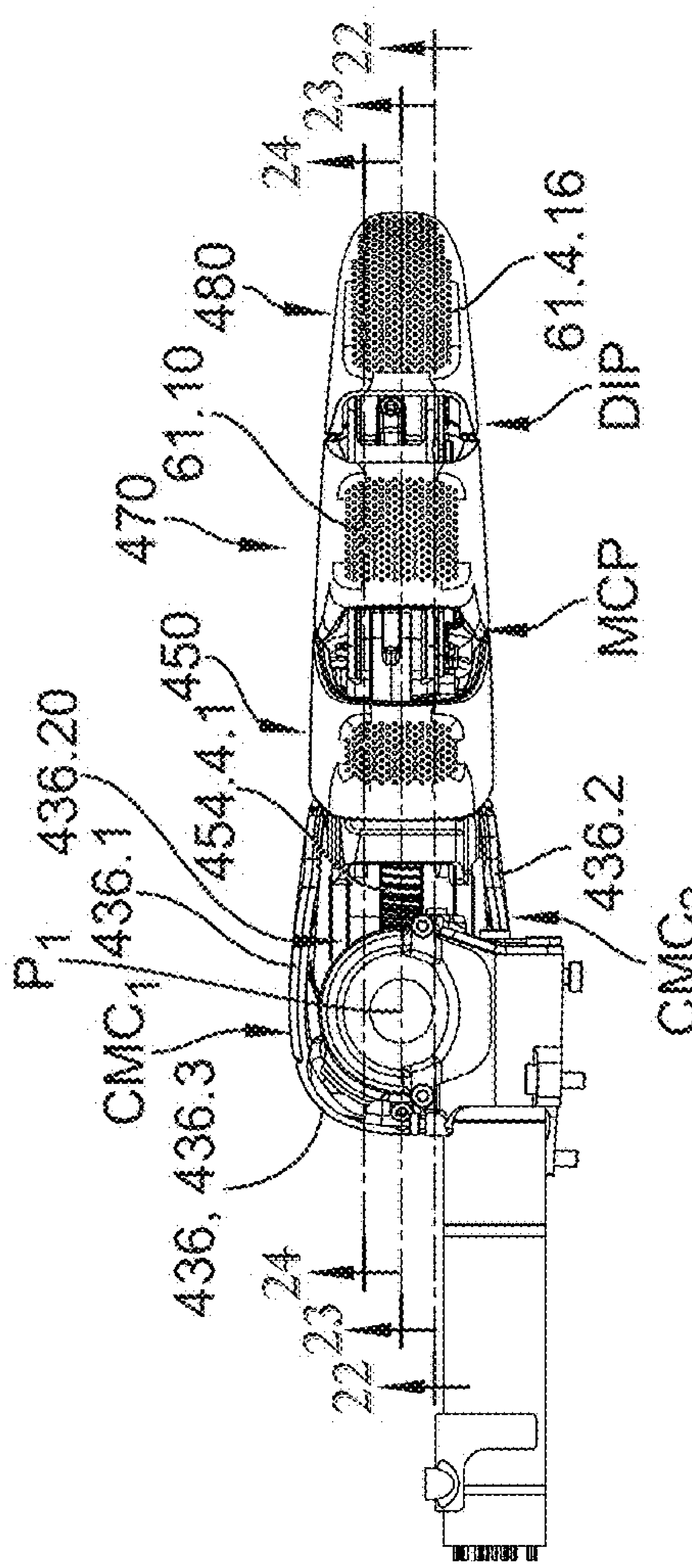

22
23
24
480
61.4.16
61.10
470
DIP
MCP
450
436.20
454.4.1
P1
436.1
436.2
CMC1
CMC2
436, 436.3

FIG. 21

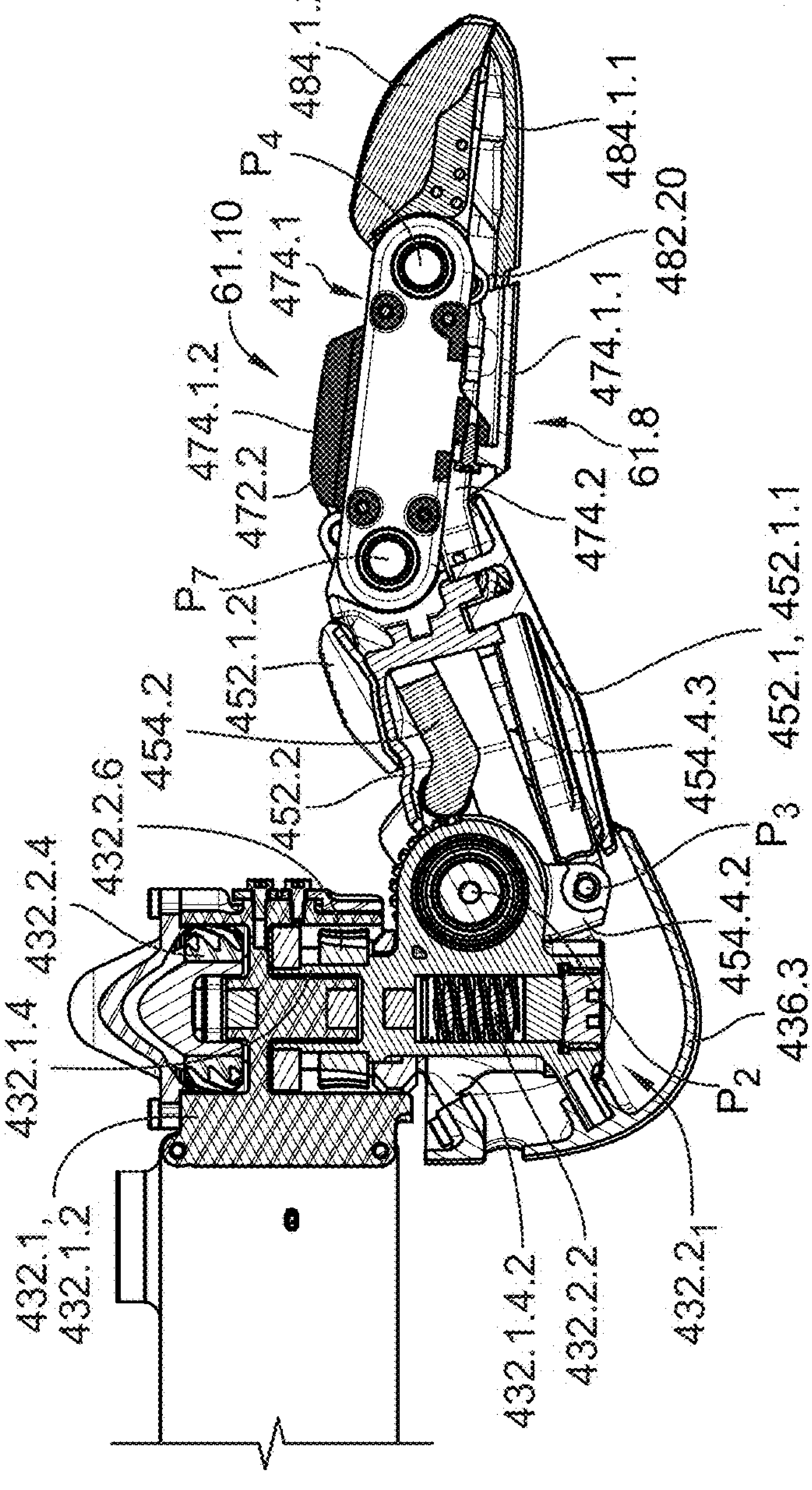

484.1.2
484.1.1
P4
482.20
61.10
474.1
474.1.1
474.1.2
472.2
474.2
61.8
P7
452.1.2
452.1, 452.1.1
454.2
454.4.3
452.2.6
452.2
P3
432.2.4
454.4.2
436.3
432.1.4
P2
432.1, 432.1.2
432.1.4.2
432.2.2
432.2

FIG. 22

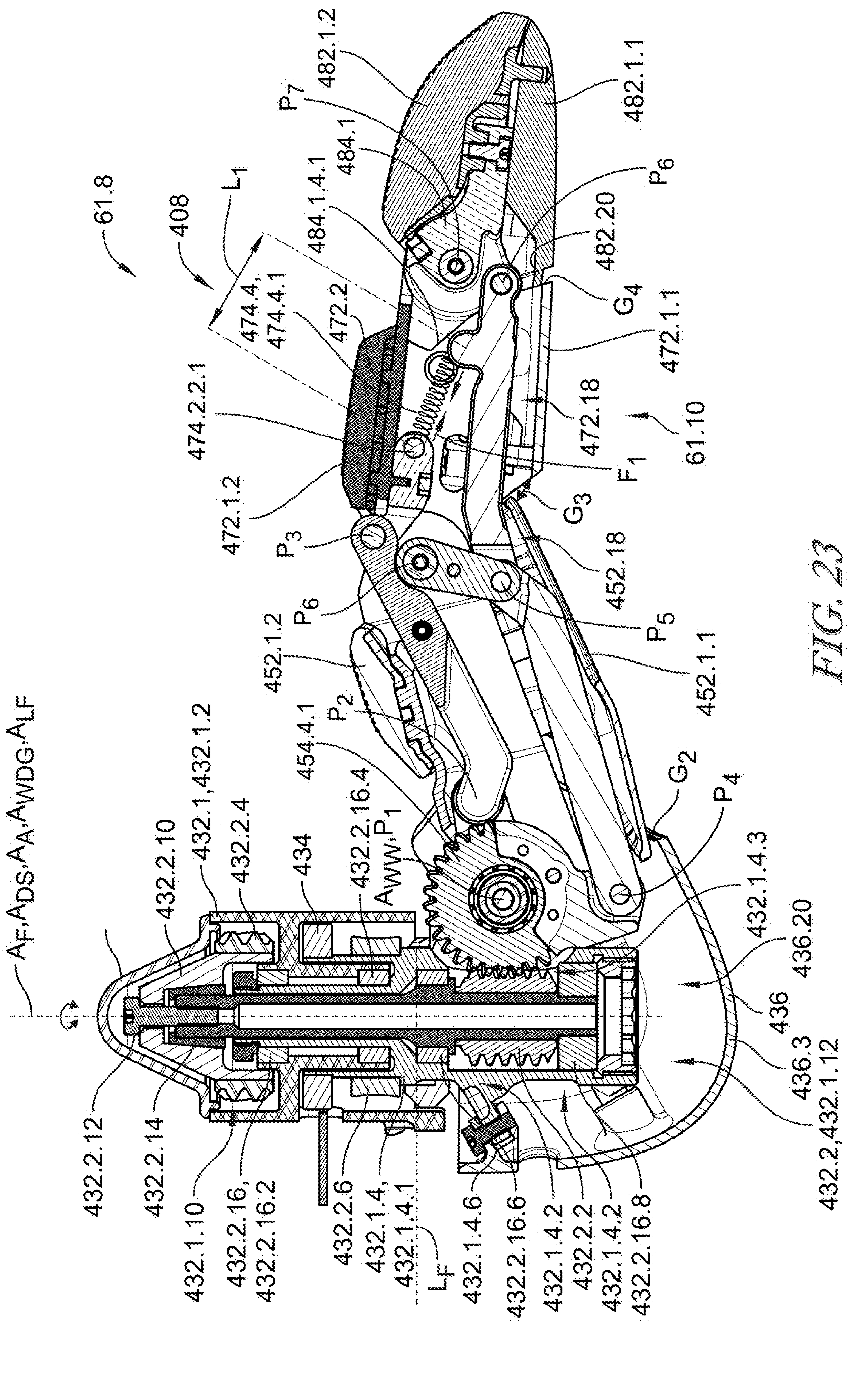

61.8
408
L_1
474.4,
474.4.1
472.2
474.2.2.1
472.1.2
P_3
P_6
452.1.2
P_2
454.4.1
432.2.16.4
A_{WW},P_1
A_F,A_{DS},A_A,A_{WDG},A_{LF}
432.2.10
432.1,432.1.2
432.2.4
434
482.1.2
P_7
484.1
484.1.4.1
P_6
482.1.1
482.20
G_4
472.1.1
472.18
F_1
61.10
G_3
452.18
P_5
452.1.1
G_2
P_4
432.1.4.3
436.20
436
436.3
432.2,432.1.12
432.2.12
432.2.14
432.1.10
432.2.16,
432.2.16.2
432.2.6
432.1.4,
432.1.4.1
L_F
432.1.4.6
432.2.16.6
432.1.4.2
432.2.2
432.1.4.2
432.2.16.8

FIG. 23

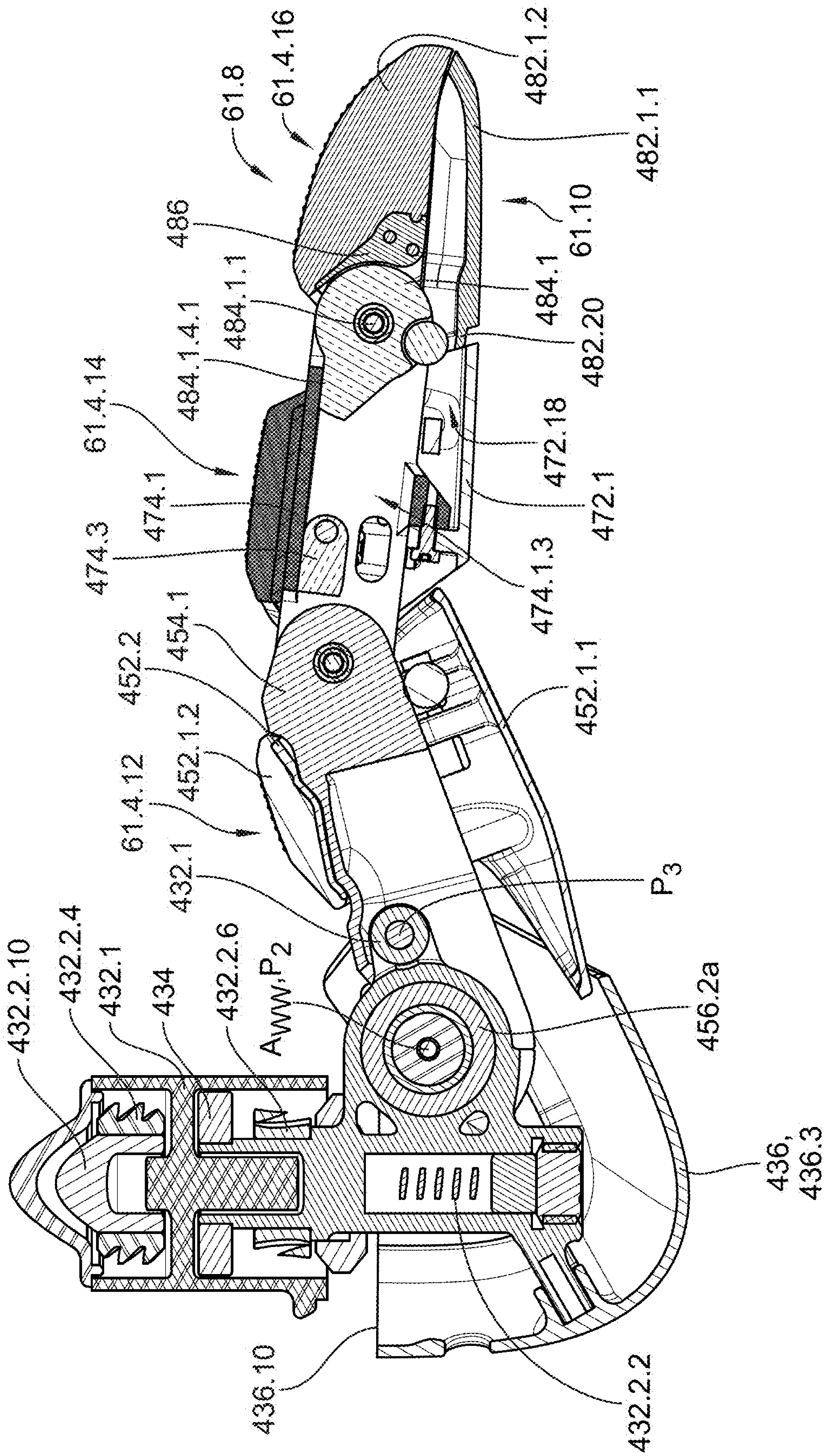

61.8
61.4.16
482.1.2
482.1.1
61.10
486
484.1.1
484.1
482.20
61.4.14
484.1.4.1
472.18
472.1
474.1
474.3
474.1.3
454.1
452.2
452.1.1
452.1.2
61.4.12
432.1
P3
432.2.10
432.2.4
432.1
434
432.2.6
AWW,P2
456.2a
436,
436.3
436.10
432.2.2

FIG. 24

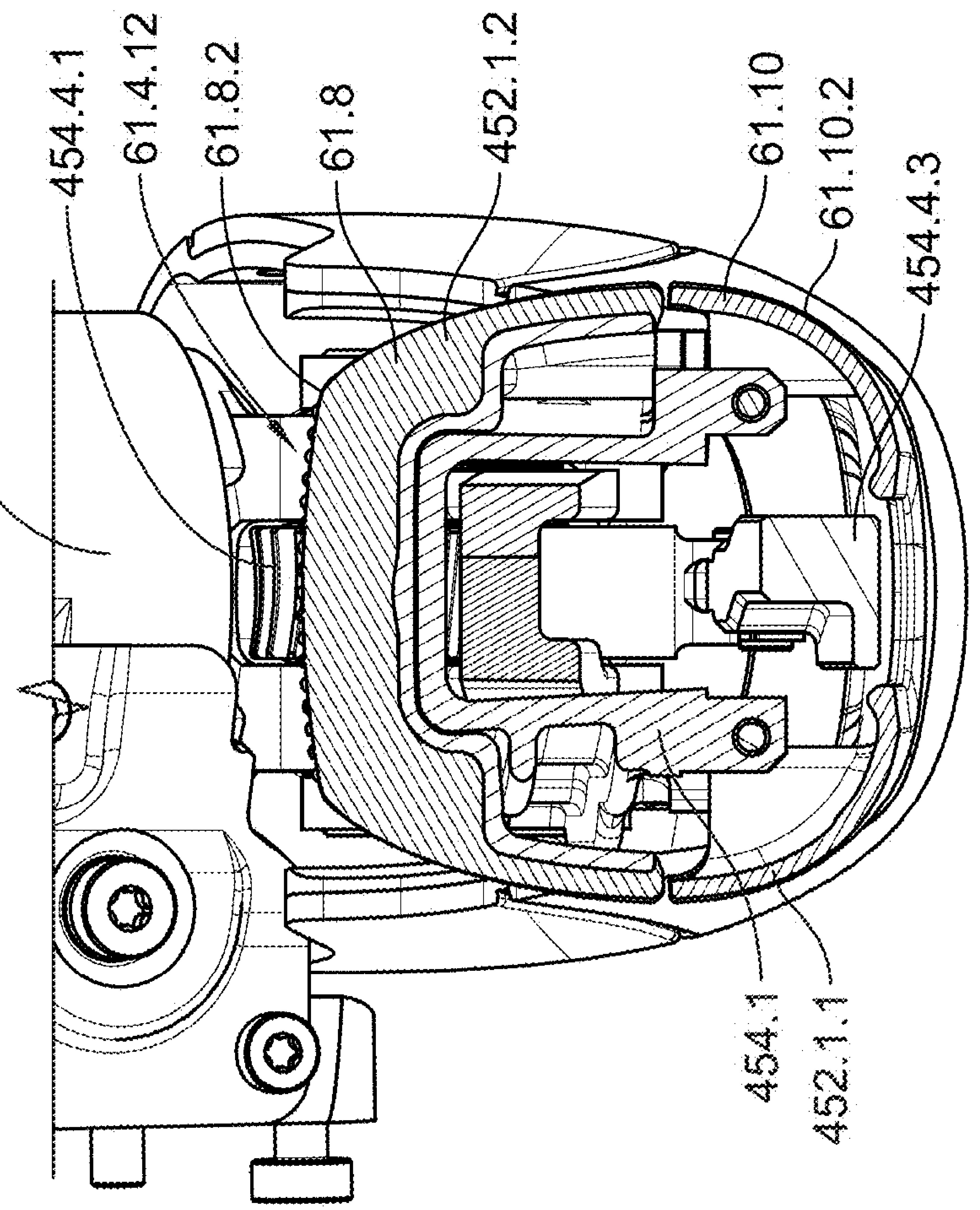


FIG. 26

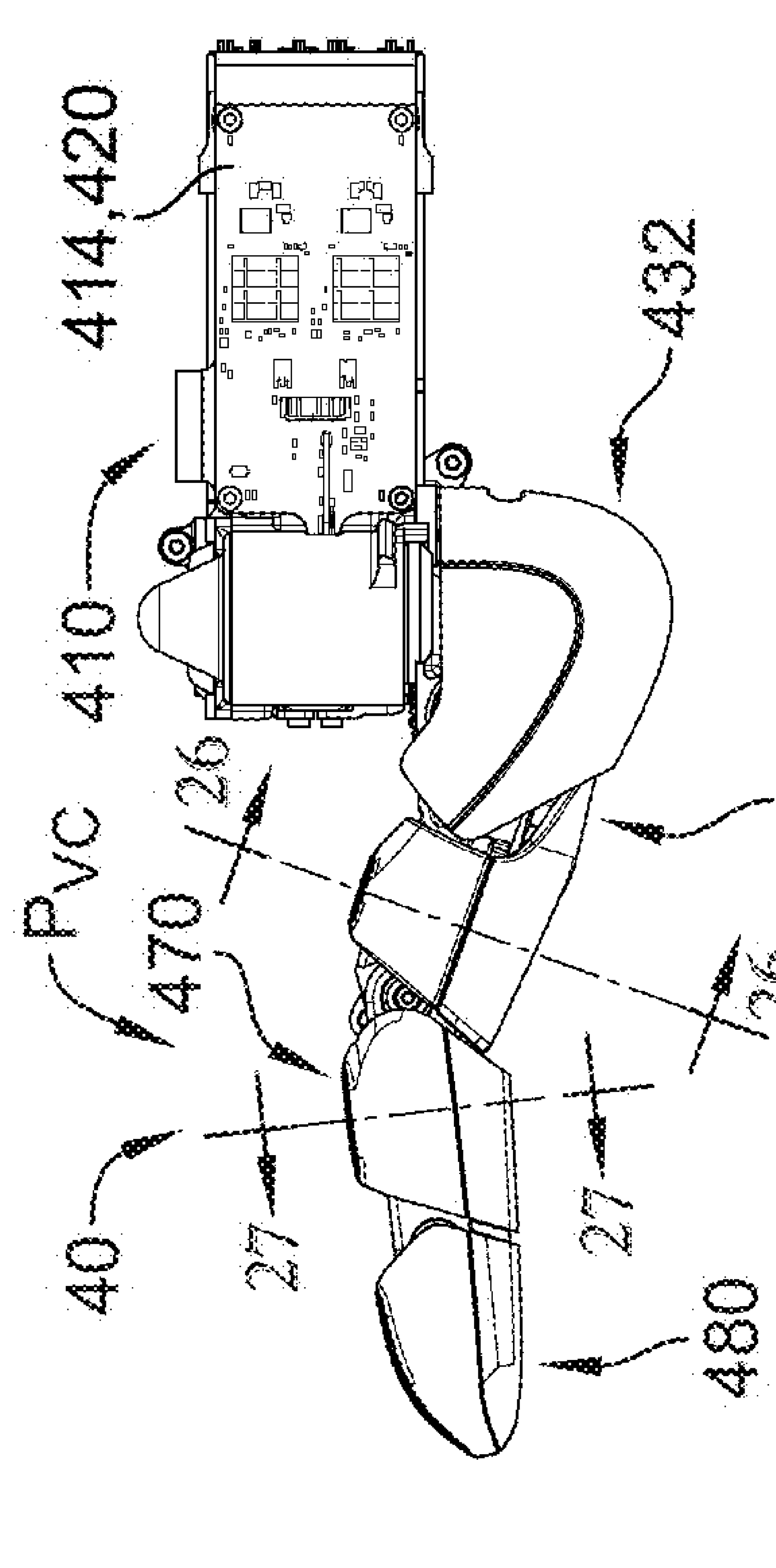


FIG. 25

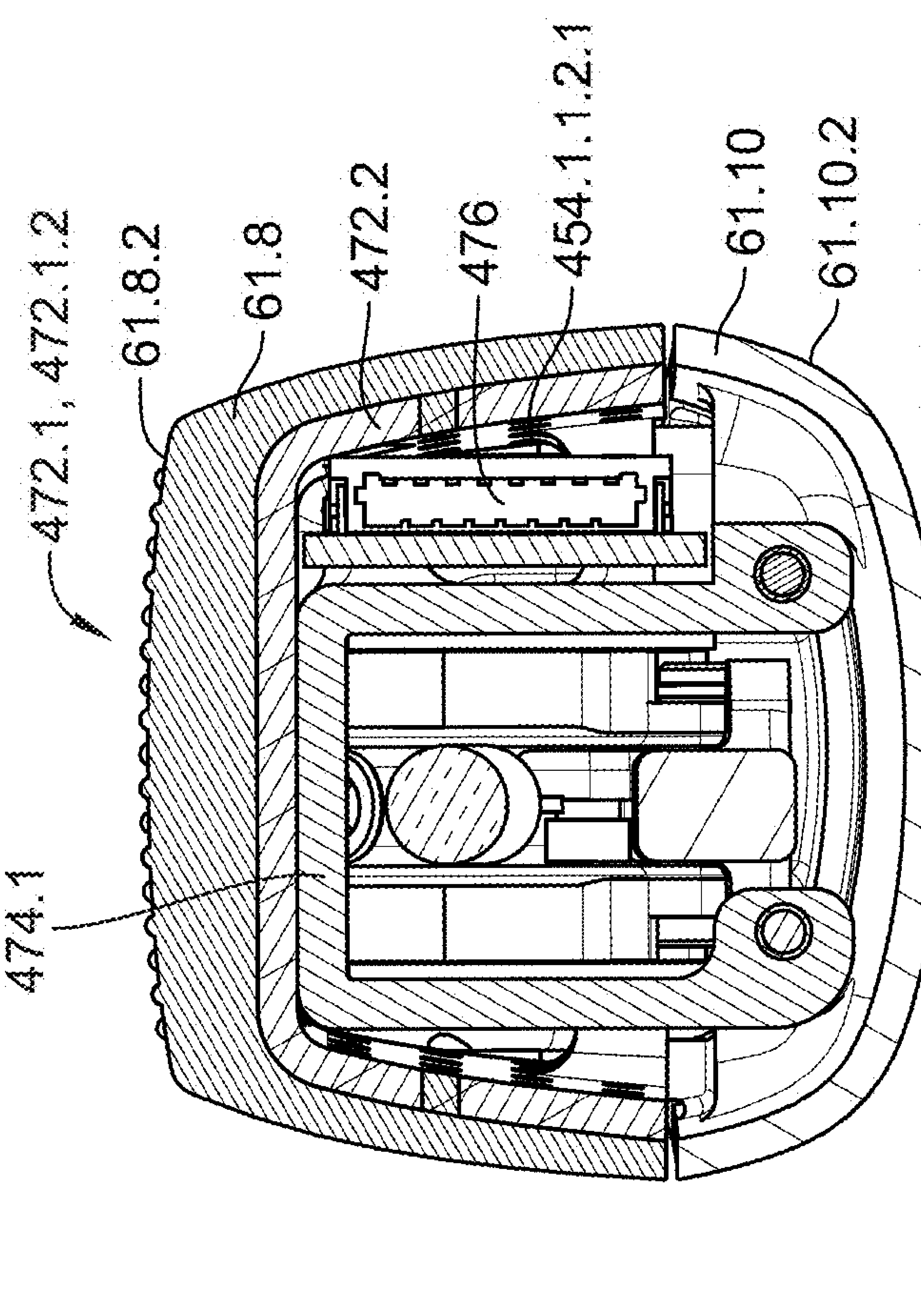


FIG. 27

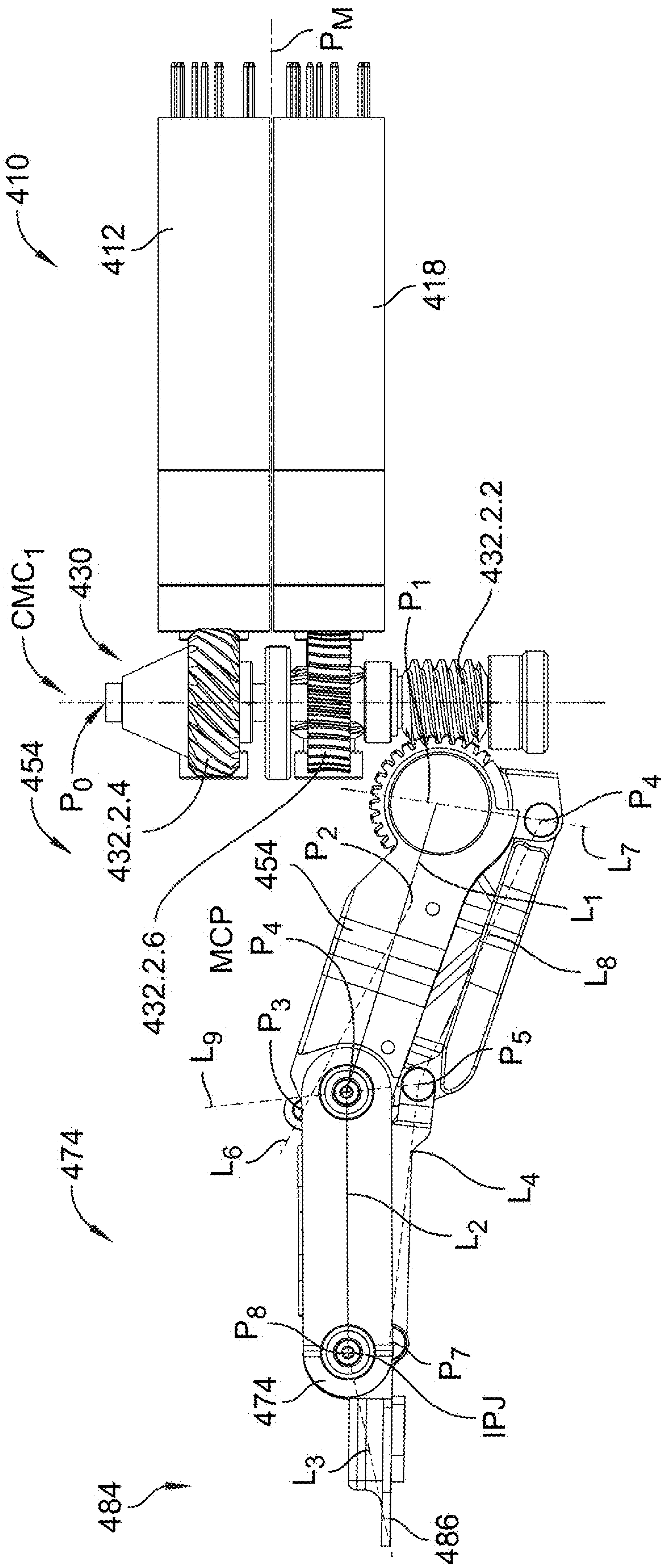

410
412
418
P_M
CMC_1
430
432.2.2
P_1
454
P_0
432.2.4
432.2.6
P_4
P_2
L_7
L_1
L_8
MCP
P_3
P_5
L_9
L_6
L_4
L_2
474
P_8
P_7
IPJ
L_3
484
486

FIG. 28A

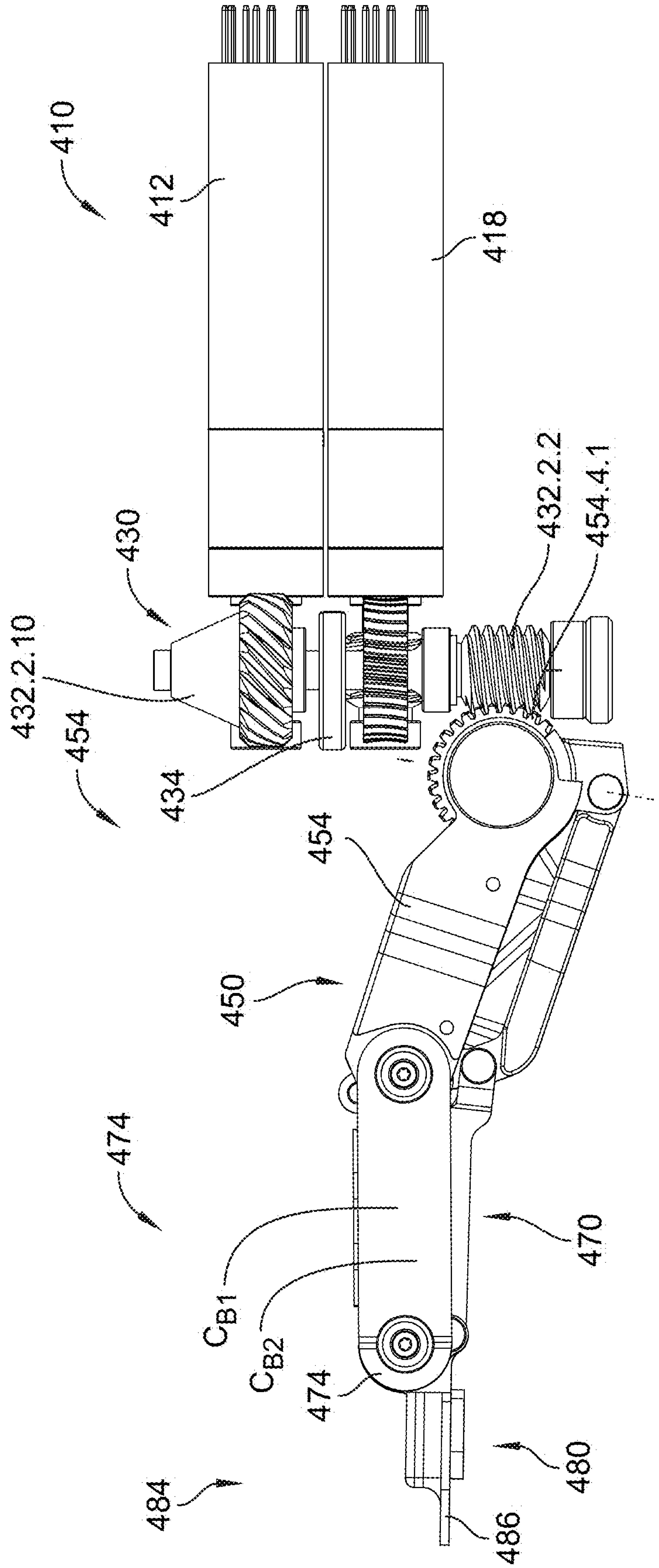

410
412
418
430
432.2.2
454.4.1
432.2.10
454
434
454
450
474
470
C_{B1}
C_{B2}
474
480
484
486

FIG. 28B

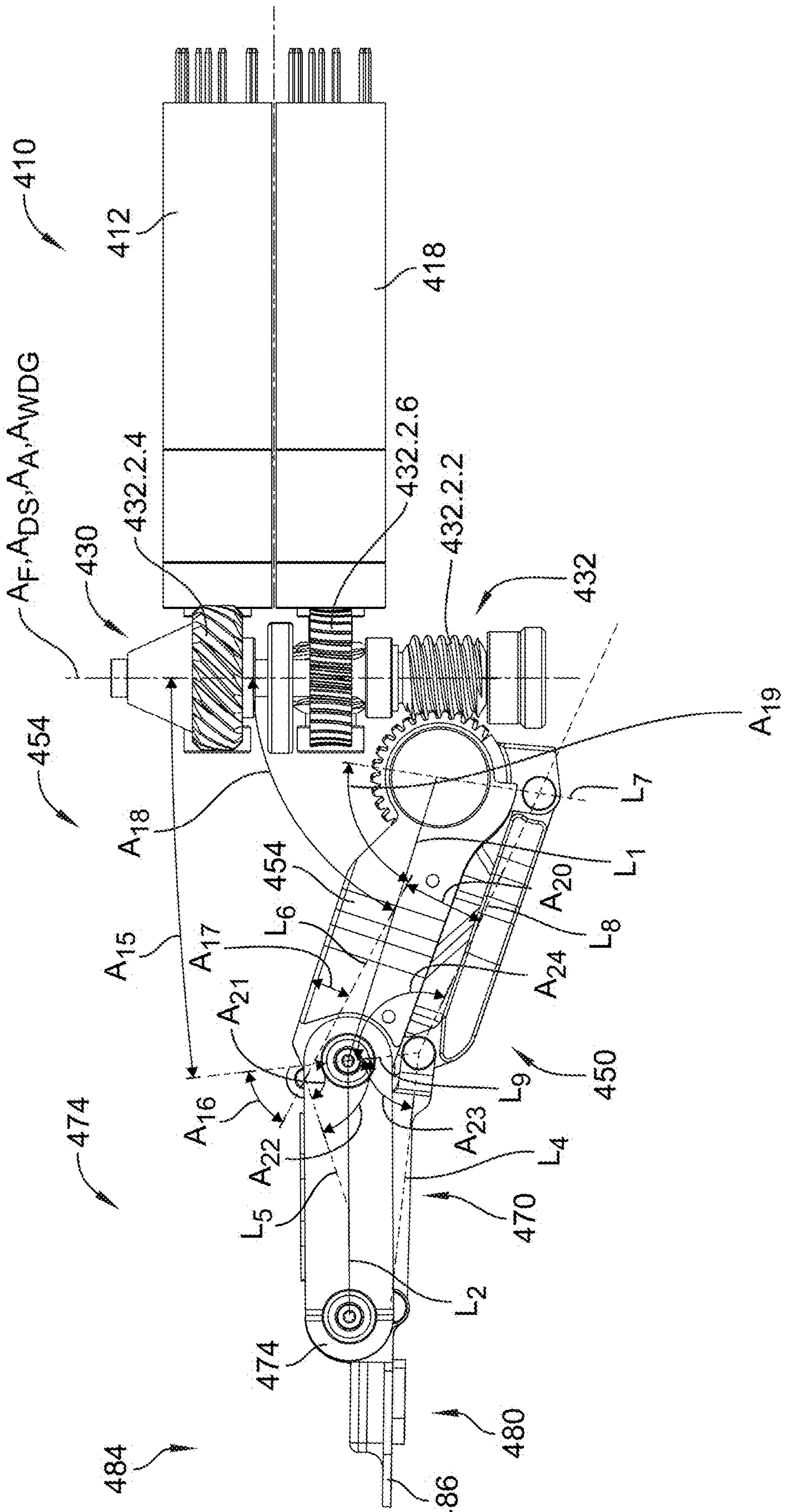

410
412
418
$A_F, A_{DS}, A_A, A_{WDG}$
430
432.2.4
432.2.6
432.2.2
432
454
A_{19}
A_{18}
L_7
L_1
454
A_{20}
L_6
L_8
A_{15}
A_{17}
A_{24}
A_{21}
450
L_9
A_{16}
A_{23}
474
A_{22}
L_4
L_5
470
L_2
474
480
484
486

FIG. 28C

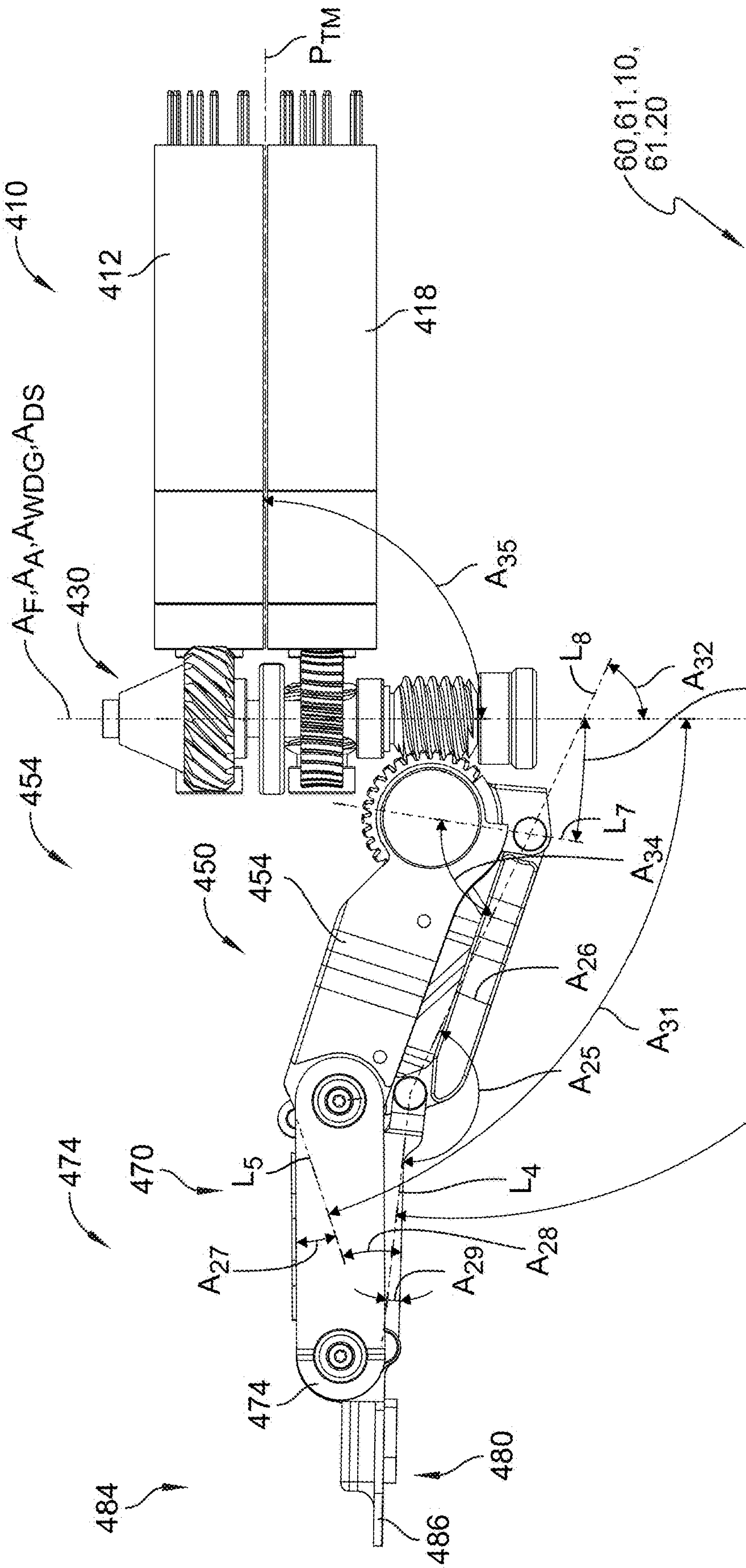


FIG. 28D

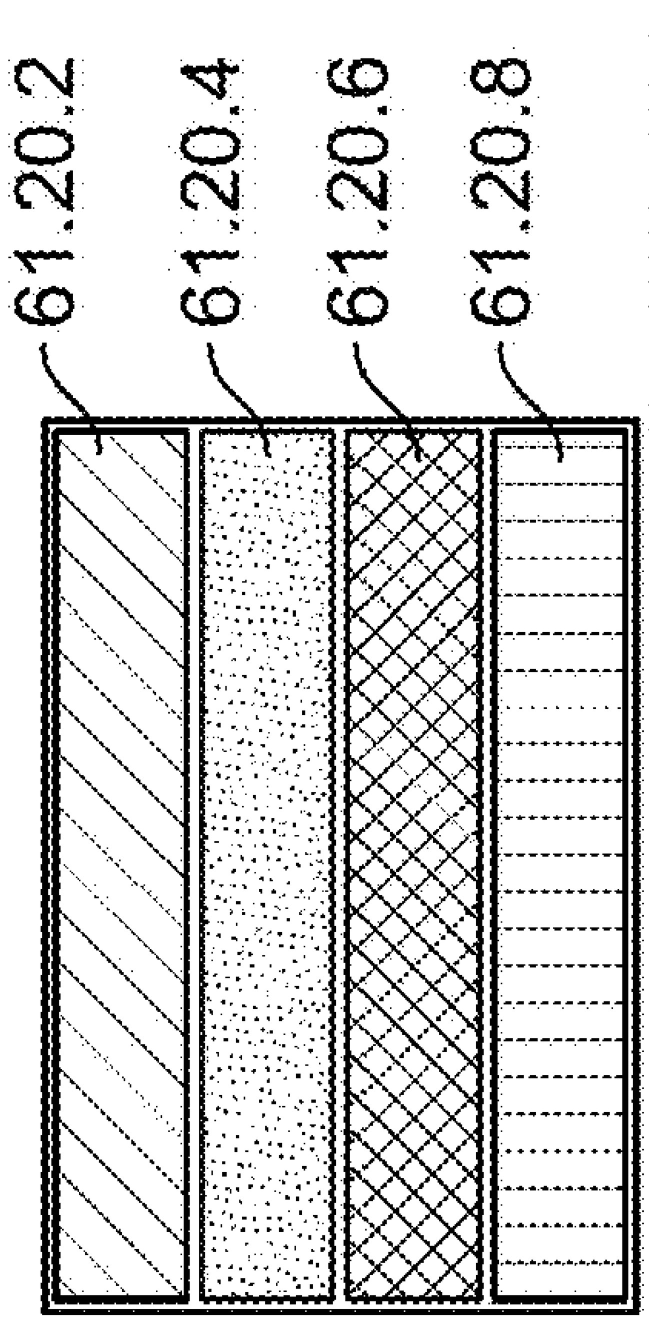


FIG. 29

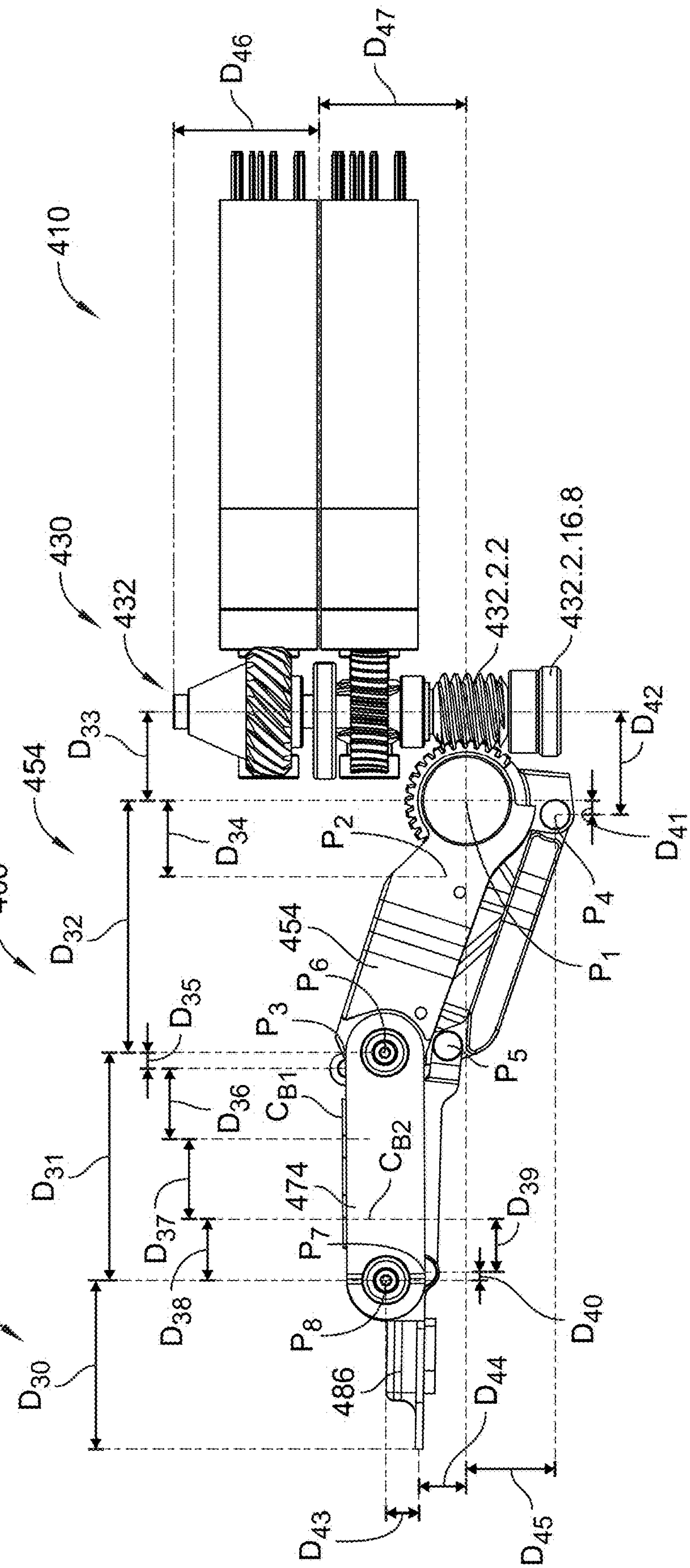

D_{46}
D_{47}
410
430
432
432.2.2
432.2.16.8
D_{33}
D_{42}
454
D_{34}
D_{41}
P_2
P_4
408
D_{32}
454
P_1
P_6
D_{35}
P_3
P_5
D_{36}
C_{B1}
C_{B2}
D_{31}
474
D_{39}
D_{37}
P_7
484
D_{38}
D_{40}
P_8
D_{30}
486
D_{44}
D_{43}
D_{45}

FIG. 30

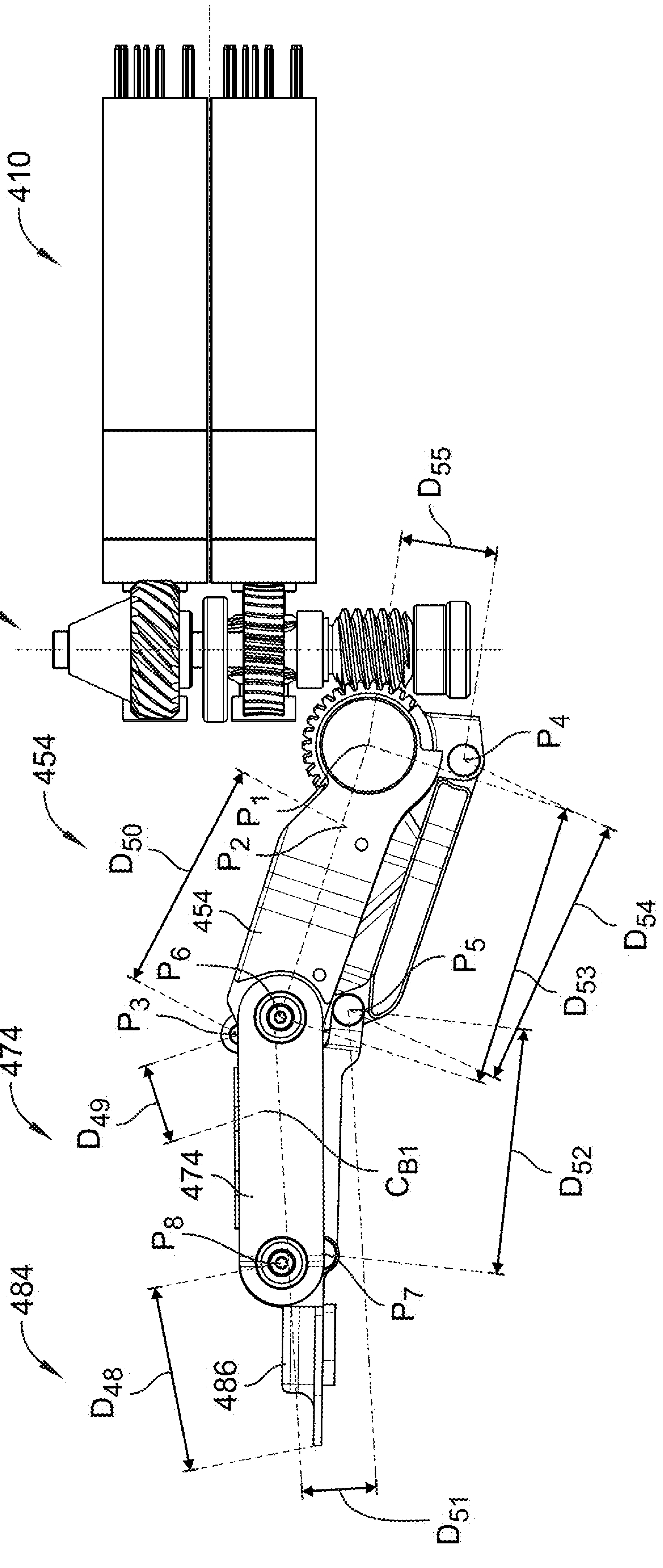

410
430
408
454
D_{55}
P_4
P_1
P_2
D_{50}
454
P_6
P_5
P_3
D_{54}
D_{53}
474
D_{49}
C_{B1}
474
D_{52}
P_8
P_7
484
D_{48}
486
D_{51}

FIG. 31

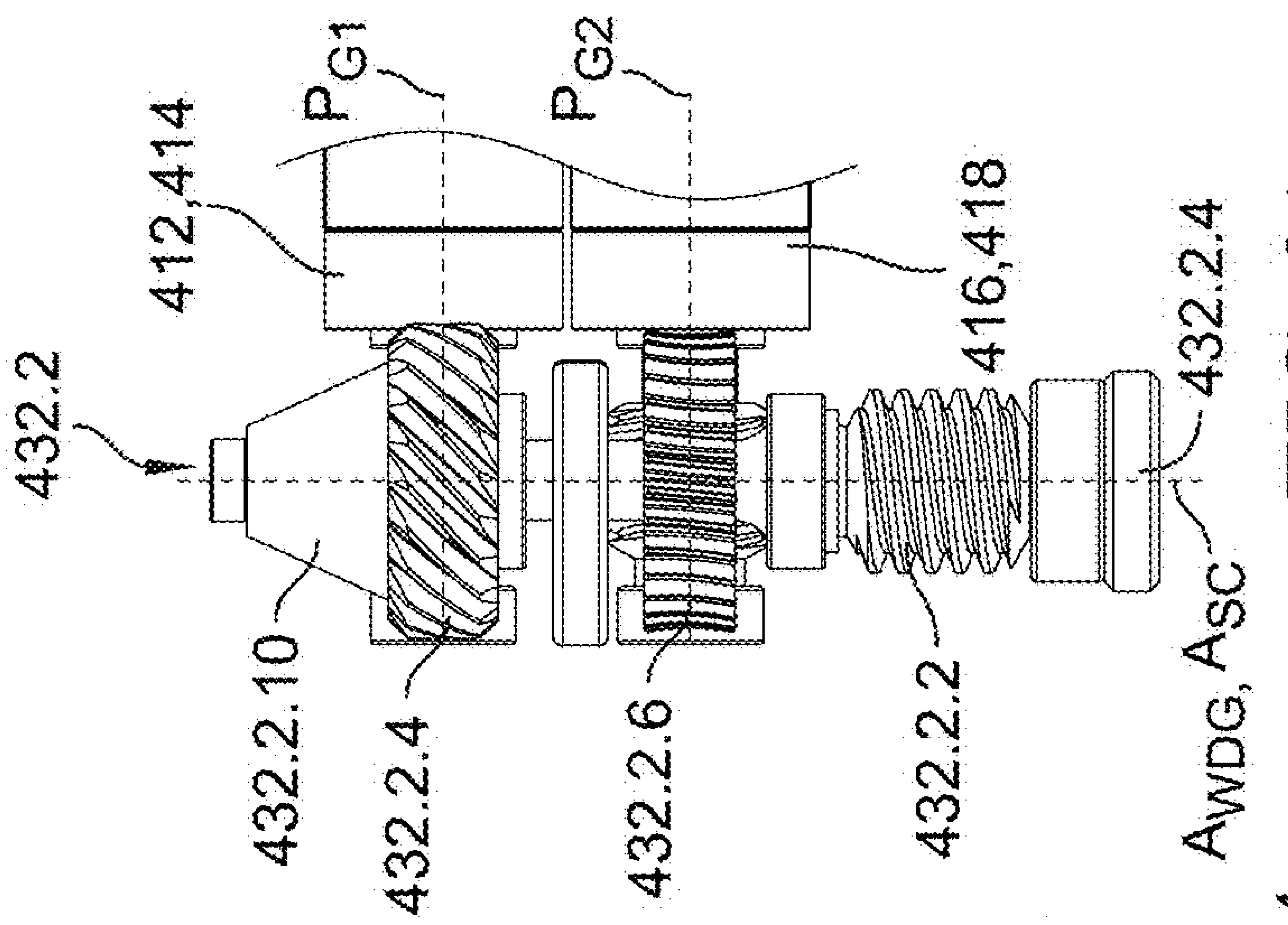


FIG. 34

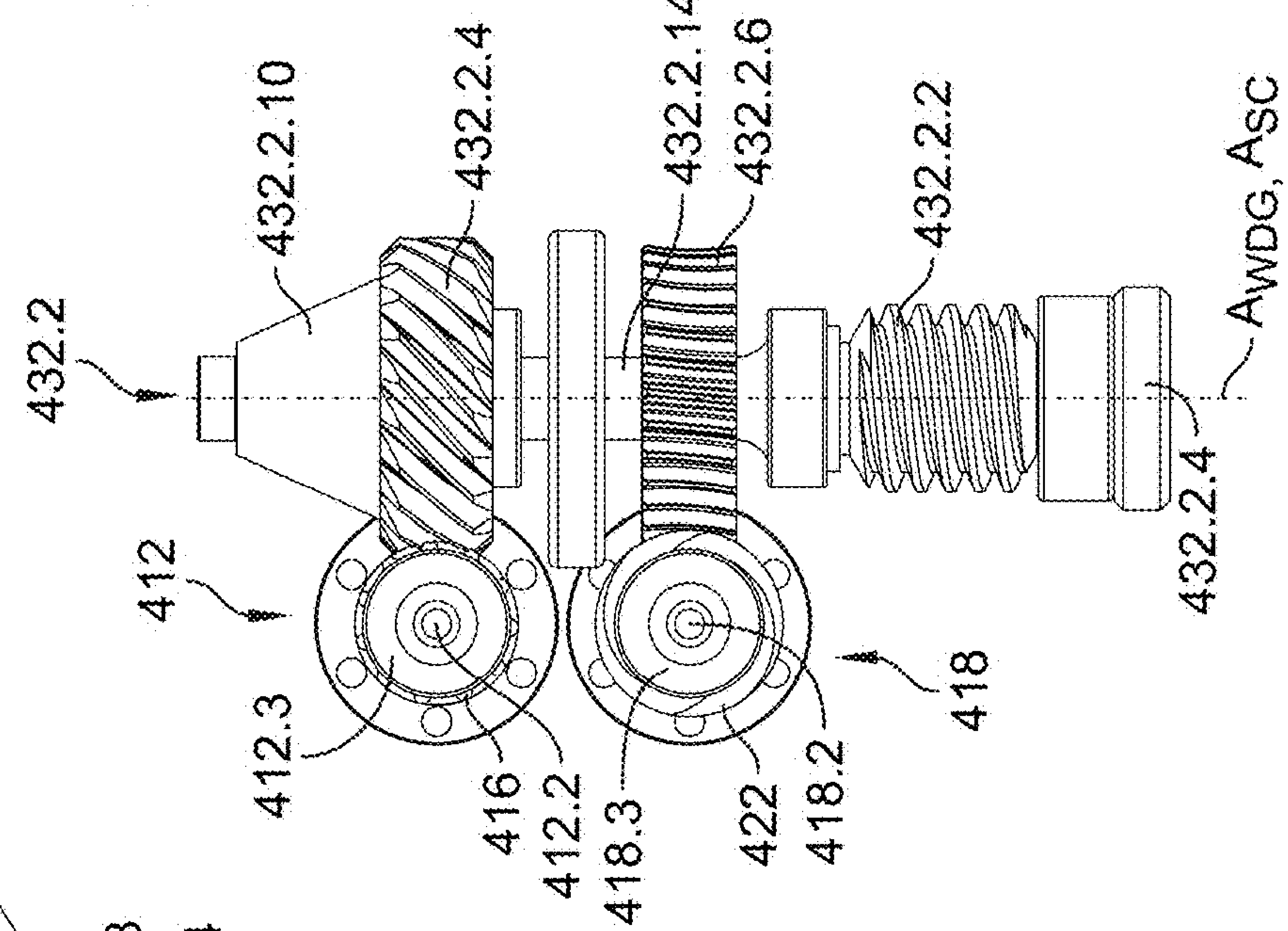


FIG. 33

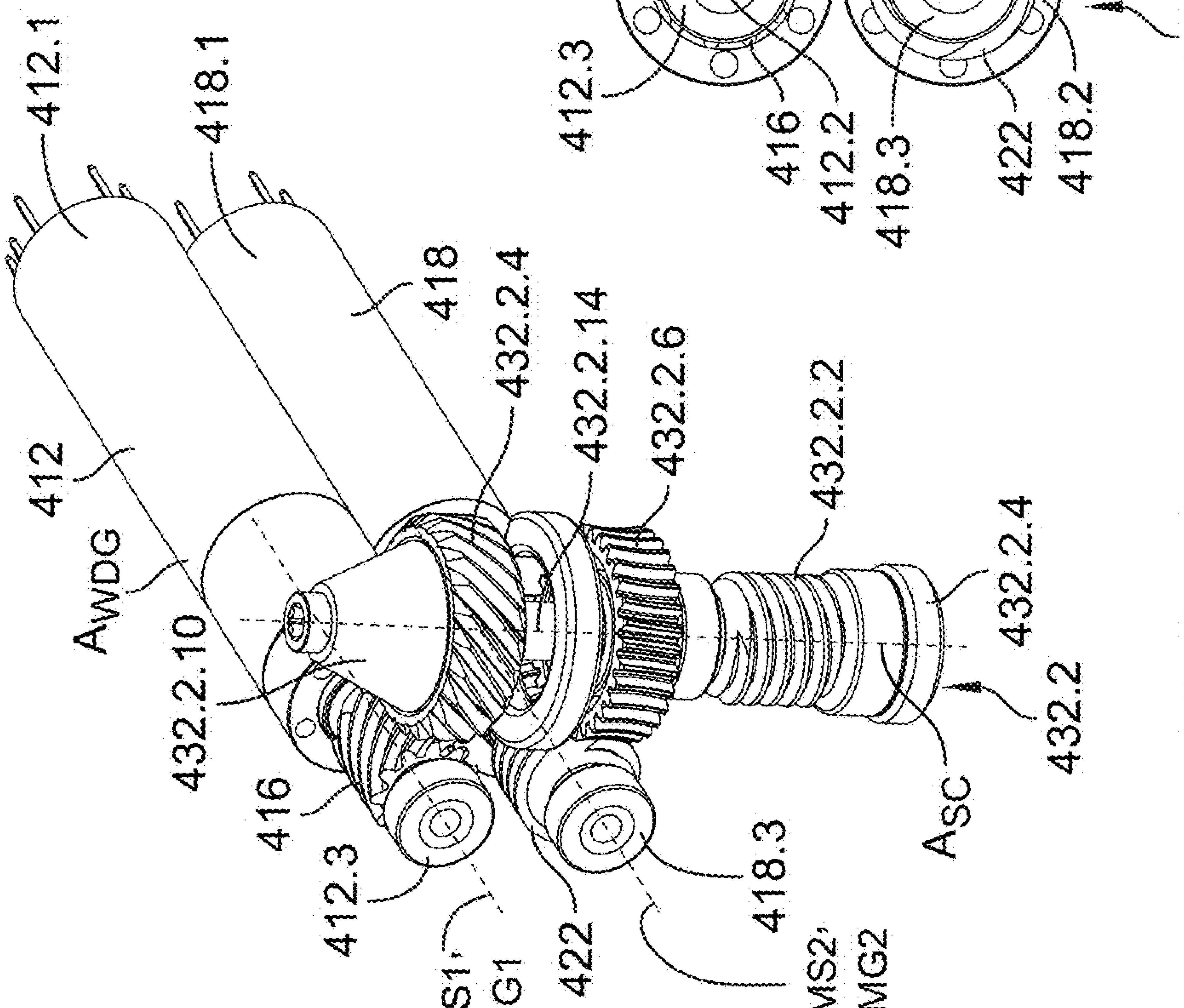


FIG. 32

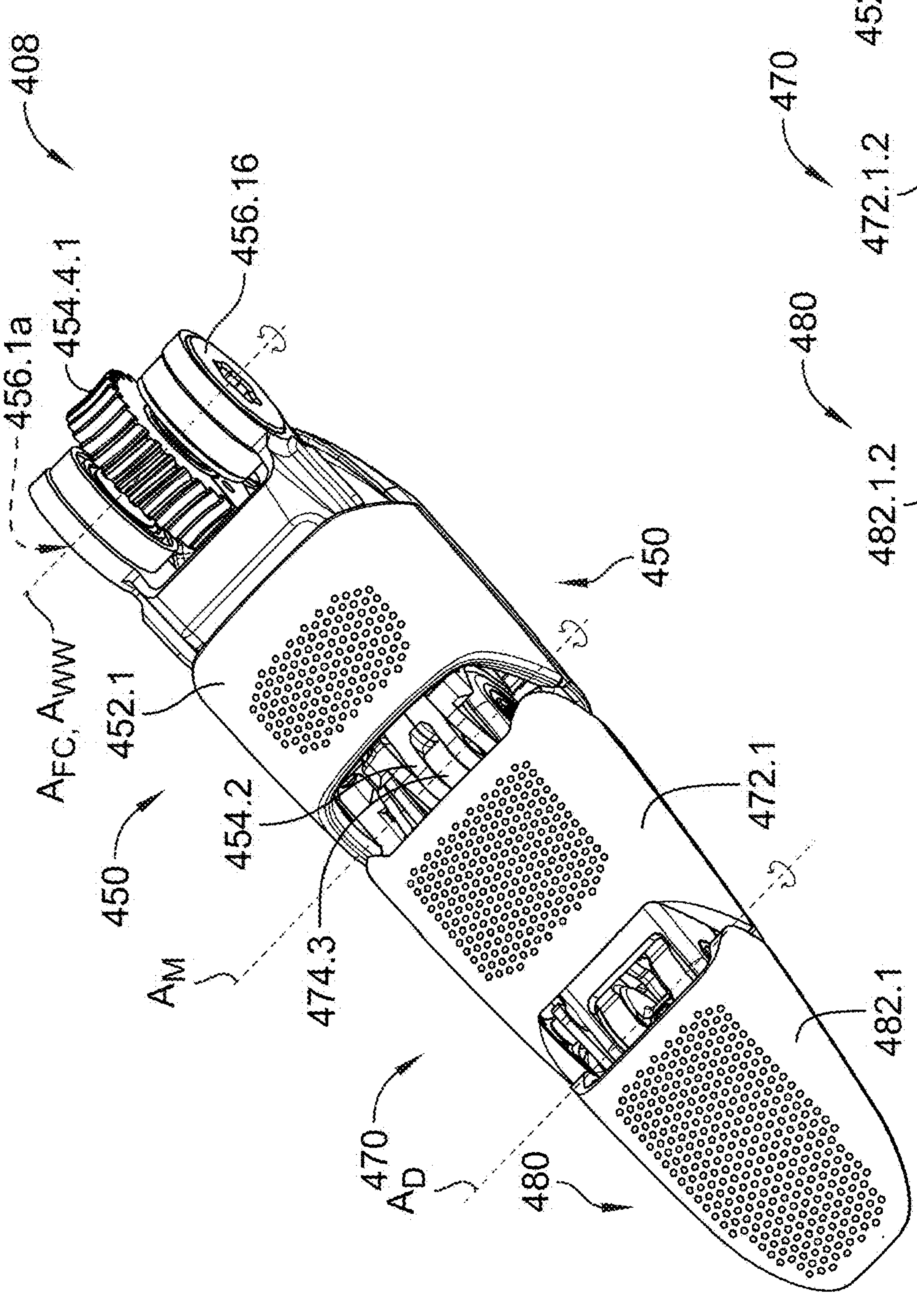

408
456.1a
454.4.1
456.16
A_{FC}, A_{WW}
452.1
450
450
454.2
474.3
472.1
A_M
482.1
470
A_D
480

FIG. 35

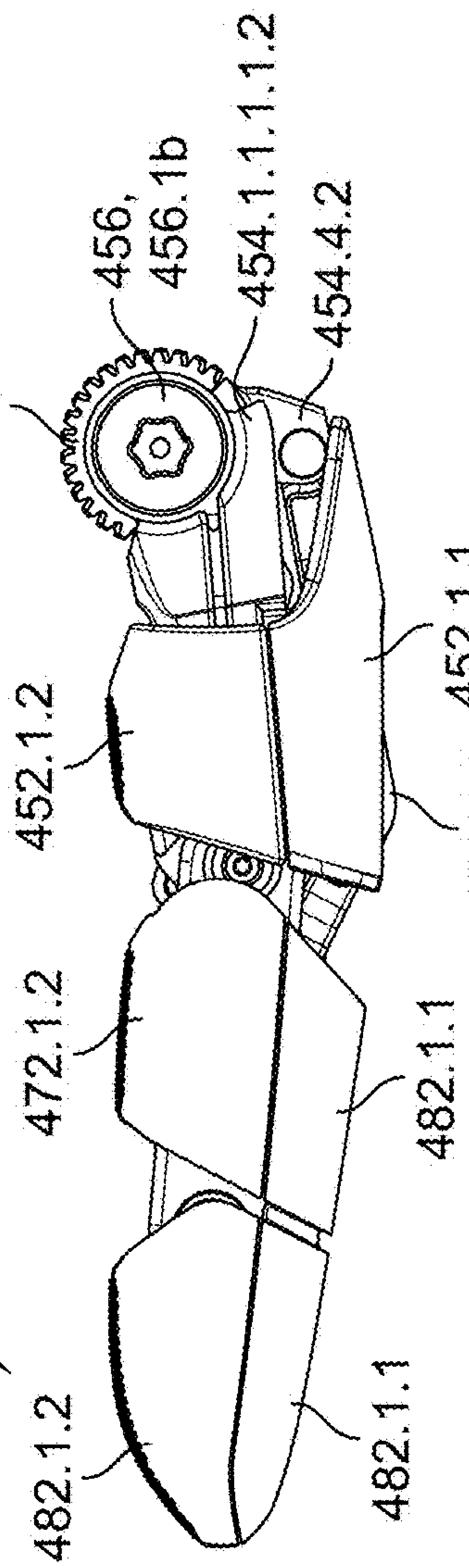

454.1.1.1.2
456,
456.1b
454.4.2
454.4.1
450
408
452.1.2
452.1.1
454.4.3
470
472.1.2
482.1.1
480
482.1.2
482.1.1

FIG. 36

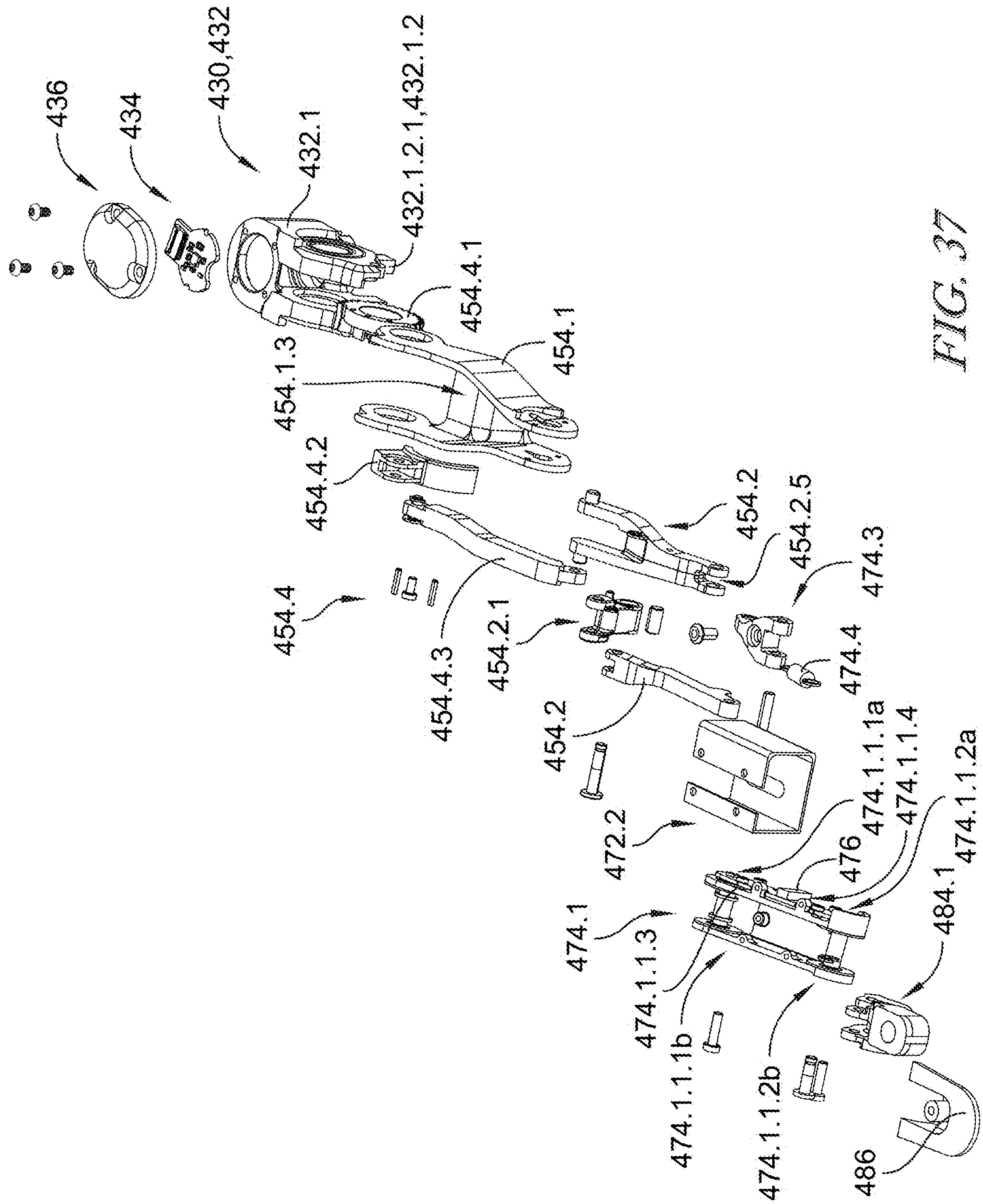

436
434
430,432
432.1
432.1.2.1,432.1.2
454.4.1
454.1
454.1.3
454.4.2
454.2
454.2.5
474.3
454.4
454.4.3
454.2.1
474.4
454.2
474.1.1.1a
474.1.1.4
474.1.1.2a
472.2
476
474.1
484.1
474.1.1.3
474.1.1.1b
474.1.1.2b
486

FIG. 37

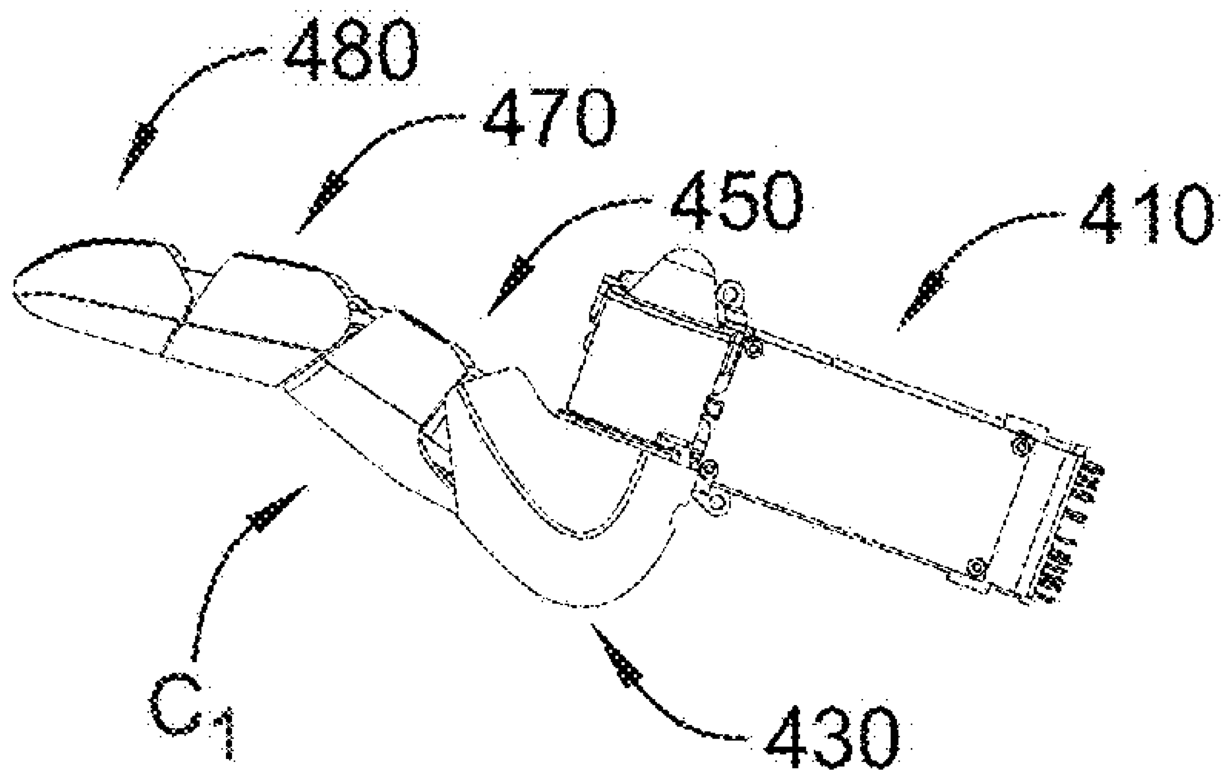


FIG. 38

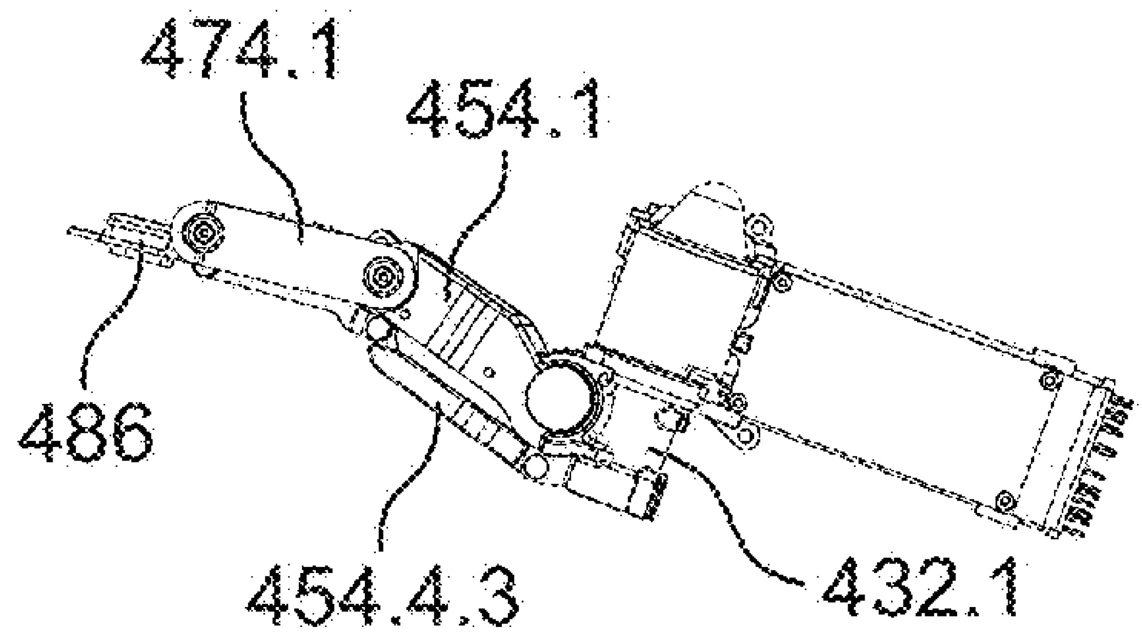


FIG. 39

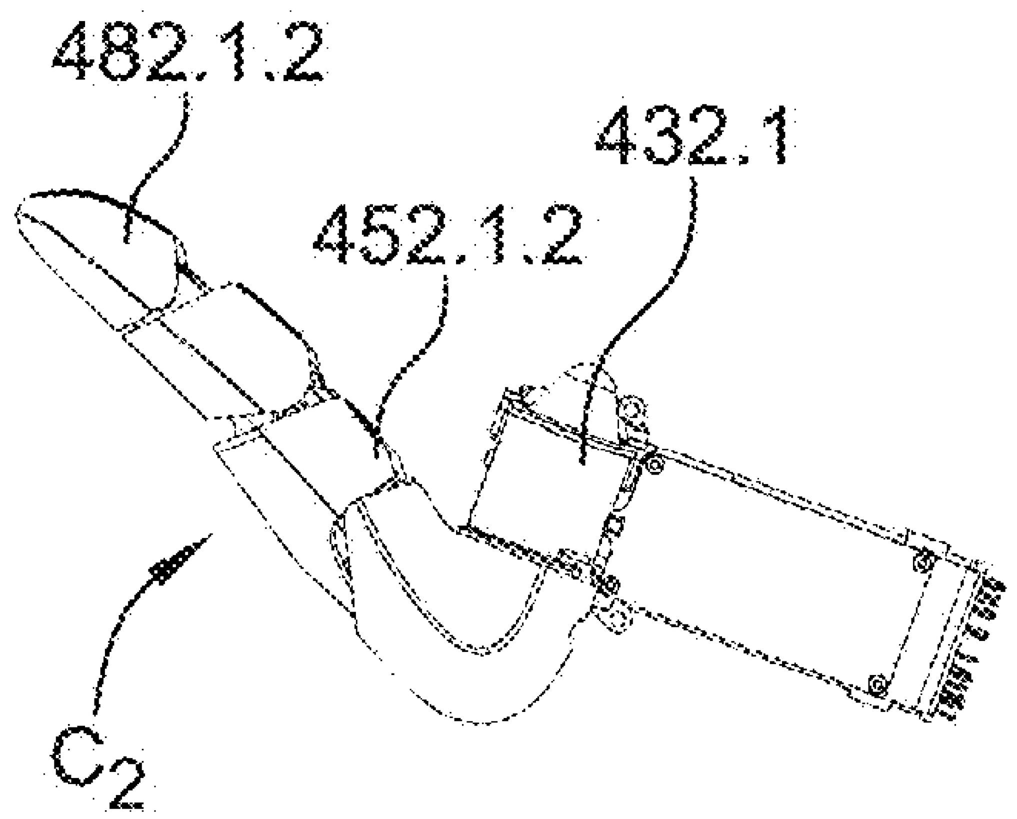


FIG. 40

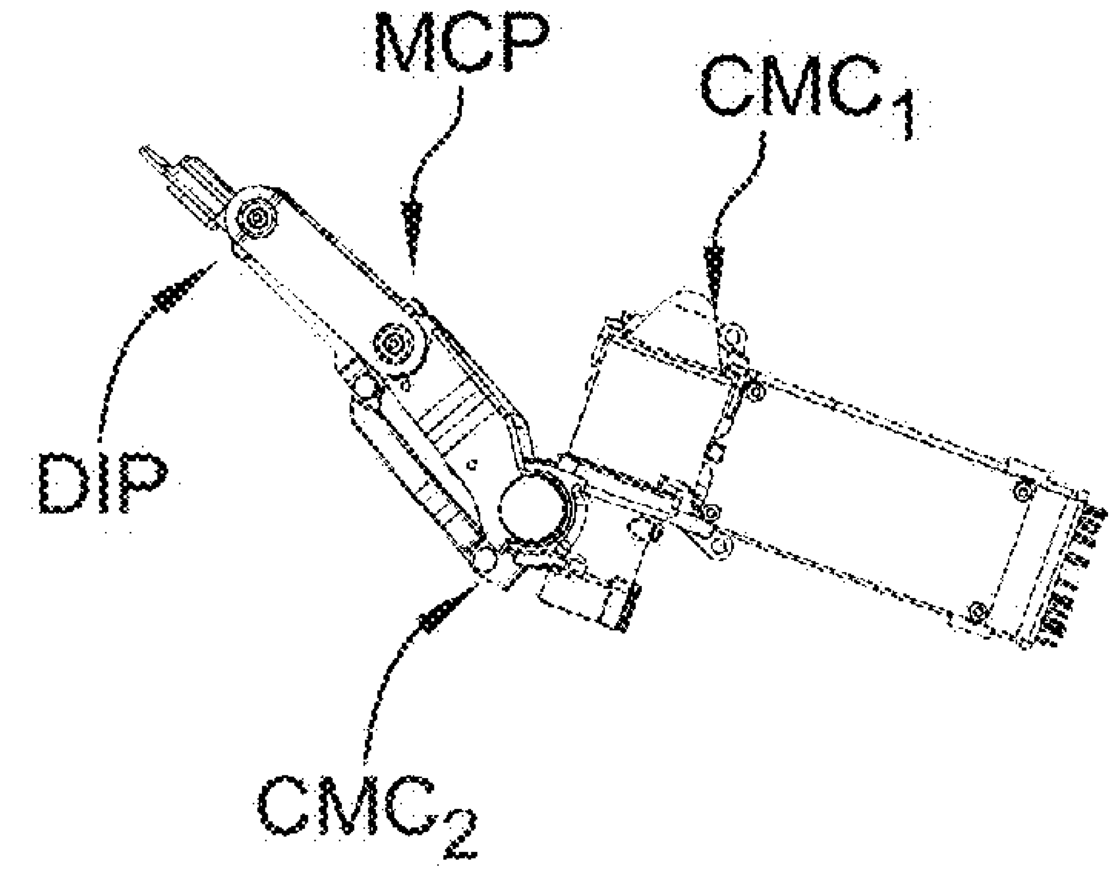


FIG. 41

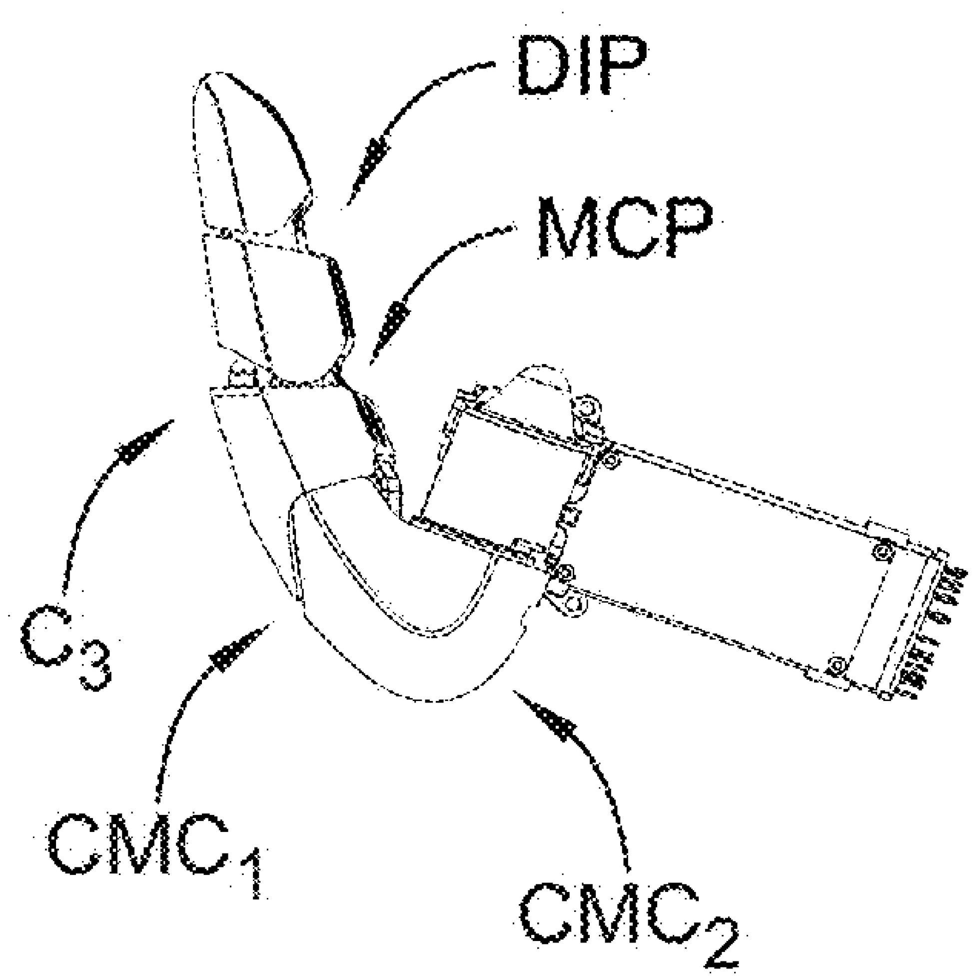


FIG. 42

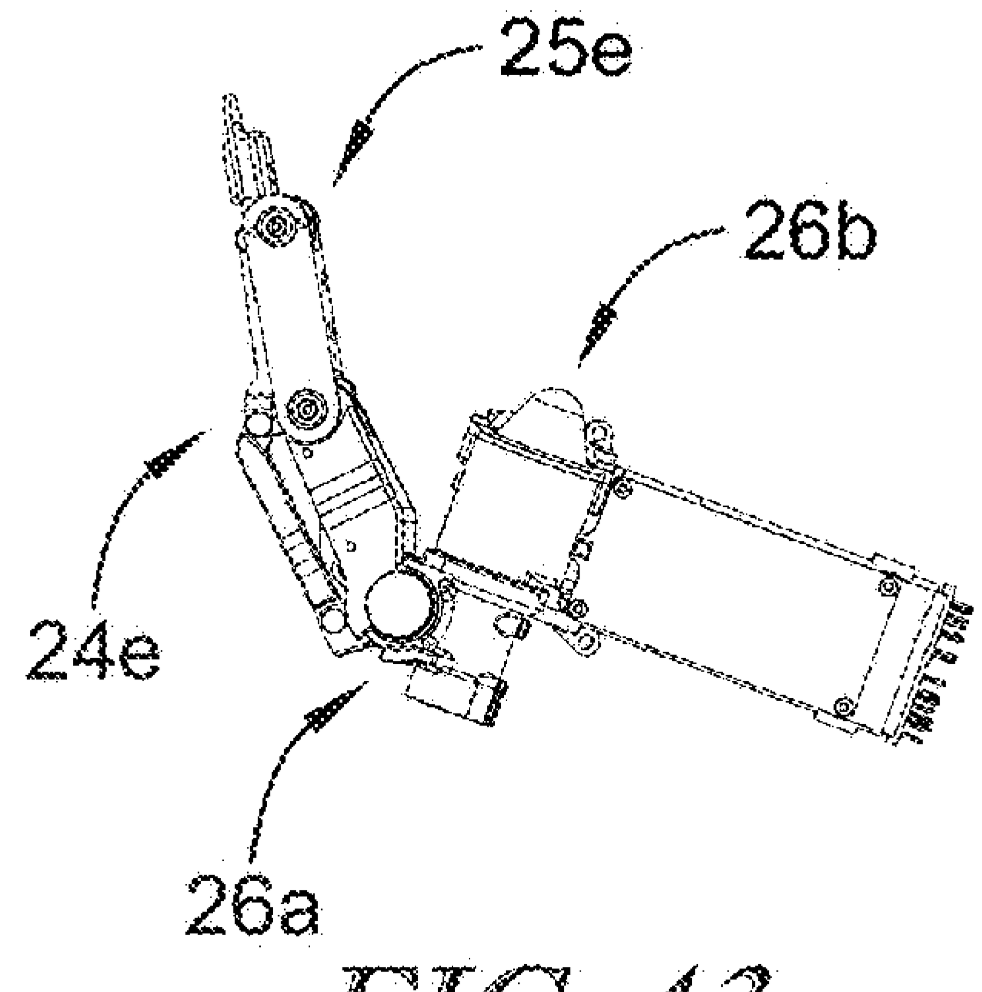


FIG. 43

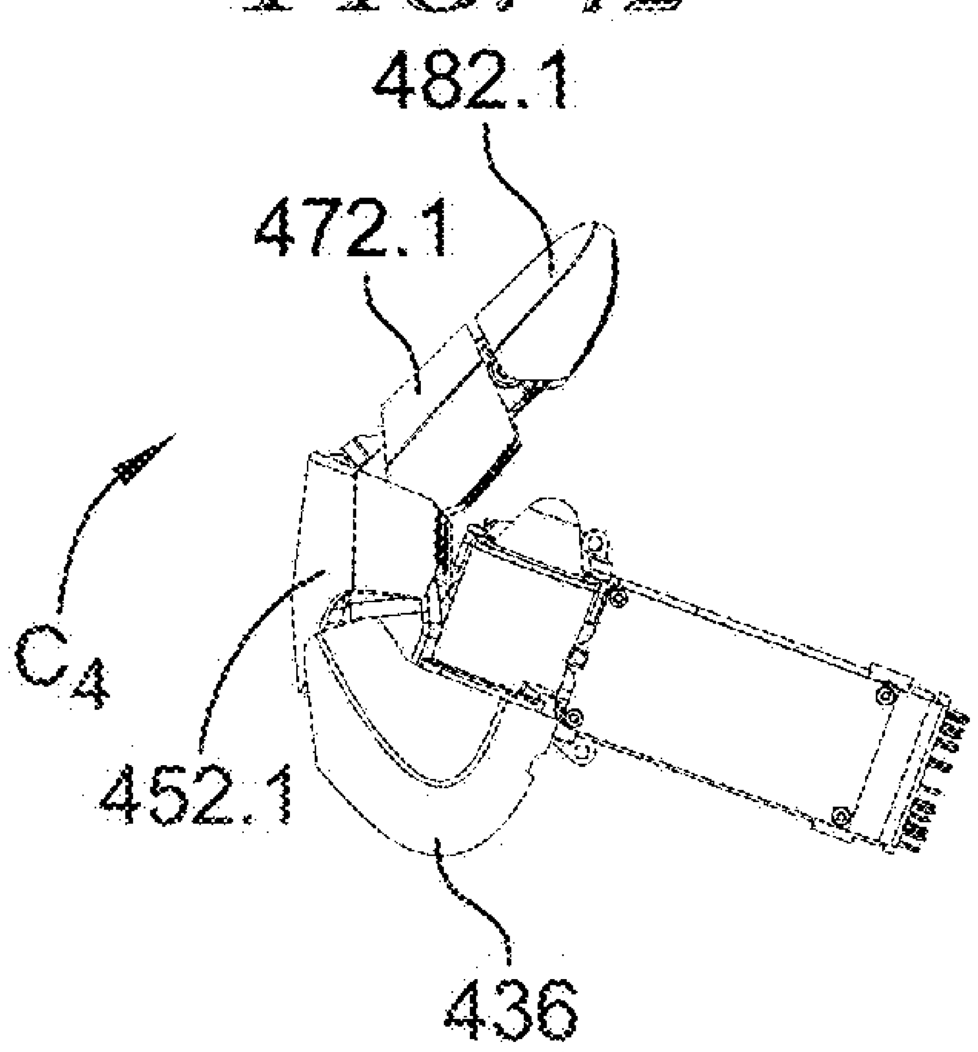


FIG. 44

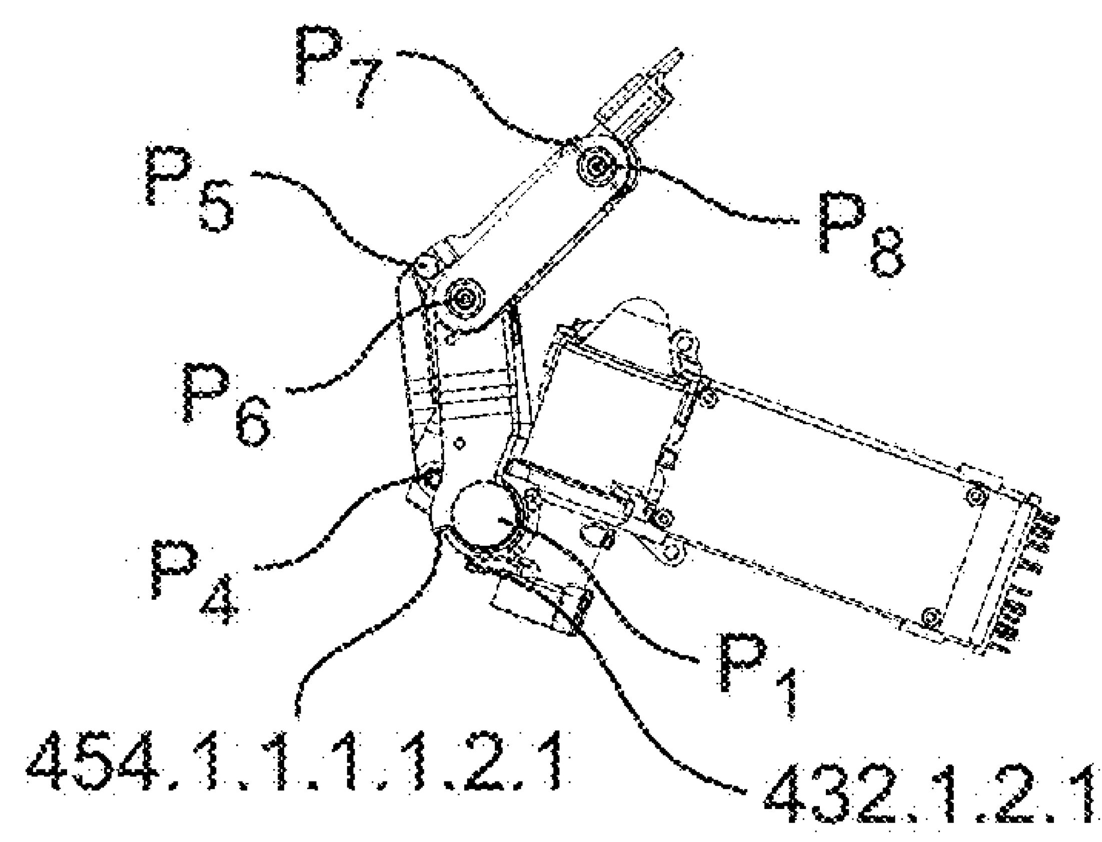


FIG. 45

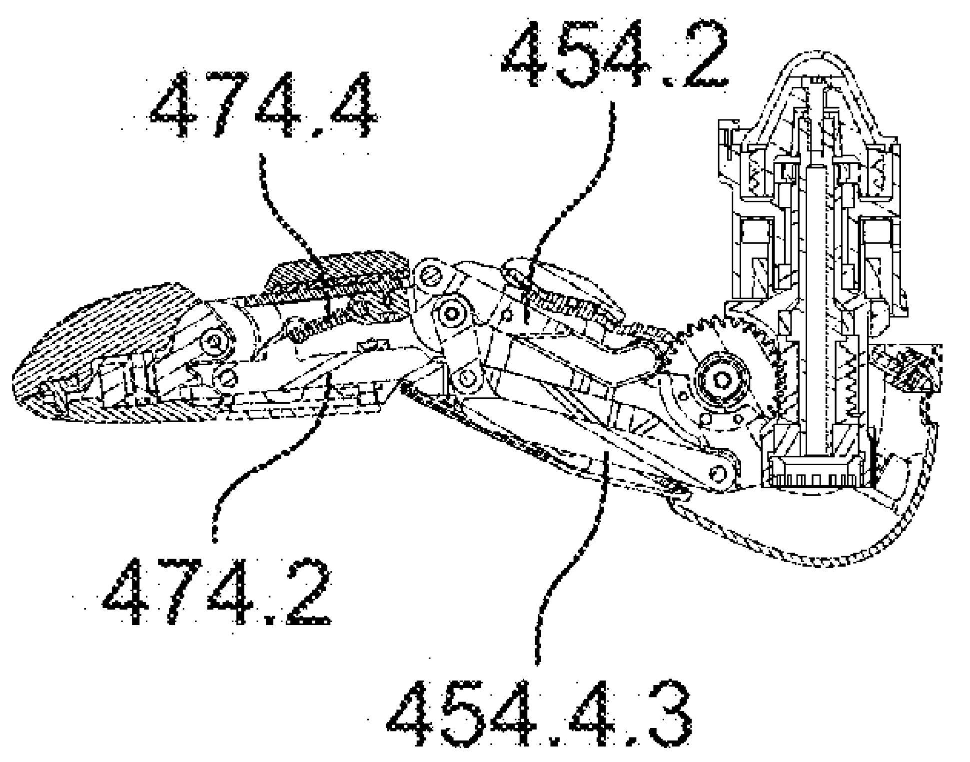


FIG. 46

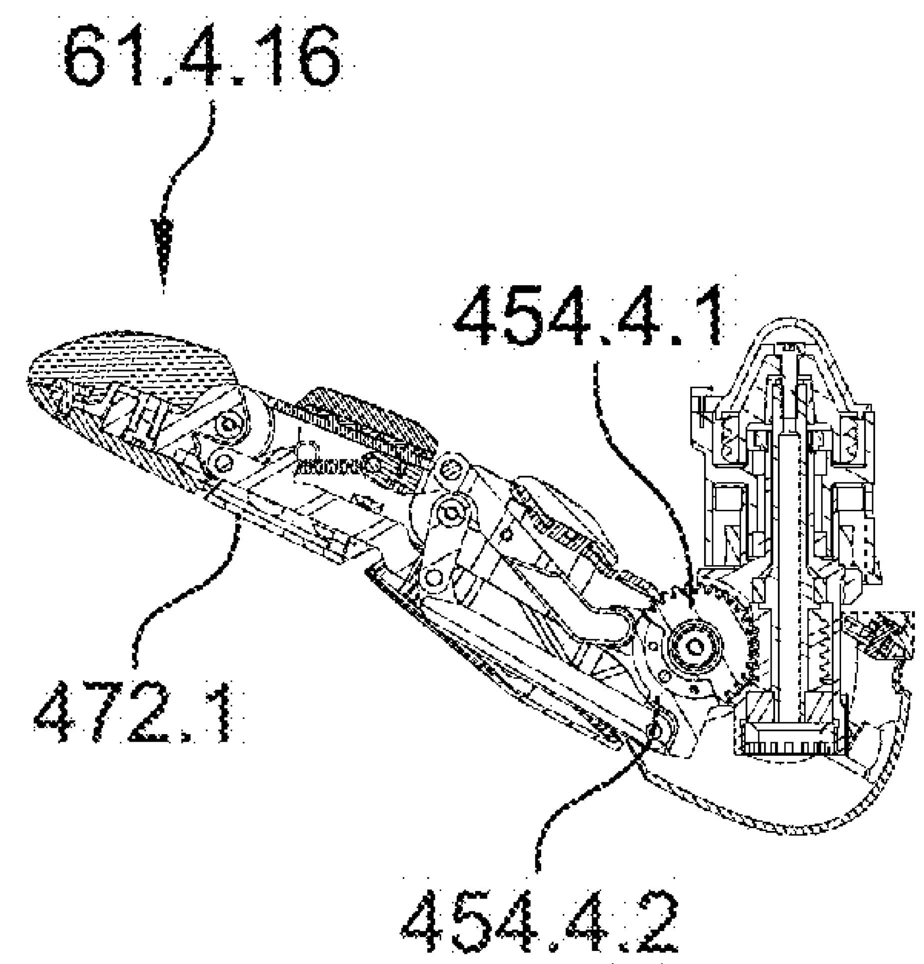


FIG. 47

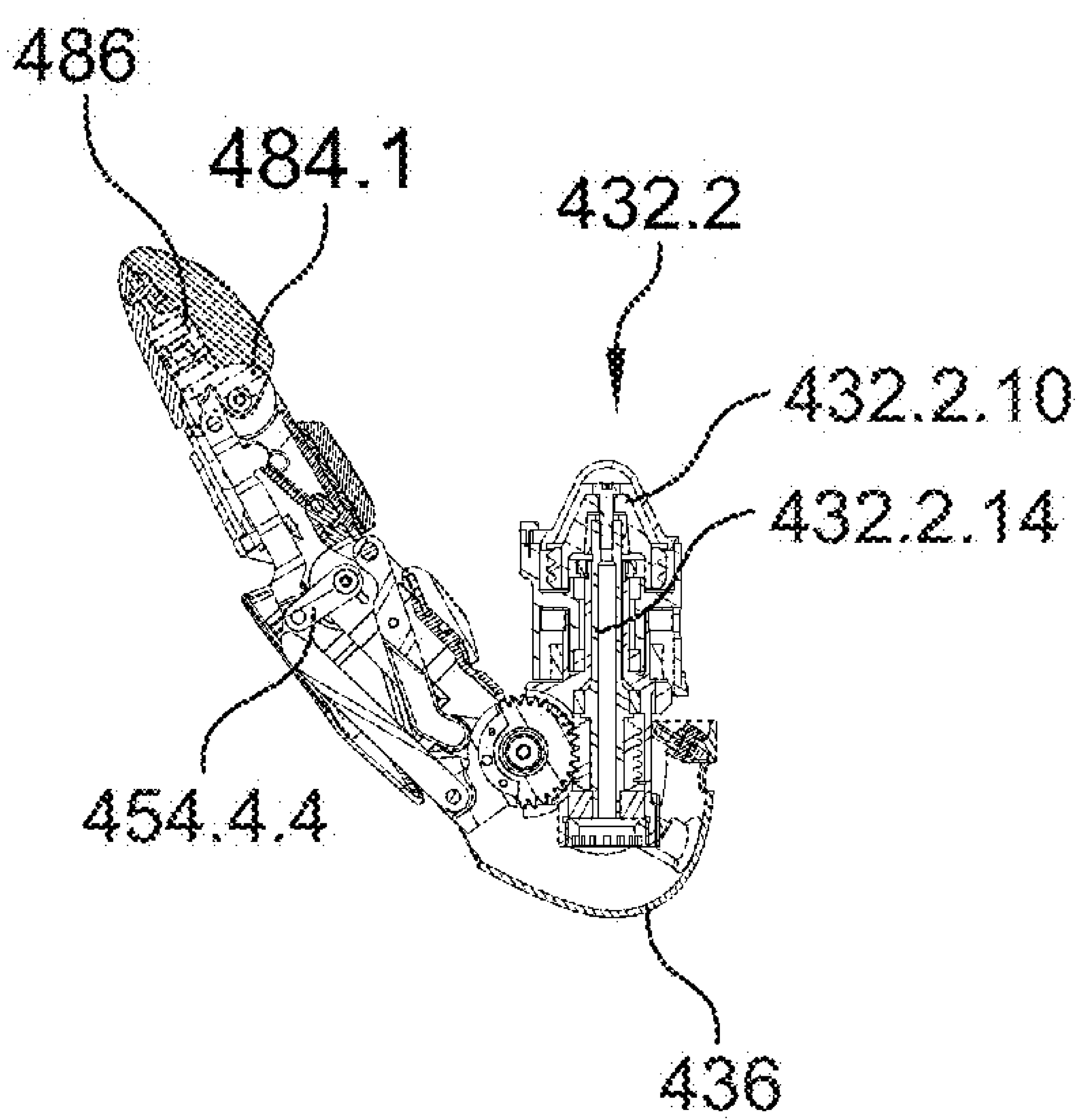


FIG. 48

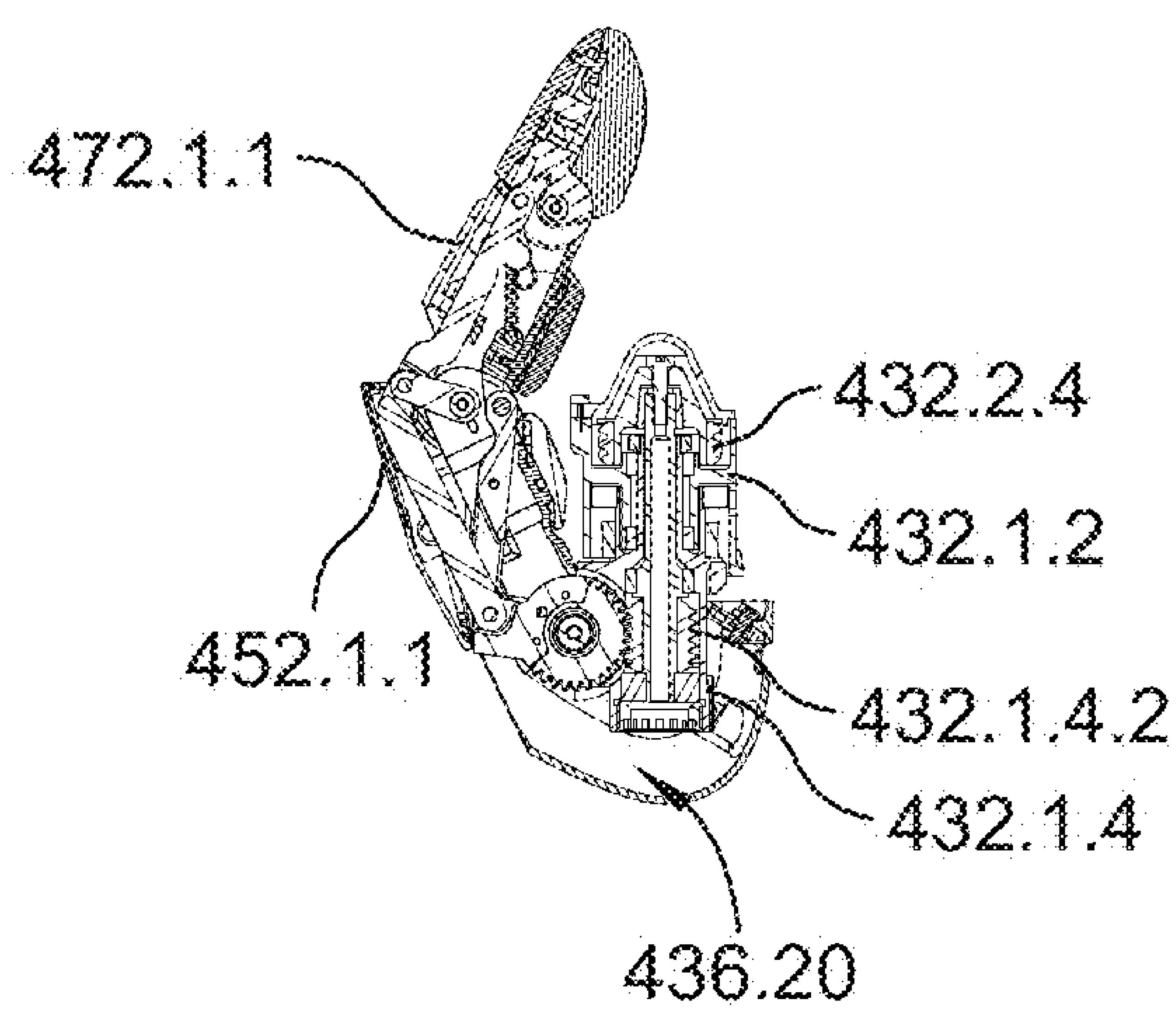


FIG. 49

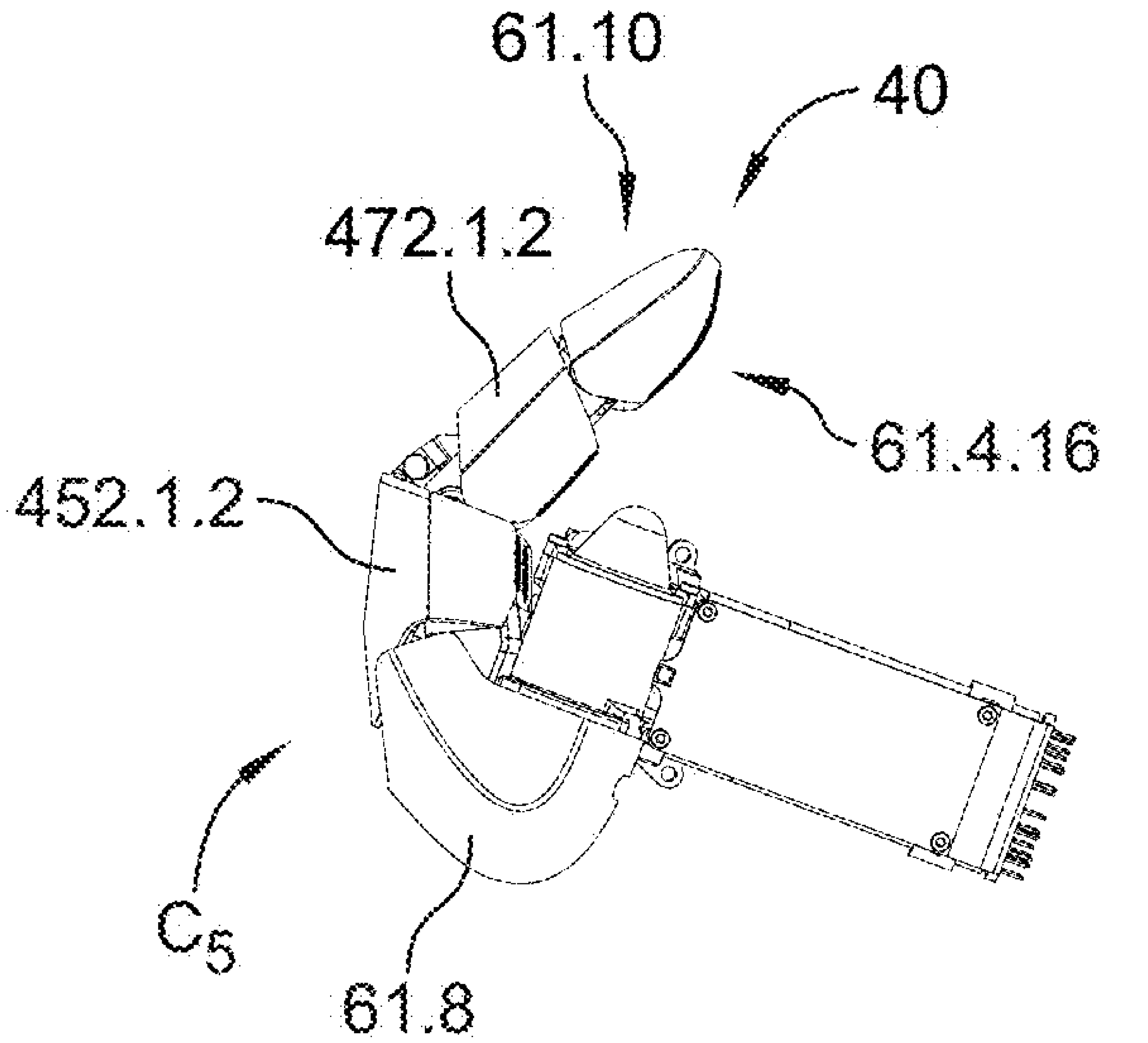


FIG. 50

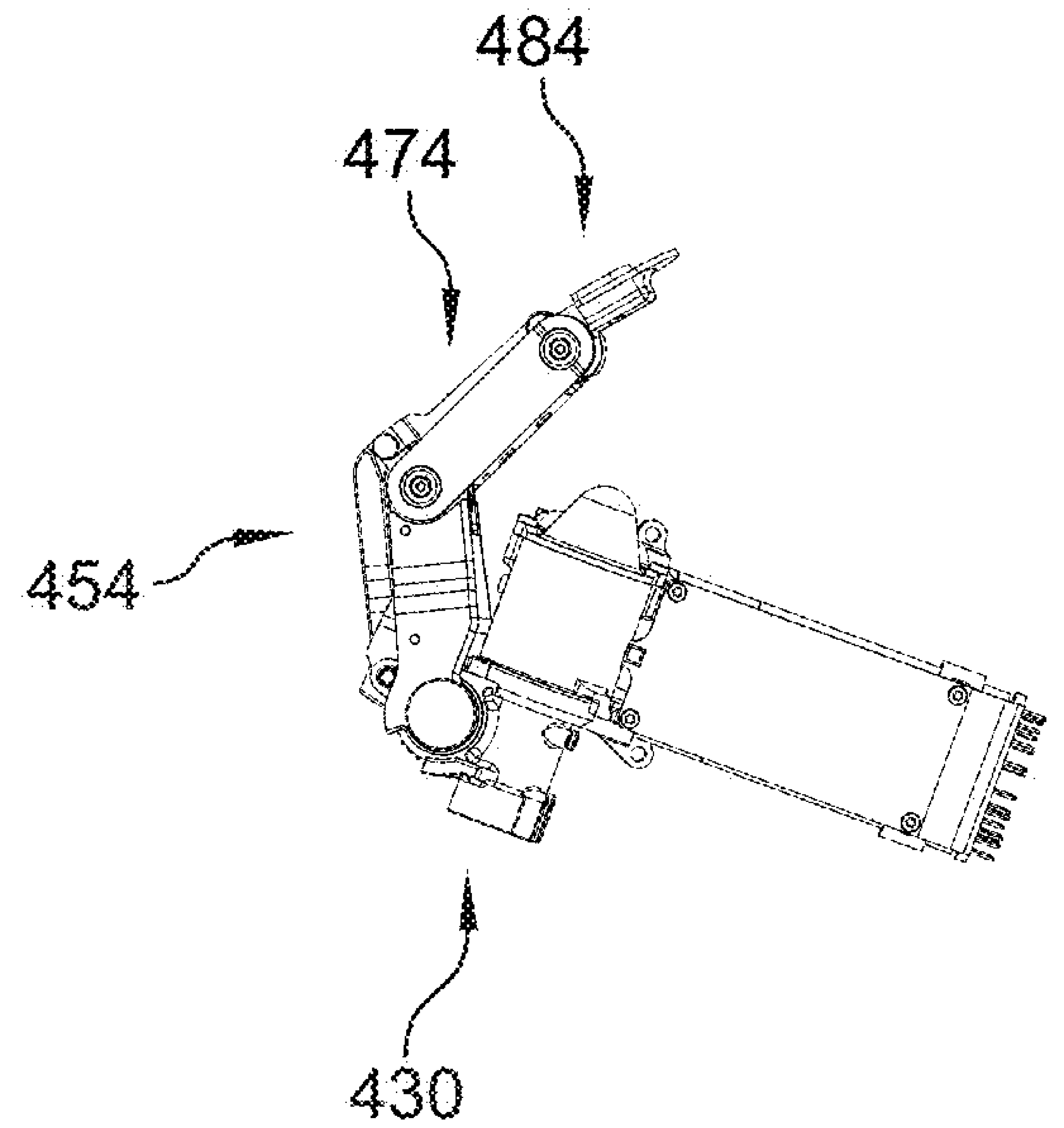


FIG. 51

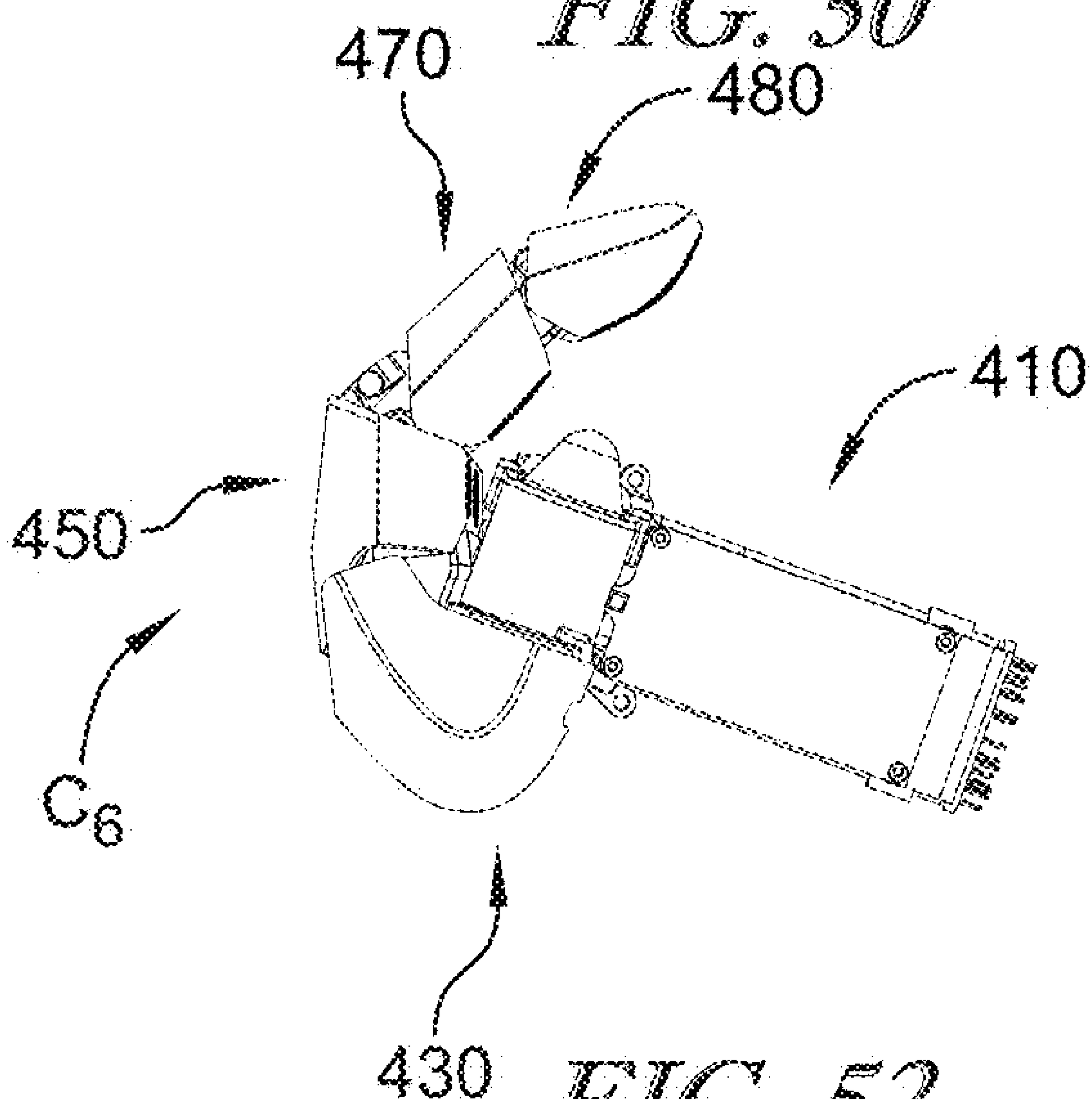


FIG. 52

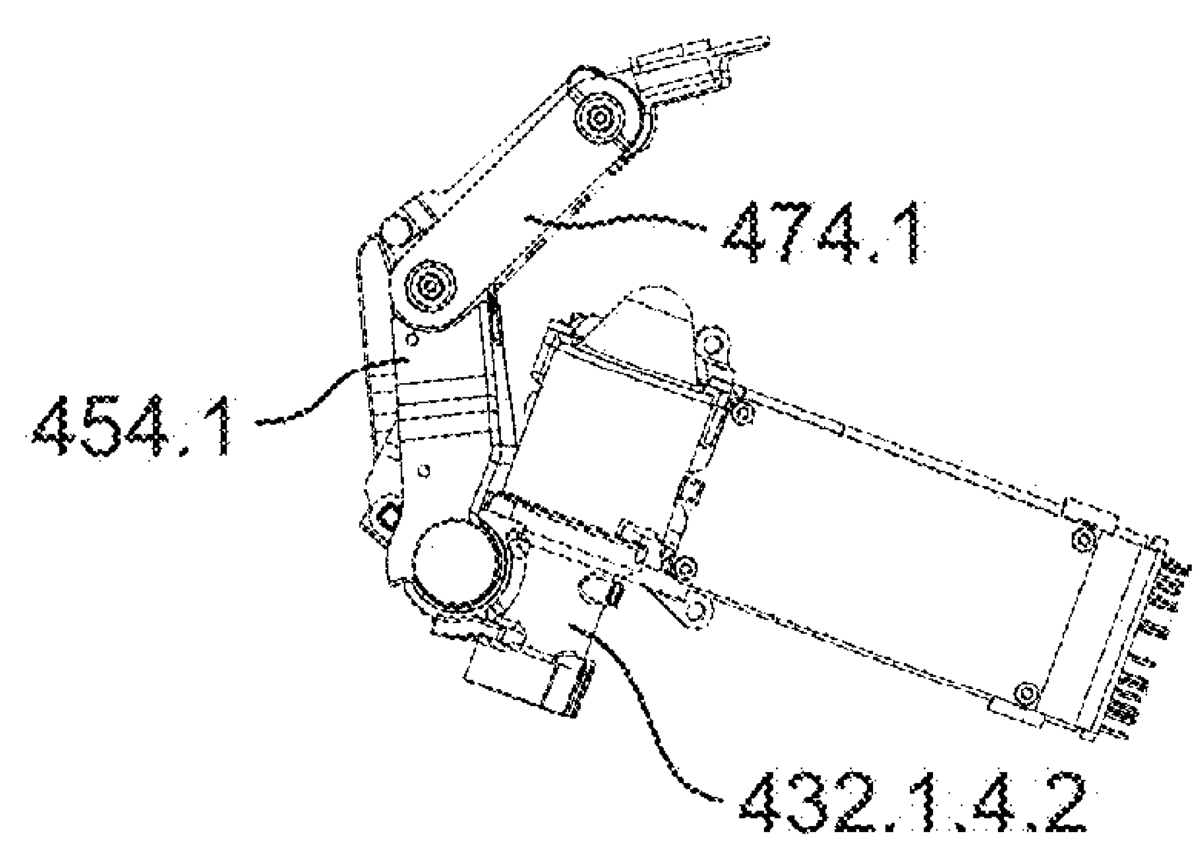


FIG. 53

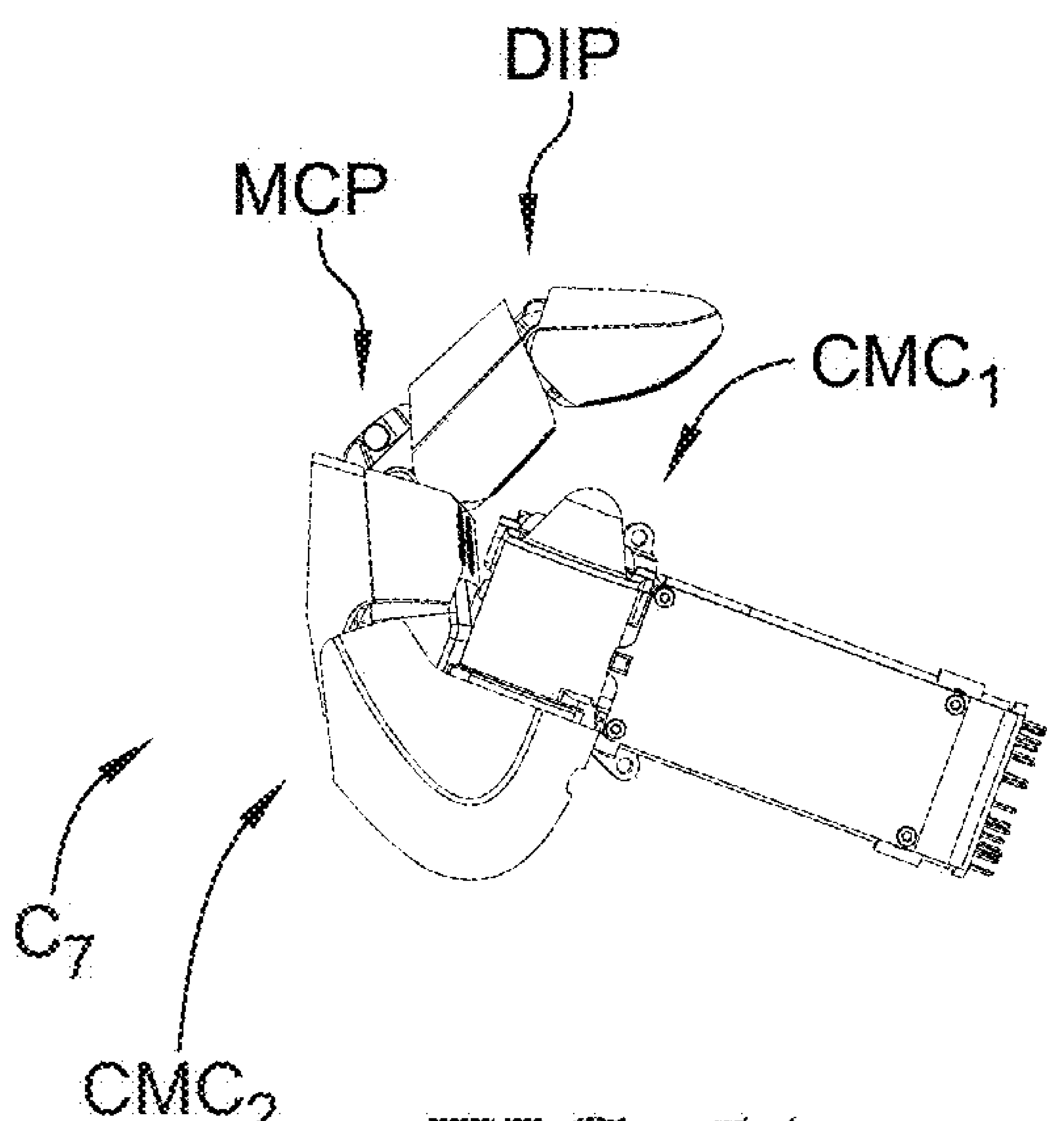


FIG. 54

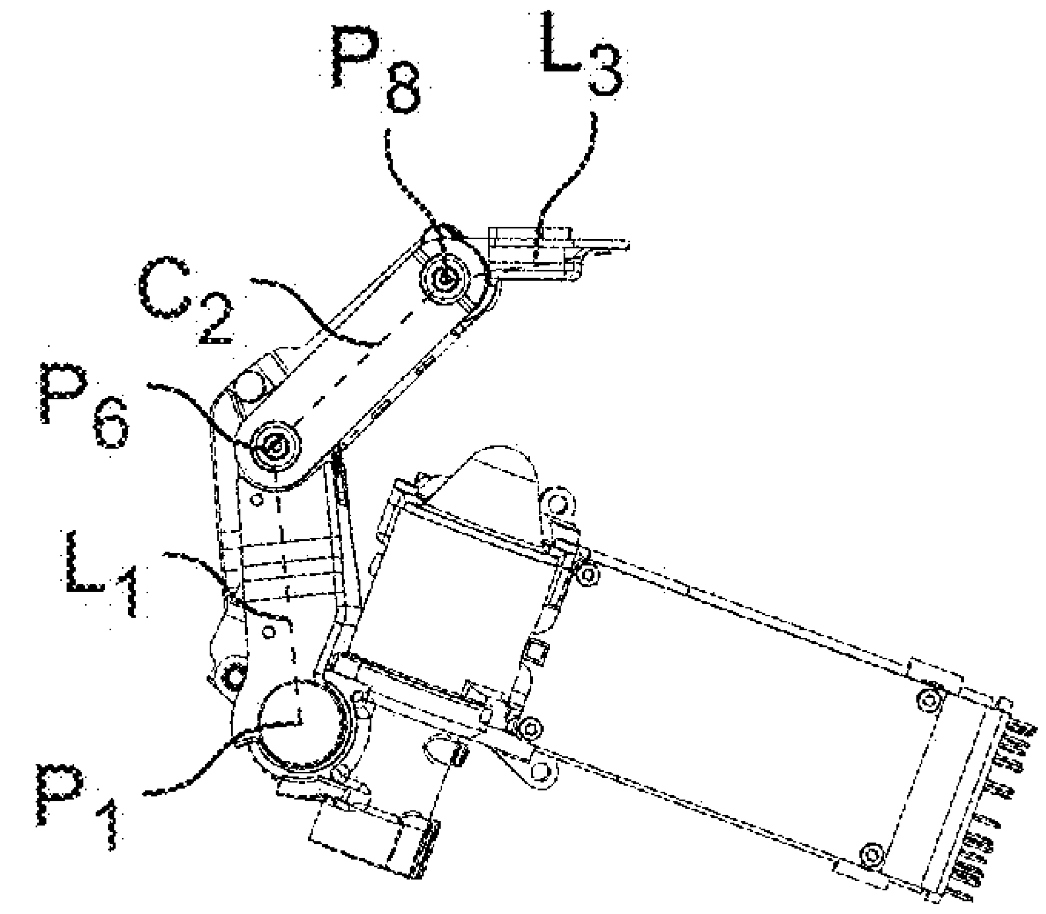


FIG. 55

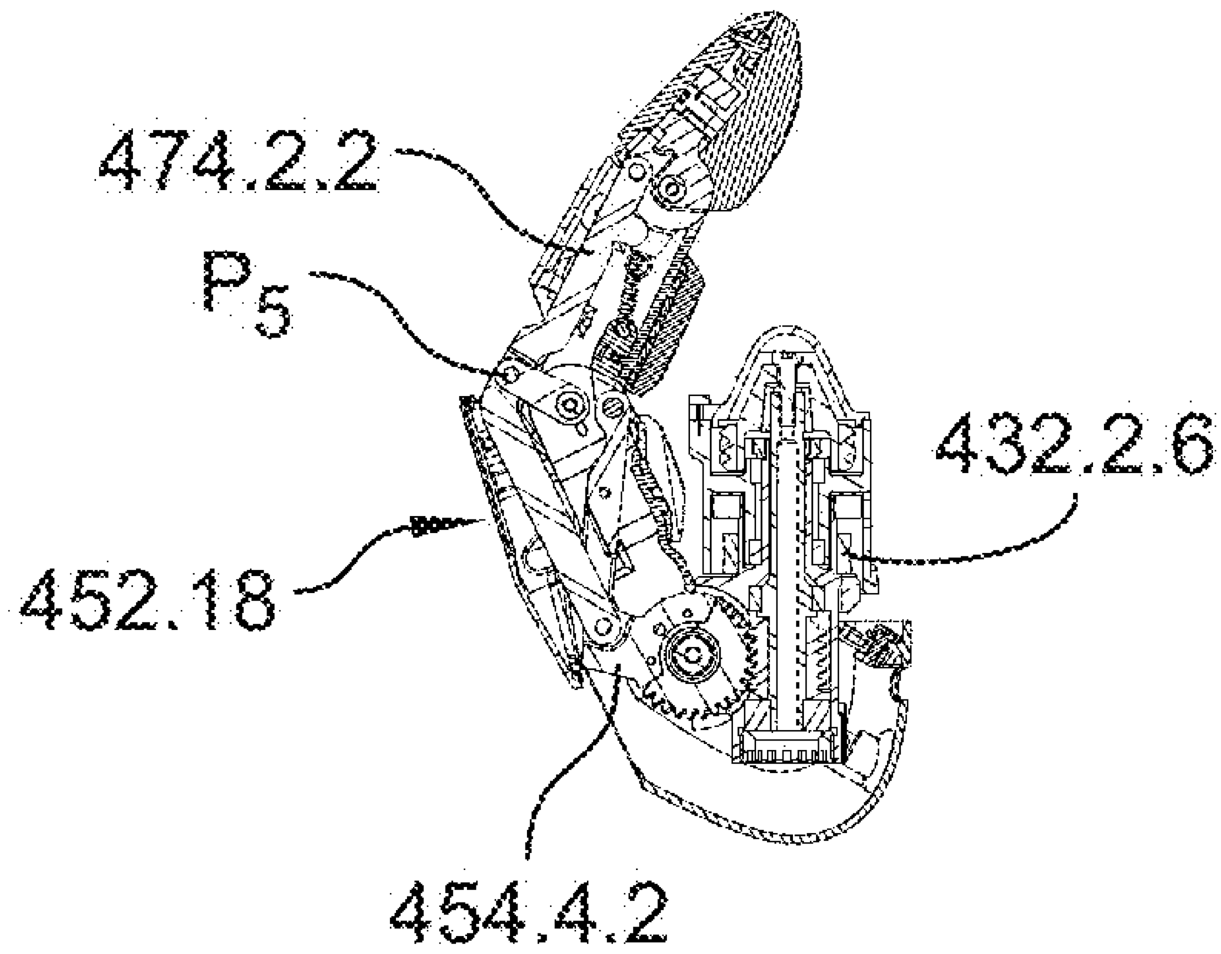


FIG. 56

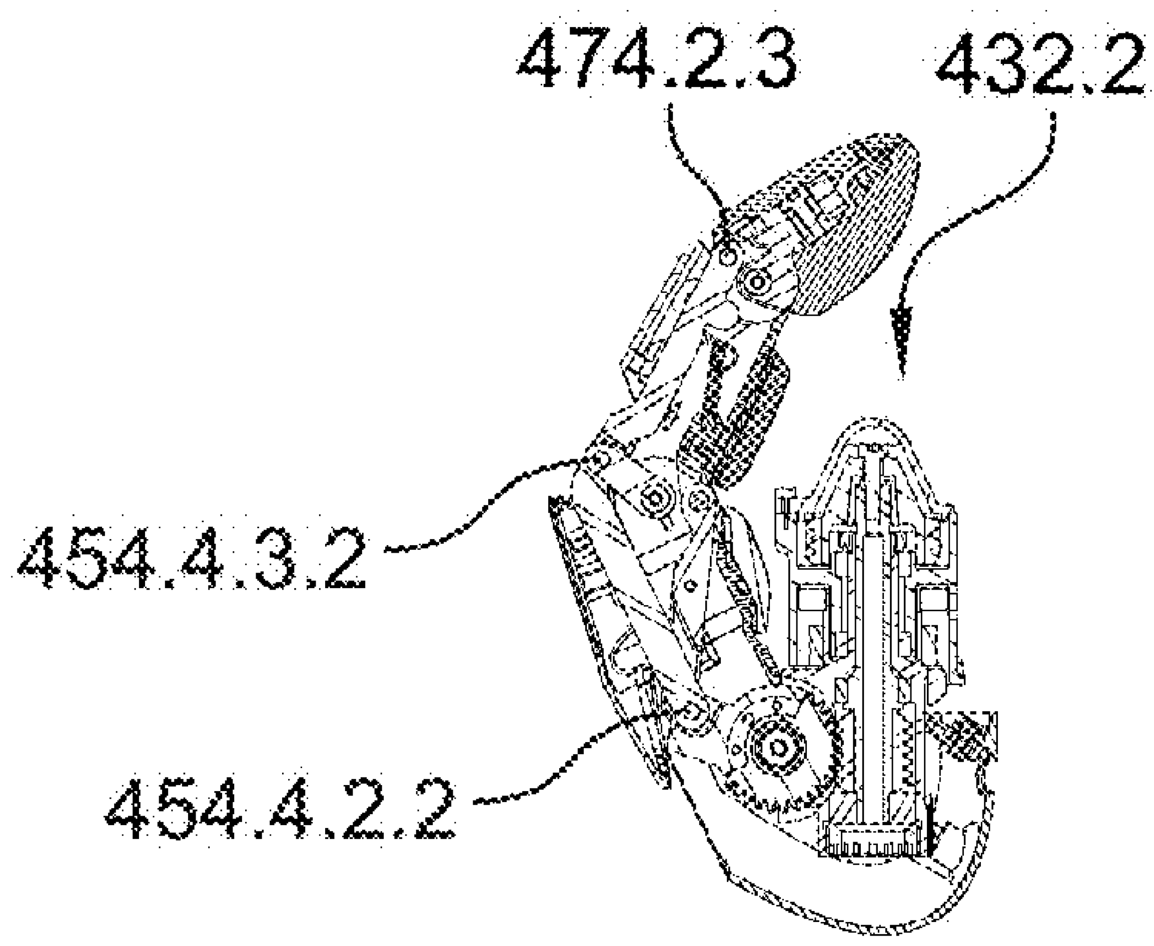


FIG. 57

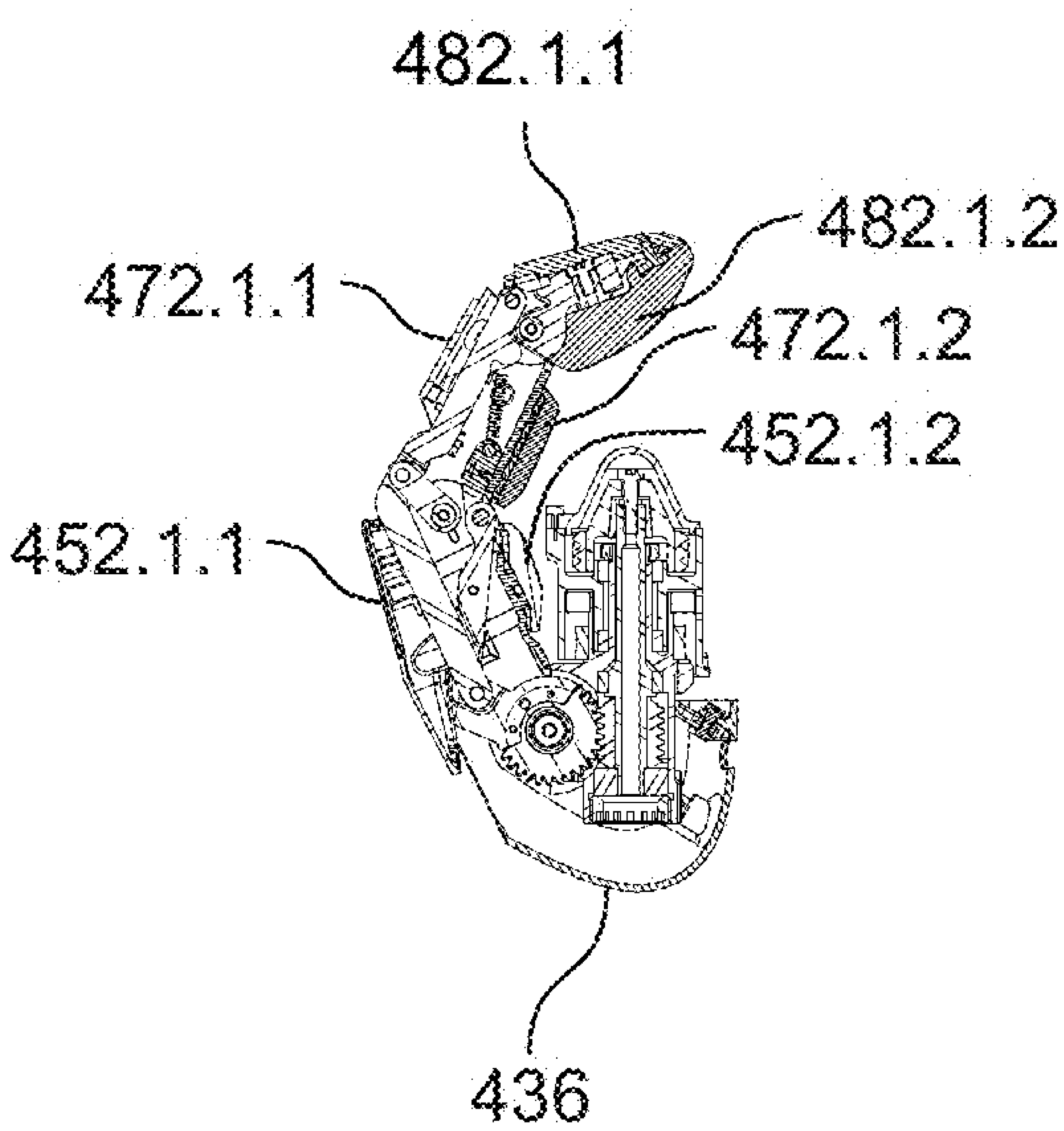
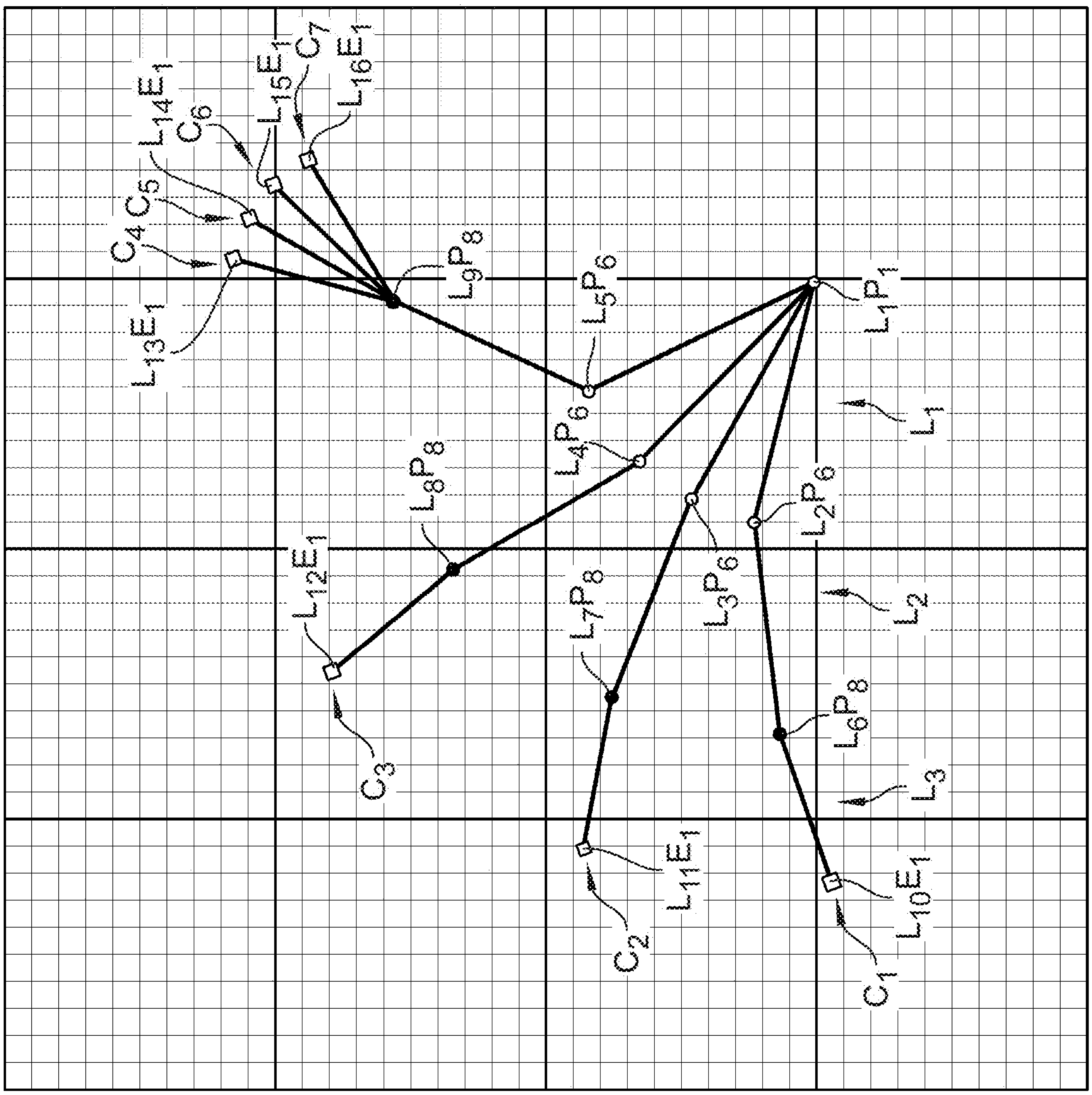


FIG. 58

FIG. 59


L_1P_1
L_2P_6
L_3P_6
L_4P_6
L_5P_6
L_6P_8
L_7P_8
L_8P_8
L_9P_8
$L_{10}E_1$
$L_{11}E_1$
$L_{12}E_1$
$L_{13}E_1$
$L_{14}E_1$
$L_{15}E_1$
$L_{16}E_1$
L_1
L_2
L_3
C_1
C_2
C_3
C_4
C_5
C_6
C_7

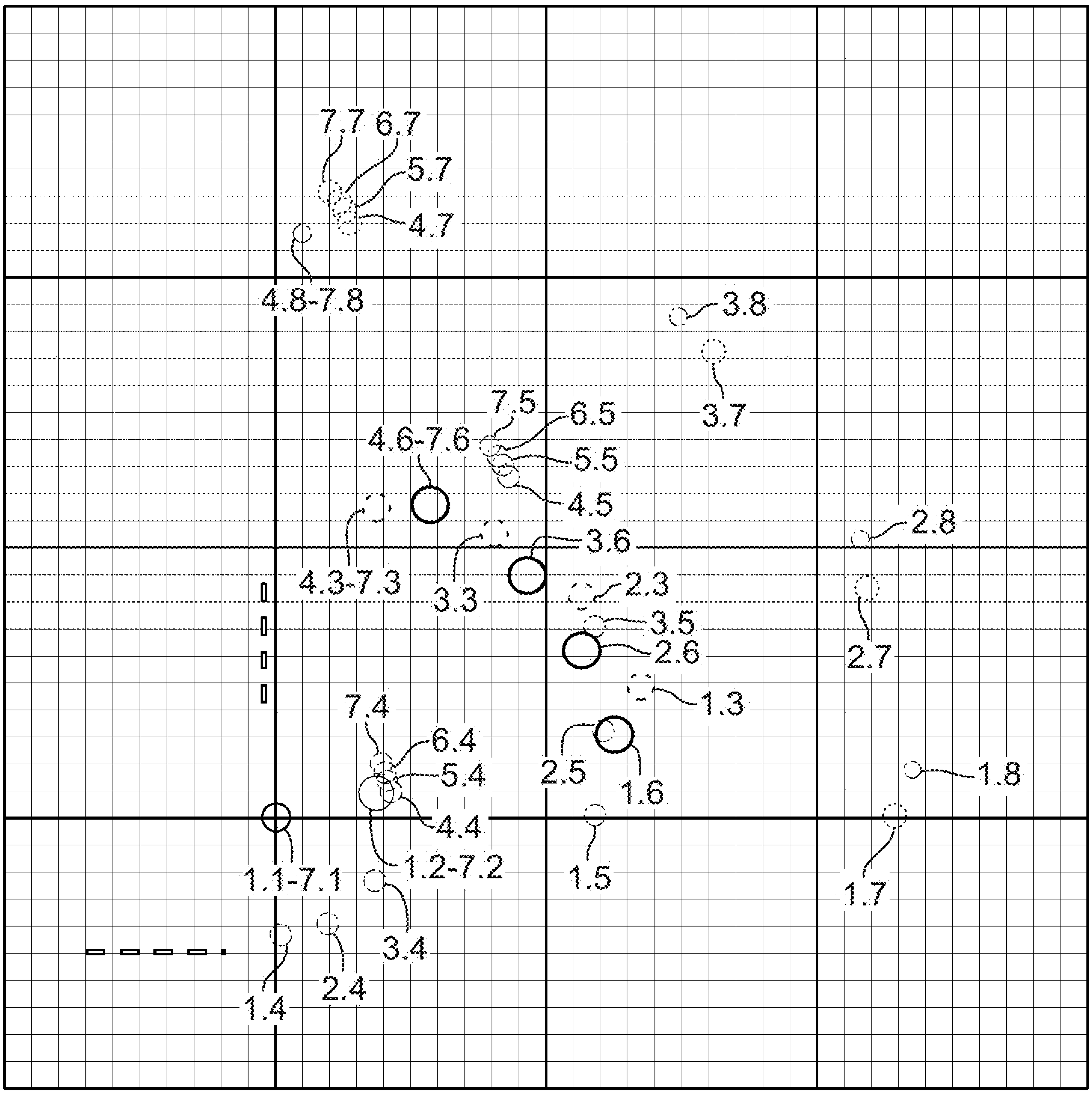
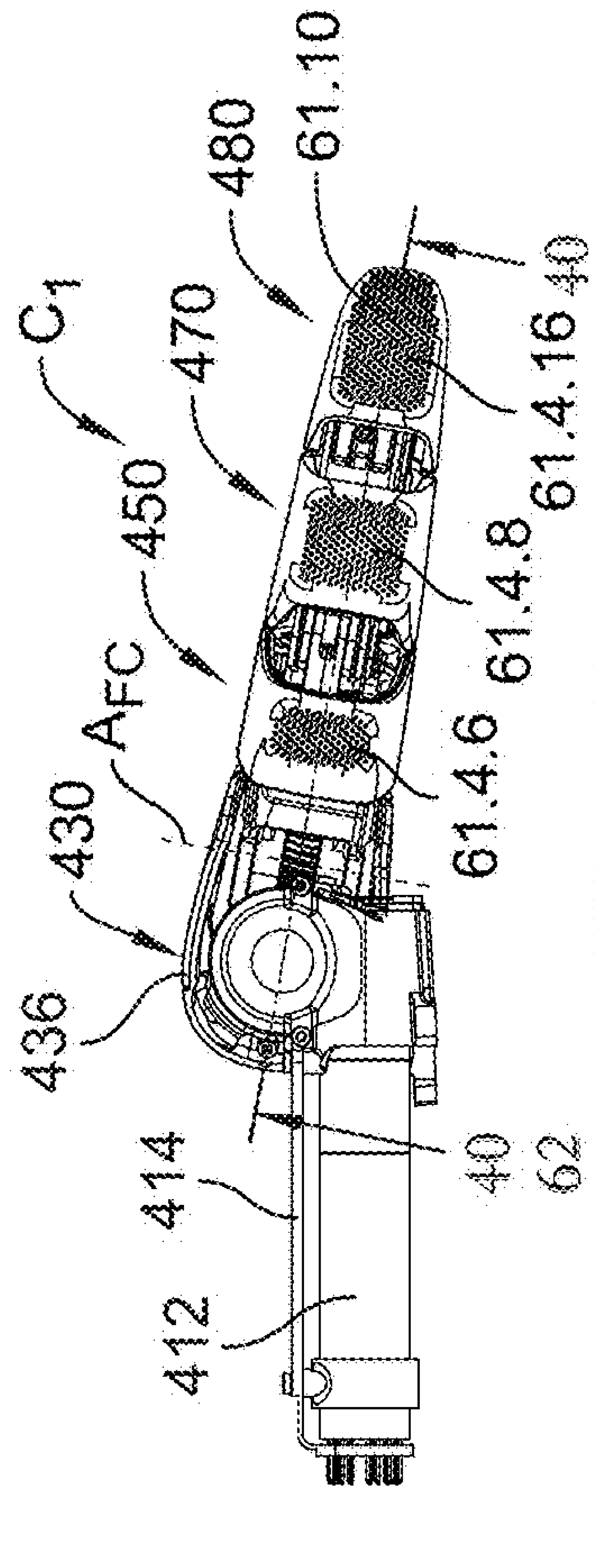
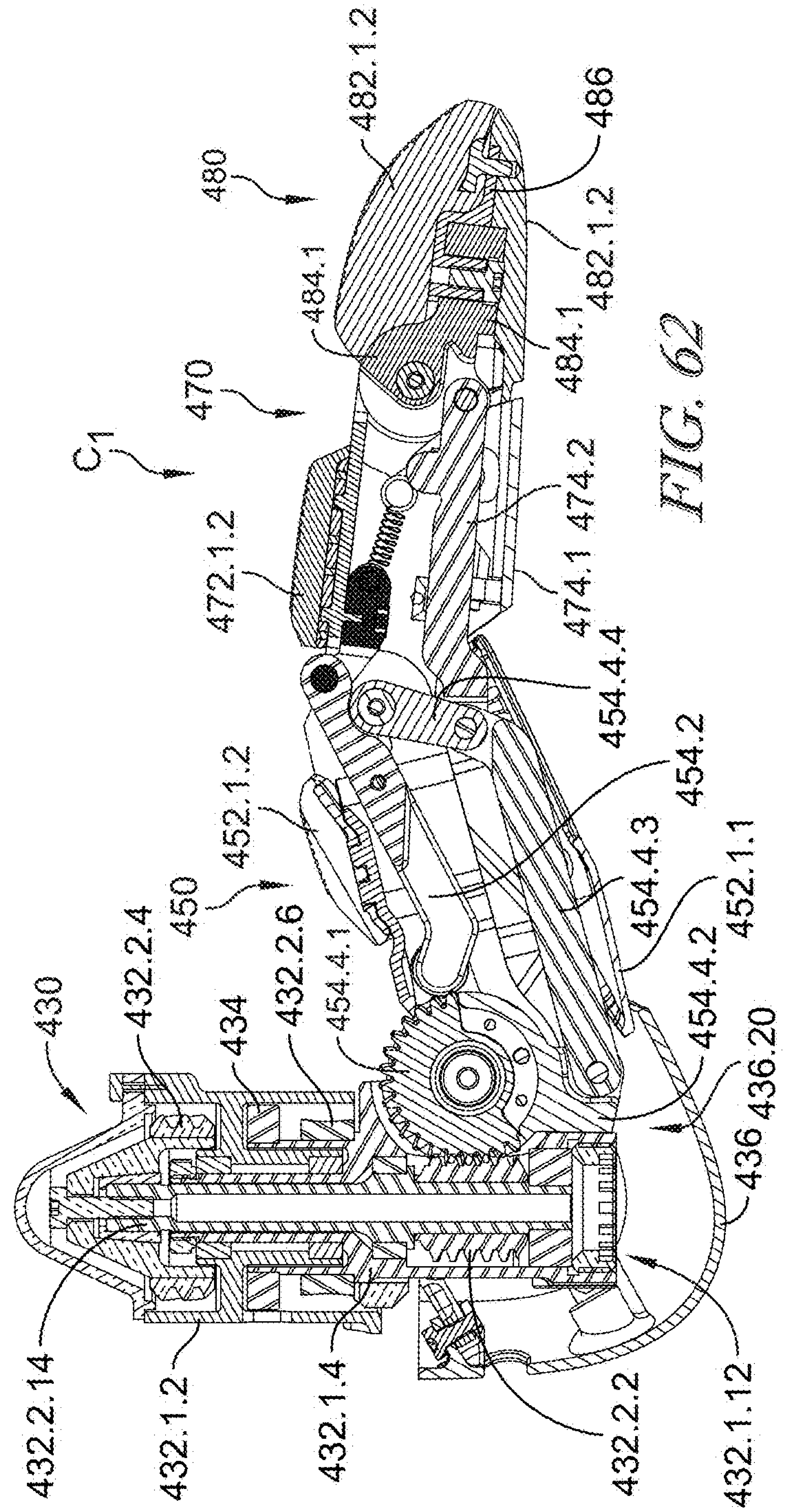

7.7
6.7
5.7
4.7
4.8-7.8
3.8
3.7
7.5
6.5
4.6-7.6
5.5
4.5
2.8
3.6
4.3-7.3
3.3
2.3
3.5
2.6
2.7
1.3
7.4
6.4
5.4
2.5
1.6
1.8
4.4
1.5
1.2-7.2
1.1-7.1
1.7
3.4
2.4
1.4

FIG. 60



C1
AFC
430
436
450
470
480
61.10
61.4.16
61.4.8
61.4.6
40
62
414
412

FIG. 61



482.1.2
486
480
482.1.2
484.1
484.1
470
C1
474.2
472.1.2
474.1
454.4.4
452.1.2
454.2
450
454.4.3
430
432.2.4
434
432.2.6
454.4.1
454.4.2
452.1.1
436.20
436
432.2.14
432.1.2
432.1.4
432.2.2
432.1.12

FIG. 62

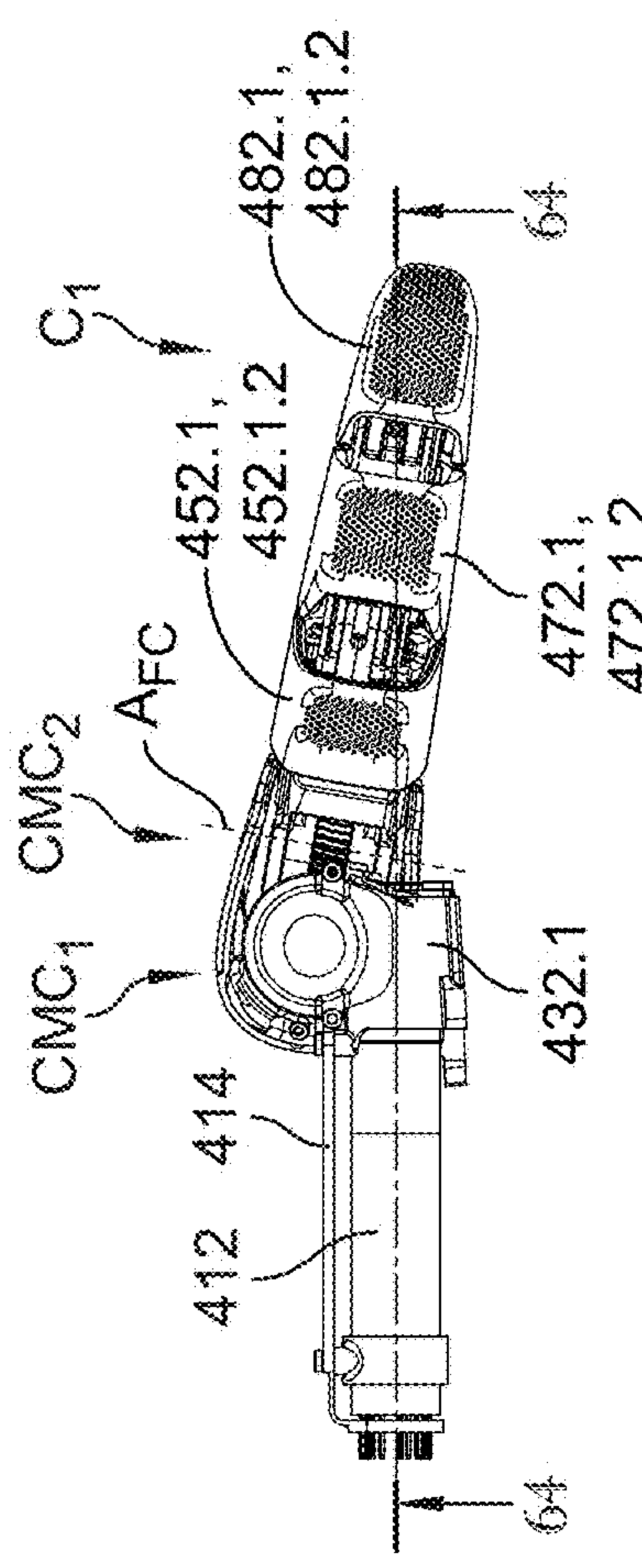

C_1
482.1,
482.1.2
452.1,
452.1.2
472.1,
472.1.2
A_{FC}
CMC_2
CMC_1
432.1
414
412
64
64

FIG. 63

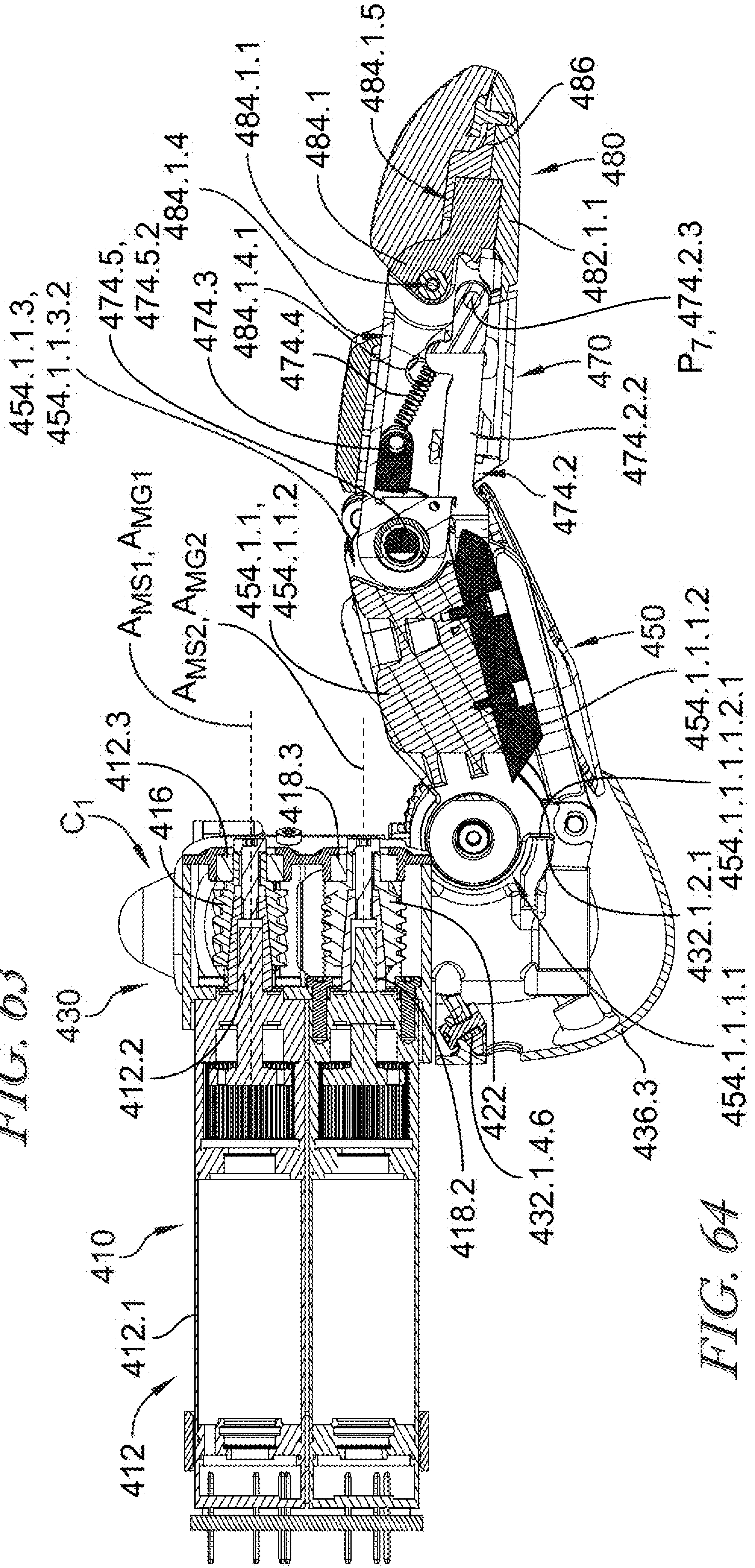

484.1.5
484.1.1
486
484.1
480
484.1.4
482.1.1
474.5,
474.5.2
484.1.4.1
474.3
474.4
P_7, 474.2.3
470
454.1.1.3,
454.1.1.3.2
474.2.2
474.2
A_{MS1}, A_{MG1}
A_{MS2}, A_{MG2}
454.1.1,
454.1.1.2
450
454.1.1.1.2
454.1.1.1.2.1
412.3
C_1
416
418.3
432.1.2.1
454.1.1.1.1
430
412.2
422
436.3
454.1.1.1.1
432.1.4.6
418.2
410
412.1
412

FIG. 64

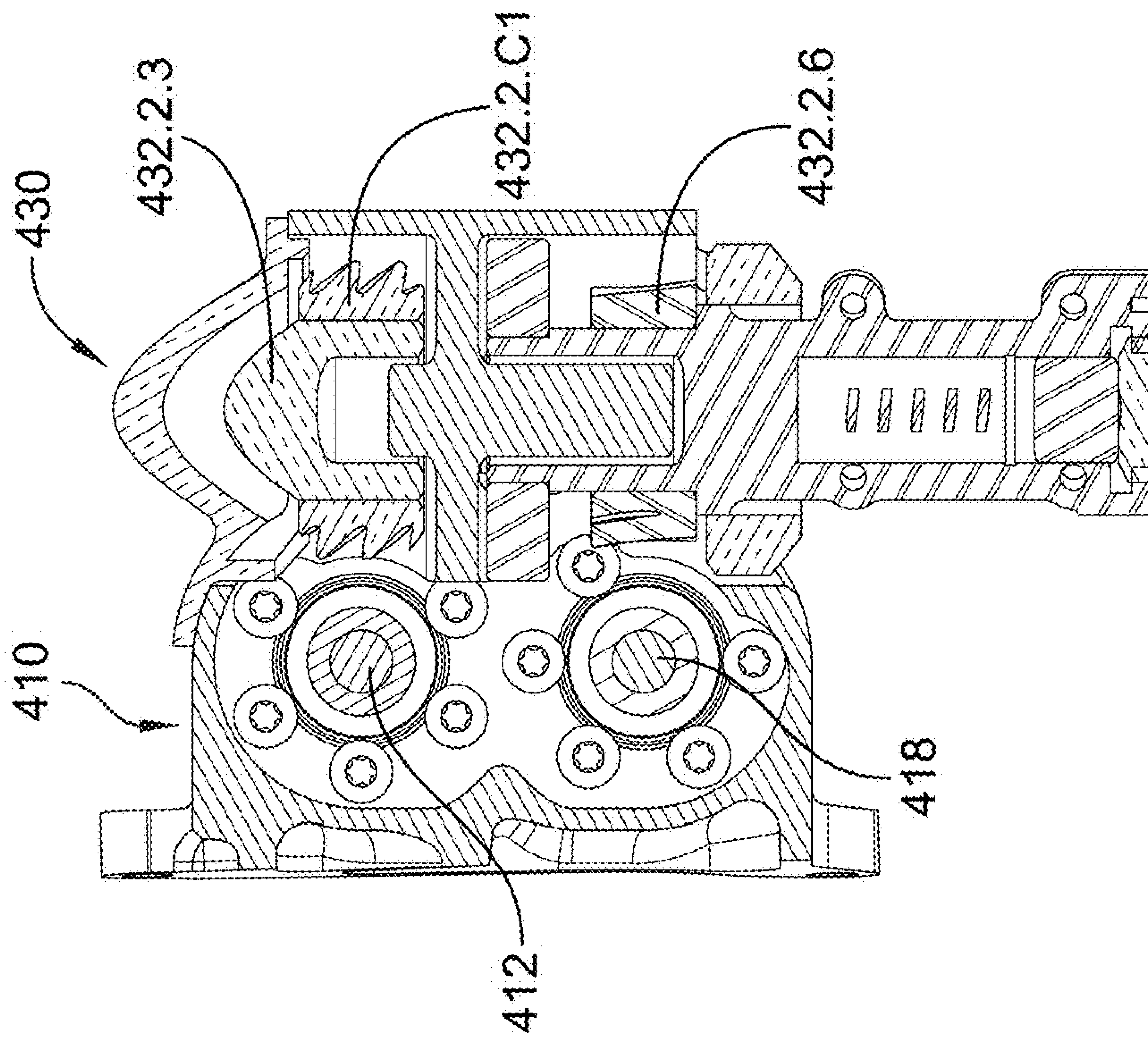

430
432.2.3
432.2.C1
432.2.6
410
412
418

FIG. 66

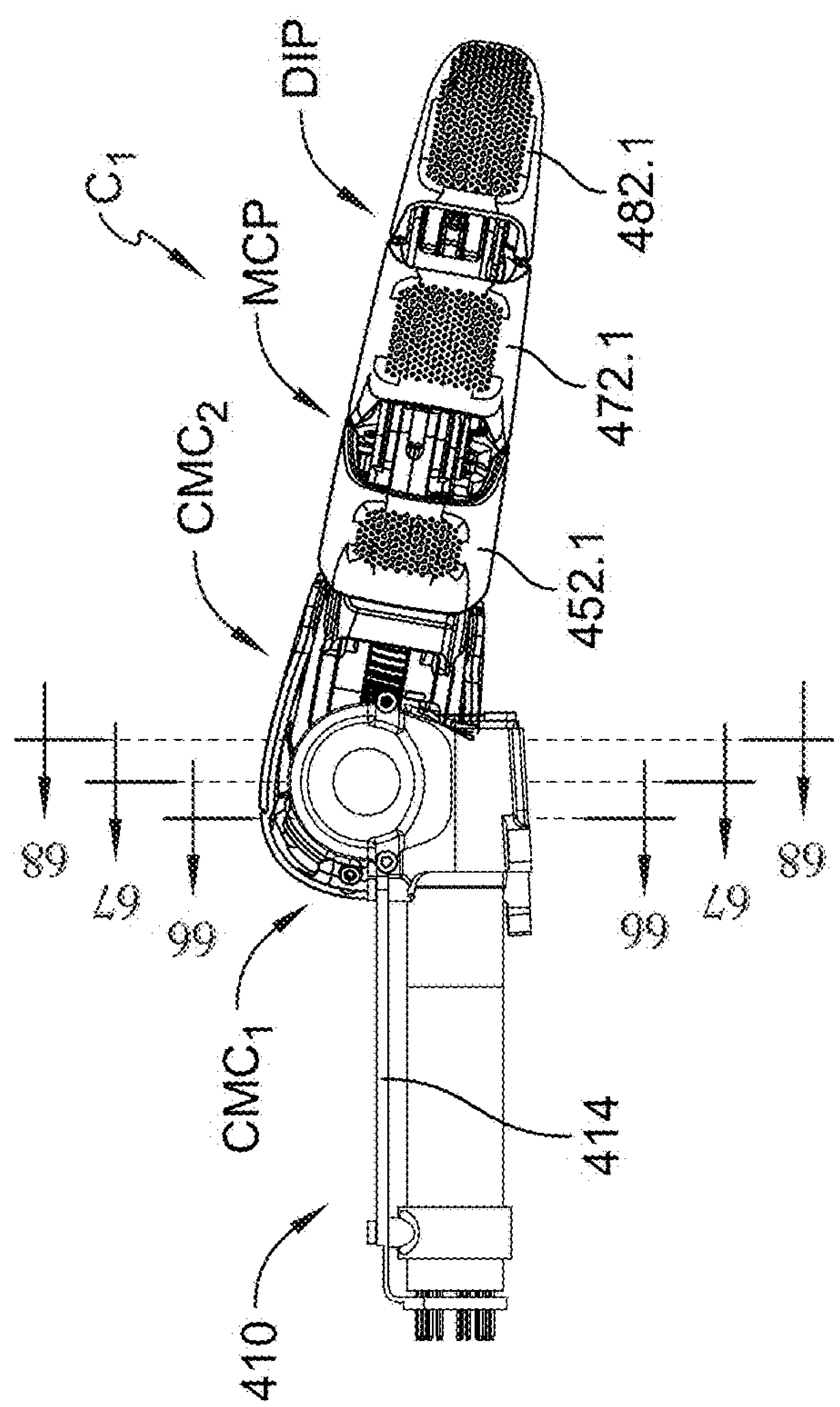

C_1
DIP
MCP
CMC_2
CMC_1
482.1
472.1
452.1
414
410
66
67
68
66
67
68

FIG. 65

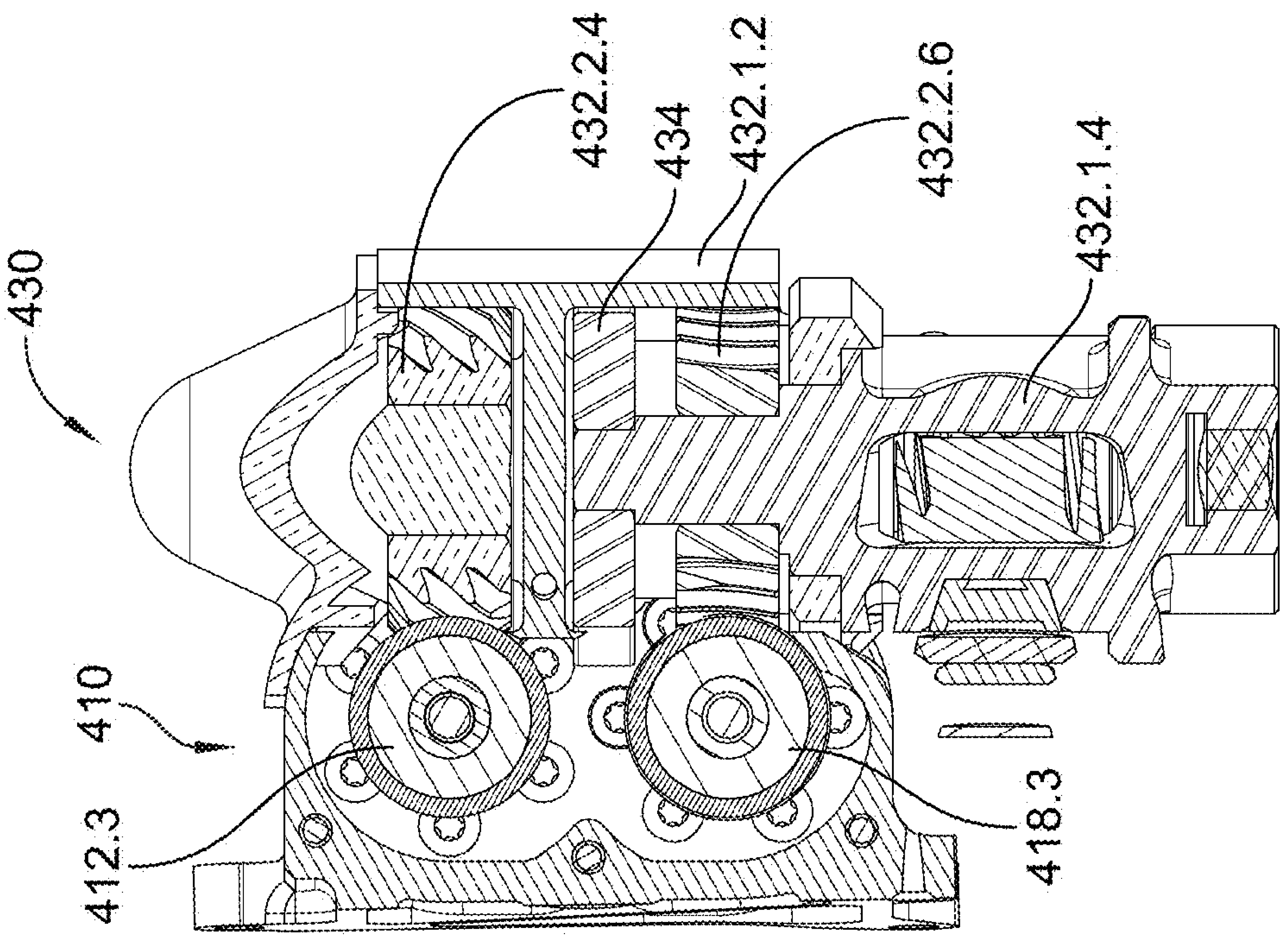

430
432.2.4
434
432.1.2
432.2.6
432.1.4
410
412.3
418.3

FIG. 68

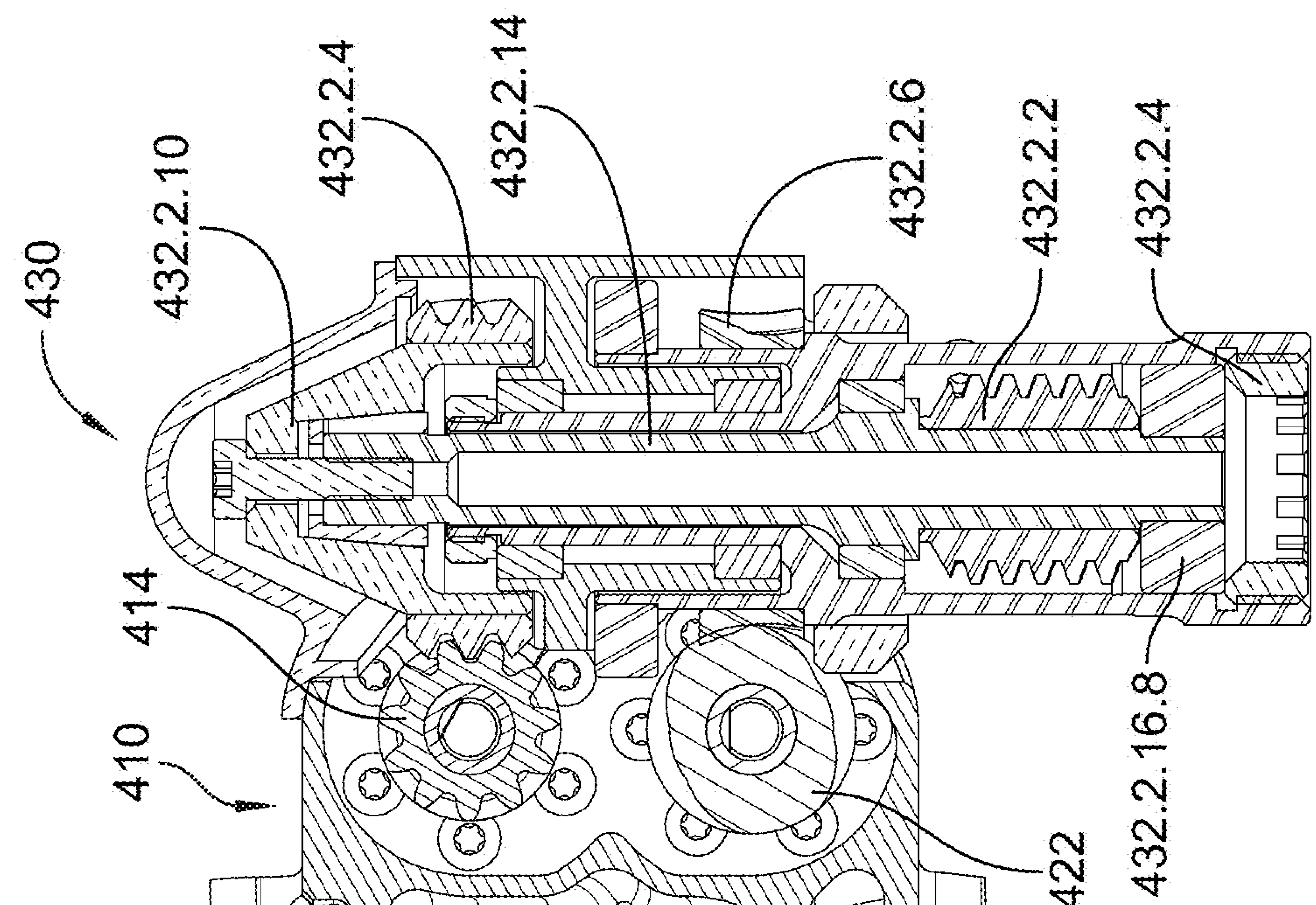

430
432.2.10
432.2.4
432.2.14
432.2.6
432.2.2
432.2.4
414
410
422
432.2.16.8

FIG. 67

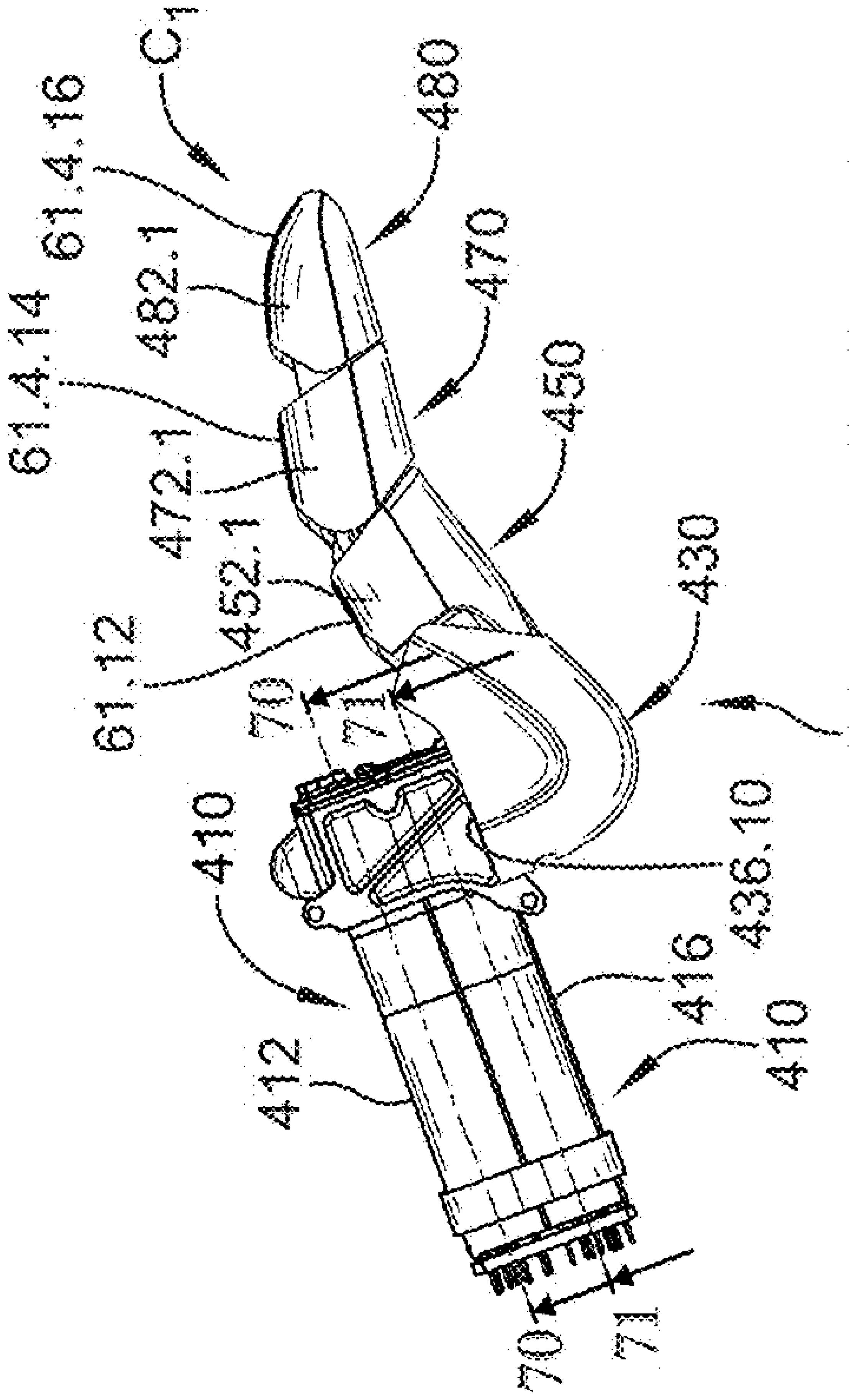


FIG. 69

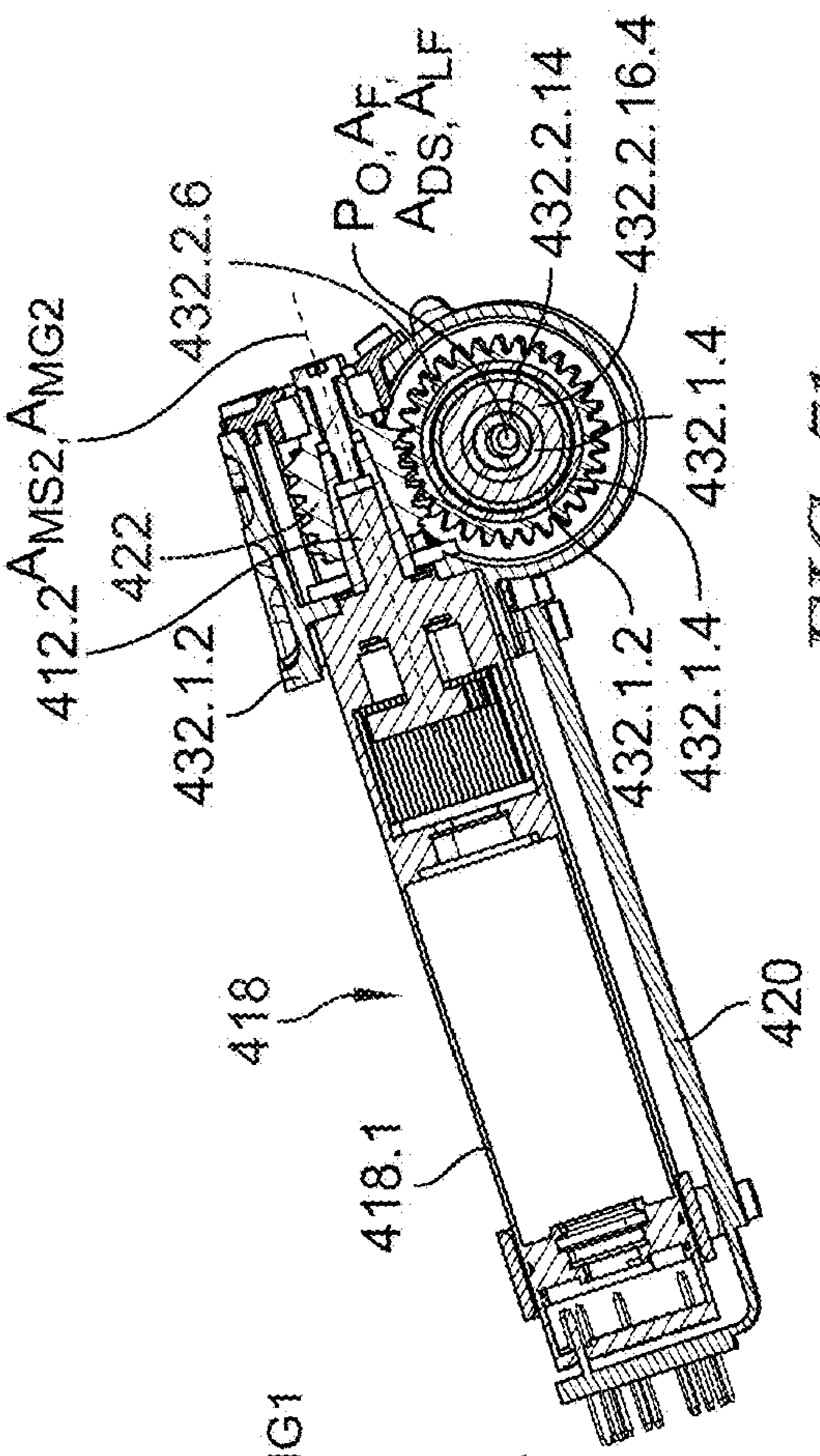


FIG. 71

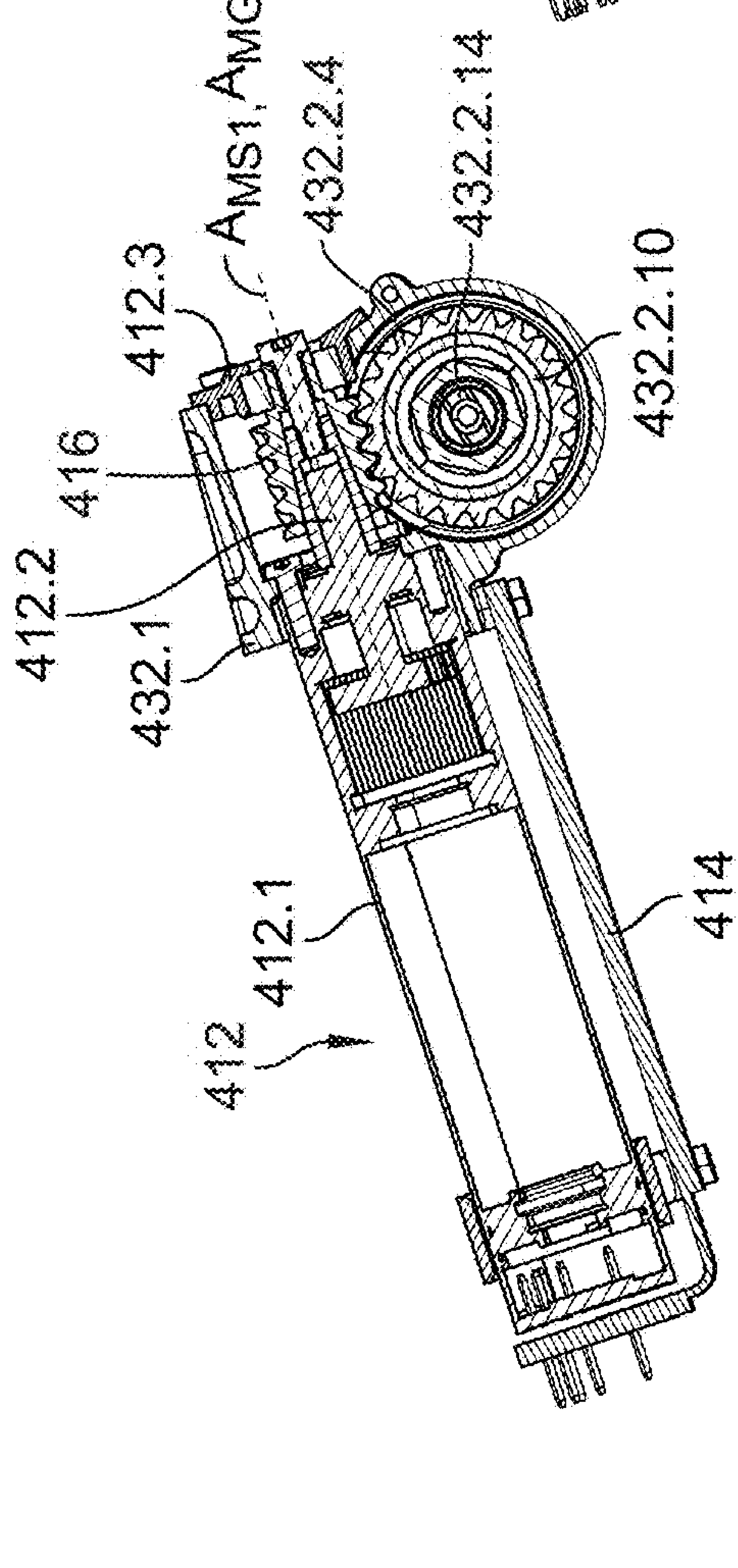


FIG. 70

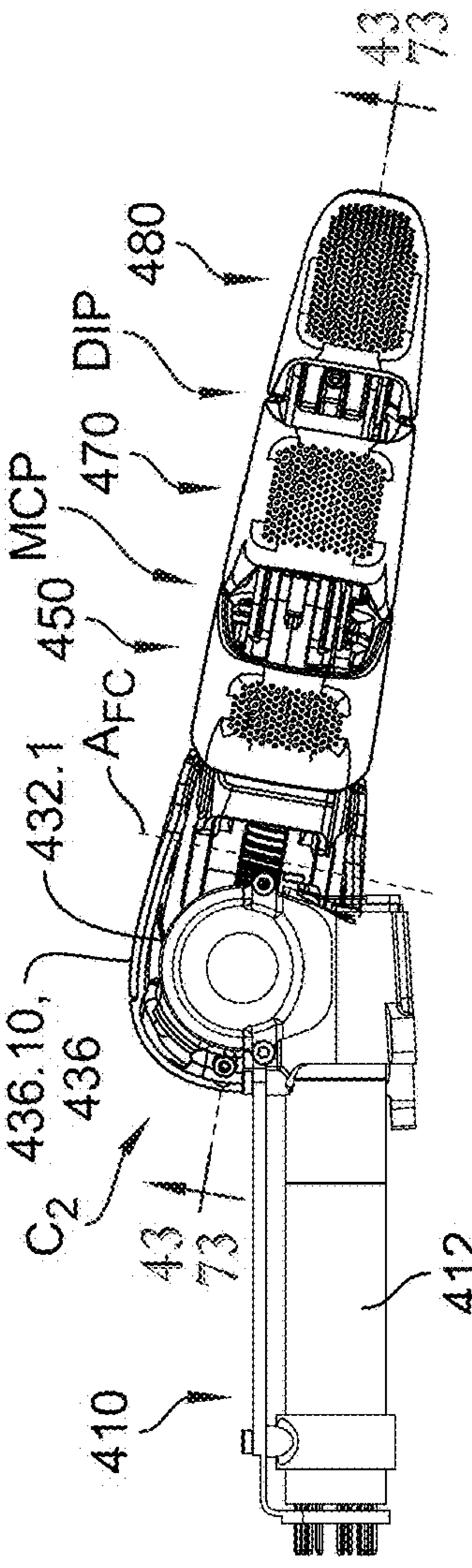

410
412
C_2
43
73
436.10,
436
432.1
A_{FC}
450
MCP
470
DIP
480
43
73

FIG. 72

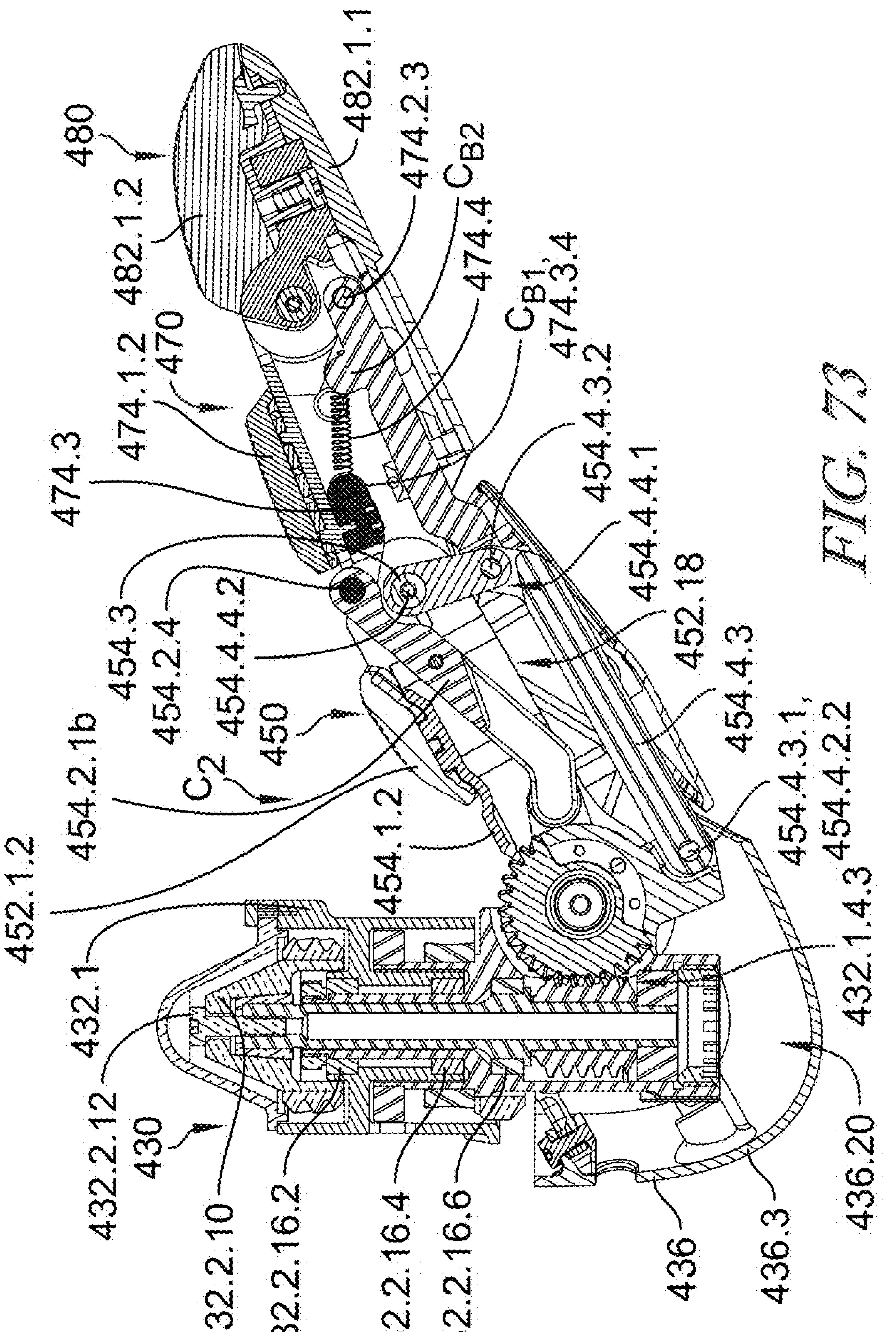

480
482.1.1
482.1.2
474.2.3
C_{B2}
474.4
C_{B1},
474.3.4
474.1.2
470
474.3
454.4.3.2
454.4.4.1
454.3
454.4.4.2
454.2.4
452.18
454.4.3
454.4.3.1,
454.4.2.2
450
C_2
454.2.1b
454.1.2
452.1.2
432.1
432.1.4.3
432.2.12
430
432.2.10
432.2.16.2
432.2.16.4
432.2.16.6
436
436.3
436.20

FIG. 73

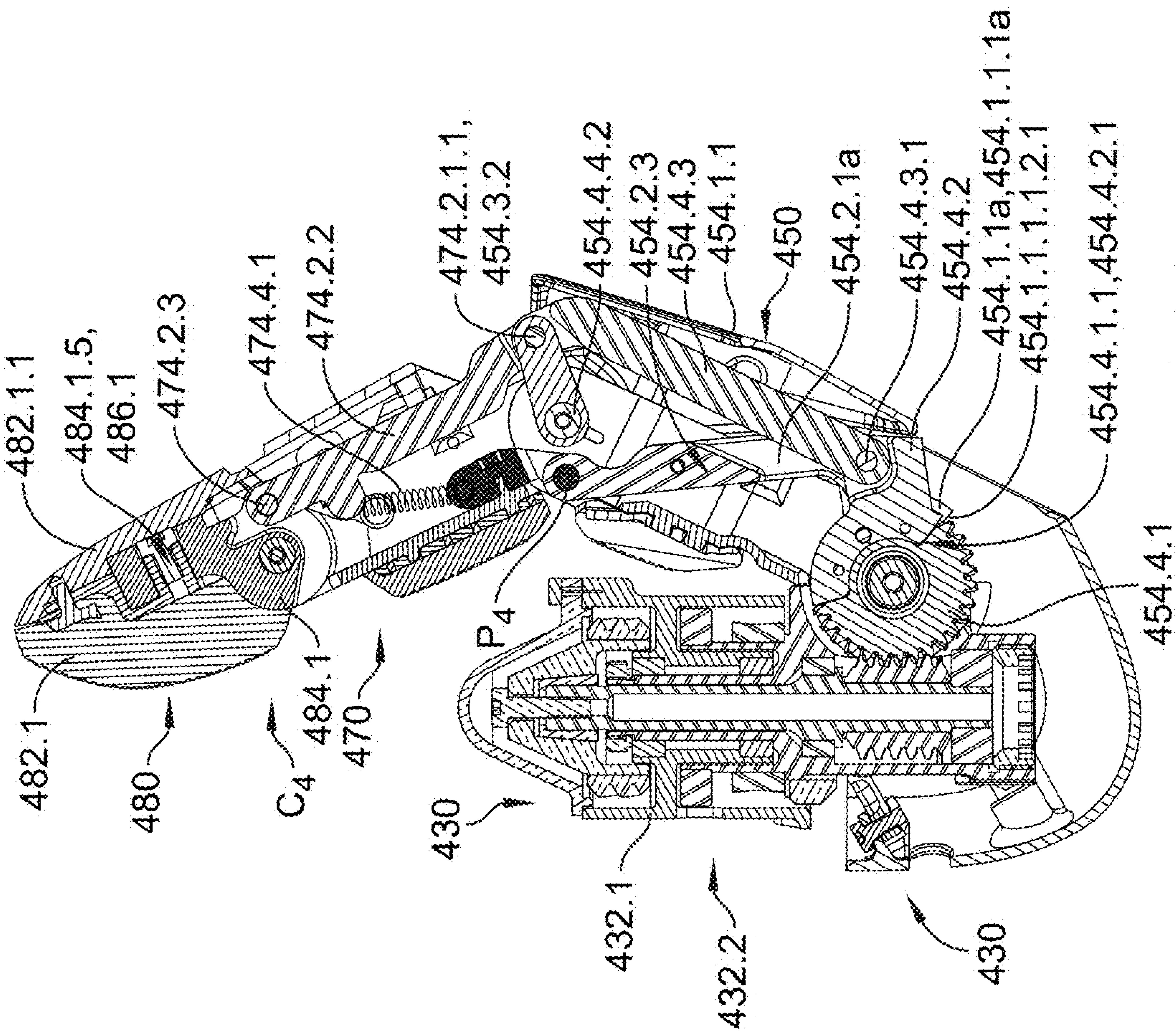

482.1.1
484.1.5,
486.1
474.2.3
474.4.1
474.2.2
474.2.1.1,
454.3.2
454.4.4.2
454.2.3
454.4.3
454.1.1
450
454.2.1a
454.4.3.1
454.4.2
454.1.1.1a
454.1.1a,454.1.1.1a
454.1.1.1.2.1
454.4.1.1,454.4.2.1
454.4.1
482.1
480
C4
484.1
P4
470
430
432.1
432.2
430

FIG. 75

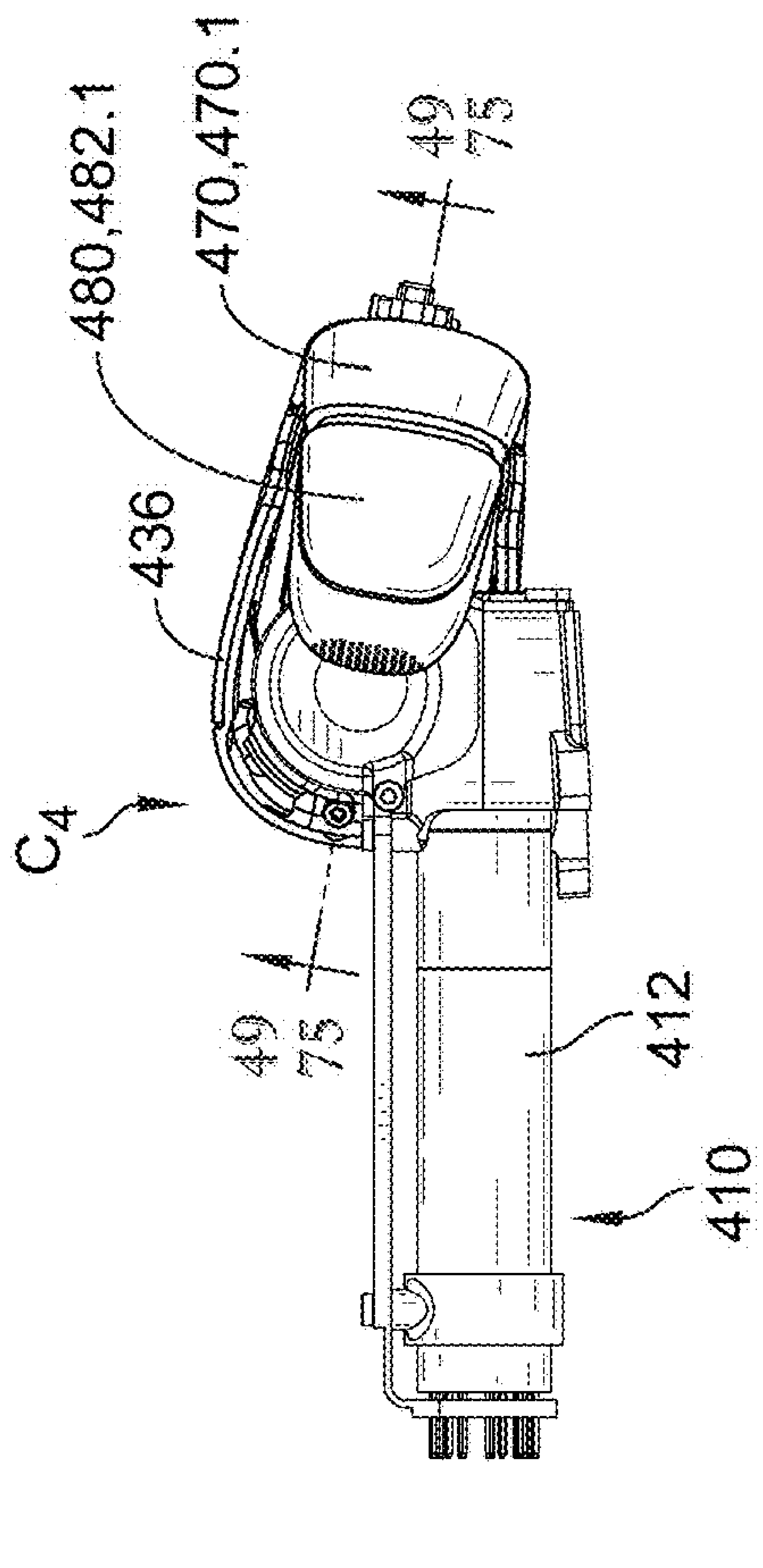

480,482.1
470,470.1
49
75
436
C4
49
75
412
410

FIG. 74

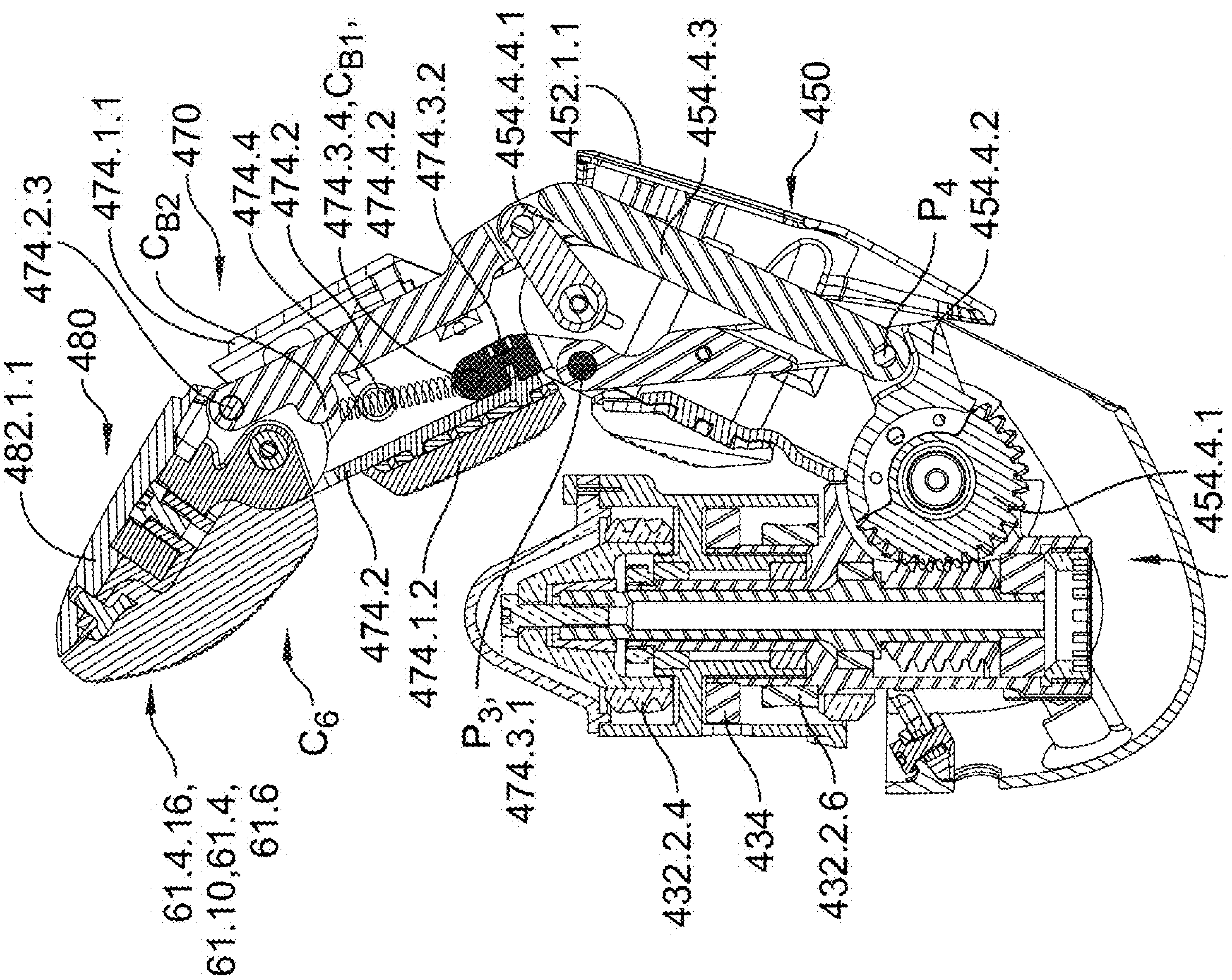

482.1.1
480
474.2.3
474.1.1
C_{B2}
470
474.4
474.2
474.3.4,C_{B1},
474.4.2
474.3.2
454.4.4.1
452.1.1
454.4.3
450
P_4
454.4.2
454.4.1
432.20
432.2.6
434
432.2.4
P_3,
474.3.1
474.1.2
474.2
C_6
61.4.16,
61.10,61.4,
61.6

FIG. 77

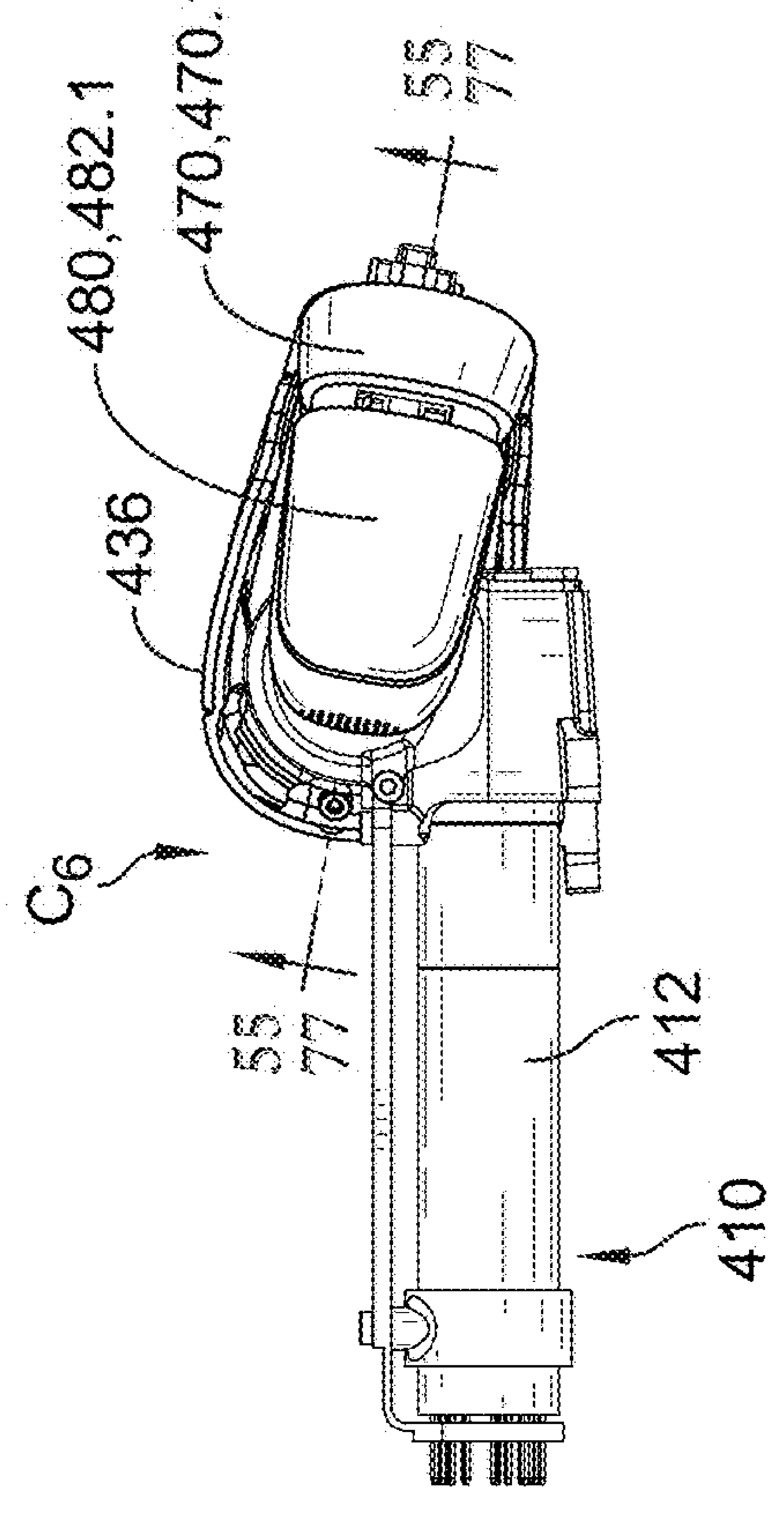
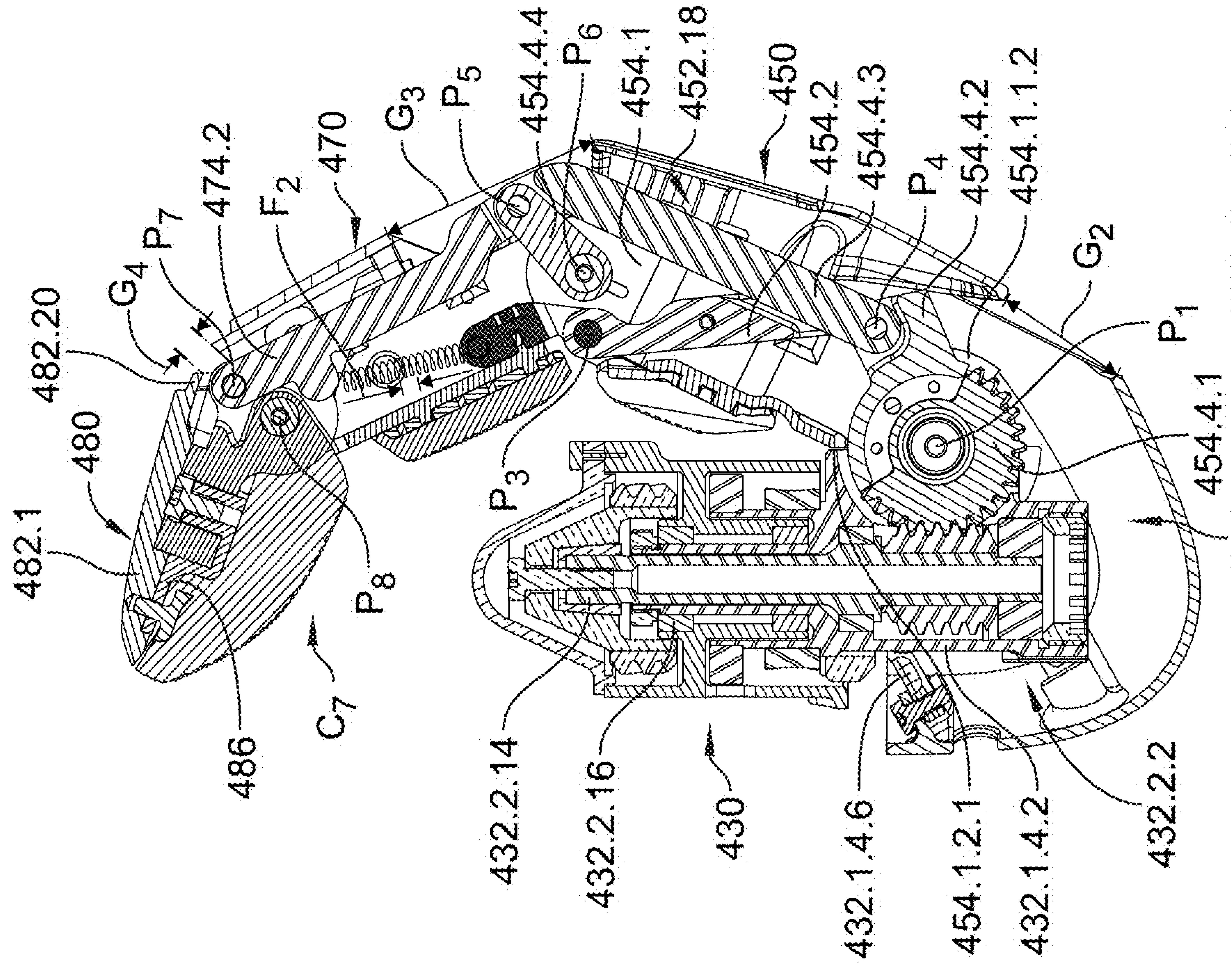
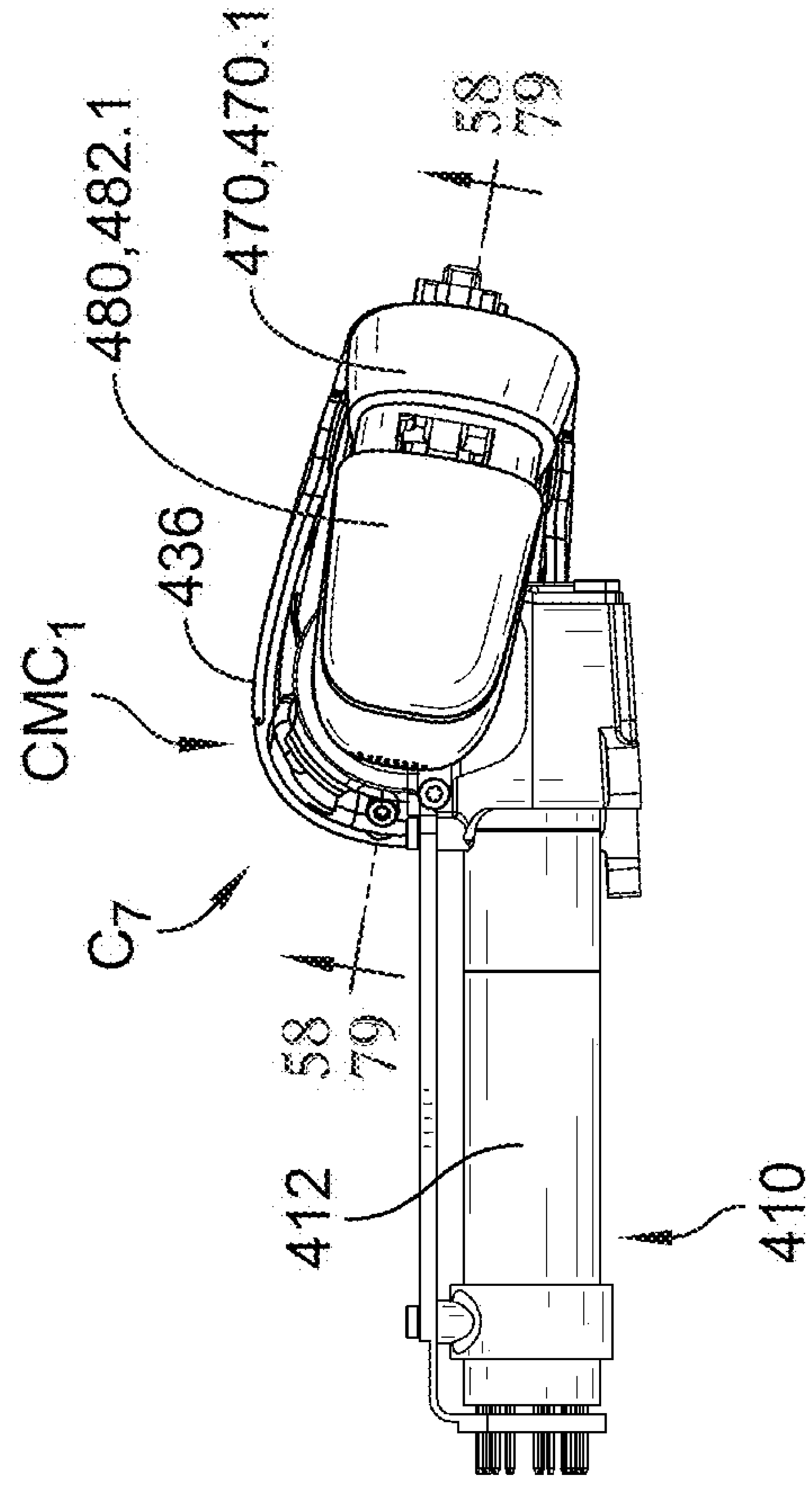

480,482.1
470,470.1
55
77
436
C_6
55
77
412
410

FIG. 76



482.20
G_4
P_7
474.2
F_2
470
G_3
P_5
454.4.4
P_6
454.1
452.18
450
454.2
454.4.3
P_4
454.4.2
454.1.1.2
G_2
P_1
454.4.1
432.20
480
482.1
P_3
P_8
486
C_7
432.2.14
432.2.16
430
432.1.4.6
454.1.2.1
432.1.4.2
432.2.2

FIG. 79



CMC_1
436
480,482.1
470,470.1
58
79
C_7
58
79
412
410

FIG. 78

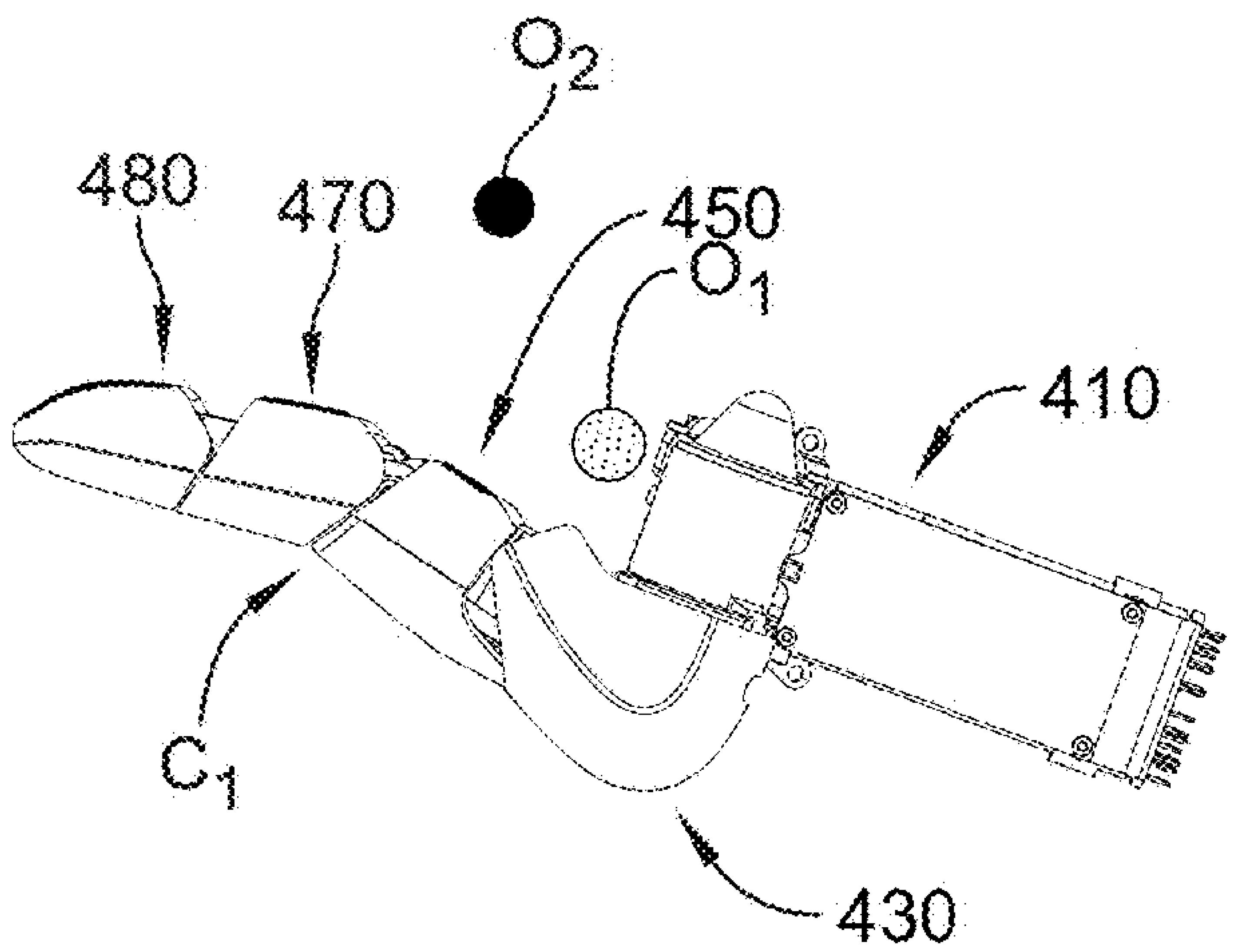


FIG. 80

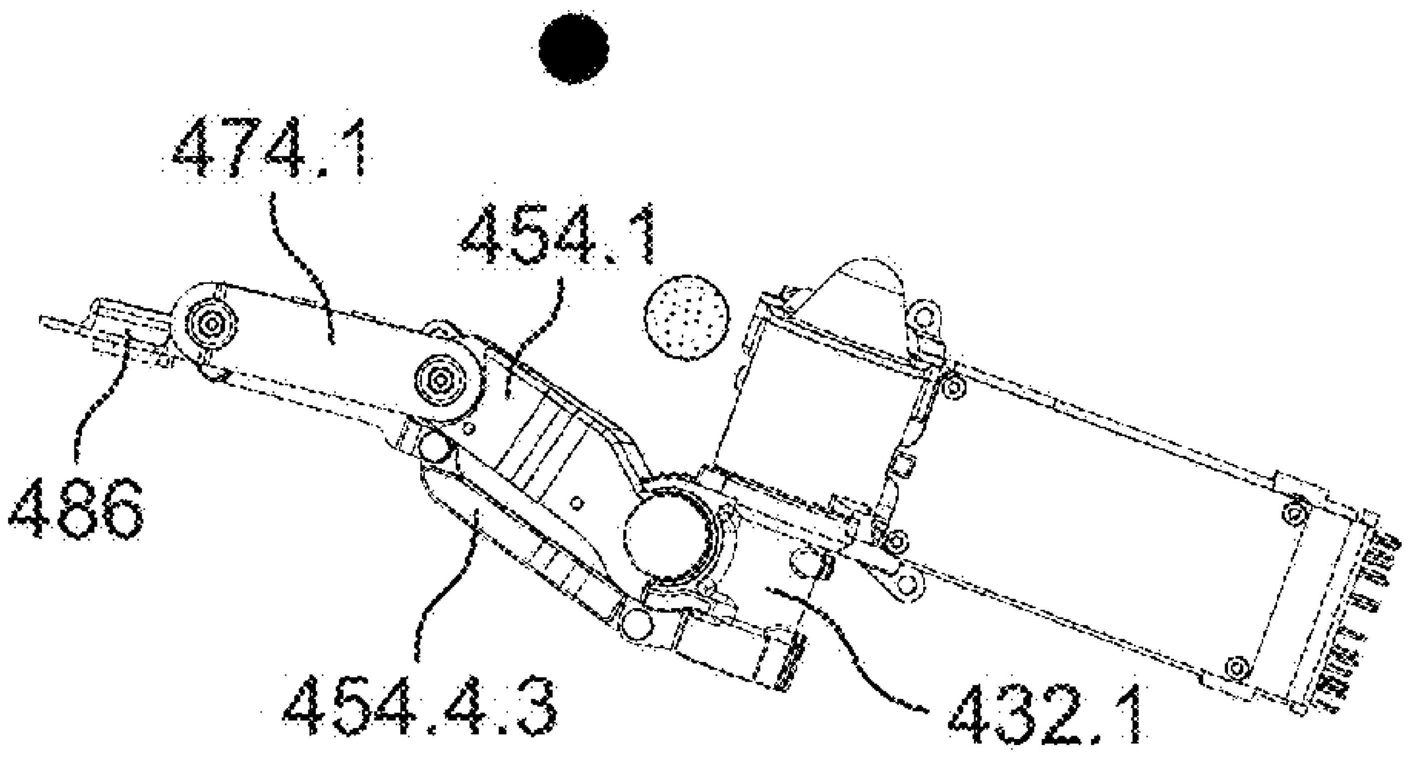


FIG. 81

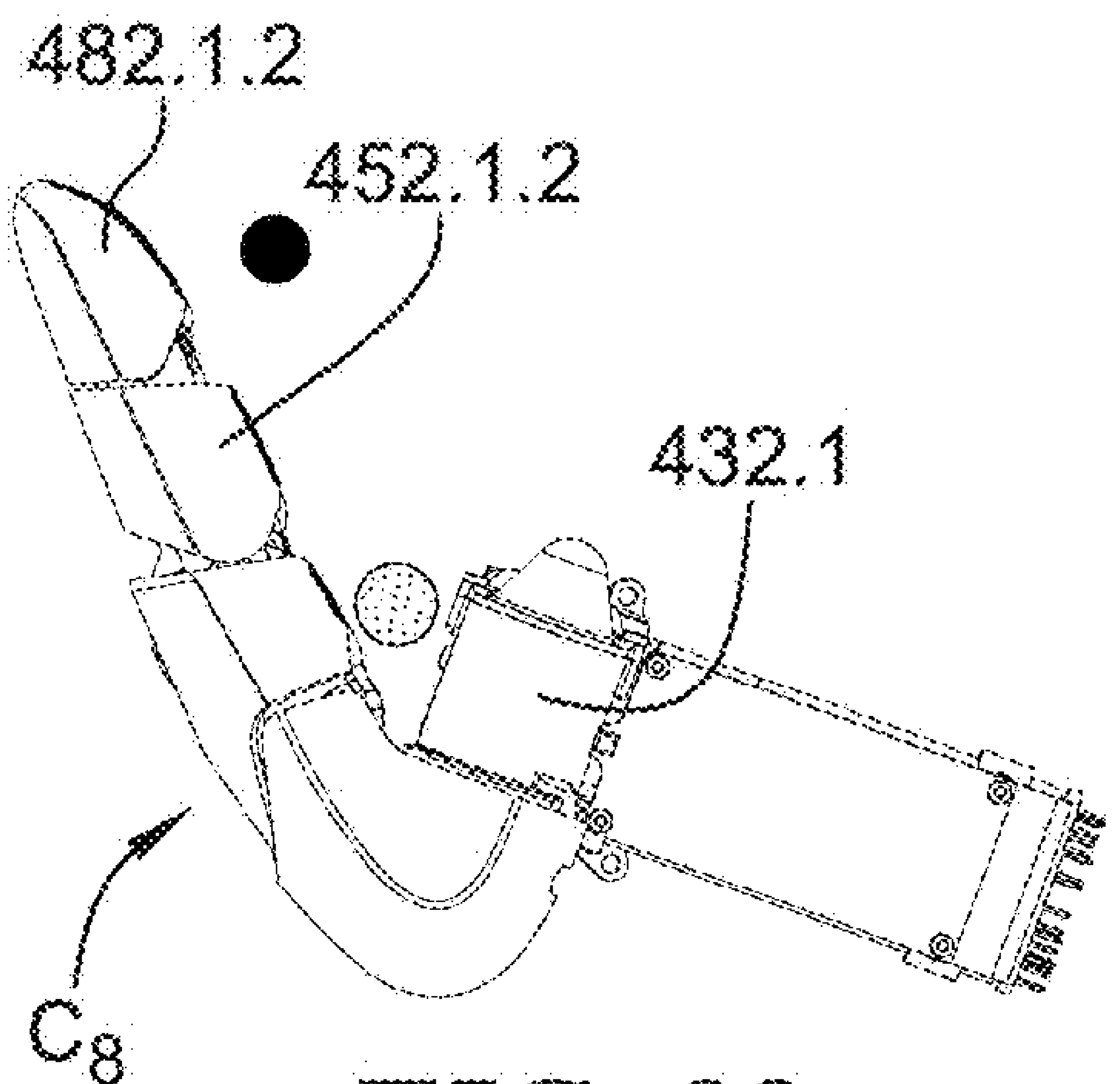


FIG. 82

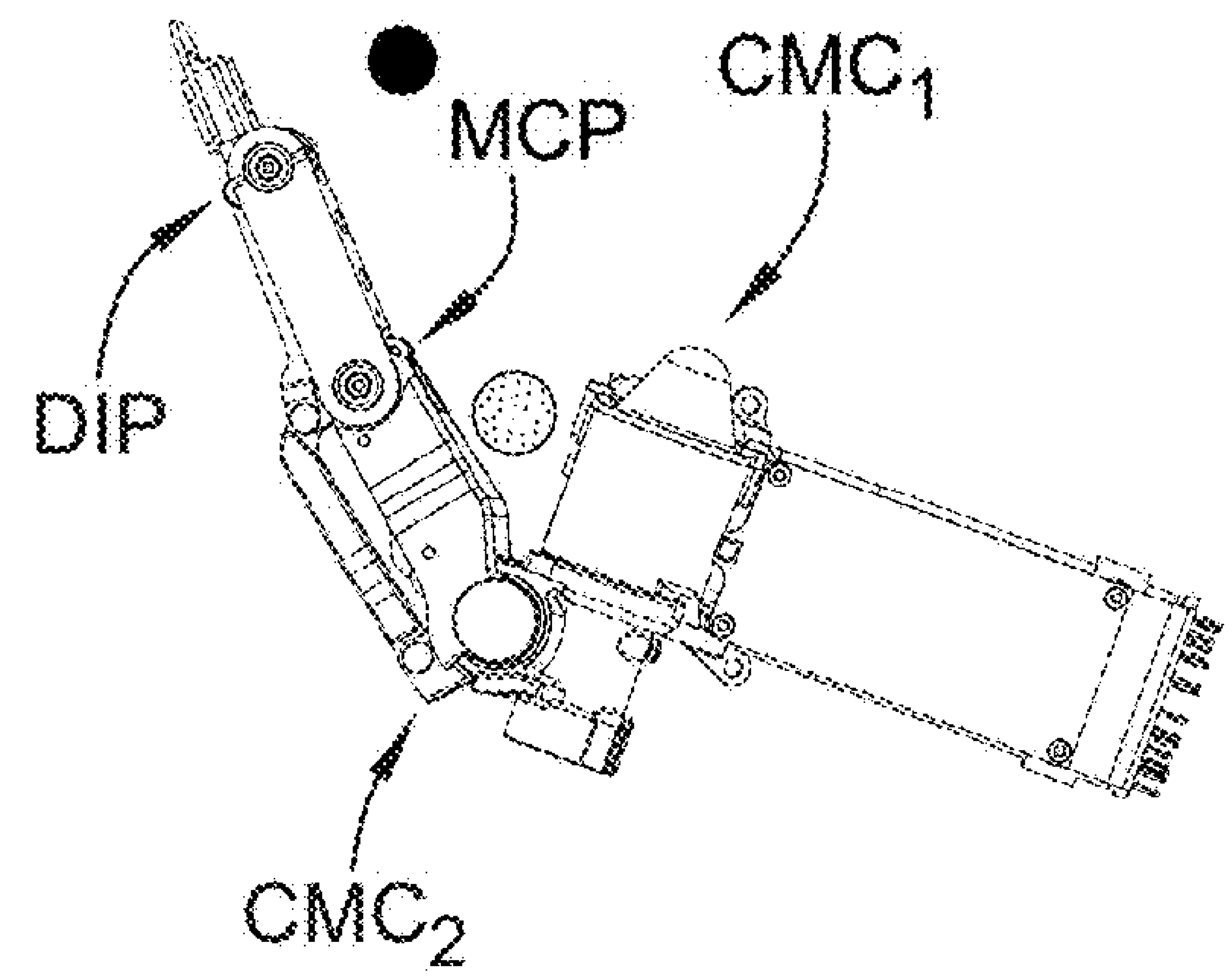


FIG. 83

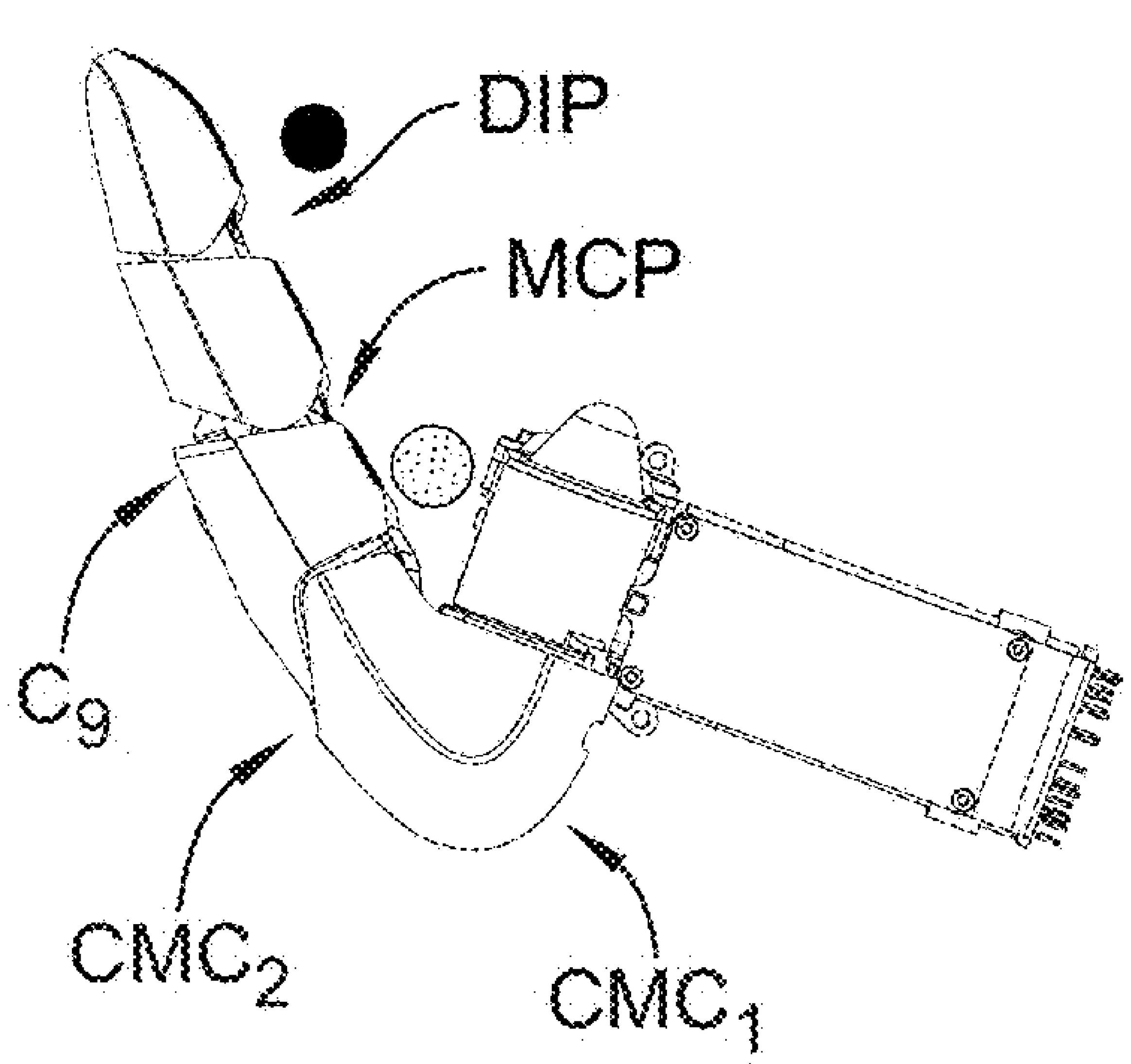


FIG. 84

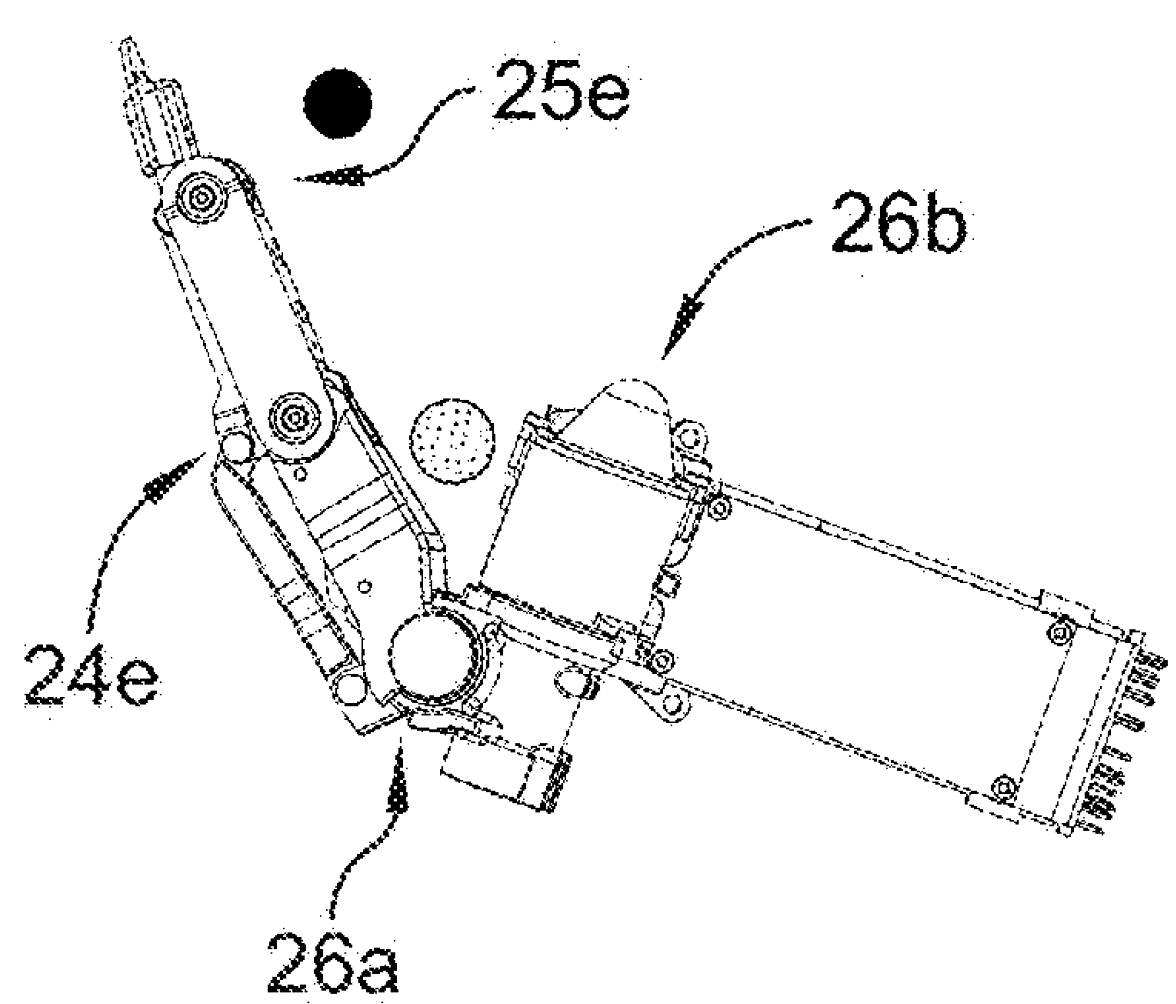


FIG. 85

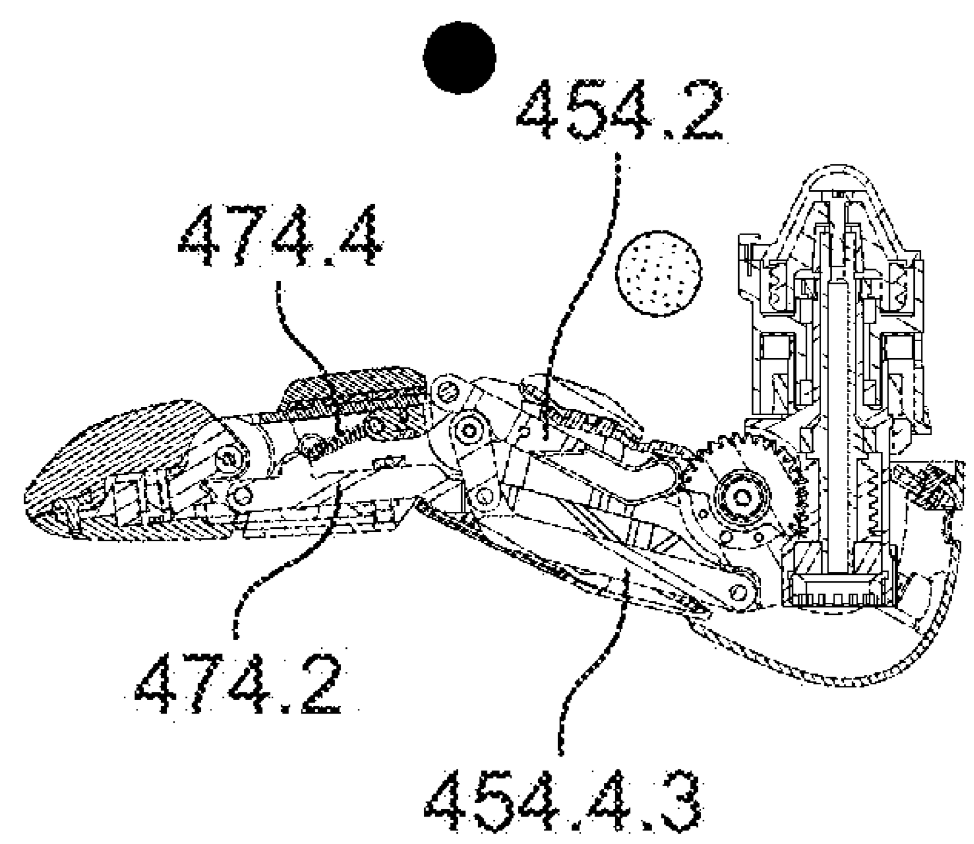


FIG. 86

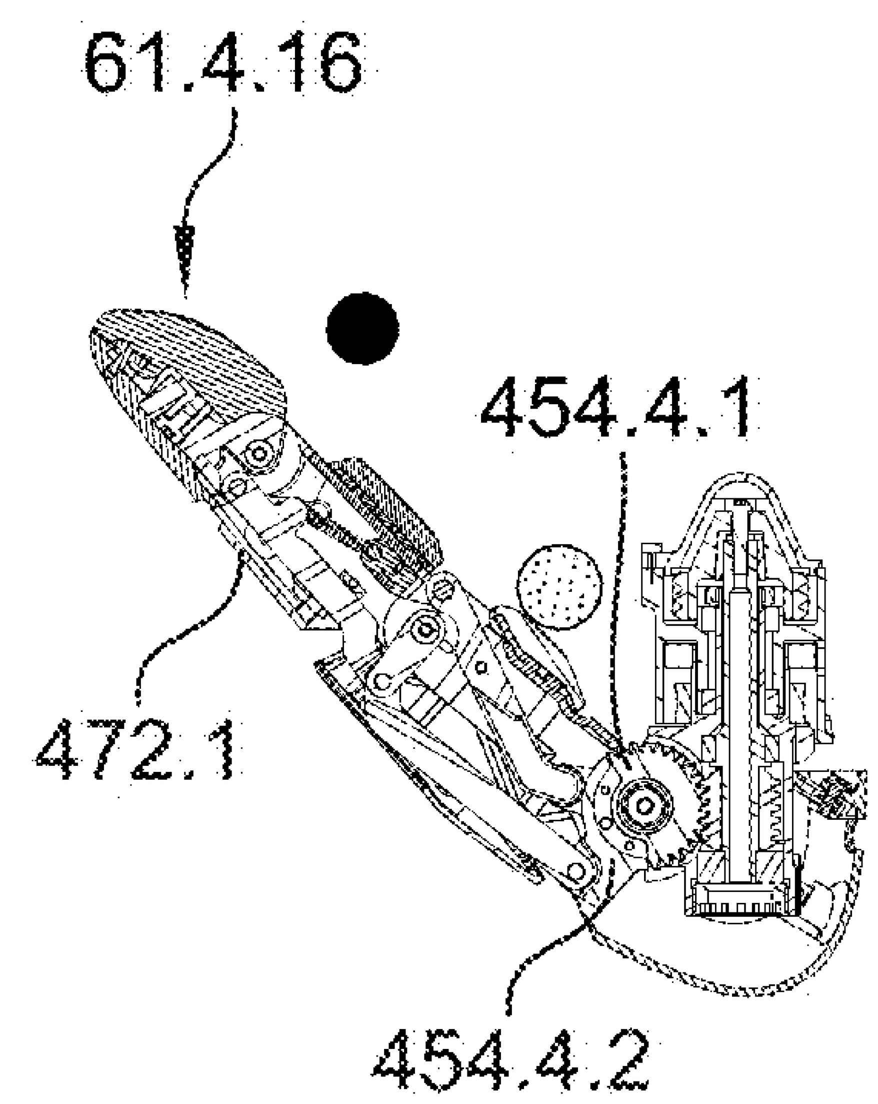


FIG. 87

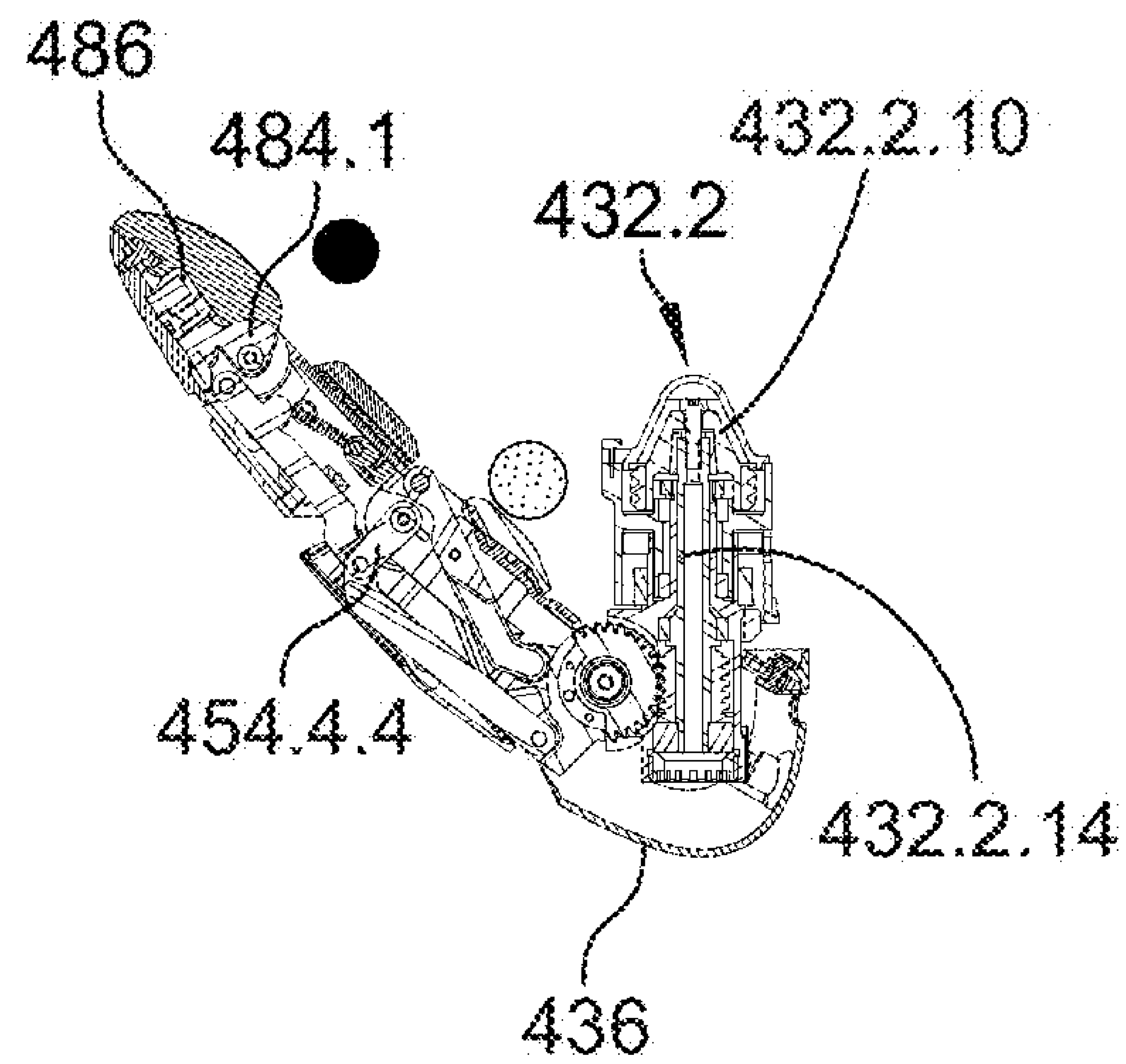


FIG. 88

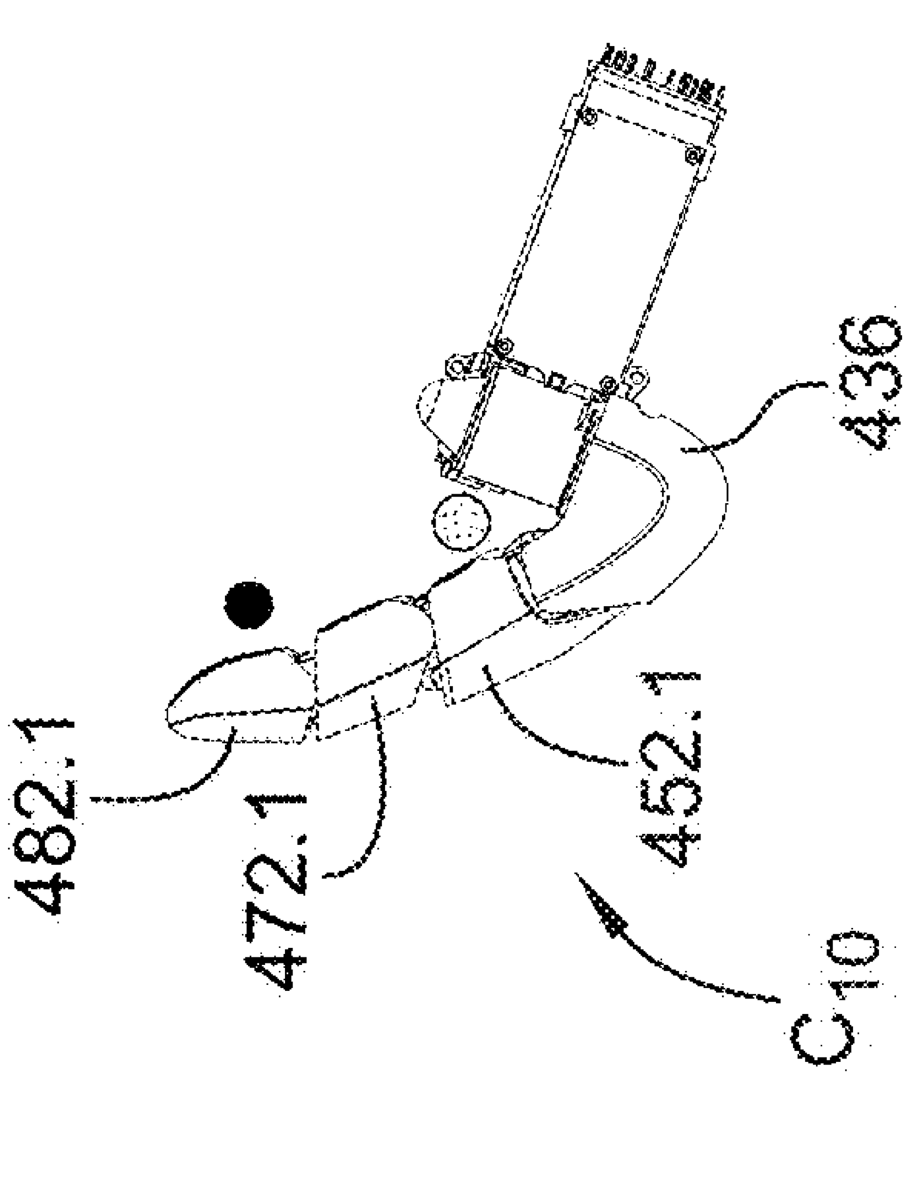


FIG. 89

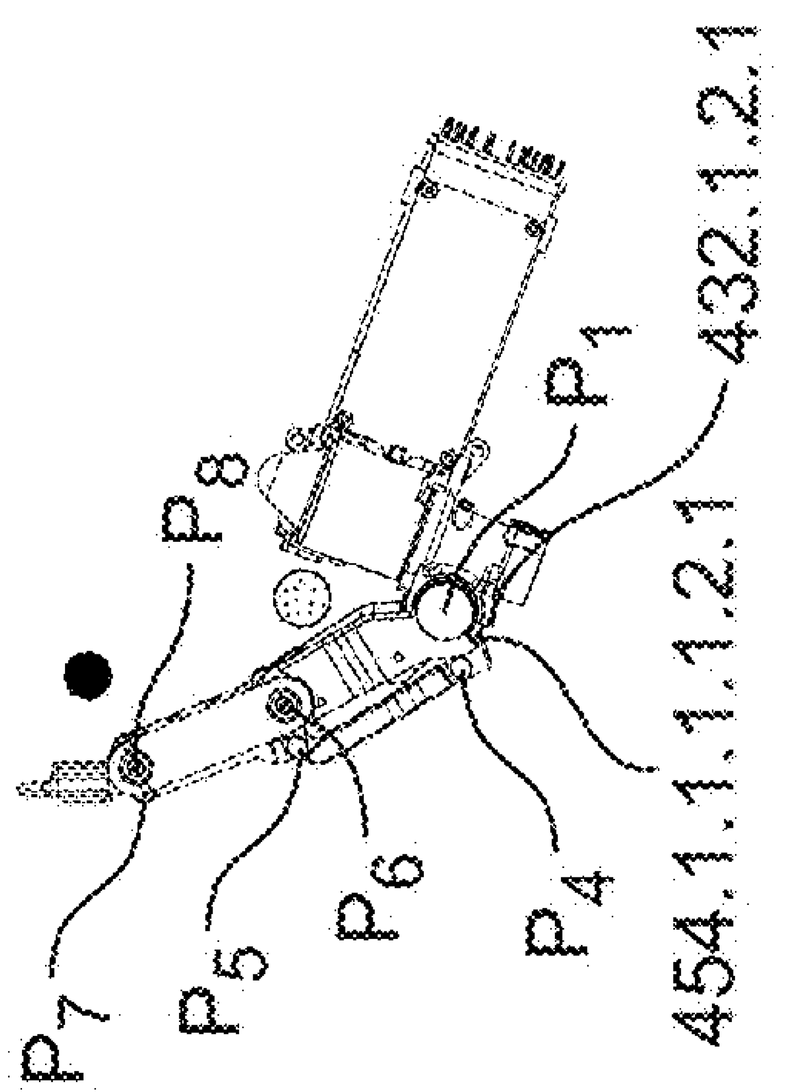


FIG. 90

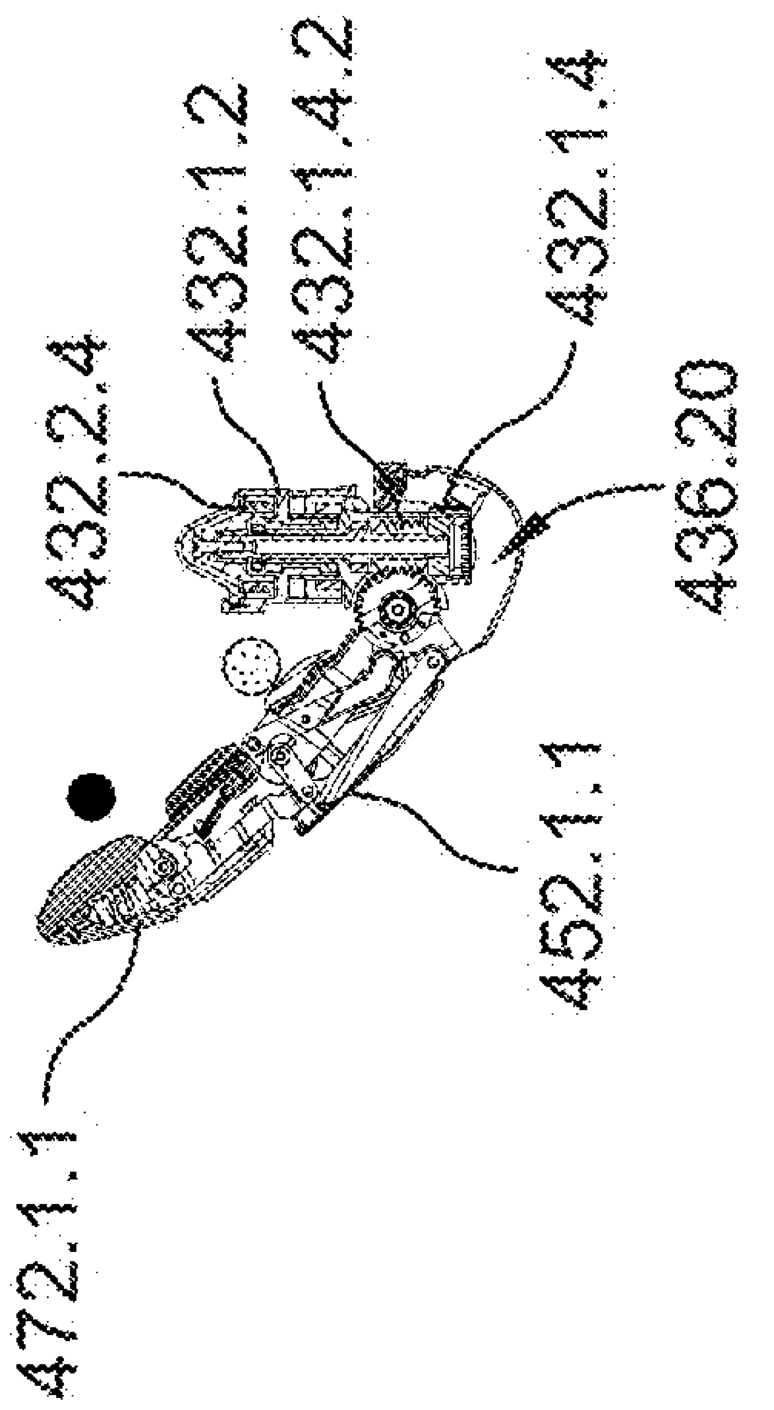


FIG. 91

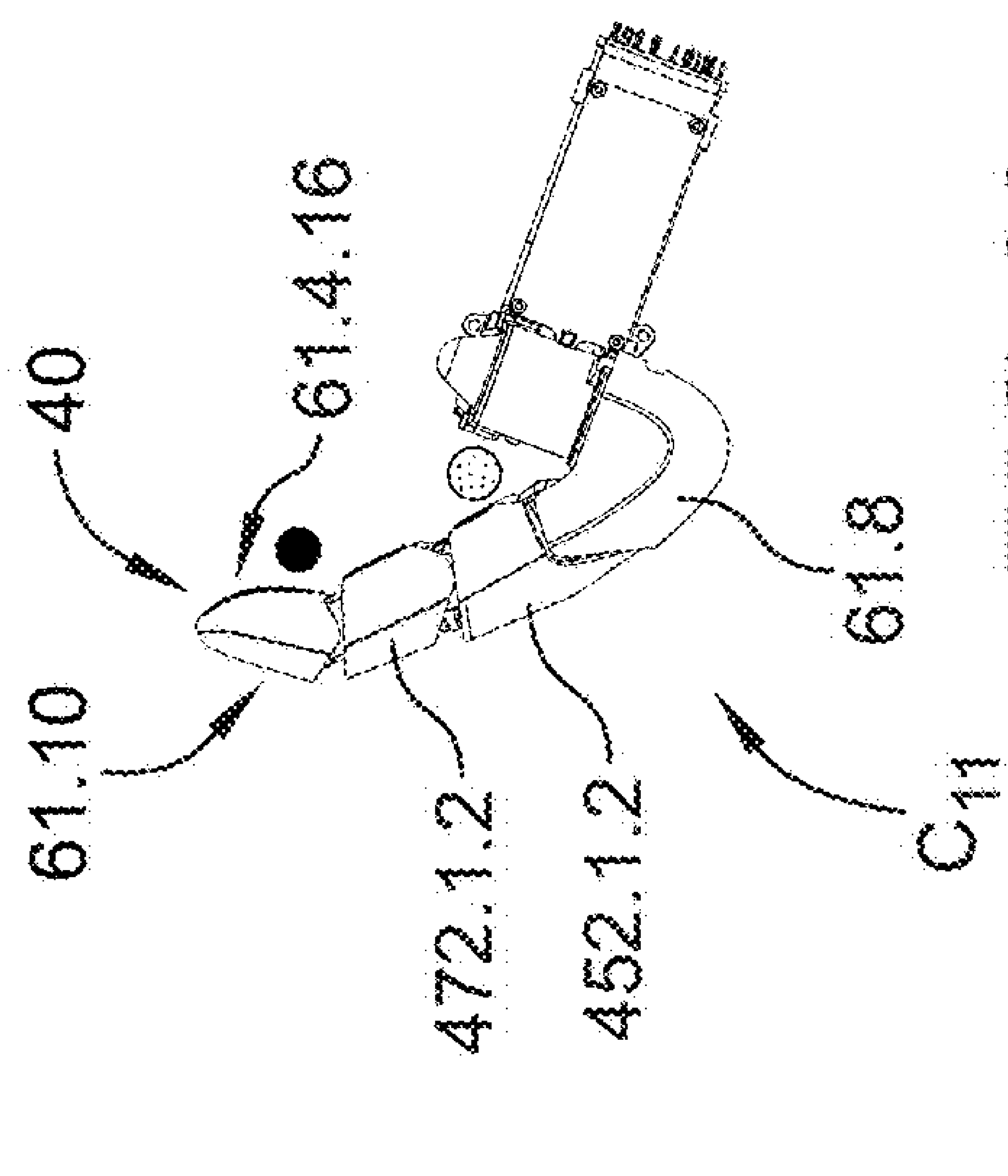


FIG. 92

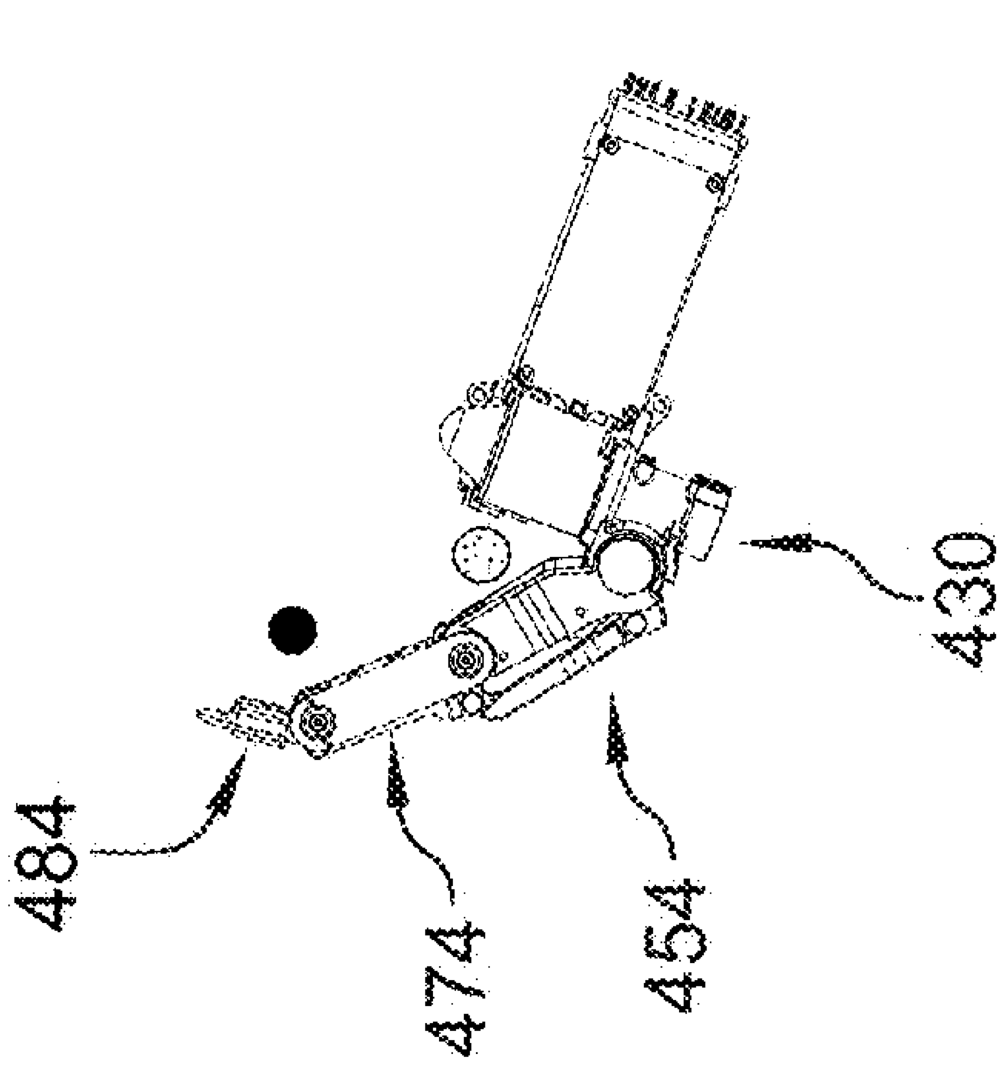


FIG. 93

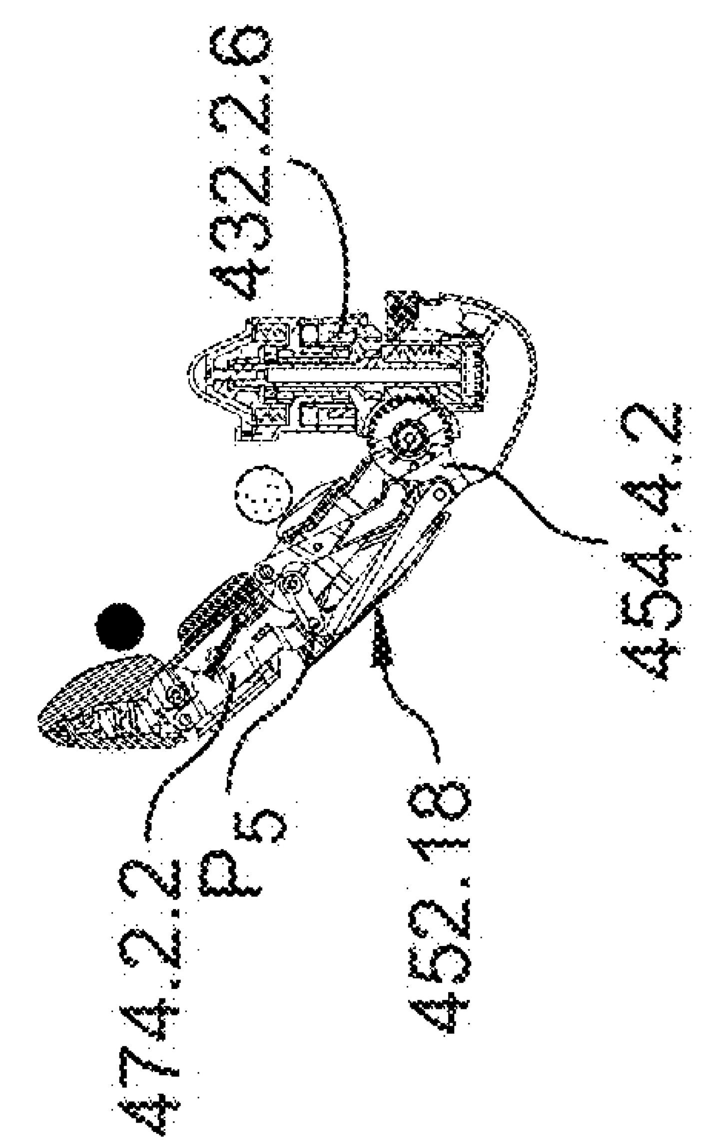


FIG. 94

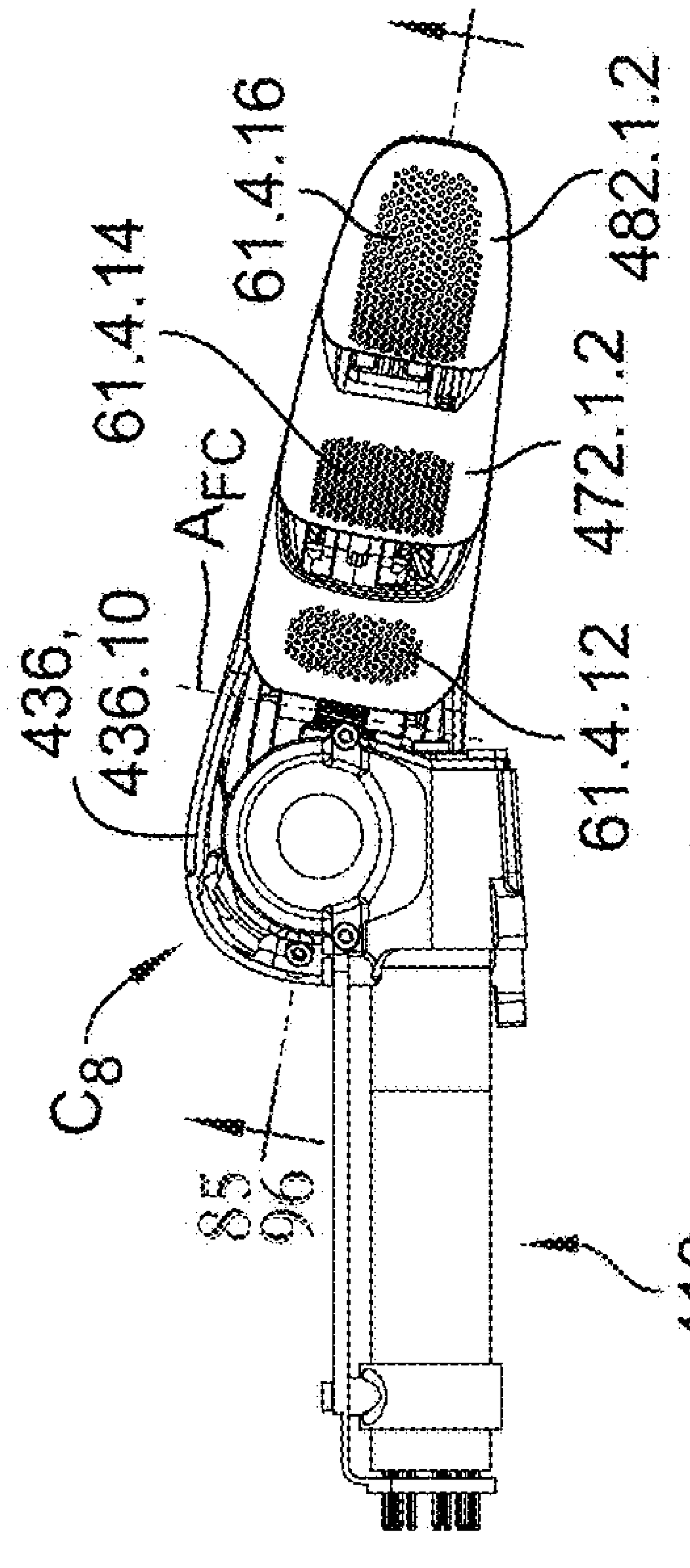

410
C_8
85
96
436,
436.10
A_{FC}
61.4.12
61.4.14
472.1.2
61.4.16
482.1.2
85
96

FIG. 95

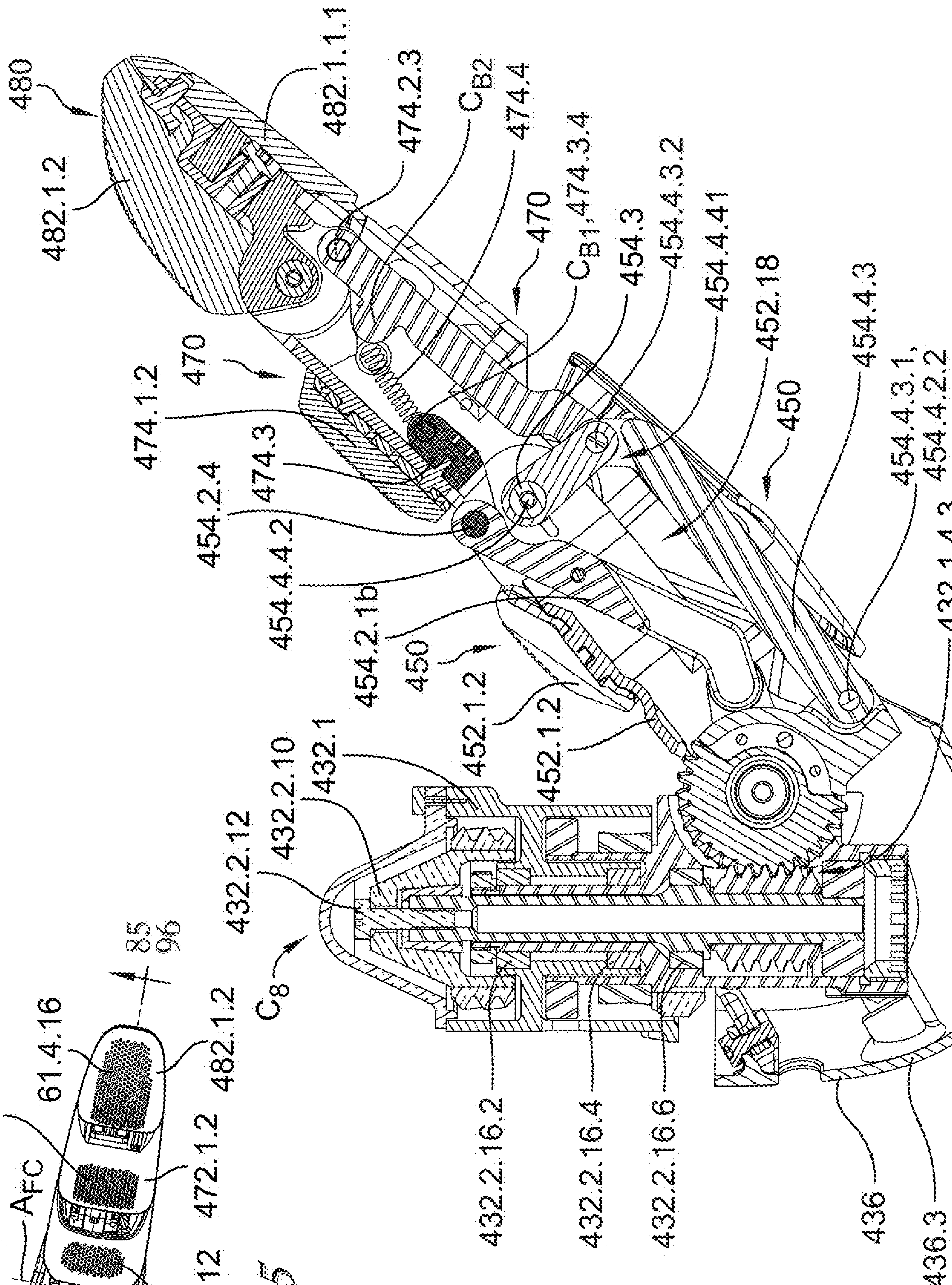
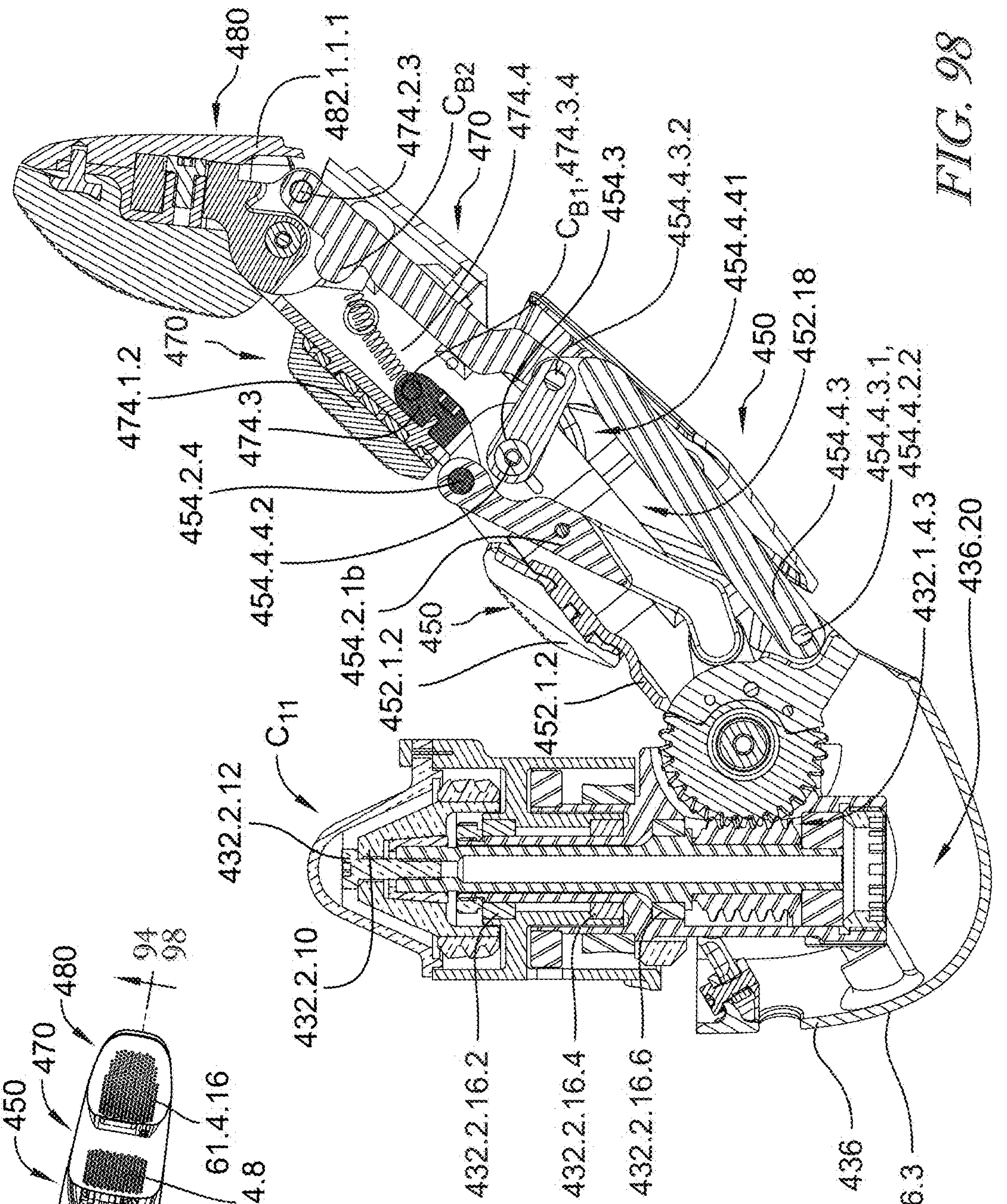

480
482.1.2
482.1.1.1
474.2.3
C_{B2}
474.4
470
C_{B1},474.3.4
454.3
454.4.3.2
454.4.41
452.18
470
474.1.2
474.3
454.2.4
454.4.4.2
454.2.1b
450
450
454.4.3
454.4.3.1,
454.4.2.2
452.1.2
452.1.2
432.1
432.2.10
432.2.12
C_8
432.1.4.3
436.20
432.2.16.2
432.2.16.4
432.2.16.6
436
436.3

FIG. 96


480
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474.2.3
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474.4
C_{B1}, 474.3.4
454.3
454.4.3.2
454.4.41
450
452.18
474.1.2
470
474.3
454.2.4
454.4.4.2
454.2.1b
450
452.1.2
452.1.2
454.4.3
454.4.3.1,
454.4.2.2
432.1.4.3
436.20
C_{11}
432.2.12
432.2.10
432.2.16.2
432.2.16.4
432.2.16.6
436
436.3

FIG. 98

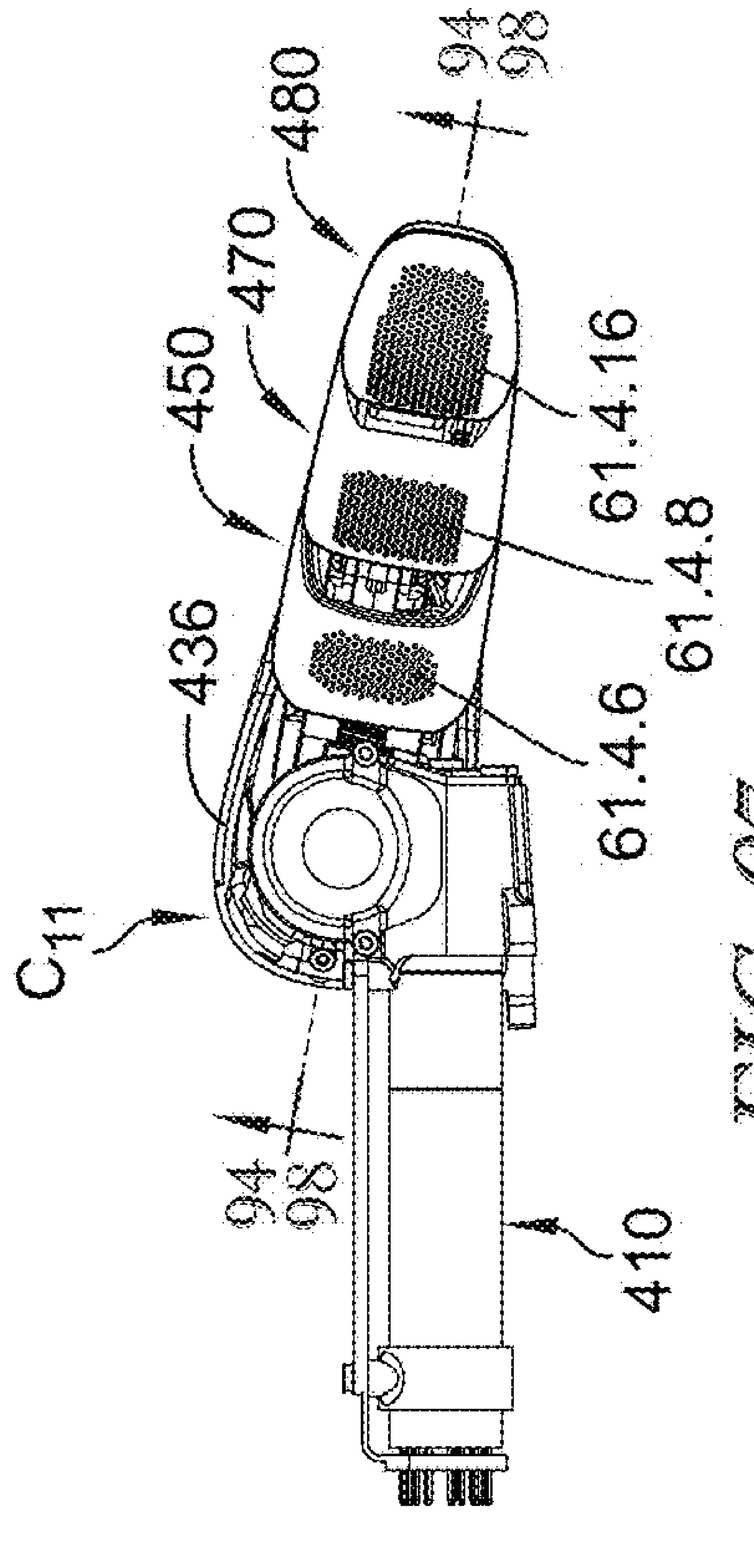
94
98
480
470
450
436
C_{11}
61.4.16
61.4.8
61.4.6
94
98
410

FIG. 97

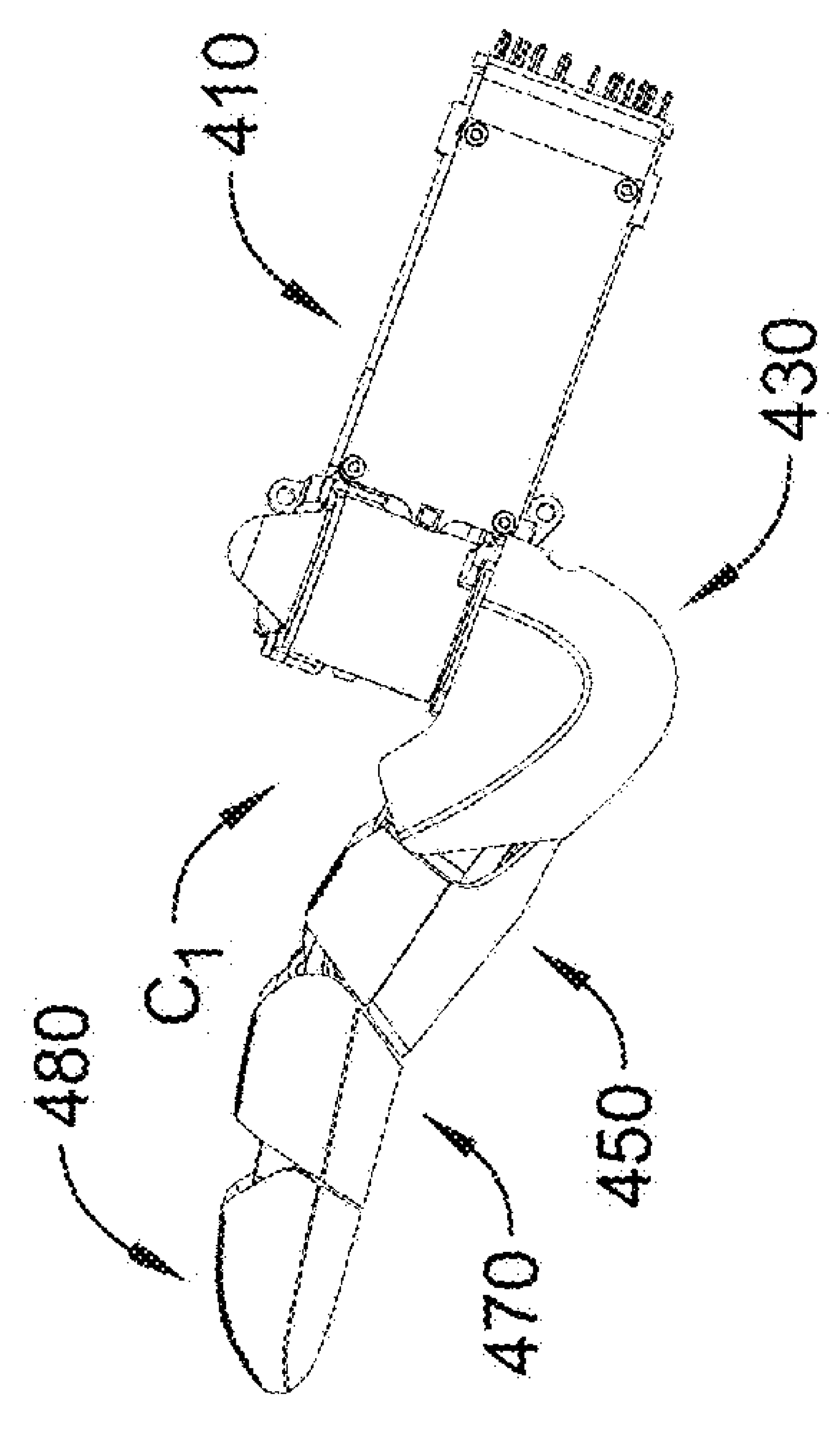

FIG. 99

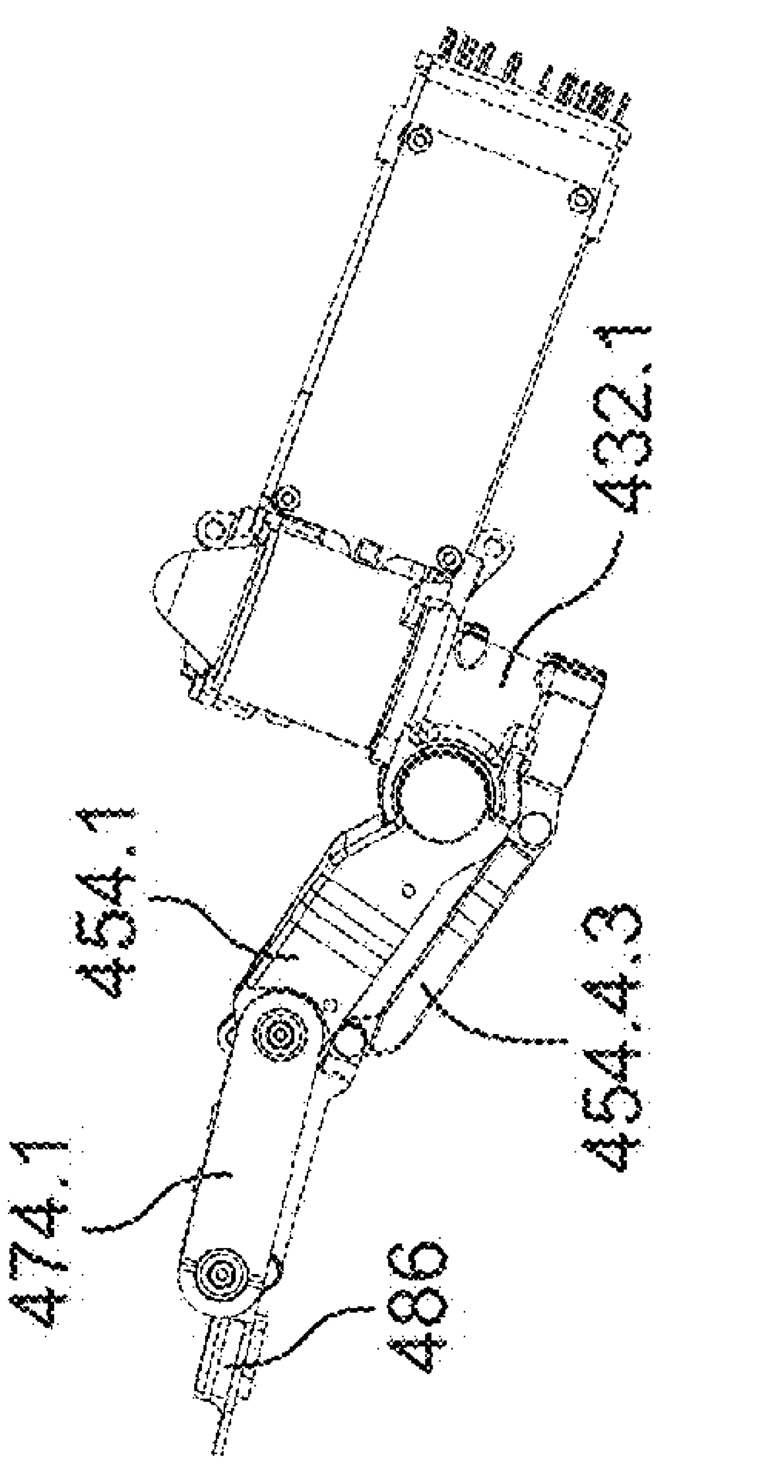

FIG. 100

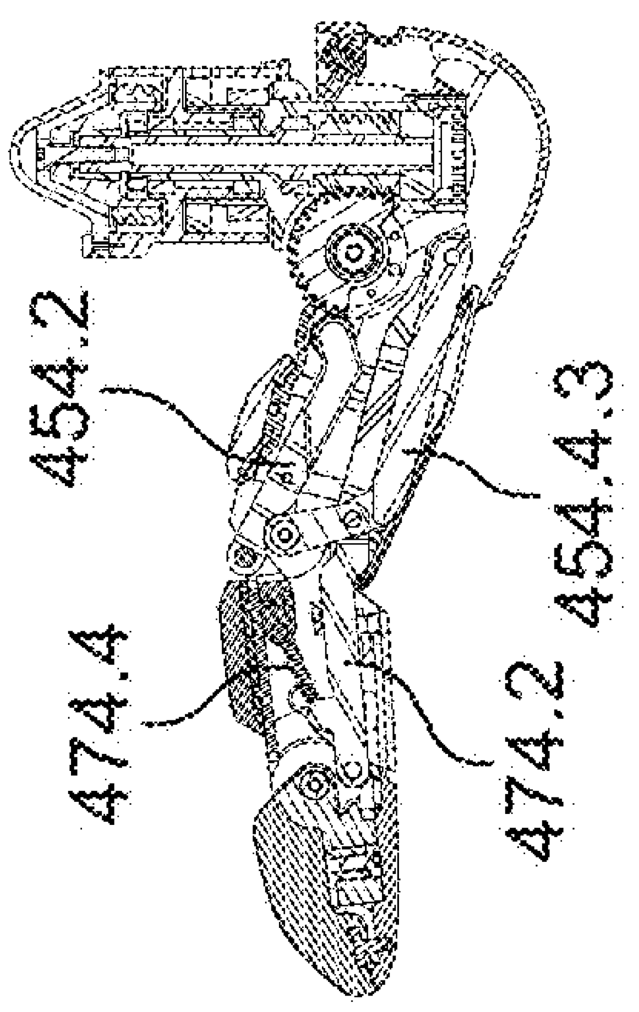

FIG. 101

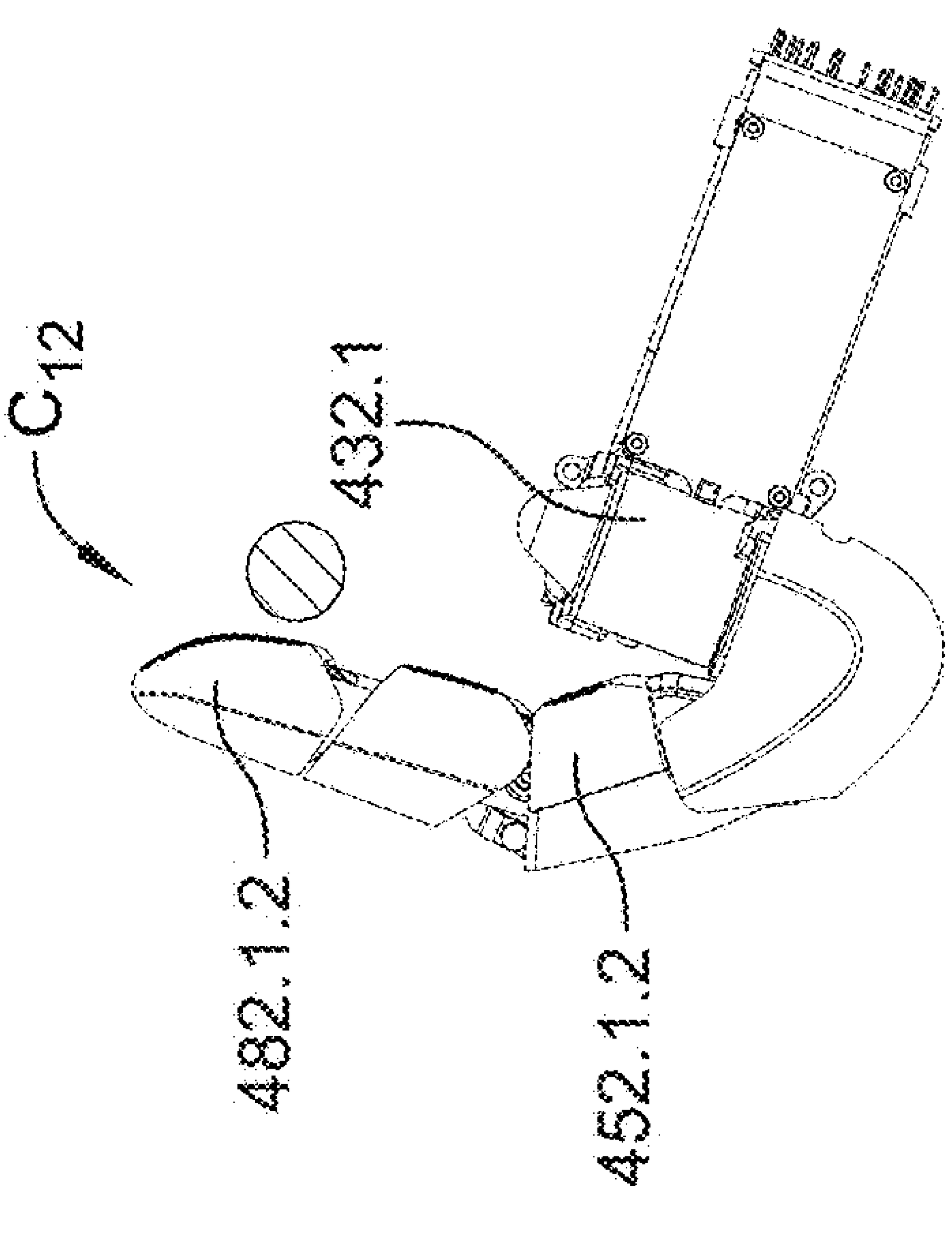

FIG. 102

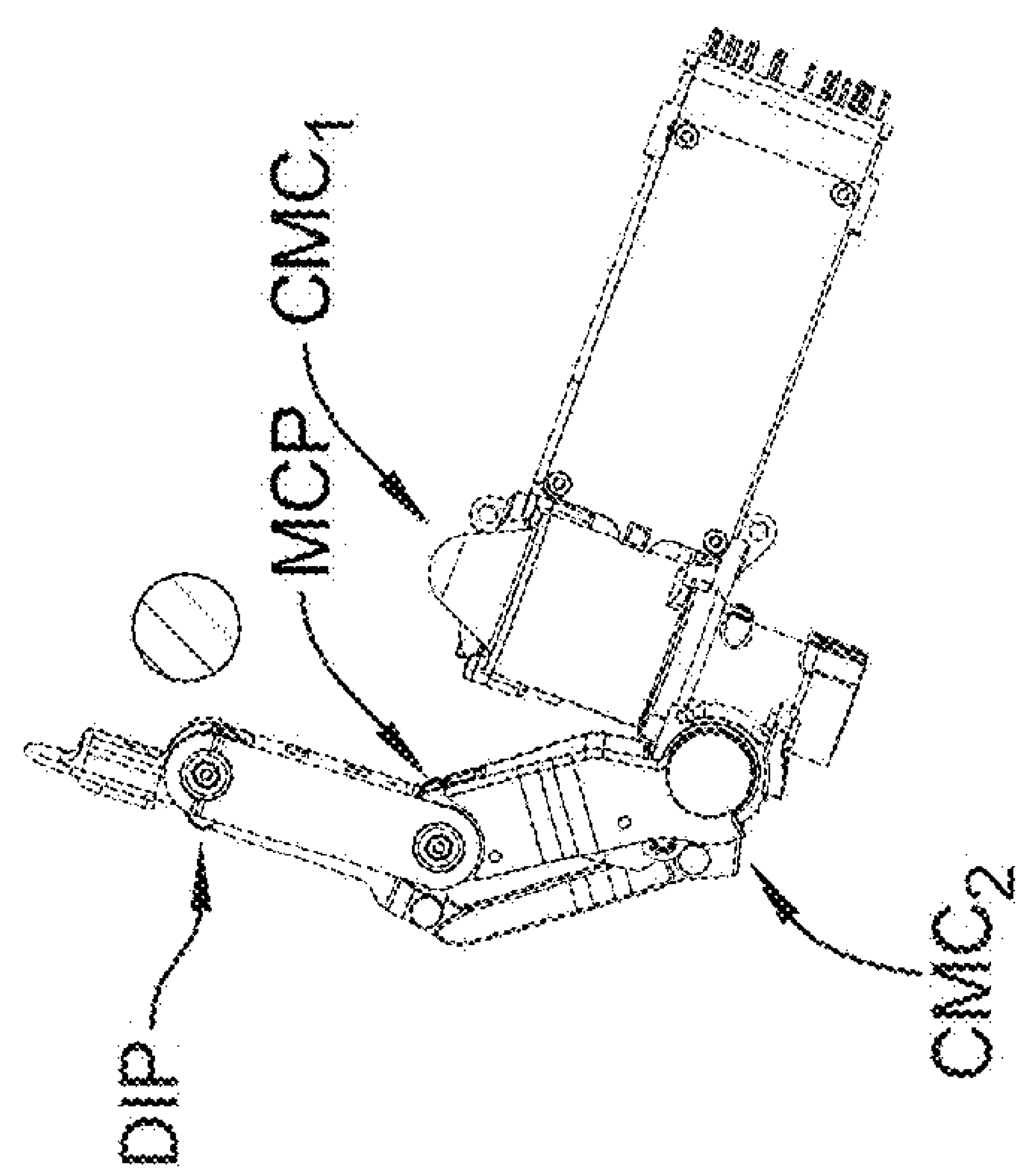

FIG. 103

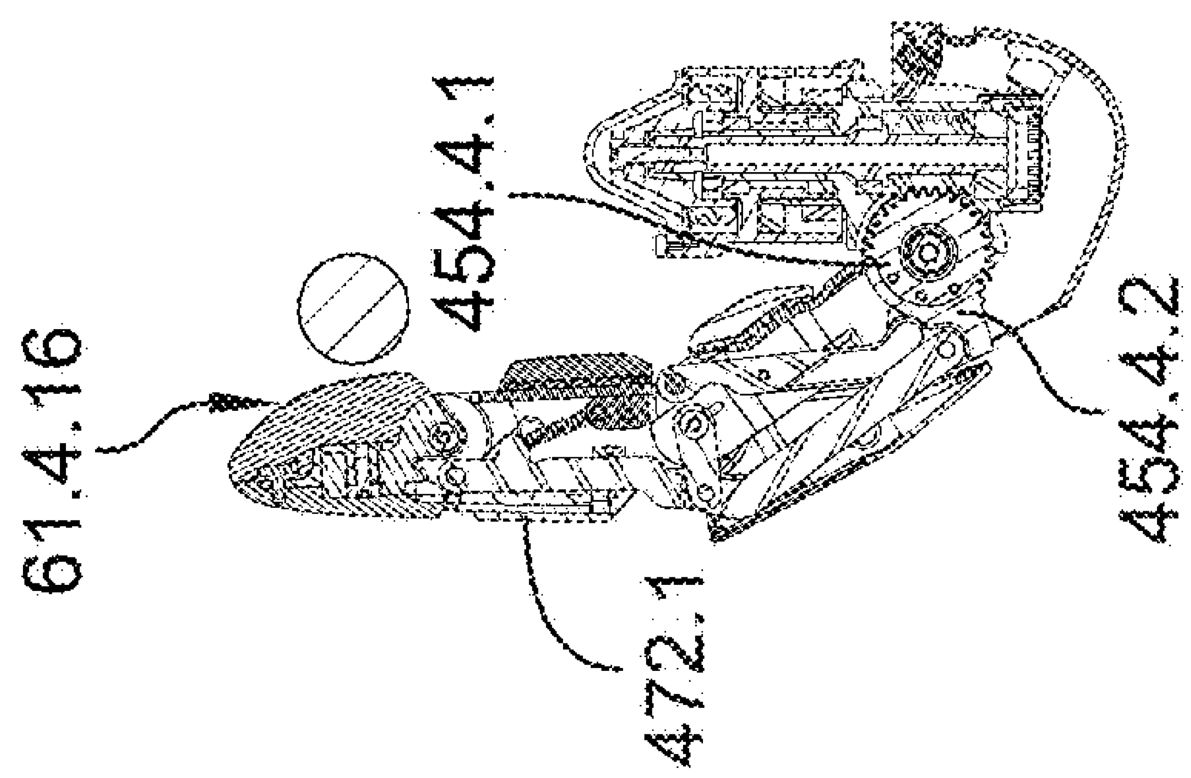

FIG. 104

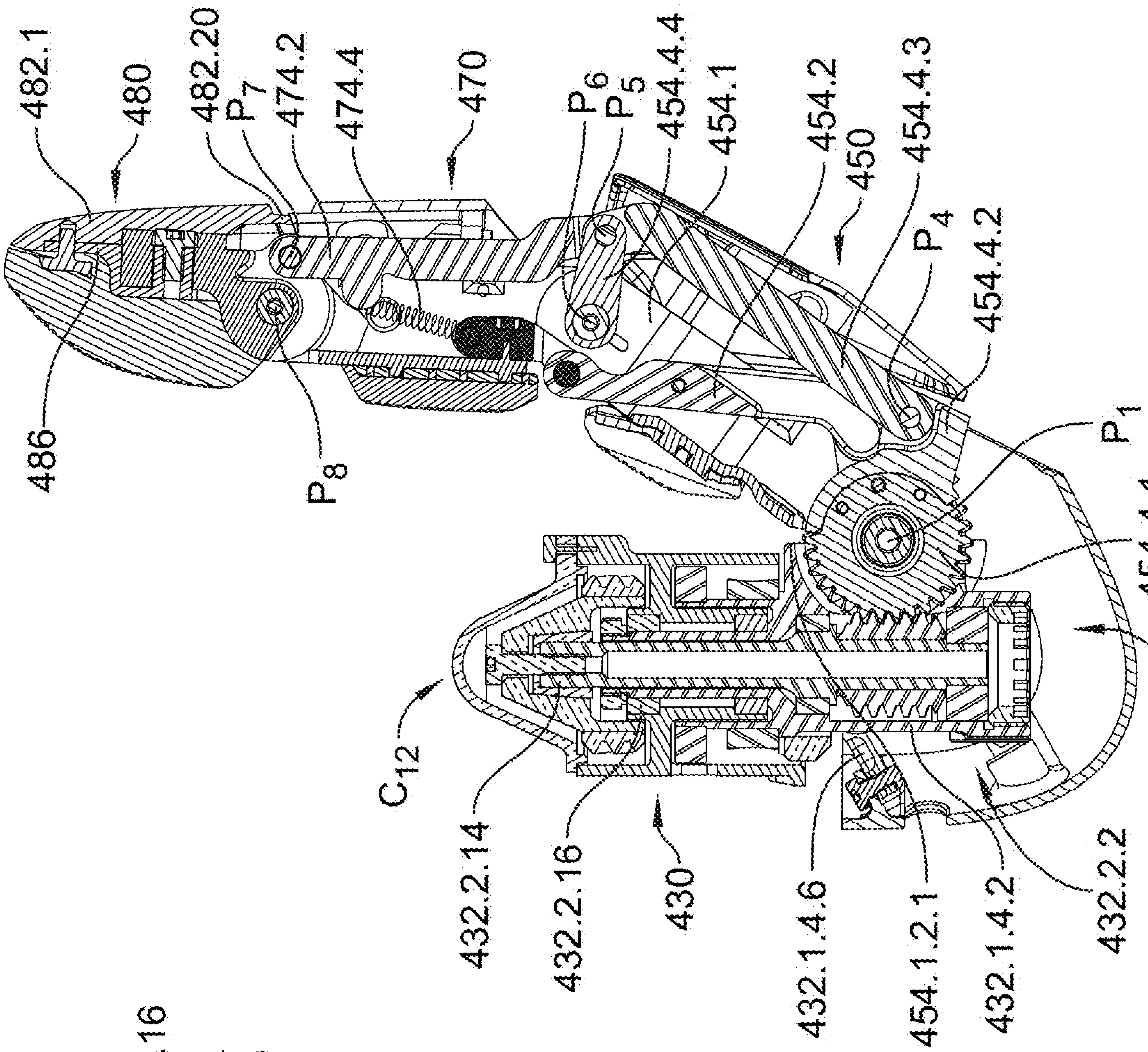

FIG. 106

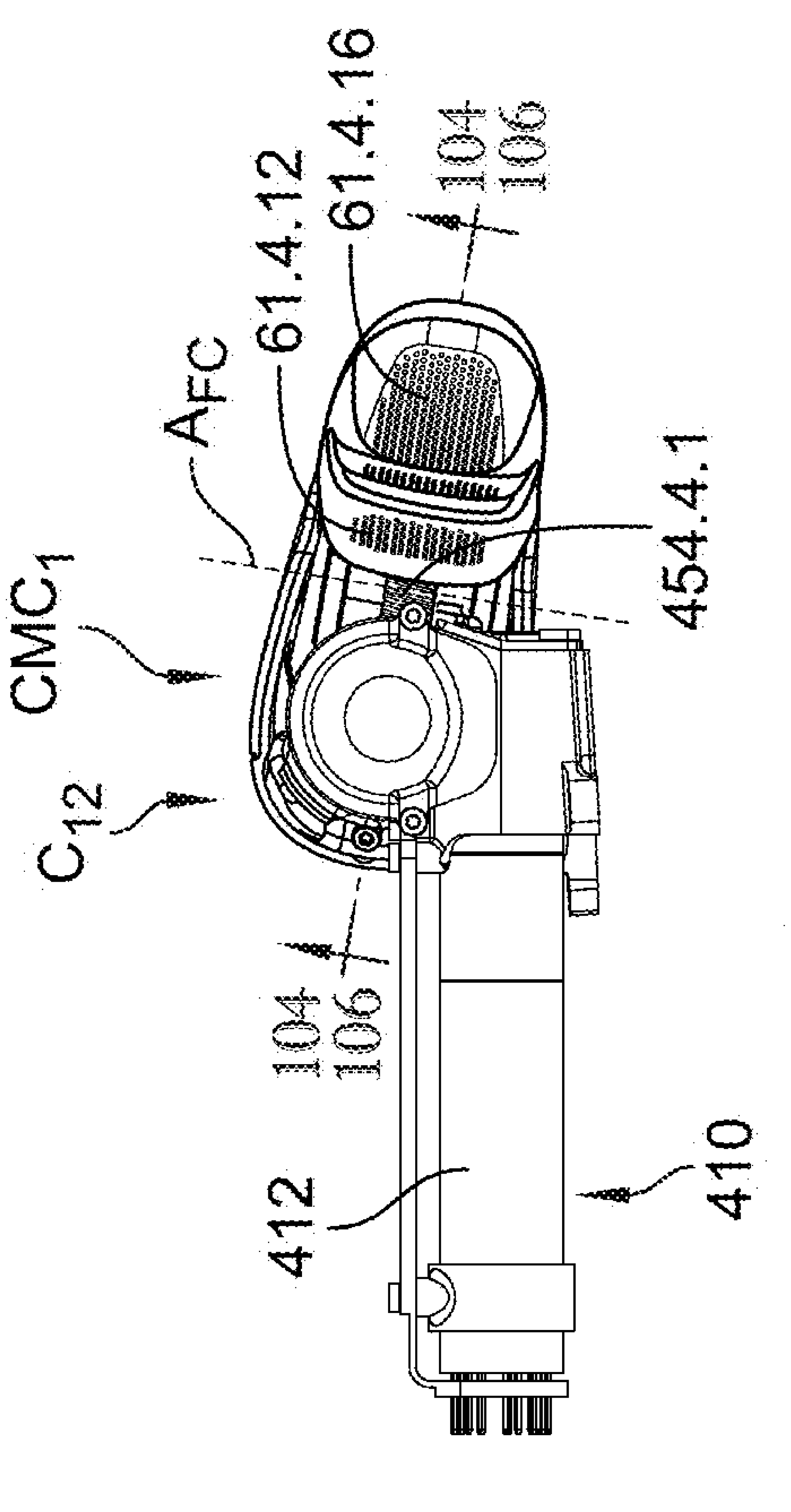

FIG. 105

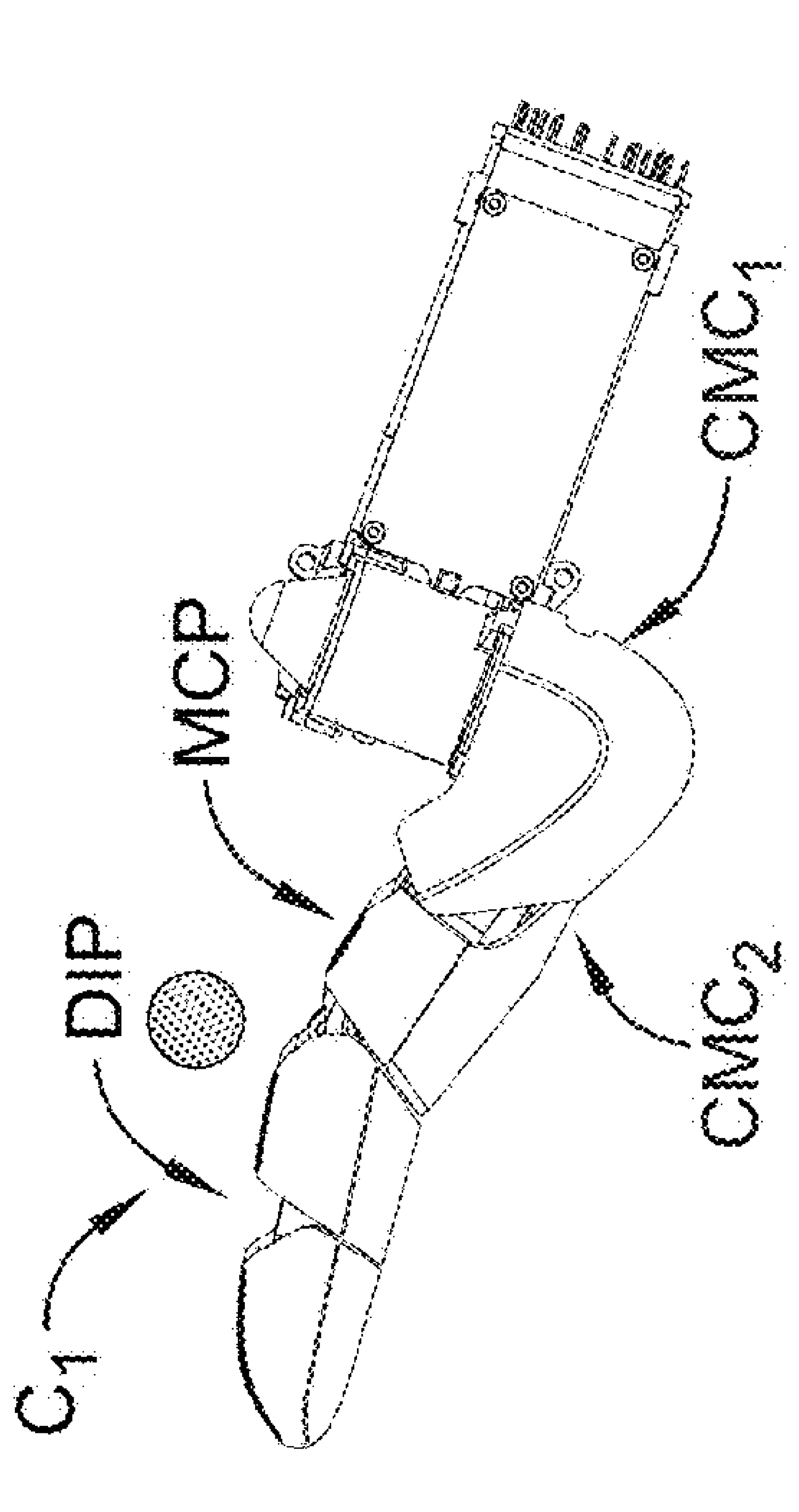

FIG. 107

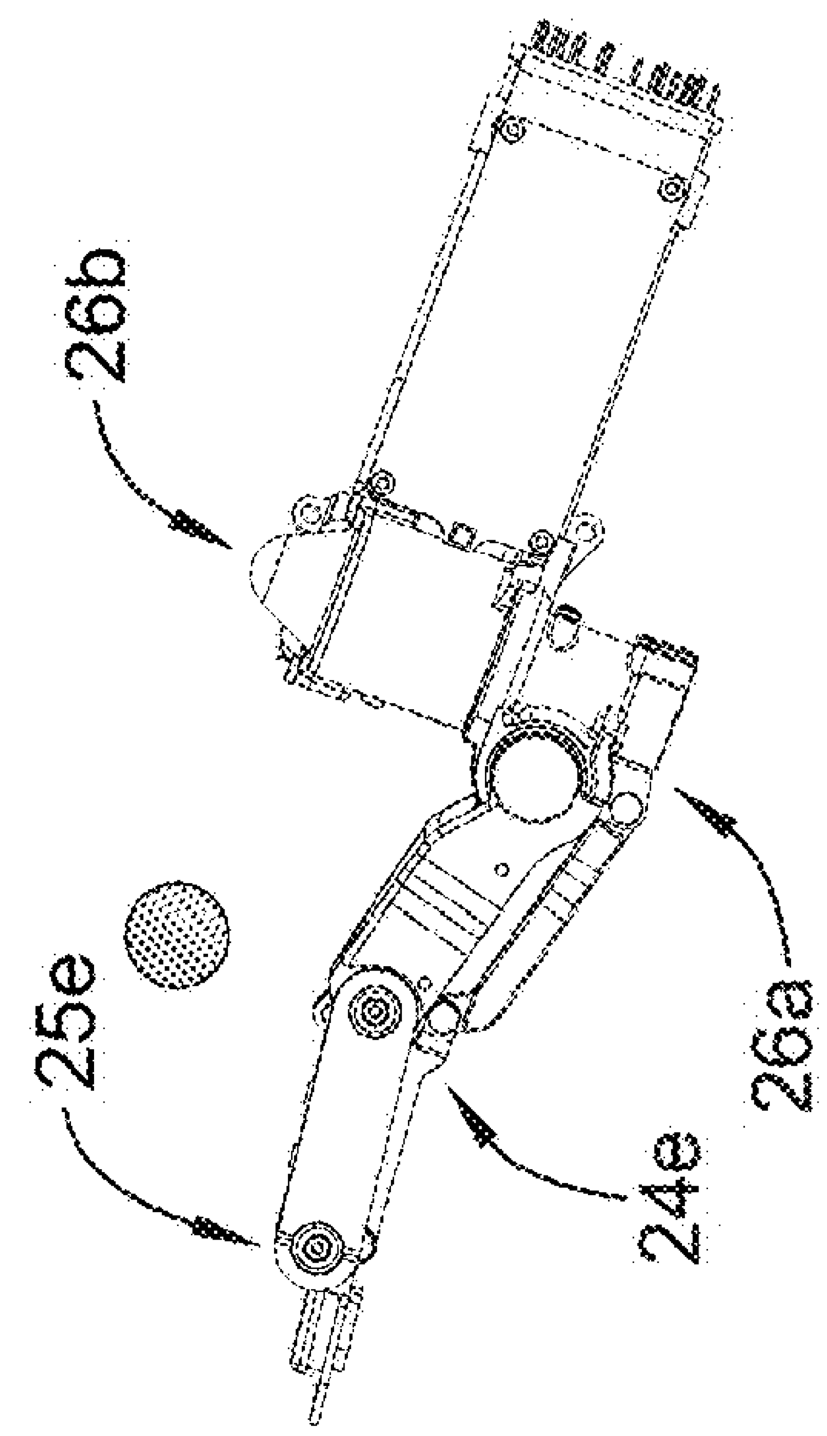

FIG. 108

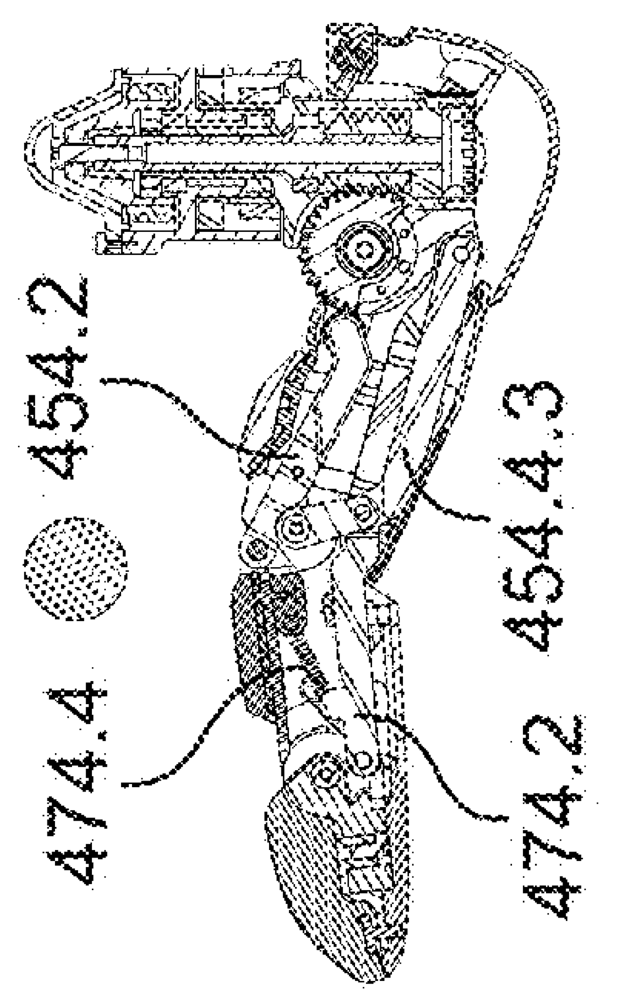

FIG. 109

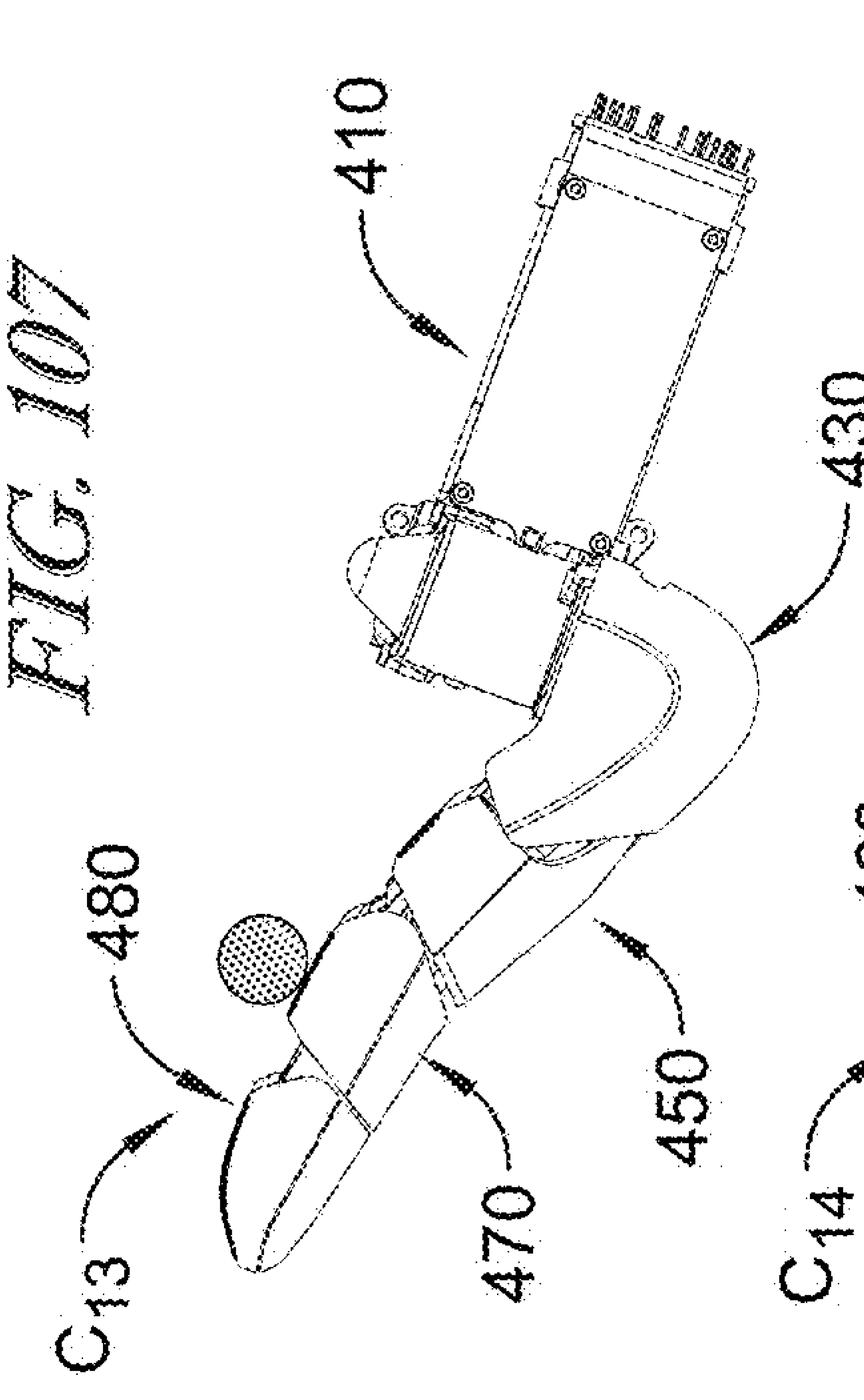

FIG. 110

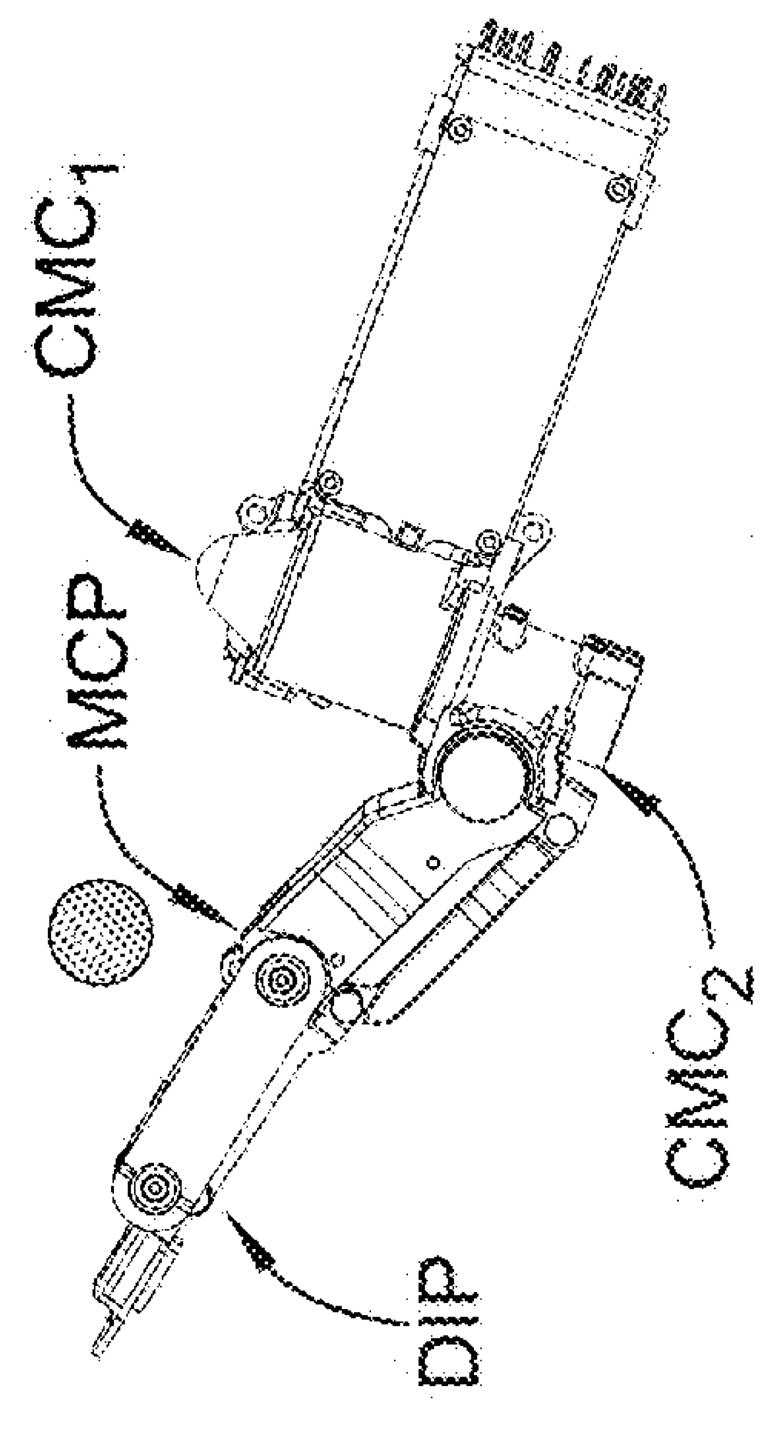

FIG. 111

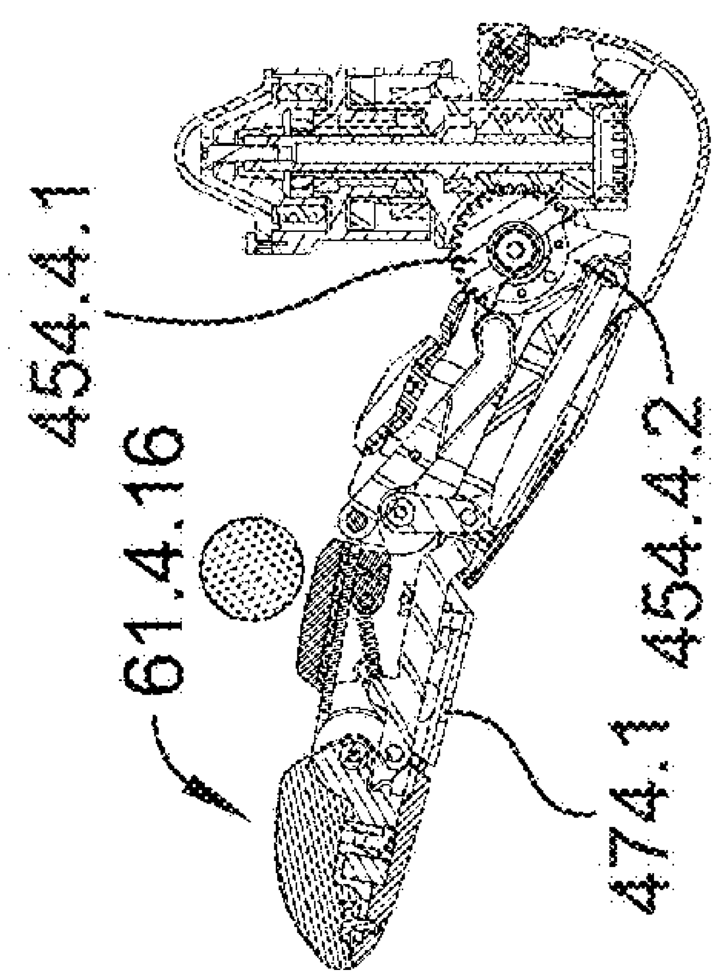

FIG. 112

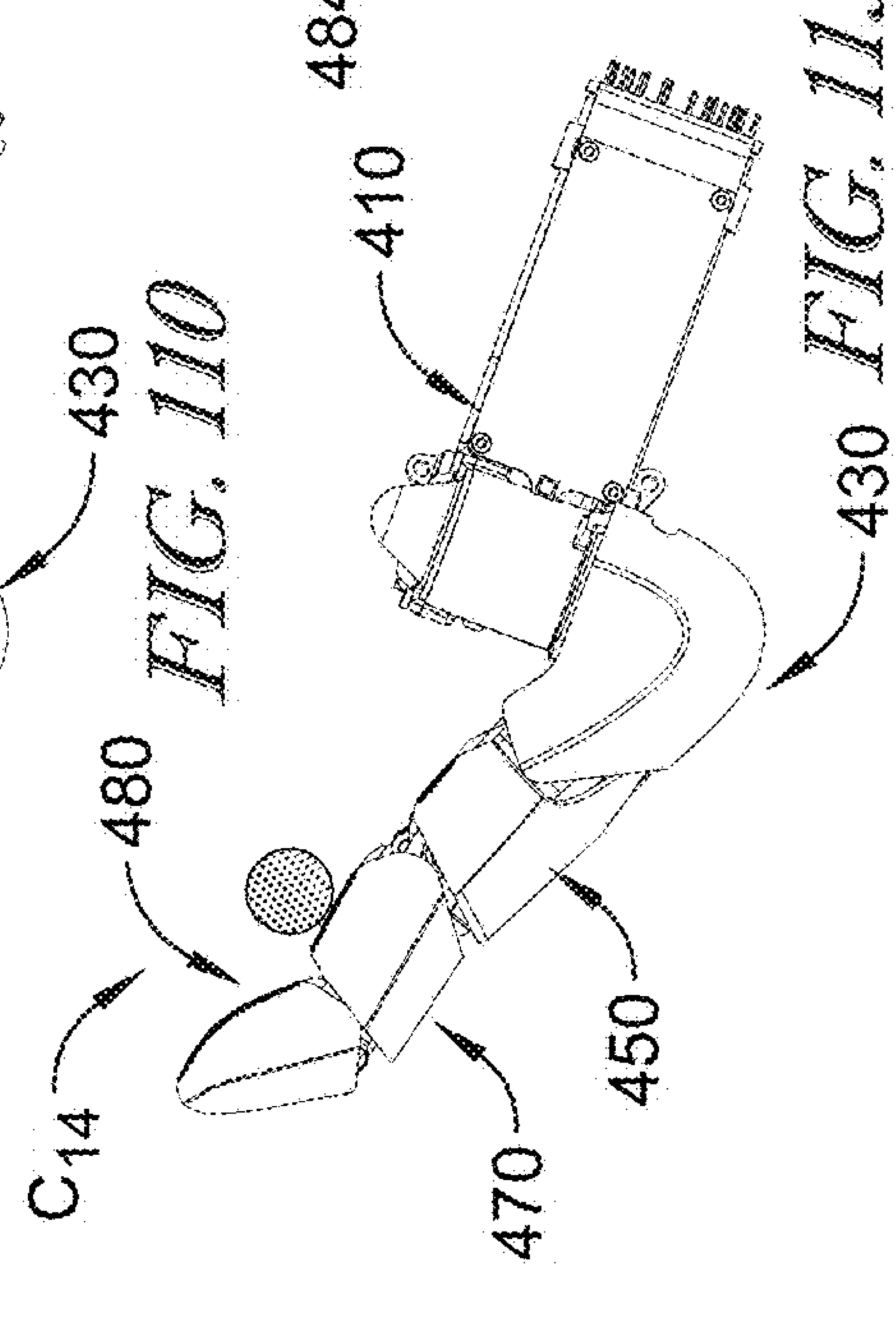

FIG. 113

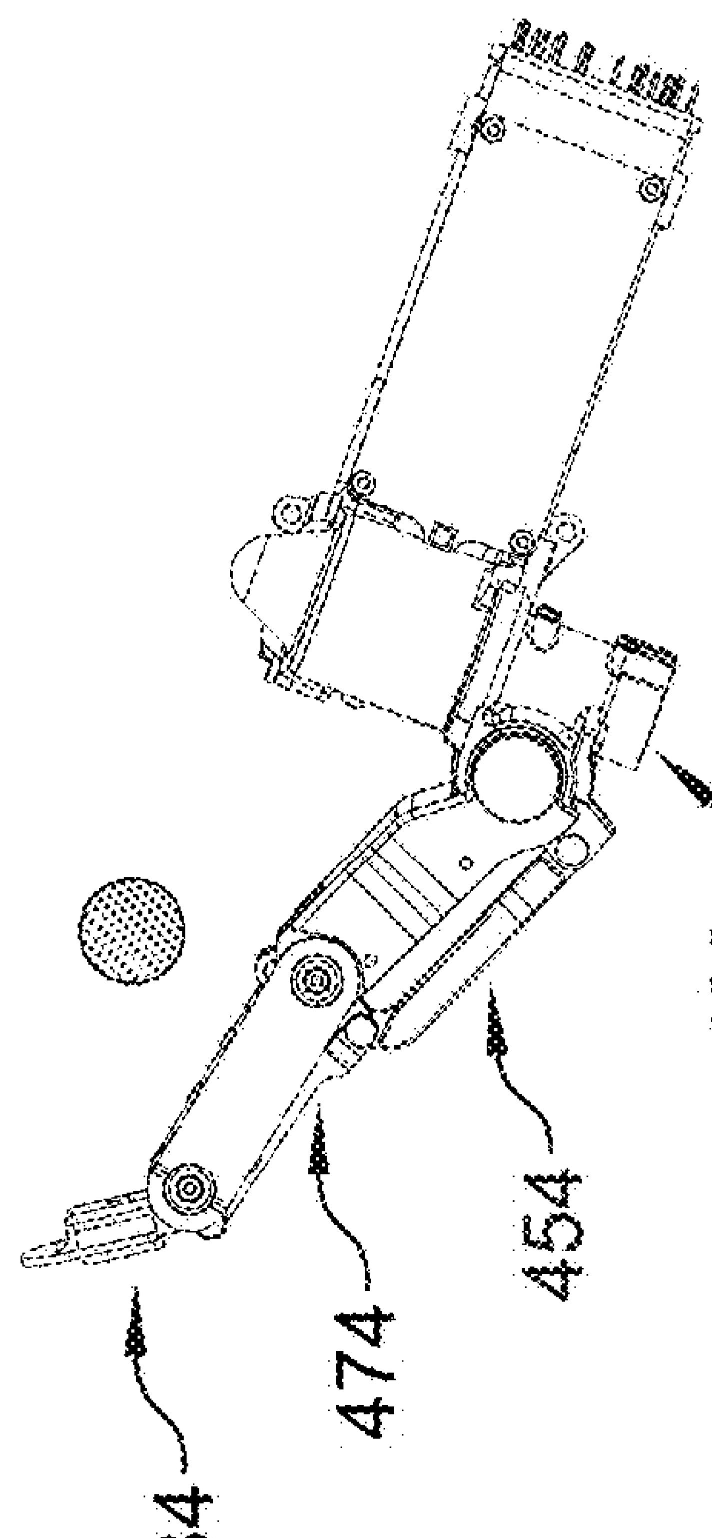

FIG. 114

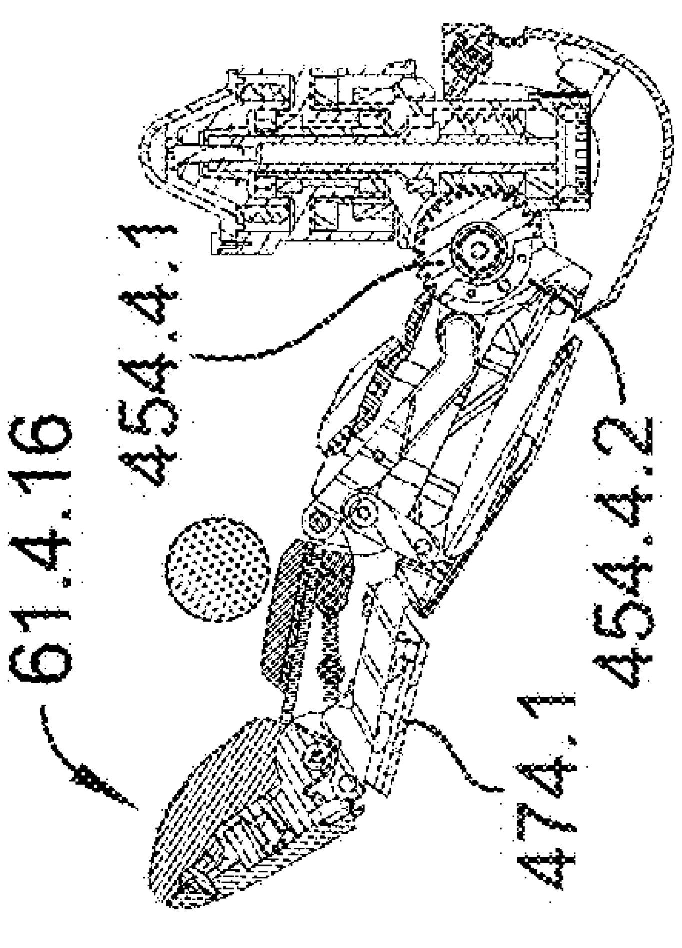

FIG. 115

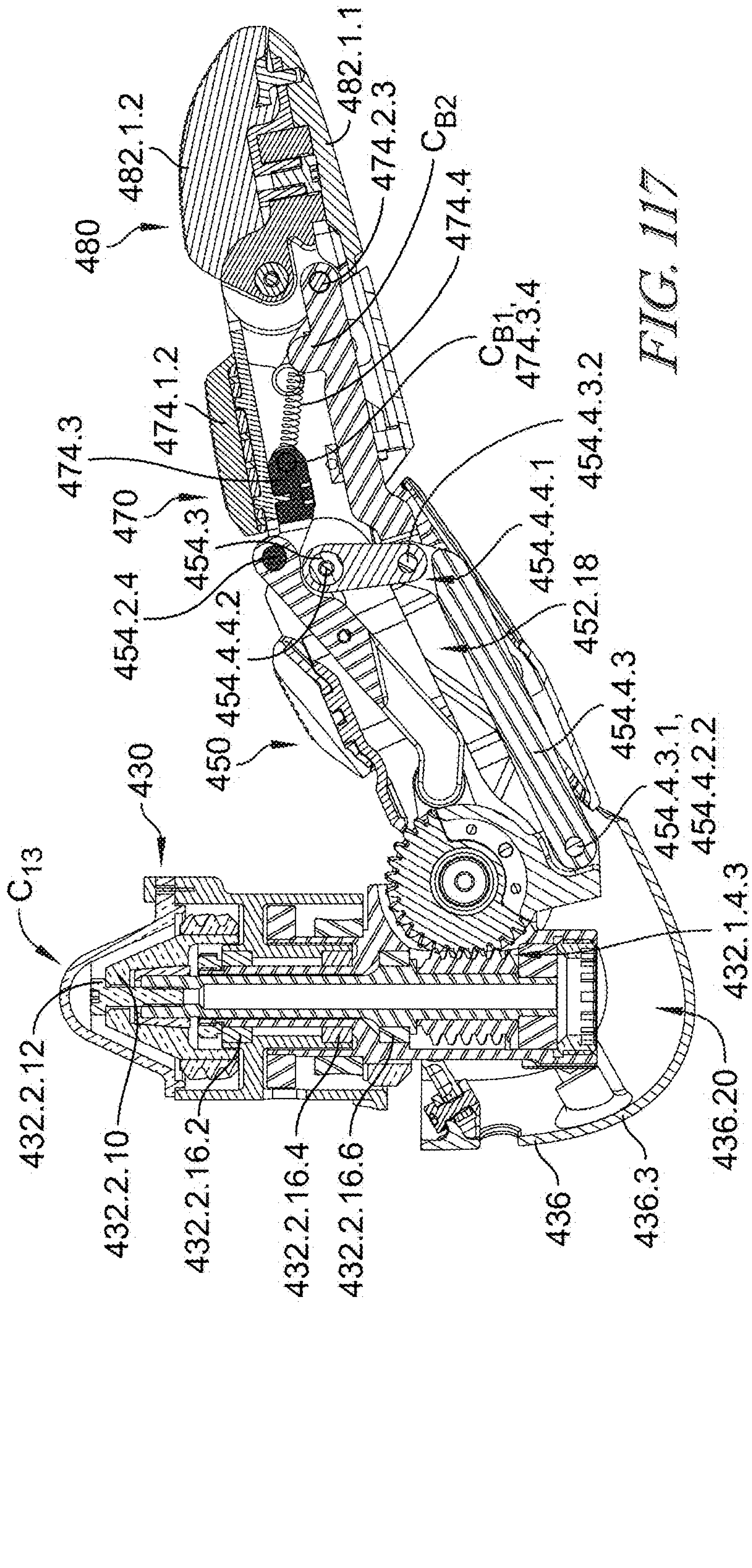

FIG. 117

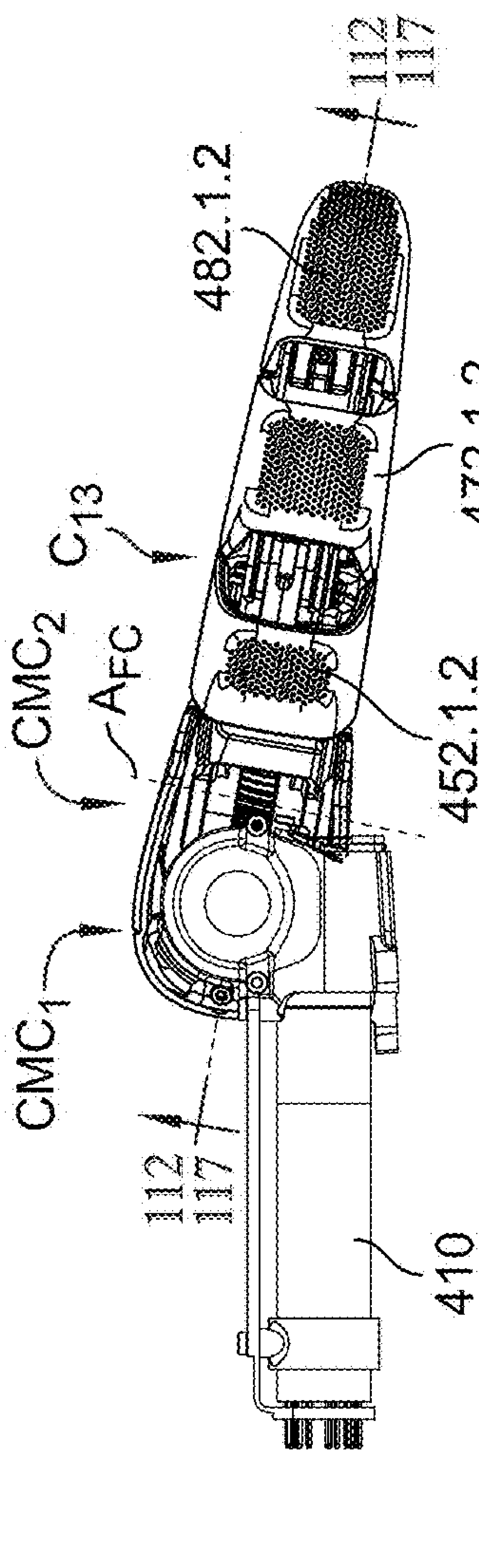

FIG. 116

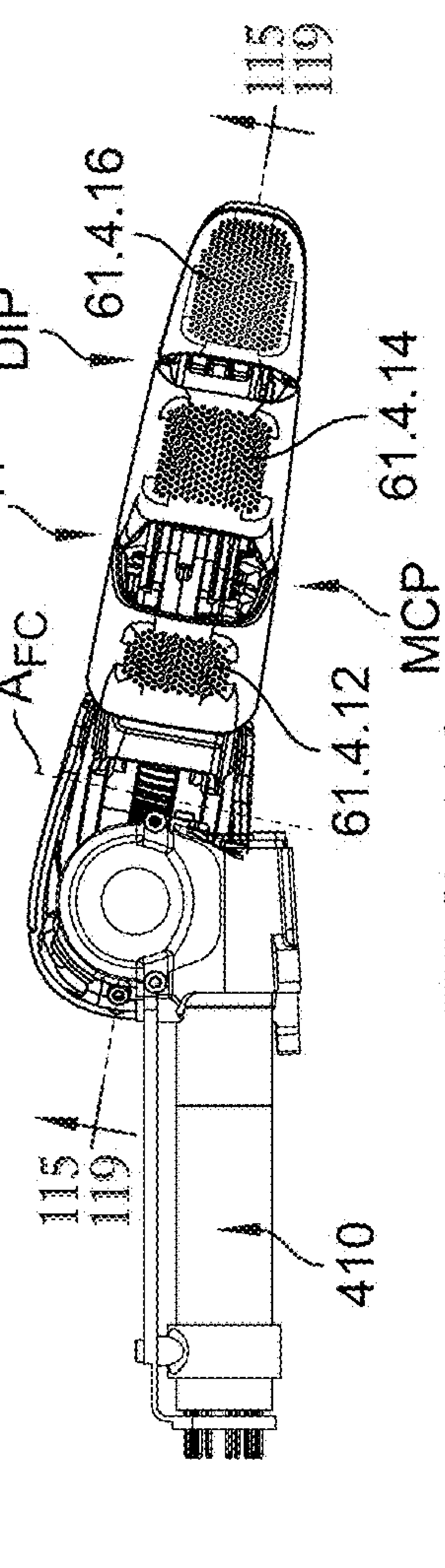

FIG. 118

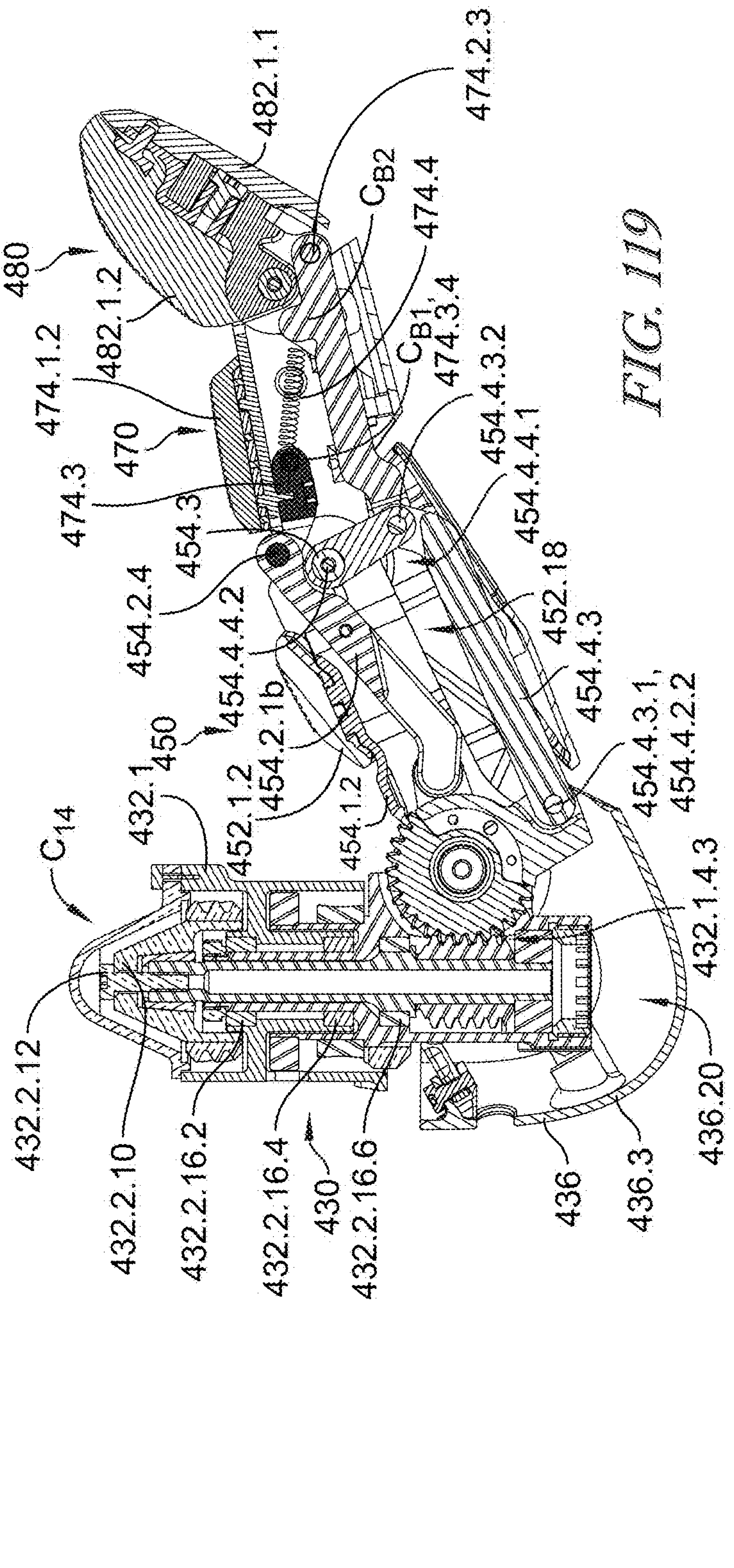

FIG. 119

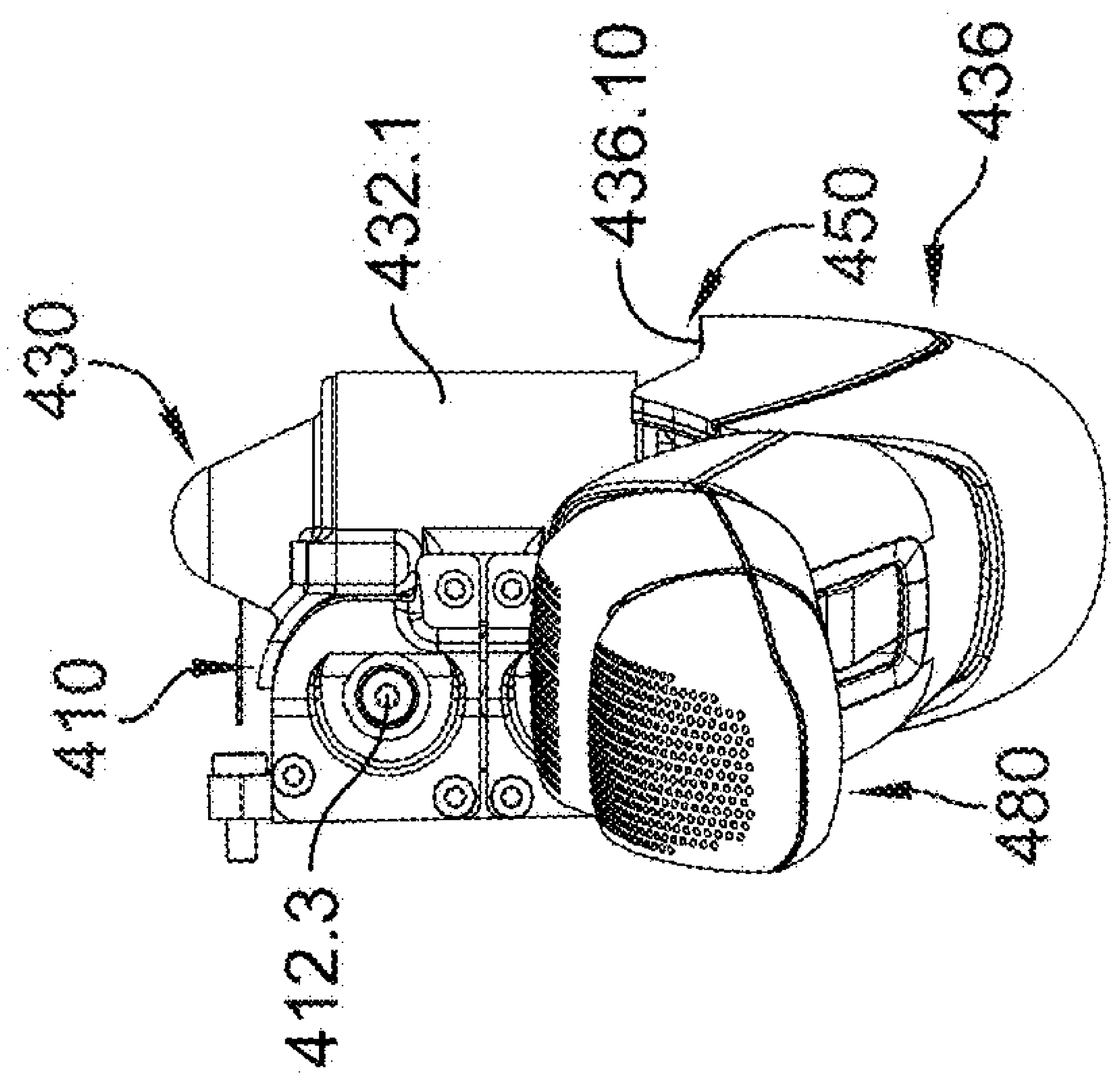

FIG. 120

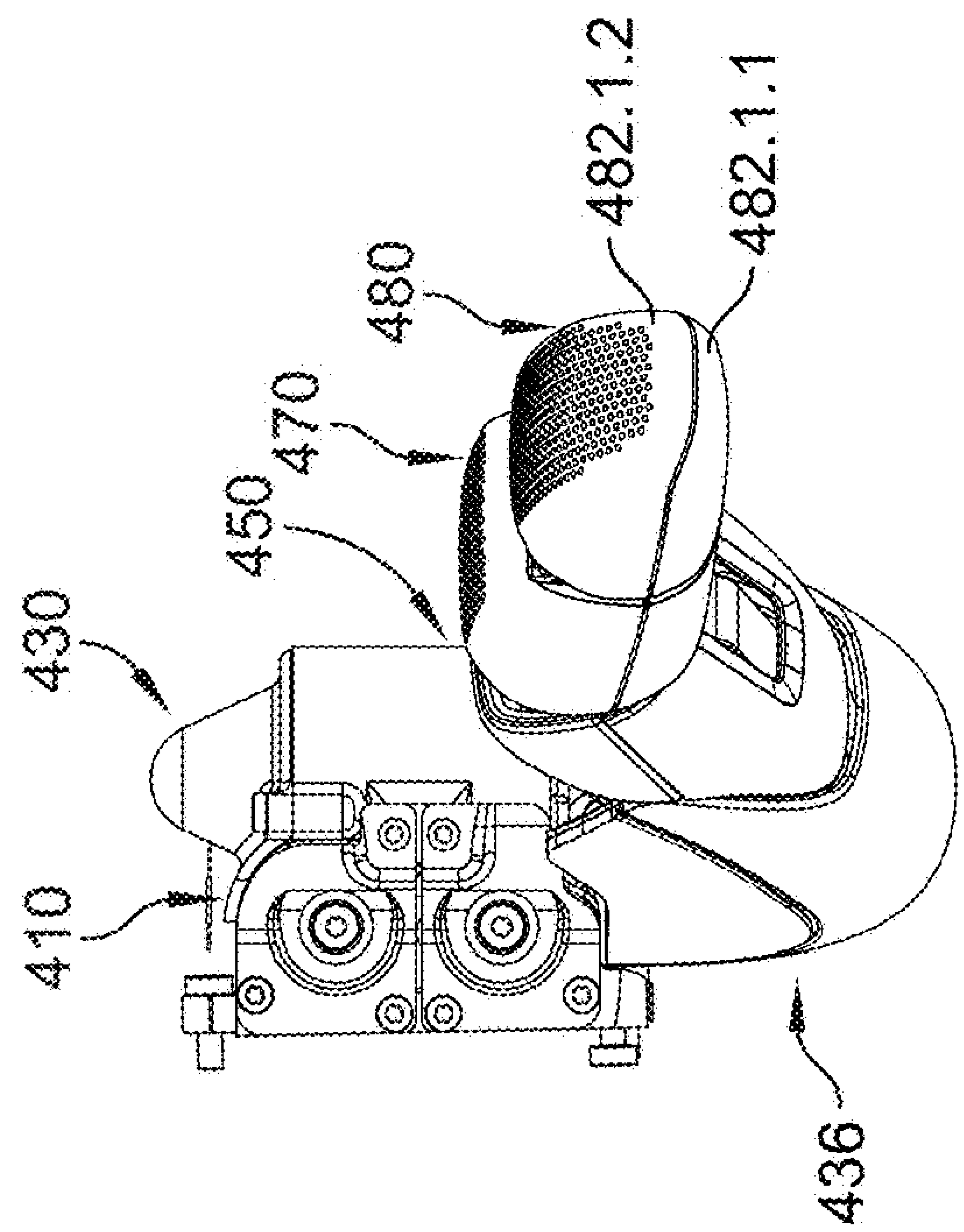

FIG. 121

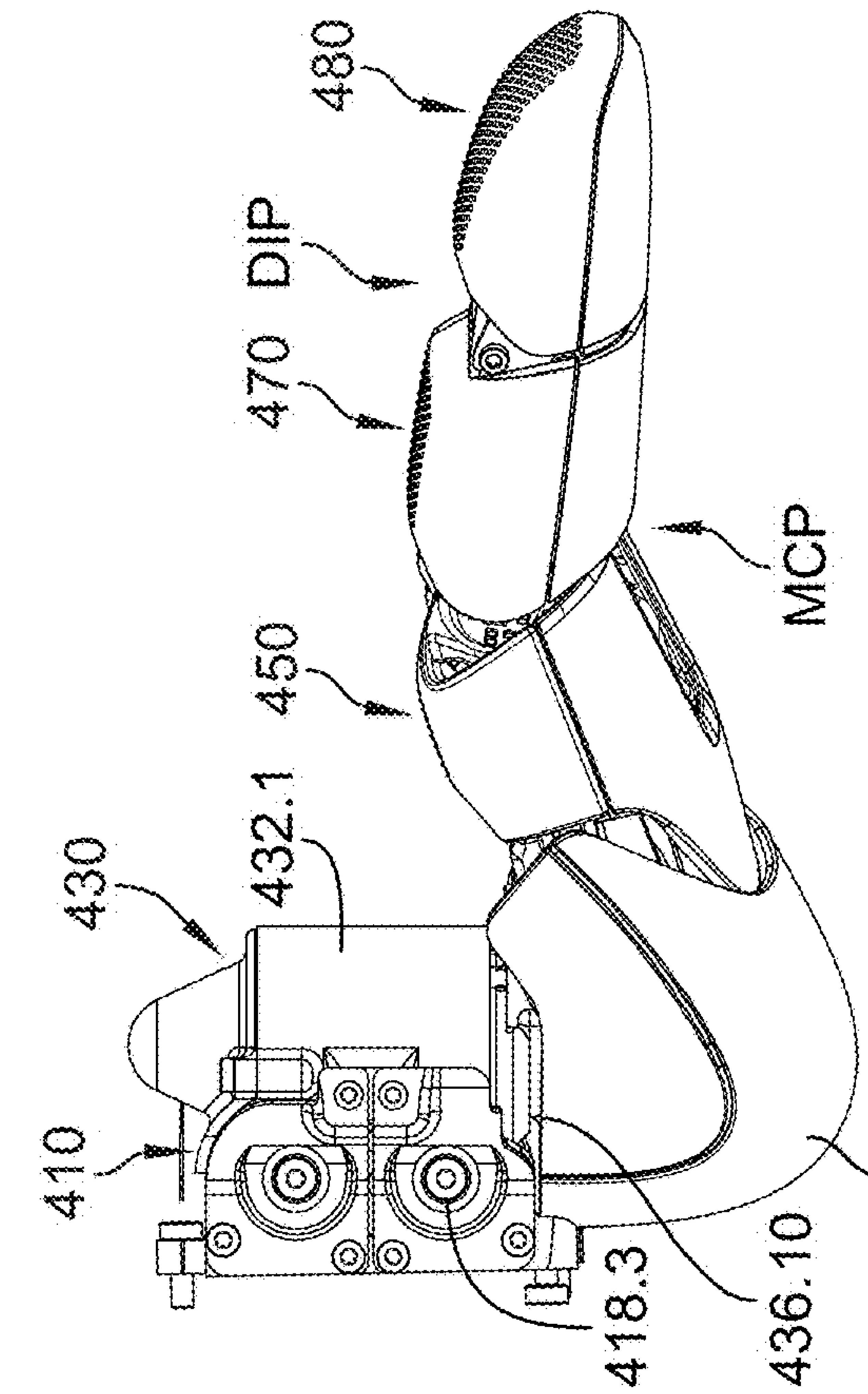

FIG. 122

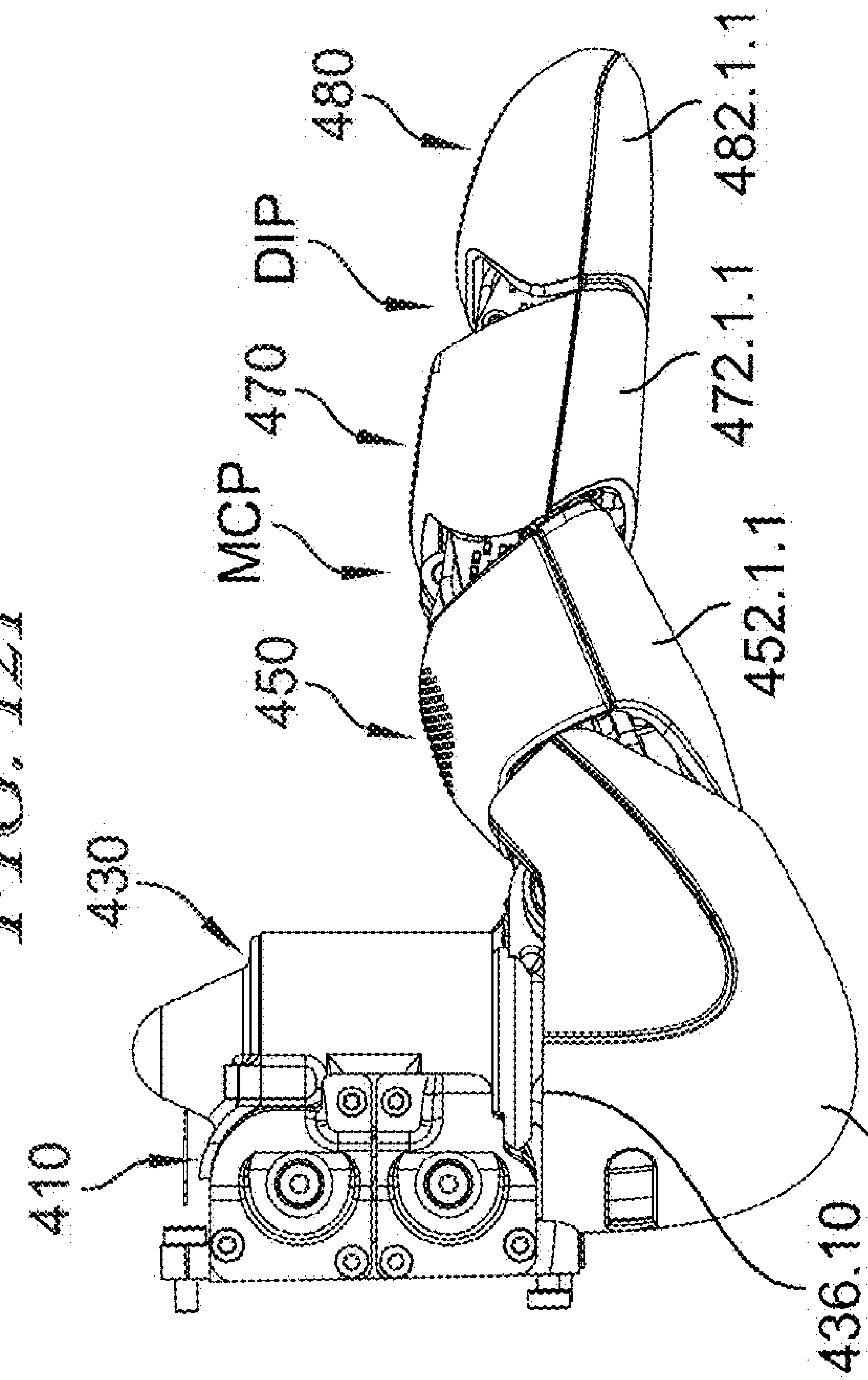

FIG. 123

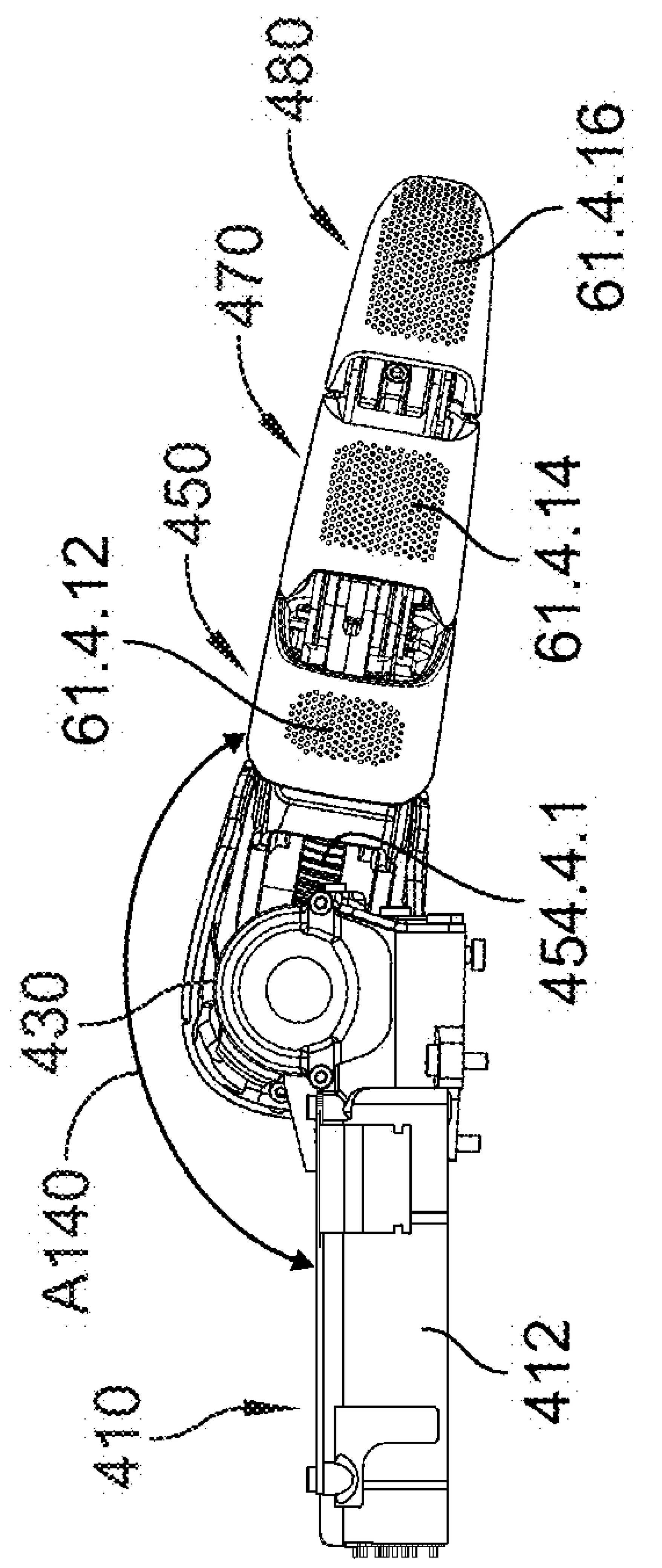

FIG. 124

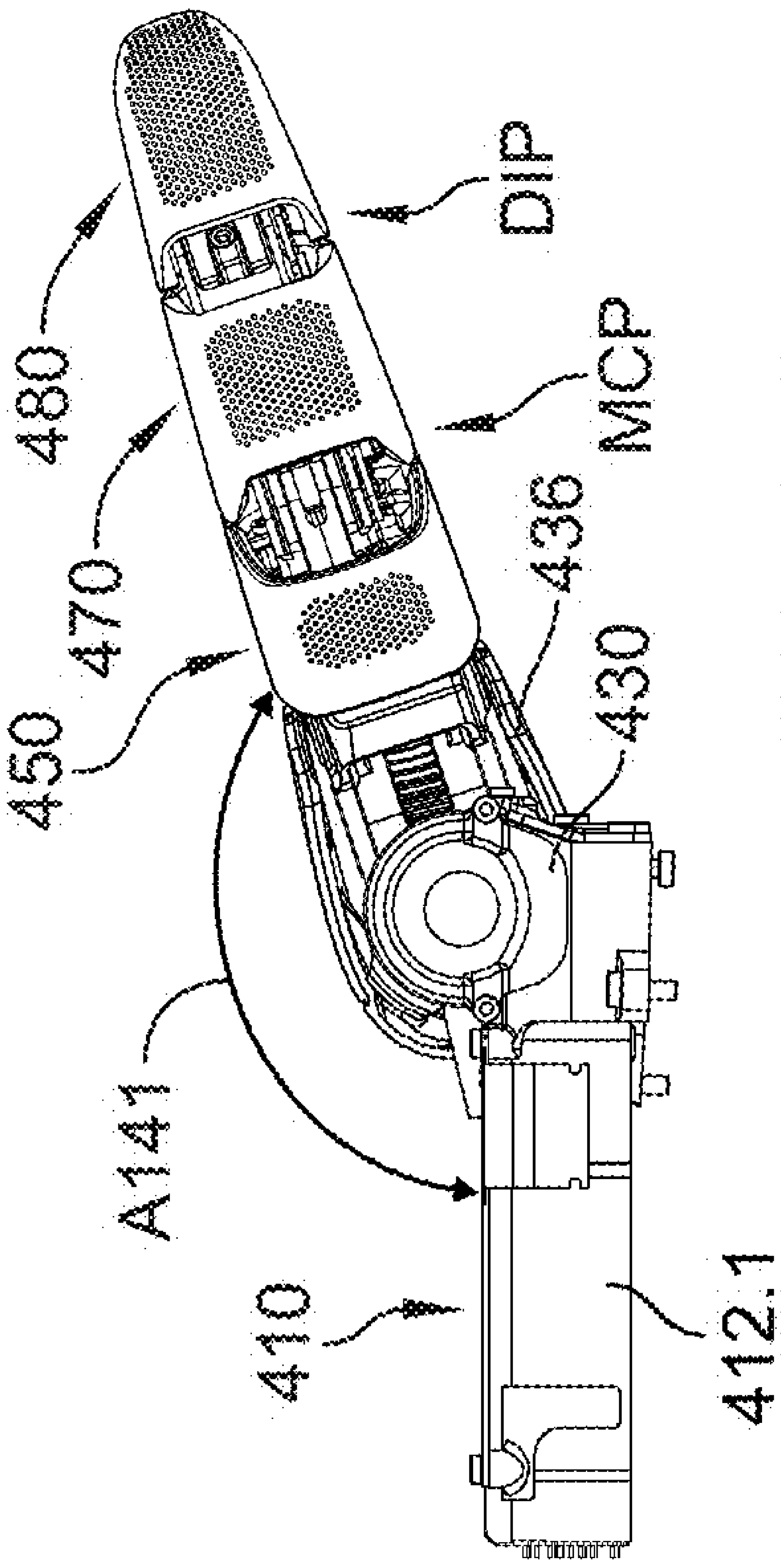

FIG. 125

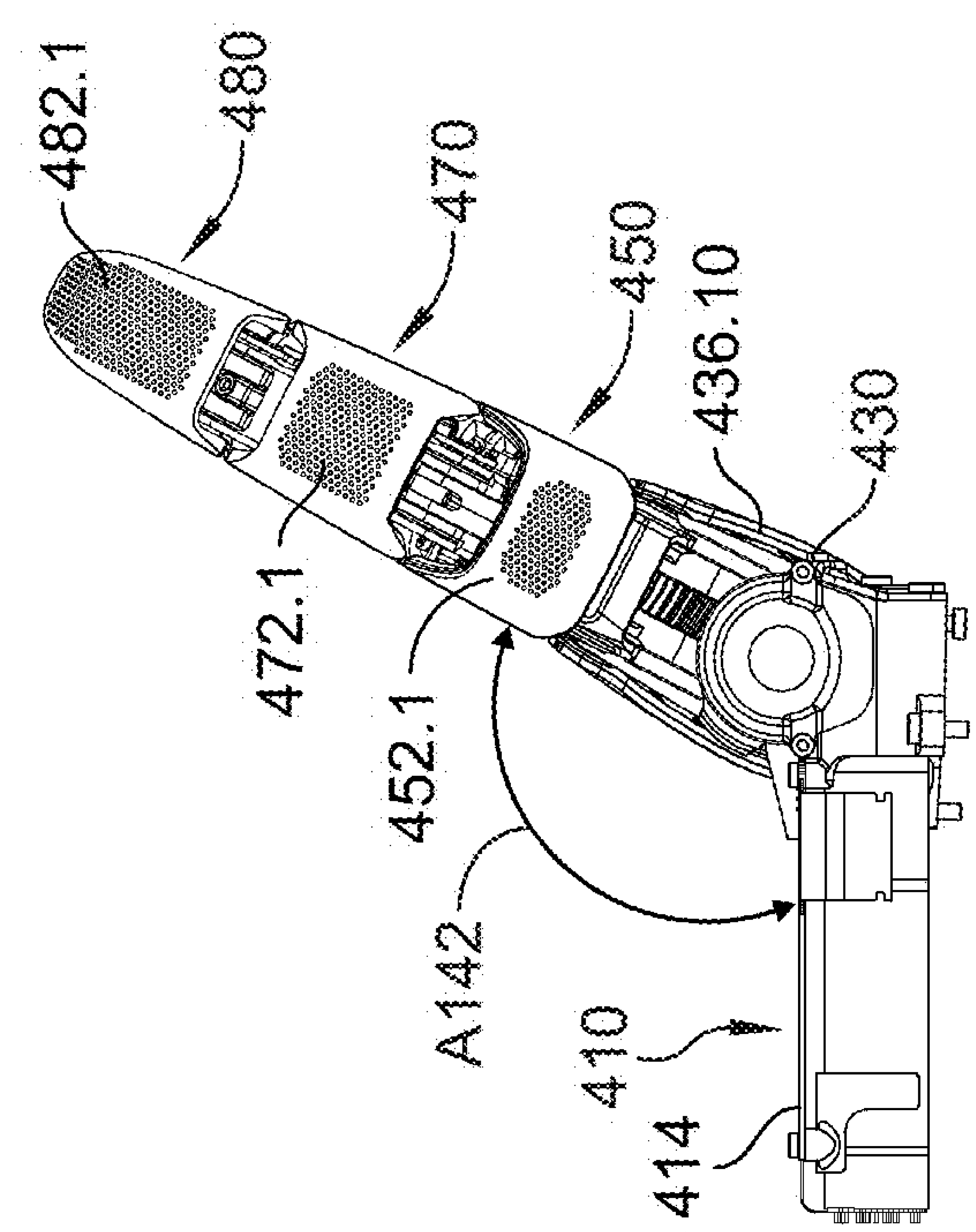

FIG. 126

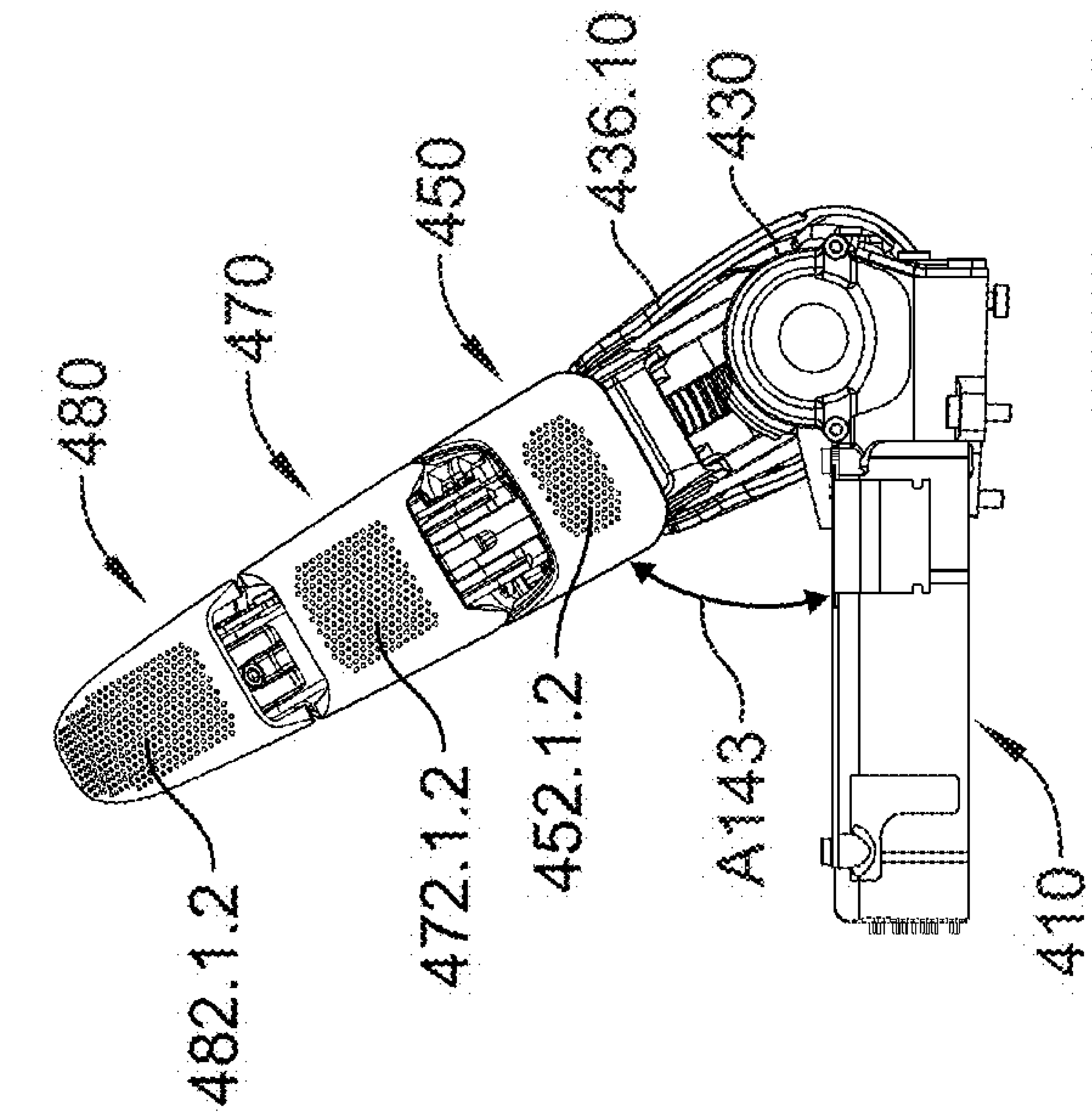

FIG. 127

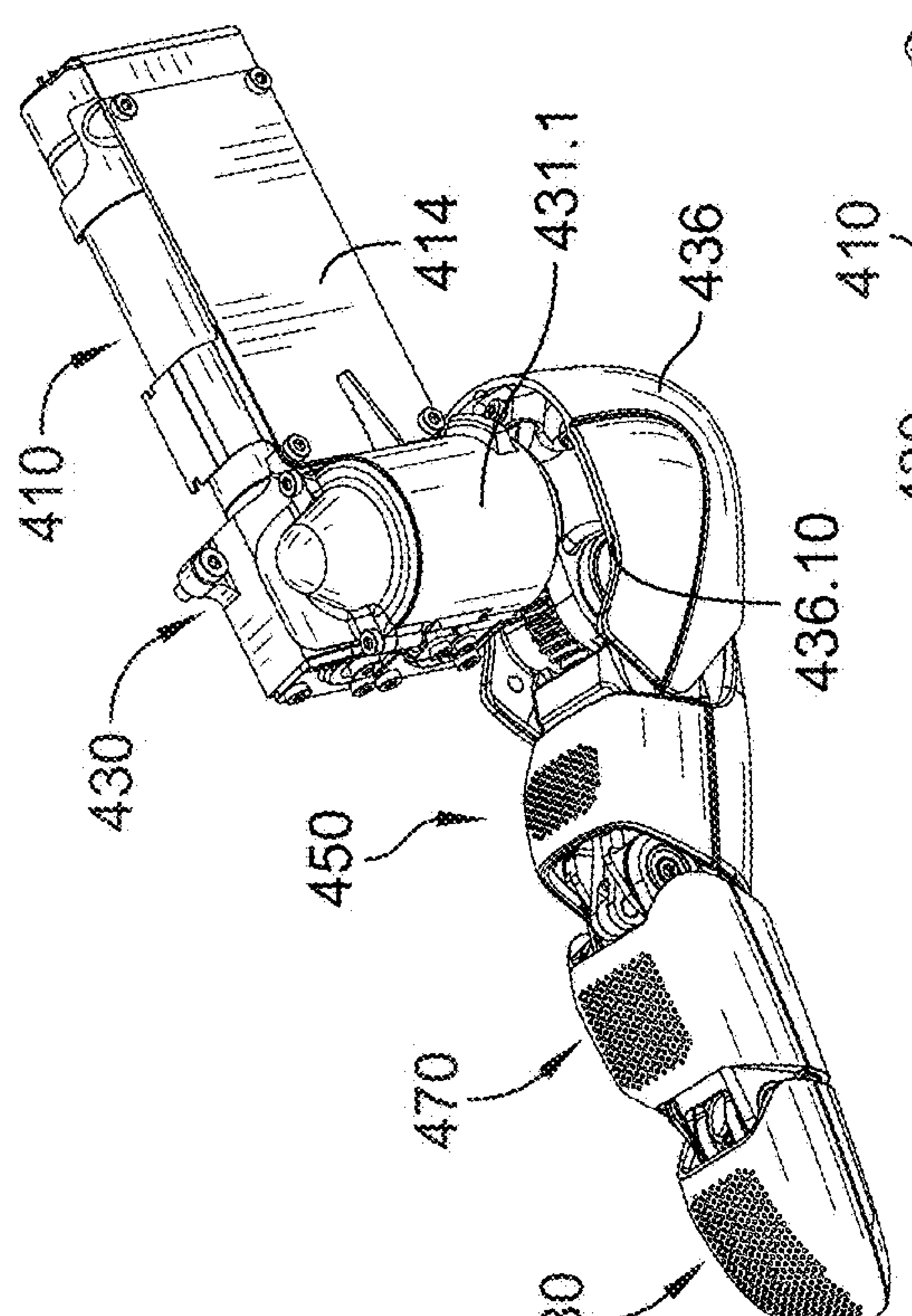

FIG. 128

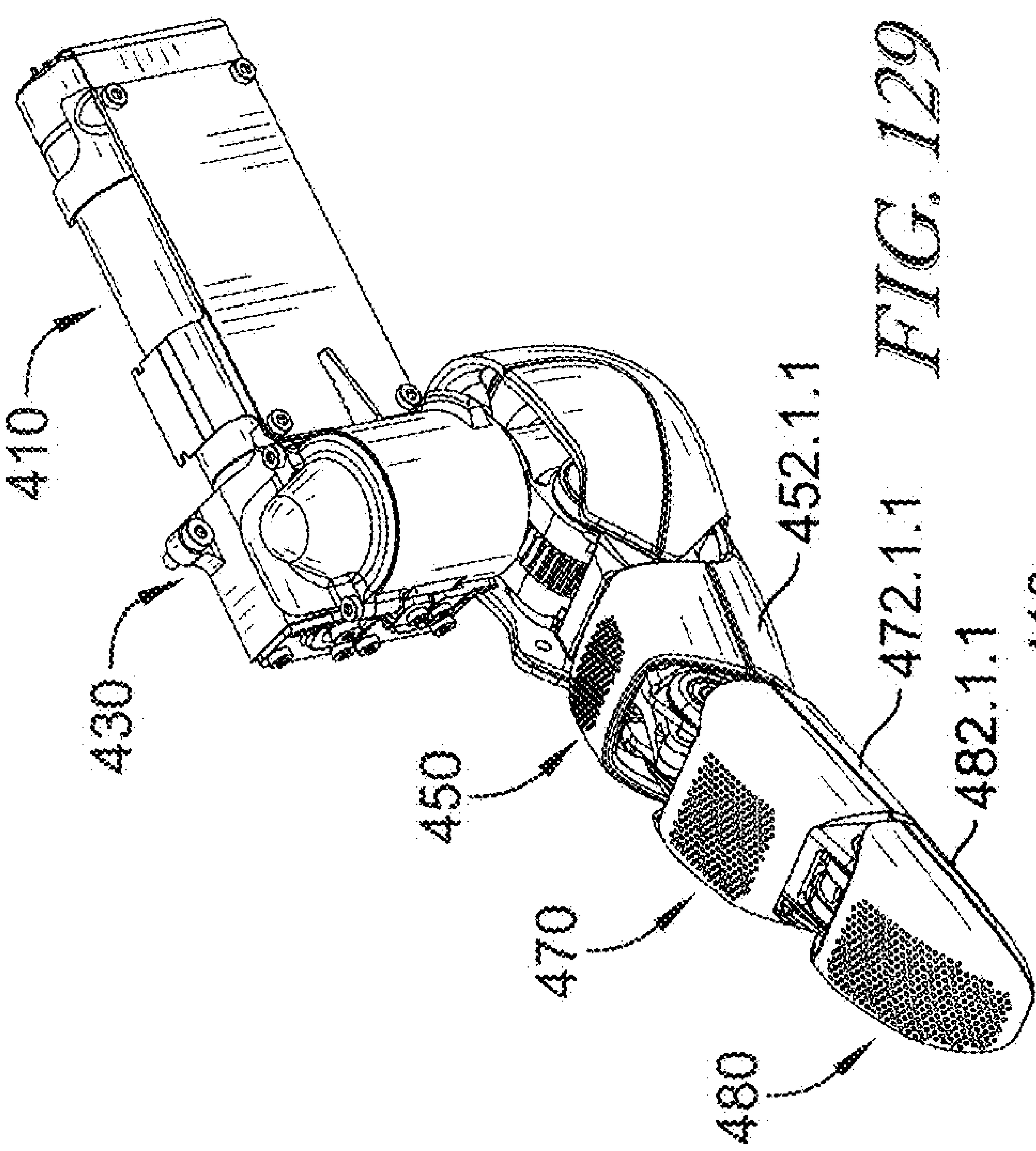

FIG. 129

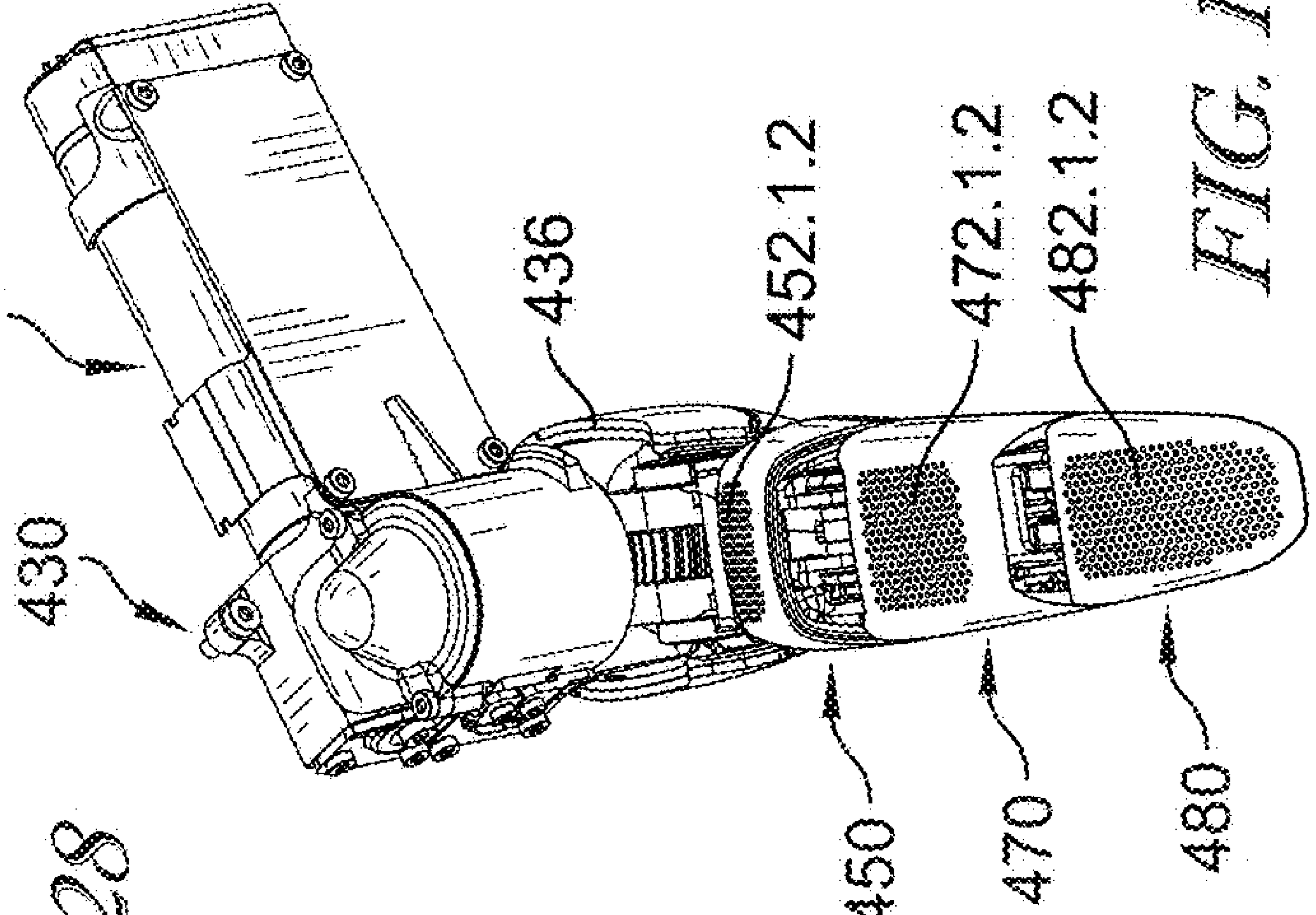

FIG. 130

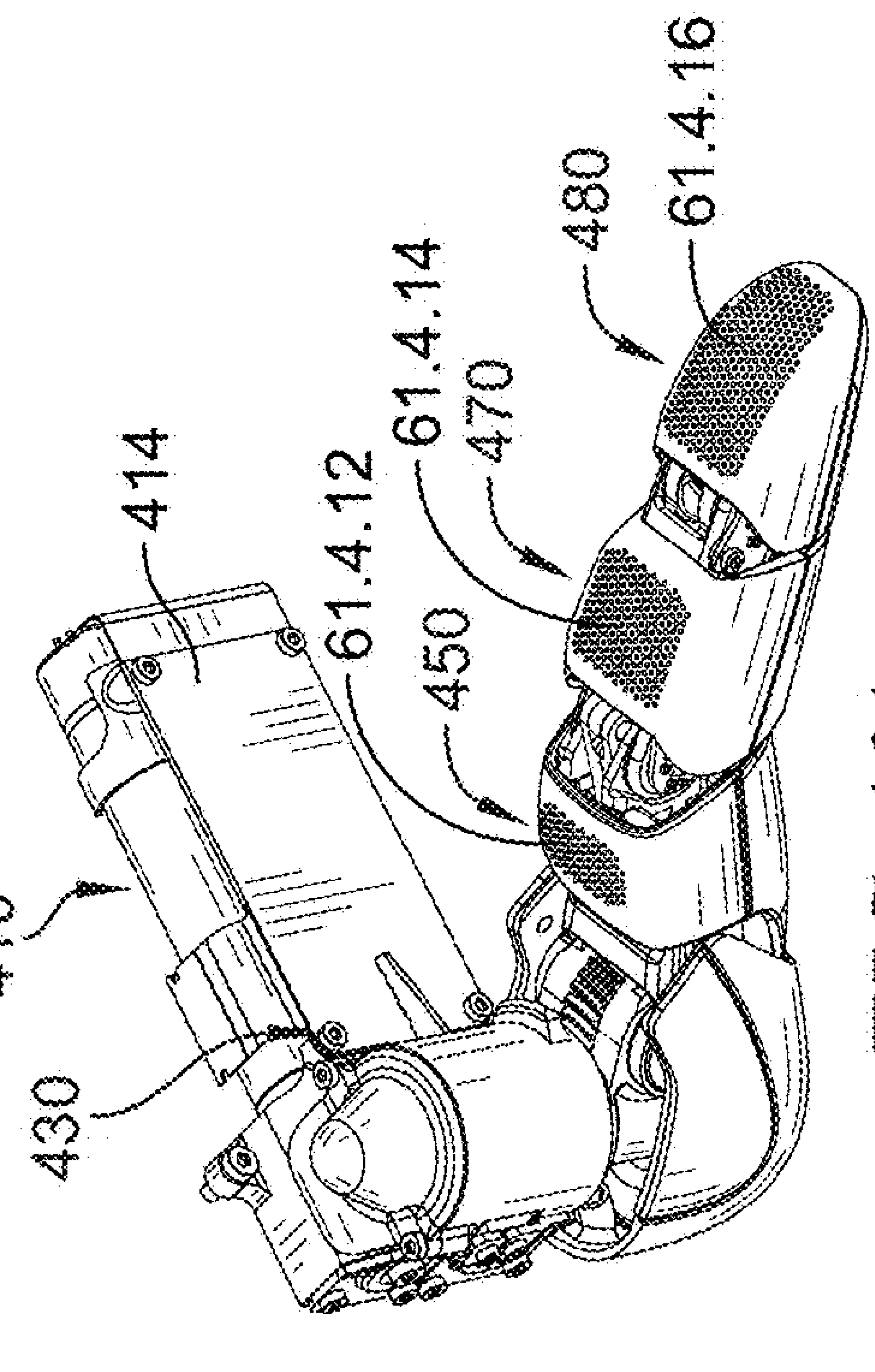

FIG. 131

KINEMATICS OF A MECHANICAL END EFFECTOR FOR A HUMANOID ROBOT

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation application of PCT Application No. PCT/US25/11450 which claims benefit under 35 U.S.C. § 119 of U.S. Provisional Patent Applications Nos. 63/561,315, 63/573,226, 63/620,633 all of which are incorporated herein by reference for any purpose. U.S. patents application Ser. Nos. 19/006,191, 19/000,626, 18/919,263 and 18/919,274, and U.S. Provisional Patent Application Nos. 63/614,499, 63/617,762, 63/615,766, 63/557,874, 63/626,040, 63/626,105, 63/625,362, 63/625,370, 63/625,381, 63/625,384, 63/625,389, 63/625,405, 63/625,423, 63/625,431, 63/685,856, 63/696,507, 63/696,533, 63/706,768, 63/722,057, and 63/700,749 are all incorporated herein by reference for any purpose. PCT Application No. PCT/US25/10425 is incorporated by reference for any purpose.

TECHNICAL FIELD

[0002] This disclosure relates to a mechanical end effector for a robot, specifically a general-purpose humanoid robot. The mechanical end effector includes various assemblies, components contained in the various assemblies, and connections between said components that provide the mechanical end effector with the ability to substantially mimic the movements, capabilities, and configuration of a human hand.

BACKGROUND

[0003] The current workplace landscape is marked by an unparalleled labor shortage, evident in over 10 million unsafe or undesirable jobs within the United States. These positions often encompass tasks in high-risk sectors—such as manufacturing, construction, and materials handling—where human labor faces safety challenges or heightened physical strain. To mitigate this widening labor gap, there is a pronounced need for high-performance robotic systems that can assume responsibility for a variety of demanding, repetitive, or potentially dangerous operations. Consequently, ongoing advancements in robotics research have concentrated on the development of sophisticated, general-purpose humanoid robots, which are specifically engineered to function within environments originally designed for human workers. These general-purpose humanoid robots are equipped with hardware and software architectures optimized for performing diverse tasks with efficiency, accuracy, and reliability in human-centric environments.

[0004] In order to fulfill the functional and ergonomic requirements of human-centric environments, general-purpose humanoid robots are commonly outfitted with anthropomorphic features, including two legs, two arms, a torso, and a head or face-like interface that may provide user feedback or display information. Central to this anthropomorphic design philosophy is the mechanical end effector of the robot, which should be able to approximate most of the capability of the human hand in terms of dexterity, strength, and overall versatility. By being able to approximate most of the capability of the human hand, the end effector can more effectively interact with complex, real-world objects, thereby performing functions such as grasping, rotating, and manipulating items with minimal risk of slippage or damage. In addition to providing a high level of dexterity, the design must satisfy operational constraints related to energy consumption, cost efficiency, and mechanical durability. As such, there is a need for a mechanical end effector that can provide humanoid robots with the ability to execute tasks with human-equivalent precision, robustness, and adaptability in dynamic and unpredictable work environments.

SUMMARY

[0005] The present disclosure provides a thumb assembly for an end effector for a humanoid robot, comprising: a digit assembly comprising a proximal assembly, a medial assembly, a distal assembly, a proximal interphalangeal joint pivotably coupling the proximal assembly to the medial assembly, and a distal interphalangeal joint pivotably coupling the distal assembly to the medial assembly; a motor assembly comprising a first motor and a second motor; and a gear assembly comprising a flexion gear configured to be driven by the first motor, wherein said driving of the flexion gear causes the digit assembly to move about a second carpometacarpal joint axis, and an interposition gear configured to be driven by the second motor, wherein driving of the interposition gear causes the digit assembly to move about a first carpometacarpal joint axis.

[0006] The present disclosure also provides an underactuated end effector for a humanoid robot, comprising: a frame defining a palm region; a finger assembly removably connected to the frame, wherein the finger assembly has a sagittal plane extending along a length of said finger assembly; a thumb assembly removably connected to the frame proximate the palm region, the thumb assembly comprising: a motor assembly having a first motor including a first motor shaft, wherein the first motor shaft has a first motor shaft axis, and wherein the first motor shaft is configured to rotate about the first motor shaft axis; and a second motor including a second motor shaft, wherein the second motor shaft has a second motor shaft axis, wherein the second motor shaft is configured to rotate about the second motor shaft axis; wherein the first motor shaft axis is oriented at a first acute angle relative to the sagittal plane; and wherein the second motor shaft axis is oriented at a second acute angle relative to the sagittal plane.

[0007] The present disclosure further provides a humanoid robot with an end effector for a humanoid robot, the end effector comprising: a frame; a motor assembly including: (i) a first motor removably coupled to the frame, and (ii) a second motor removably coupled to the frame and positioned adjacent to the first motor; a gear assembly coupled to a digit assembly and comprising: a flexion gear configured to be rotated by the first motor, and wherein said rotation of the flexion gear moves the digit assembly from a hyperextended state to a flexed state; and an interposition gear configured to be driven by the second motor, and wherein said rotation of the interposition gear moves the digit assembly from an unrotated state to a rotated state.

[0008] The present disclosure additionally provides an underactuated end effector for a humanoid robot, comprising: a frame; a plurality of finger assemblies removably connected to the frame, wherein each finger assembly of the plurality of finger assemblies includes a finger motor assembly; and a thumb assembly removably connected to the frame, the thumb assembly comprising: a first motor with a first motor shaft, wherein the first motor shaft is rotatable

about a first motor shaft axis; a first motor gear connected to the first motor shaft and being rotatable about: the first motor shaft, and a first motor gear axis that is coaxial the first motor shaft; a second motor with a second motor shaft, wherein the second motor shaft is rotatable about a second motor shaft axis; a second motor gear connected to the second motor shaft and configured for rotation about: the second motor shaft, and a second motor gear axis that is coaxial with the second motor shaft; and wherein (i) the first motor shaft axis is oriented substantially parallel to the second motor shaft axis, and (ii) the first motor gear axis is oriented substantially parallel to the second motor gear axis.

[0009] The present disclosure also provides an underactuated end effector for a humanoid robot, comprising: a frame; a plurality of finger assemblies connected to the frame, each finger assembly of the plurality of finger assemblies comprising: a metacarpophalangeal joint; a proximal finger interphalangeal joint; a distal finger interphalangeal joint; and a thumb assembly removably connected to the frame, the thumb assembly comprising: a first carpometacarpal joint; a second carpometacarpal joint; a metacarpophalangeal joint; an interphalangeal joint; a carpometacarpal encoder positioned proximate the first carpometacarpal joint and configured to collect data related to rotation of the first carpometacarpal joint; a first thumb encoder positioned proximate the metacarpophalangeal joint and configured to collect data related to rotation of the metacarpophalangeal joint; and a second thumb encoder positioned proximate the interphalangeal joint and configured to collect data related to rotation of the interphalangeal joint, and wherein the first thumb encoder and second thumb encoder are positioned adjacent to a main medial link of the thumb assembly.

[0010] The present disclosure further provides a humanoid robot with an underactuated end effector, the end effector comprising: an end effector frame; a palm housing coupled to the end effector frame and having a sagittal plane; a plurality of finger assemblies removably connected to a first side of the end effector frame, wherein the sagittal plane of the palm housing is aligned with a longitudinal plane of a finger assembly of the plurality of finger assemblies; a thumb assembly removably connected to a second side of the end effector frame, the thumb assembly comprising: a motor assembly, the motor assembly comprising: a first motor with a first motor shaft, wherein the first motor shaft is configured to rotate about a first motor shaft axis; a second motor with a second motor shaft, wherein the second motor shaft is configured to rotate about a second motor shaft axis; wherein at least an extent of the first motor and the second motor are positioned between the frame and the palm housing; and wherein both the first motor shaft axis and the second motor shaft axis are not arranged parallel to the sagittal plane.

[0011] The described thumb assembly for a robotic or prosthetic hand includes various configurations of motors, gears, joints, and encoders to achieve a range of motion and functionality. The carpometacarpal joint axes, both first and second, may or may not intersect depending on the design configuration. The assembly integrates a first motor and a second motor, with each motor shaft oriented at acute angles relative to the sagittal plane of the end effector. The motor shaft axes and motor gear axes are configured to be substantially parallel to each other to ensure synchronized movement. Additionally, the motors are connected to a drive system that includes flexion gears, interposition gears, and worm drive gears to facilitate controlled movement of the thumb assembly between curled and uncurled positions.

[0012] The thumb assembly is equipped with a housing assembly that encases various components. This carpometacarpal joint housing assembly is designed to rotate in response to motor-driven gear rotations and includes a base joint receiver that accommodates the proximal housing assembly in different thumb positions. The assembly may also feature a textile covering for protective or other purposes. Encoders are strategically positioned near the carpometacarpal joint, proximal interphalangeal joint, and distal interphalangeal joint to collect data on the thumb's range of motion and provide feedback for precise control. The joints exhibit specific ranges of motion: the proximal interphalangeal joint between 55° and 90°, the distal interphalangeal joint between 35° and 57°, and the carpometacarpal joints between 35° and 160°, depending on the joint.

[0013] In some embodiments, the end effector may include a worm wheel and worm drive system. Bearings in the worm wheel assembly allow for slippage to protect the system from damage if resistance is encountered. The thumb drive assembly includes a combination of flexion gears, worm drive gears, and drive shafts to achieve smooth digit movement with four degrees of freedom using only two motors. Finger assemblies with three degrees of freedom are removably connected to the frame and driven by individual motors. The palm region of the frame houses the motors, and the thumb drive assembly further incorporates an interposition gear coupled to a lower frame member, enabling rotational movement. The assembly lacks mechanical cables for actuation and may be equipped with a biasing member to maintain the thumb in an uncurled position, enhancing the robustness and functionality of the overall system.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The drawing figures depict one or more implementations in accord with the present teachings, by way of example only, not by way of limitation. In the figures, like reference numerals refer to the same or similar elements.

[0015] FIG. **1**A is a front perspective view of a humanoid robot in an upright, standing position P**1** having a wrist coupler and a mechanical end effector, wherein the mechanical end effector includes a plurality of finger assemblies, a thumb assembly, a housing, and electronics for controlling the finger assemblies and the thumb assembly;

[0016] FIG. **1**B is a perspective view of the wrist coupler and the mechanical end effector of FIG. **1**A, wherein said wrist coupler is removably secured to a lower extent of a robot arm;

[0017] FIG. **2** is a perspective view of the wrist coupler and a mechanical end effector of FIGS. **1**A-**1**B;

[0018] FIG. **3** is a front or palm view of the mechanical end effector of FIGS. **1**A-**2**;

[0019] FIG. **4** is a back or top view of the mechanical end effector of FIGS. **1**A-**2**;

[0020] FIG. **5** is a right side or thumb view of the mechanical end effector of FIGS. **1**A-**2**;

[0021] FIG. **6** is a left side or finger view of the mechanical end effector of FIGS. **1**A-**2**;

[0022] FIG. **7** is a bottom view of the mechanical end effector of FIGS. **1**A-**2**;

[0023] FIG. **8** is a top view of the mechanical end effector of FIGS. **1**A-**2**;

[0024] FIG. **9** is a perspective view of the mechanical end effector of FIGS. **1A-2**, wherein an extent of the housing has been removed to show a portion of the components contained within said housing;

[0025] FIG. **10** is a perspective schematic view that shows the 16 degrees of freedom contained in the mechanical end effector of FIG. **1A-2**;

[0026] FIG. **11** is a front or palm view of the mechanical end effector of FIGS. **1A-2**, wherein an extent of the housing has been removed to show a portion of the components contained within said housing;

[0027] FIG. **12** is a palm schematic view that shows the **16** degrees of freedom contained in the mechanical end effector of FIG. **1A-2**;

[0028] FIG. **13** is a bottom perspective view of the thumb assembly of the mechanical end effector of FIGS. **1A-2** in a partially curled configuration, wherein said thumb assemblies includes a base joint assembly and a digit assembly;

[0029] FIG. **14** is a top perspective view of the thumb assembly of FIGS. **1A-2** in the partially curled configuration includes: (i) a motor assembly with drive gears, (ii) a base joint assembly, (iii) a proximal assembly, (iv) a medial assembly, and (v) a distal assembly;

[0030] FIG. **15** is a right side view of the thumb assembly of FIGS. **13-14**;

[0031] FIG. **16** is a left side view of the thumb assembly of FIGS. **13-14**;

[0032] FIG. **17** is a top view of the thumb assembly of FIGS. **13-14**;

[0033] FIG. **18** is a bottom view of the thumb assembly of FIGS. **13-14**;

[0034] FIG. **19** is a front or palm view of the thumb assembly of FIGS. **13-14**;

[0035] FIG. **20** is a back or top view of the thumb assembly of FIGS. **13-14**;

[0036] FIG. **21** is a top view of the thumb assembly of FIGS. **13-14** in an uncurled configuration;

[0037] FIG. **22** is a cross-sectional view of the thumb assembly taken along line **22-22** of FIG. **21**;

[0038] FIG. **23** is a cross-sectional view of the thumb assembly taken along line **23-23** of FIG. **21**;

[0039] FIG. **24** is a cross-sectional view of the thumb assembly taken along line **24-24** of FIG. **21**;

[0040] FIG. **25** is a palm view of the thumb assembly of FIGS. **13-14** in a curled configuration;

[0041] FIG. **26** is a cross-sectional view of the thumb assembly taken along line **26-26** of FIG. **25**;

[0042] FIG. **27** is a cross-sectional view of the thumb assembly taken along line **27-27** of FIG. **25**;

[0043] FIGS. **28**A-**28**D show a front or palm view of the thumb assembly of FIGS. **13-14**, wherein the housing assemblies have been omitted to better illustrate the inner linkages of said thumb assembly and angles associated therewith;

[0044] FIG. **29** is a diagram showing layers of materials contained in the housing of the thumb assembly of FIGS. **11-12**;

[0045] FIGS. **30-31** show a front or palm view of the thumb assembly of FIGS. **13-14**, wherein the housing assemblies have been omitted to better illustrate the inner linkages of said thumb assembly and lengths associated therewith;

[0046] FIG. **32** is a perspective view of the motor assembly and its gear assembly of FIGS. **13-14**;

[0047] FIG. **33** is a right side view of the motor assembly of FIG. **32**;

[0048] FIG. **34** is a palm view of the motor assembly of FIG. **32**;

[0049] FIG. **35** is a perspective view of the digit assembly of FIGS. **13-14**, and wherein said digit assembly includes a proximal assembly, a medial assembly, and a distal assembly;

[0050] FIG. **36** is a front or palm view of the digit assembly of FIGS. **13-14**;

[0051] FIG. **37** is an exploded view of the base joint assembly and the digit assembly of the thumb assembly of FIGS. **13-14**;

[0052] FIG. **38** shows a palm view of the thumb assembly of FIGS. **13-14** in a first configuration C_1, and wherein: (i) the proximal, medial, and distal assemblies are in a minimum flexion position, (ii) the medial and distal assemblies are substantially aligned in a first state, and (iii) the thumb assembly is in an uncurled and unrotated state;

[0053] FIG. **39** shows a palm view of the motor and movement assembly of the thumb assembly of FIGS. **13-14** in the first configuration C_1;

[0054] FIG. **40** is a cross-sectional view of the thumb assembly in the first configuration C_1 and taken along line **40-40** of FIG. **61**;

[0055] FIG. **41** shows a palm view of the thumb assembly of FIGS. **13-14** in a second configuration C_2, and wherein: (i) the proximal and medial assemblies are in a first partially curled state, (ii) the medial and distal assemblies are substantially aligned in the first state, and (iii) the thumb assembly is in the unrotated state;

[0056] FIG. **42** shows a palm view of the motor and movement assembly of the thumb assembly of FIGS. **13-14** in the second configuration C_2;

[0057] FIG. **43** is a cross-sectional view of the thumb assembly in the second configuration C_2 and taken along line **43-43** of FIG. **72**;

[0058] FIG. **44** shows a palm view of the thumb assembly of FIGS. **13-14** in a third configuration C_3, and wherein: (i) the proximal and medial assemblies are in a second partially curled state, (ii) the medial and distal assemblies are substantially aligned in the first state, and (iii) the thumb assembly is in the unrotated state;

[0059] FIG. **45** shows a palm view of the motor and movement assembly of the thumb assembly of FIGS. **13-14** in the third configuration C_3;

[0060] FIG. **46** shows a cross-sectional view of the thumb assembly in the third configuration C_3;

[0061] FIG. **47** shows a palm view of the thumb assembly of FIGS. **13-14** in a fourth configuration C_4, and wherein: (i) the proximal and medial assemblies are in a maximum flexion position, (ii) the medial and distal assemblies are aligned in the first state, and (iii) the thumb assembly is in the unrotated state;

[0062] FIG. **48** shows a palm view of the motor and movement assembly of the thumb assembly of FIGS. **13-14** in the fourth configuration C_4;

[0063] FIG. **49** is a cross-sectional view of the thumb assembly in the fourth configuration C_4 and taken along line **49-49** of FIG. **74**;

[0064] FIG. **50** shows a palm view of the thumb assembly of FIGS. **13-14** in a fifth configuration Cs, and wherein: (i) the proximal and medial assemblies are in the maximum flexion position, (ii) the distal assembly is in a first partially curled state, and (iii) the thumb assembly is in the unrotated state;

[0065] FIG. **51** shows a palm view of the motor and movement assembly of the thumb assembly of FIGS. **13-14** in the fifth configuration Cs;

[0066] FIG. **52** shows a palm view of the thumb assembly in the fifth configuration C_5;

[0067] FIG. **53** shows a palm view of the thumb assembly of FIGS. **13-14** in a sixth configuration C_6, and wherein: (i) the proximal and medial assemblies are in the maximum flexion position, (ii) the distal assembly is in a second partially curled state, and (iii) the thumb assembly is in the unrotated state;

[0068] FIG. **54** shows a palm view of the motor and movement assembly of the thumb assembly of FIGS. **13-14** in the sixth configuration C_6;

[0069] FIG. **55** is a cross-sectional view of the thumb assembly in the sixth configuration C_6 and taken along line **55-55** of FIG. **76**;

[0070] FIG. **56** shows a palm view of the thumb assembly of FIGS. **13-14** in a seventh configuration C_7, and wherein: (i) the proximal, medial, and distal assemblies are at a maximum flexion position, and (ii) said thumb assembly is in the fully curled state, but in the unrotated state;

[0071] FIG. **57** shows a palm view of the motor and movement assembly of the thumb assembly of FIGS. **13-14** in the seventh configuration C_7;

[0072] FIG. **58** is a cross-sectional view of the thumb assembly in the seventh configuration C_7 and taken along line **58-58** of FIG. **78**;

[0073] FIG. **59** is a schematic showing the movement assembly moving of the thumb assembly from the first configuration C_1 to the seventh configuration C_7;

[0074] FIG. **60** is a schematic showing the movement of the pivot points as the movement assembly of the thumb assembly moves from the first configuration C_1 to the seventh configuration C_7;

[0075] FIG. **61** is a top view of the thumb assembly in the first configuration C_1;

[0076] FIG. **62** is a cross-sectional view of the thumb assembly in the first configuration C_1 and taken along line **62-62** of FIG. **61**;

[0077] FIG. **63** is a top view of the thumb assembly in the first configuration C_1;

[0078] FIG. **64** is a cross-sectional view of the thumb assembly in the first configuration C_1 and taken along the **64-64** line of FIG. **63**;

[0079] FIG. **65** is a top view of the thumb assembly of FIGS. **13-14** in the first configuration C_1;

[0080] FIG. **66** is a cross-sectional view of the thumb assembly in the first configuration C_1 taken along the **66-66** line of FIG. **65**;

[0081] FIG. **67** is a cross-sectional view of the thumb assembly in the first configuration C_1 taken along the **67-67** line of FIG. **65**;

[0082] FIG. **68** is a cross-sectional view of the thumb assembly in the first configuration C_1 taken along the **68-68** line of FIG. **65**;

[0083] FIG. **69** is a back or rear view of the thumb assembly of FIGS. **13-14** in the first configuration C_1;

[0084] FIG. **70** is a cross-sectional view of the thumb assembly in the first configuration C_1 and taken along the **70-70** line of FIG. **69**;

[0085] FIG. **71** is a cross-sectional view of the thumb assembly in the first configuration C_1 and taken along the **71-71** line of FIG. **69**;

[0086] FIG. **72** is a top view of the thumb assembly of FIGS. **13-14** in the second configuration C_2;

[0087] FIG. **73** is a cross-sectional view of the thumb assembly in the second configuration C_2 and taken along **73-73** line of FIG. **72**;

[0088] FIG. **74** is a top view of the thumb assembly of FIGS. **13-14** in the fourth configuration C_4;

[0089] FIG. **75** is a cross-sectional view of the thumb assembly in the fourth configuration C_4 and taken along the **75-75** line of FIG. **74**;

[0090] FIG. **76** is a top view of the thumb assembly of FIGS. **13-14** in the sixth configuration C_6;

[0091] FIG. **77** is a cross-sectional view of the thumb assembly in the sixth configuration C_6 and taken along the **77-77** line of FIG. **76**;

[0092] FIG. **78** is a top view of the thumb assembly of FIGS. **13-14** in the seventh configuration C_7;

[0093] FIG. **79** is a cross-sectional view of the thumb assembly in the seventh configuration C_7 and taken along the **79-79** line of FIG. **78**;

[0094] FIG. **80** shows a palm view of the thumb assembly of FIGS. **13-14** in the first configuration C_1, and wherein: (i) the proximal, medial, and distal assemblies are in the minimum flexion position, (ii) the medial and distal assemblies are substantially aligned in the first state, and (iii) the thumb assembly is in the uncurled and unrotated state;

[0095] FIG. **81** shows a palm view of the motor and movement assembly of the thumb assembly of FIGS. **13-14** in the first configuration C_1;

[0096] FIG. **82** shows a cross-sectional view of the thumb assembly in the first configuration C_1;

[0097] FIG. **83** shows a palm view of the thumb assembly of FIGS. **13-14** in an eighth configuration C_8, and wherein: (i) the proximal and medial assemblies are in the third partially curled state, (ii) the proximal assembly is in contact with the first object, (iii) the medial and distal assemblies are substantially aligned in the first state, and (iv) the thumb assembly is in the unrotated state;

[0098] FIG. **84** shows a palm view of the motor and movement assembly of the thumb assembly of FIGS. **13-14** in the eighth configuration C_8;

[0099] FIG. **85** shows a cross-sectional view of the thumb assembly in the eighth configuration C_8 and taken along **85-85** line of FIG. **95**;

[0100] FIG. **86** shows a palm view of the thumb assembly of FIGS. **13-14** in a ninth configuration C_9, and wherein: (i) the proximal and medial assemblies are in the third partially curled state, (ii) the proximal assembly is in contact with the first object, (iii) the distal assembly is in the third partially curled state, and (iv) the thumb assembly is in the unrotated state;

[0101] FIG. **87** shows a palm view of the motor and movement assembly of the thumb assembly of FIGS. **13-14** in the ninth configuration C_9;

[0102] FIG. **88** shows a palm view of the thumb assembly in the ninth configuration C_9;

[0103] FIG. **89** shows a palm view of the thumb assembly of FIGS. **13-14** in a tenth configuration C_{10}, and wherein: (i) the proximal and medial assemblies are in the third partially curled state, (ii) the proximal assembly is in contact with the first object, (iii) the distal assembly is in the fourth partially curled state, and (iv) the thumb assembly is in the unrotated state;

[0104] FIG. **90** shows a palm view of the motor and movement assembly of the thumb assembly of FIGS. **13-14** in the tenth configuration C_{10};

[0105] FIG. **91** shows a palm view of the thumb assembly in the tenth configuration C_{10};

[0106] FIG. **92** shows a palm view of the thumb assembly of FIGS. **13-14** in an eleventh configuration C_{11}, and wherein: (i) the proximal and medial assemblies are in the third partially curled state, (ii) the proximal assembly is in contact with the first object, (iii) the distal assembly is in the fifth partially curled state and in contact with the second object, and (iv) the thumb assembly is in the unrotated state;

[0107] FIG. **93** shows a palm view of the motor and movement assembly of the thumb assembly of FIGS. **13-14** in the eleventh configuration C_{11} and taken along **93-93** line of FIG. **97**;

[0108] FIG. **94** shows a palm view of the thumb assembly in the eleventh configuration Cn;

[0109] FIG. **95** is a top view of the thumb assembly of FIGS. **13-14** in the eighth configuration C_8;

[0110] FIG. **96** is a cross-sectional view of the thumb assembly in the eighth configuration C_8 and taken along **96-96** line of FIG. **95**;

[0111] FIG. **97** is a top view of the thumb assembly of FIGS. **13-14** in the eleventh configuration C_{11};

[0112] FIG. **98** is a cross-sectional view of the thumb assembly in the eleventh configuration C_{11} and taken along **98-98** line of FIG. **97**;

[0113] FIG. **99** shows a palm view of the thumb assembly in the first configuration C_1, and wherein: (i) the proximal, medial, and distal assemblies are in the minimum flexion position, (ii) the medial and distal assemblies are aligned in the first state, and (iii) the thumb assembly is in the uncurled and unrotated state;

[0114] FIG. **100** shows a palm view of the motor and movement assembly of the thumb assembly of FIGS. **13-14** in the first configuration C_1;

[0115] FIG. **101** shows a palm view of the thumb assembly in the first configuration C_1;

[0116] FIG. **102** shows a palm view of the thumb assembly of FIGS. **13-14** in a twelfth configuration C_{12}, and wherein: (i) the proximal and medial assemblies are in the fourth partially curled state, (ii) the medial and distal assemblies are aligned in the first state, (iii) the distal assembly is in contact with an object, and (iv) the thumb assembly is in the unrotated state;

[0117] FIG. **103** shows a palm view of the motor and movement assembly of the thumb assembly of FIGS. **13-14** in the twelfth configuration C_{12};

[0118] FIG. **104** is a cross-sectional view of the thumb assembly in the twelfth configuration C_{12} and taken along line **104-104** of FIG. **105**;

[0119] FIG. **105** is a top side view of the thumb assembly of FIGS. **13-14** in the twelfth configuration C_{12};

[0120] FIG. **106** is a cross-sectional view of the thumb assembly in the twelfth configuration C_{12} and taken along **106-106** line of FIG. **105**;

[0121] FIG. **107** shows a palm view of the thumb assembly of FIGS. **13-14** in the first configuration C_1, and wherein: (i) the proximal, medial, and distal assemblies are in the minimum flexion position, (ii) the medial and distal assemblies are aligned in the first state, and (iii) the thumb assembly is in the uncurled and unrotated state;

[0122] FIG. **108** shows a palm view of the motor and movement assembly of the thumb assembly of FIGS. **13-14** in the first configuration C_1;

[0123] FIG. **109** shows a cross-sectional view of the thumb assembly in the first configuration C_1;

[0124] FIG. **110** shows a palm view of the thumb assembly of FIGS. **13-14** in a thirteenth configuration C_{13}, and wherein: (i) the proximal and medial assemblies are in the fifth partially curled state, (ii) the medial assembly is in contact with an object, (iii) the medial and distal assemblies are aligned in the first state, and (iv) the thumb assembly is in the unrotated state;

[0125] FIG. **111** shows a palm view of the motor and movement assembly of the thumb assembly of FIGS. **13-14** in the thirteenth configuration C_{13};

[0126] FIG. **112** is a cross-sectional view of the thumb assembly in the thirteenth configuration C_{13} and taken along line **112-112** of FIG. **116**;

[0127] FIG. **113** shows a palm view of the thumb assembly of FIGS. **13-14** in a fourteenth configuration C_{14}, and wherein: (i) the proximal and medial assemblies are in the fifth partially curled state, (ii) the medial assembly is in contact with an object, (iii) the distal assembly is in a fourth partially curled state, and (iv) the thumb assembly is in the unrotated state;

[0128] FIG. **114** shows a palm view of the motor and movement assembly of the thumb assembly of FIGS. **13-14** in the fourteenth configuration C_{14};

[0129] FIG. **115** is a cross-sectional view of the thumb assembly in the fourteenth configuration C_{14} and taken along line **115-115** of FIG. **118**;

[0130] FIG. **116** is a top view of the thumb assembly of FIGS. **13-14** in the thirteenth configuration C_{13};

[0131] FIG. **117** is a cross-sectional view of the thumb assembly in the thirteenth configuration C_{13} and taken along;

[0132] FIG. **118** is a top view of the thumb assembly in the thirteenth configuration;

[0133] FIG. **119** is a cross-sectional view of the thumb assembly in the thirteenth configuration taken along **119-119** line of FIG. **118**;

[0134] FIG. **120** shows a right side view of the thumb assembly of FIGS. **13-14** in the first configuration C_1, and wherein: (i) the proximal, medial, and distal assemblies are in the minimum flexion position, (ii) the medial and distal assemblies are substantially aligned in the first state, and (iii) the thumb assembly is in the uncurled and unrotated state;

[0135] FIG. **121** shows a right side view of the thumb assembly of FIGS. **13-14** in the fifteenth configuration C_{15}, and wherein: (i) the proximal, medial, and distal assemblies are in the minimum flexion position, (ii) the medial and distal assemblies are aligned in the first state, and (iii) the thumb assembly is in a first partially rotated state, but remains in the uncurled state;

[0136] FIG. **122** shows a right side view of the thumb assembly of FIGS. **13-14** in the sixteenth configuration C_{16}, and wherein: (i) the proximal, medial, and distal assemblies are in the minimum flexion position, (ii) the medial and distal assemblies are substantially aligned in the first state, and (iii) the thumb assembly is in a second partially rotated state, but remains in the uncurled state;

[0137] FIG. **123** shows a right side view of the thumb assembly of FIGS. **13-14** in the seventeenth configuration

C_{17}, and wherein: (i) the proximal, medial, and distal assemblies are in the minimum flexion position, (ii) the medial and distal assemblies are substantially aligned in the first state, and (iii) the thumb assembly is in a fully rotated state, but remains in the uncurled state;

[0138] FIG. **124** is a top view of the thumb assembly of FIGS. **13-14** and **120** in the fifteenth configuration C_1;

[0139] FIG. **125** is a top view of the thumb assembly of FIGS. **13-14** and **121** in the fifteenth configuration C_{15};

[0140] FIG. **126** is a top view of the thumb assembly of FIGS. **13-14** and **122** in the sixteenth configuration C_{16};

[0141] FIG. **127** is a top view of the thumb assembly of FIGS. **13-14** and **123** in the seventeenth configuration C_{17};

[0142] FIG. **128** is a perspective view of the thumb assembly of FIGS. **13-14** and **120** in the fifteenth configuration C_1;

[0143] FIG. **129** is a perspective view of the thumb assembly of FIGS. **13-14** and **121** in the fifteenth configuration C_{15};

[0144] FIG. **130** is a perspective view of the thumb assembly of FIGS. **13-14** and **122** in the sixteenth configuration C_{16}; and

[0145] FIG. **131** is a perspective view of the thumb assembly of FIGS. **13-14** and **123** in the seventeenth configuration C_{17}.

DETAILED DESCRIPTION

[0146] In the following detailed description, numerous specific details are set forth by way of examples in order to provide a thorough understanding of the relevant teachings. However, it should be apparent to those skilled in the art that the present teachings may be practiced without such details. In other instances, well-known methods, procedures, components, and/or circuitry have been described at a relatively high-level, without detail, in order to avoid unnecessarily obscuring aspects of the present disclosure.

[0147] While this disclosure includes several embodiments in many different forms, there is shown in the drawings and will herein be described in detail embodiments with the understanding that the present disclosure is to be considered as an exemplification of the principles of the disclosed methods and systems, and is not intended to limit the broad aspects of the disclosed concepts to the embodiments illustrated. As will be realized, the disclosed methods and systems are capable of other and different configurations and several details are capable of being modified all without departing from the scope of the disclosed methods and systems. For example, one or more of the following embodiments, in part or whole, may be combined consistent with the disclosed methods and systems. As such, one or more steps from the flow charts or components in the Figures may be selectively omitted and/or combined consistent with the disclosed methods and systems. Additionally, one or more steps from the flow charts may be performed in a different order. Accordingly, the drawings, flow charts and detailed description are to be regarded as illustrative in nature, not restrictive or limiting.

A. Introduction

[0148] The mechanical end effector **10** disclosed in this Application is designed to be a component within a robot system, potentially a versatile humanoid robot. Enabling such a robot system to execute general human tasks poses a challenge due to the vast array of potential positions, locations, and states said robots could occupy at any given time in a challenging environment. The multitude of these permutations can be minimized by training the robot system through various methods such as: (i) imitation learning or teleoperation, (ii) supervised learning, (iii) unsupervised learning, (iv) reinforcement learning, (v) inverse reinforcement learning, (vi) regression techniques, or (vii) other established methodologies. To further streamline the vast array of possible positions, locations, and states, reduce manufacturing steps, complexities and costs, minimize components within the robot system, enhance component modularity, and achieve several other advantages that would be apparent to those skilled in the field, two or more components of the end effector **10** can be either: (i) linked, or (ii) fixed to one another. When two or more components are linked or fused, movement of one component results in movement in another component. In contrast to conventional end effectors that fuse the medial and distal assemblies to one another, the disclosed thumb assembly **40** allows for: (i) some independent movement of the medial assembly **470** in relation to the distal assembly **480**, and (ii) certain movement of the medial assembly **470** to result in movement of the distal assembly **480**. Such linking allows the thumb assembly **40** to become underactuated, that is, to retain its ability to flex, curl, or rotate around an object while eliminating the necessity for multiple actuators, motors, or effectors for each movement of the thumb assembly **40**. Indeed, the disclosed thumb assembly **40** includes only two motors that drive linkages that provide four degrees of freedom (DoF). Thus, the end effector **10** has at least twelve DoF, and in a preferred configuration sixteen (16) DoF.

[0149] While the disclosed thumb assembly **40** in the end effector **10** utilizes a single biasing member (e.g., spring), the thumb assembly **40** utilizes a direct drive linkage system to eliminate the need to use more than one (e.g., multiple) biasing members (e.g., springs) to force the thumb assembly **40** to remain in a predefined position (e.g., open, uncurled, or neutral). Eliminating the need to use multiple biasing members (e.g., springs) to force the thumb assembly **40** to remain open, uncurled, or in a neutral position. Eliminating the use of multiple biasing members for this purpose provides a significant benefit over conventional end effectors because it: (i) removes the need for the motor assembly to overcome a significant biasing force applied by the biasing members to move the thumb assembly **40**, (ii) increases durability, robustness, and life of the end effector **10** due to the fact that said biasing members can rapidly degrade over time, and (iii) makes the control of the digit assembly simpler as the same force is exerted on the housing frame regardless of the direction (i.e., towards the palm or away from the palm) the digit assembly is moving.

[0150] Additionally, the disclosed direct drive linkages include components that nest within one another. The use of nesting components is beneficial over a conventional thumb assembly of end effectors because each link is supported by at least one coupling point on either side of a plane extending through the center of the thumb assembly **40**. In other words, each link in the disclosed thumb assembly **40** is coupled on multiple sides, not simply coupled on a single side, which increases the durability of the assembly.

[0151] The disclosed thumb assembly **40** in the end effector **10** has a proximal assembly **450** that includes: (i) one component that is directly tied to the movement of the motor, and (ii) one component that is not directly tied to the movement of the motor. For example, the movement of the proximal drive link assembly is directly tied to the movement of the motor, while the proximal housing **452** is not directly tied to the movement of the motor. In fact, the proximal assembly **450** utilizes bearings to allow slippage between the motor and at least the proximal housing **452** when an extent of the proximal assembly **450** has come into contact with a resistance point or surface. This configuration is beneficial over conventional end effectors because it allows a single motor to drive the thumb assembly **40**, while allowing specific components within the proximal assembly **450** to stop moving even though the motor still drives other components.

[0152] Unlike conventional end effectors with thumb assemblies, the end effector **10** disclosed in this Application includes two motors that are positioned within the palm **62** of the end effector **10**, wherein: (i) both motors are designed to interact with a single gear assembly, (ii) the first motor is configured to control the digit assembly's adduction/abduction and the second motor is configured to control the digit assembly's flexion/extension. This configuration allows for a compact package that is capable of controlling multiple movements of the thumb assembly **40**. Other benefits of the movement assembly are disclosed below in greater detail and/or may be obvious to one of skill in the art.

[0153] While the structural configuration of the thumb assembly **40** will be discussed in greater detail below, it should be understood that the thumb assembly **40** is configured to be a separate component of the end effector **10** that is modular and removably coupled to a frame **61**.**2** of the end effector **10**. As such, the thumb assembly **40** is swappable (and in certain embodiments hot-swappable) with another thumb assembly **40**. The separate, modular, and swappable nature of the thumb assembly **40** means that: (i) pulleys, articulation cables, and pneumatic or hydraulic mechanisms may be omitted from the end effector **10**, and (ii) components of the end effector **10** are not located in the wrist, lower arm, or generally outside of the thumb assembly **40**. In other words, a majority of the motors, PCBs, encoders and other electronic components needed to move the thumb assembly **40** are fully contained within said thumb assembly **40** and are not distributed throughout the end effector **10** and/or robot. This containment aspect is desirable because it increases serviceability and thus decreases the cost of ownership and operation of the robot. In other embodiments, all components (e.g., motors, PCBs, encoders, etc.) needed to move the thumb assembly **40** may be fully contained within said thumb assembly **40**. In other words, the palm **62** of the end effector **10** and/or other components of the robot may not contain any components needed to move the thumb assembly **40**.

[0154] Finally, the end effector **10** disclosed herein may lack several components typically found in conventional end effectors. For example, the disclosed end effector **10** (including each finger assembly **22***a*-**22***d* and the thumb assembly **40**) lacks pulleys, articulation cables, more than two motors used in connection with the thumb assembly **40**, and force sensors, and other components typically found in conventional end effectors. Eliminating these components reduces cost and complexity, while increasing modularity, serviceability, and durability. Other benefits of the disclosed end effector **10** and its various assemblies and components should be apparent to one of skill in the art based on this disclosure and the accompanying figures.

B. Humanoid Robot

[0155] The humanoid robot **5** is designed to have a substantial similarities in form factor and anatomy to human beings including many of the same major appendages that human beings have. The humanoid robot **5** includes an upper region **6**, a lower region **7** spaced apart from the upper region **6**, and a central region **8** interconnecting the upper region **6** and the lower region **7**. The humanoid robot **5** is shown in FIG. **1**A in an upright, standing position P**1** where a pair of feet **132***a*, **132***b* of the lower region **7** are standing on a floor or ground surface G such that the lower region **7** supports the upper region **6** and the central region **8** above the floor G.

[0156] The upper region **200** includes the following parts: (a) a head and neck assembly **102**, (b) a torso **104**, (c) left and right shoulders **106***a*, **106***b*, (d) and left and right arm assemblies **108***a*, **108***b* each including: (c) a humerus **110***a*, **110***b*, (f) a forearm **112***a*, **112***b*, (g) a wrist **114***a*, **114***b*, and (h) hand or end effector **10** (e.g., **11***a*, **11***b*). The lower region **7** includes left and right leg assemblies **120***a*, **120***b* each including: (a) a thigh **124***a*, **124***b*, (b) a knee **126***a*, **126***b*, (c) a shin **128***a*, **128***b*, (d) an ankle **130***a*, **130***b*, and (c) a foot **132***a*, **132***b*. The central region **8** is located generally in, or provides, a pelvis region of the humanoid robot **5**. Each of the components of the upper region **6** and the lower region **7** noted above includes at least one actuator configured to move the components relative to one another. The central region **8** is also configured to allow movement of the upper and lower regions **6**, **7** relative to one another in a three-dimensional manner.

C. End Effector

[0157] With reference, for example, to FIGS. **1**A-**12**, the end effector **10** includes: (i) a set of finger assemblies **20** with at least one finger assembly **22***n* (as shown, the set of finger assemblies **20** includes four finger assemblies **22***a*, **22***b*, **22***c*, **22***d*), (ii) a thumb assembly **40**, (iii) a housing assembly **60**, and (iv) electronics **80** that are configured to control each finger assembly **22***n* of the set of finger assemblies **20** and the thumb assembly **40**. As shown in the Figures, the housing assembly **60** is configured to: (i) encase and protect the electronics **80**, and (ii) securely locate each of the finger assemblies **22***a*-**22***d* and the thumb assembly **40** in a particular position relative to each other and the housing assembly **60**. The housing assembly **60** may be covered by a glove and can have: (i) a palm region **62**, (ii) a back region **64**, (iii) left and right sides **66**, **68**, and (iv) a front region **70**. Additionally. as discussed in great detail below, said housing assembly **60** is comprised of: (i) a palm housing **60.1**, (ii) a back housing **60.2**, (iii) a base joint or carpometacarpal joint housing assembly **436**, a proximal housing assembly **452**, a medial housing assembly **472**, and a distal housing assembly **482**. It should be understood that the housing assembly **60** may include additional or fewer components or assemblies. It should further be understood that in alternative embodiments, the end effector **10** may include a single finger, two fingers, three fingers, or five fingers. In a further alternative, the end effector **10** may not include a single finger assembly **22***a*-**22***d*, but instead may include a plurality of thumb assemblies **40**.

[0158] As shown in FIGS. 12-26 and 29, said housing assembly 60 may include multiple components that are made from different materials, may include multiple layers that are made from different materials, and/or may be made from materials that have different rigidities, densities, C/D ratios, durabilities, fabrication methods, and the like. As such, the housing assembly 60 may incorporate a gradient of materials with varying rigidities, densities, and durabilities from the interior to the exterior. In some aspects, the end effector frame 61.2 may be made from a first material with a first rigidity, the exterior top housing 61.8 may be made from a second material with a second rigidity, the interior bottom housing 61.10 may be made from a third material with a third rigidity, and wherein said first rigidity may be greater than the second rigidity, and the second rigidity may be greater than the third rigidity. For example, the end effector frame 61.2 may be made from rigid metal, the exterior top housing 61.8 may be made from rigid plastic, and the interior bottom housing 61.10 may be made from deformable silicon or soft plastic. In another example, the innermost layer could be made of a rigid metal alloy, transitioning to increasingly flexible polymer composites in the middle layers, and ending with a soft, impact-absorbing elastomer on the outermost layer. This gradient structure may provide enhanced protection for internal components while maintaining flexibility and grip on the exterior. It should be understood that these are examples of possible materials and configurations and are not intended to be limiting in any manner. In some cases, the exterior or skin of the end effector 10 may be as rigid as the internal link assemblies of the housing assembly 60, wherein the housing and the internal link assemblies may both be made from a durable and hard plastic. In other embodiments, the exterior or skin of the end effector 10 may be more rigid than the internal link assemblies of the housing assembly 60.

[0159] As described above in an alternative embodiment and as shown in FIG. 29, the interior bottom housing 61.10 may include a plurality of layers 61.20, wherein a first interior layer 61.20.2 is made from a first material having a first rigidity and a second exterior layer 61.20.4 is made from a second material having a second rigidity. In this example, the first material may be rigid plastic or metal, while the second material is deformable silicon, soft plastic, or deformable textile or fabric. As such, the thumb assembly 40 is configured to be covered by a textile covering (e.g., glove). In other examples, the plurality of layers 61.20 may have three layers, wherein the first layer 61.20.2 is rigid to provide protection for the internal components, a second layer 61.20.4 is less rigid than the first layer 61.20.2 to enable the end effector 10 to pick up delicate items, and a third layer 61.20.6 is designed to protect the second layer 61.20.4. In this example, the first layer 61.20.2 may be made from durable plastic or metal, the second layer 61.20.4 may be made from deformable thermoplastic, and the third layer 61.20.6 may be made from textile, cloth, or fabric (e.g., glove). In other embodiments, the third layer 61.20.6 may be a thin, replaceable grip layer that is comprised of high-friction materials like silicone or specialized polymers, and could be easily swapped out when worn or for different applications.

[0160] In some embodiments, the last or third layer 61.20.6 may be replaceably coupled to the end effector 10 using: magnetic fasteners, hook-and-loop fasteners (e.g., Velcro), interlocking tabs and slots molded into the layer, spring-loaded ball detents that snap into corresponding recesses, dovetail joints allowing the layer to slide on and off, a friction fit when the layer is pressed on, bayonet mounts with tabs that twist and lock into place, clasps or latches, snaps, buttons, removable fasteners, or push-pins. The coupling mechanism may be designed to allow replacement of individual sections or panels of the layer, rather than the entire layer at once. This modular approach may enable replacing only worn or damaged areas. The layer may incorporate alignment features such as pins, notches or asymmetric shapes, or self-aligning connectors or pogo pins to simplify electrical connections between layers. In some aspects, the layer may include embedded RFID tags or QR codes to allow automated verification of proper installation and tracking of replacement history. Some embodiments may use a combination of mechanical and electrical coupling methods to provide both structural attachment and data/power transfer between layers. This replaceable or modular nature is particularly beneficial in industrial or high-use settings where the end effector 10 may be subjected to frequent wear and tear. It allows for quick and cost-effective refurbishment of the end effector's surface without the need to replace the entire housing 61.10. This can be especially useful in adapting the end effector 10 for different tasks or environments by swapping out the outer layer for one with different properties (e.g., higher friction, chemical resistance, or electrostatic discharge protection). For example, the replaceable layers may be designed to be replaced when damaged or at pre-defined intervals (e.g., 1 week, 1 month, 6 months, 1 year, 5 years, or any interval between 1 day and 10 years).

[0161] In certain configurations and as discussed below, the plurality of layers 61.20 may have any number of layers, wherein layer 61.20.8 represents layer number four through the nth layer. The concept of extending this layered approach to include additional layers (up to an nth layer) suggests the potential for even more specialized designs. These could incorporate features such as embedded sensors for improved tactile feedback, layers with specific thermal properties for handling temperature-sensitive objects, or layers with electromagnetic shielding for use in sensitive electronic environments. The housing assembly 60 may incorporate smart materials that can change their rigidity or other properties in response to external stimuli. For example, the exterior housing could use shape memory polymers that become more flexible when heated above a certain temperature, allowing for improved adaptability in different operating environments. Alternatively, magnetorheological materials could be used in specific areas to allow for real-time adjustments in rigidity based on applied magnetic fields. The layered structure may include integrated cooling channels or heat-dissipating materials to manage thermal loads during operation. This could involve the use of phase-change materials or microfluidic channels embedded within specific layers to regulate temperature and prevent overheating of sensitive components. However, in other embodiments, the end effector 10 may lack some, if not all, of the above described embedded sensors.

[0162] Examples of materials that may be used in the end effector 10 include, but are not limited to, metal (e.g., aluminum, stainless steel, titanium alloys, magnesium alloys, copper alloys, nickel-based alloys), carbon fiber composites, glass fiber composites, basalt fiber composites, Kevlar® composites, polycarbonate, acrylic (PMMA), acrylonitrile butadiene styrene (ABS), nylon, polyoxymethylene (POM), polyether ether ketone (PEEK), polyetherimide (PEI), polyphenylene sulfide (PPS), polytetrafluoroethylene (PTFE), polypropylene (PP), polyethylene (PE), high-density polyethylene (HDPE), thermoplastic polyurethane (TPU), polyamide-imide (PAI), other plastic (e.g., may include a polymer composition), rubber (e.g., nitrile rubber, EPDM), silicone, polyurethane elastomers, ceramic materials (e.g., alumina, zirconia), a combination of these materials, and/or any other suitable material.

[0163] The housing assembly **60** and other components of the end effector **10** can be manufactured using a range of advanced fabrication techniques designed to optimize performance, durability, and functionality across various robotic applications. Techniques such as injection molding, additive manufacturing (3D printing), subtractive manufacturing (e.g., CNC machining), overmolding, compression molding, investment casting, powder metallurgy, electroforming, or a combination thereof. These manufacturing techniques enable the integration of advanced internal features that enhance the end effector's overall performance. For instance, internal channels can be incorporated for wiring or cooling purposes, improving thermal management and electrical routing within the housing. Weight reduction can be achieved through optimized internal structures, such as lattices or honeycomb patterns, which maintain structural integrity while minimizing mass. Sensors or electronic components can be embedded directly into the housing during fabrication, eliminating the need for additional assembly steps and improving the end effector's responsiveness. Additionally, self-lubricating surfaces or wear-resistant coatings can be integrated to reduce friction and extend the component's lifespan. Vibration-damping structures or materials can be included to improve stability during operation, particularly in high-precision tasks. The incorporation of living hinges or flexible sections within otherwise rigid components can further enhance the device's adaptability and longevity. Beyond structural enhancements, these manufacturing methods can support the integration of features that improve the end effector's resistance to environmental factors. Internal shielding for electromagnetic interference (EMI) protection can be added to safeguard sensitive electronics, while advanced cooling solutions or heat-dissipating materials can be used to manage temperature fluctuations. The use of smart materials or shape memory alloys can enable adaptive responses to environmental changes, enhancing the end effector's functionality in dynamic settings. Weight reduction, strength, and durability can be further optimized through the use of tailored material properties, such as composites or lightweight metals.

[0164] FIG. **6** shows a finger side view of the end effector **10**, wherein a surface plane P_{SU} has been added to illustrate contact points between the palm side of the housing assembly **60** and a flat or planar surface. For example, the surface plane P_{SU} may represent the outermost surface formed by a tote designed to carry parts or components of a car. As shown in this Figure, two main contact points may be formed between the surface and the end effector **10**, wherein a first contact point P_{C1} may be formed near the tip of the middle finger **22***b* and a second contact point P_{C2} may be formed near the base of the palm. The greatest distance D_{SU} between said surface plane P_{SU} and the housing assembly **60** formed near the knuckle assembly may be less than 10 mm, and in some cases may be less than 5 mm or even less than 1 mm. As shown in this Figure, having the palm or inner surface of the end effector **10** is slightly concave. In other embodiments, the palm or inner surface of the end effector **10** may be flat or nearly flat. This may help maximize the contact surface area between the end effector **10** and the surface plane P_{SU}. This design may simplify approach angles and reduce the need to perform complex grasping movements with the wrist. In some aspects, the flat or nearly flat palm surface **61.2.2** may allow for more stable and secure grasping of objects. Additionally, this configuration may enable the end effector **10** to more easily slide objects along flat surfaces during manipulation tasks.

[0165] As best shown in FIGS. **3-4**, **9**, and **11**, the housing assembly **60** includes a substantially smooth top or back surface **61.2.4** or S_B and a rough or non-smooth bottom or palm surface **61.2.2** or S_P. The rough or non-smooth palm surface **61.2.2** or S_P is created by adding a plurality of contact areas **61.4**. In other words, the entire palm surface **61.2.2** or S_P is not rough or non-smooth. Said plurality of contact areas **61.4** is designed to increase the end effector's **10** ability to grasp and hold an object. Specifically, the plurality of contact areas **61.4** are comprised of distinct regions **61.4.2-61.4.16** that include multiple bumps or projections **61.6**. Said regions **61.4.2-61.4.16** are formed on the palm **62**, each assembly (i.e., proximal, medial, and distal) contained within each thumb assembly **40**, and each assembly (i.e., proximal **450**, medial **470**, and distal **480**) contained within the thumb assembly **40**. For example, the palm **62** may have one large contact region **61.4.2**, the proximal assemblies of the fingers **22***a*-**22***d* may include two contact regions **61.4.4**, **61.4.6**, the medial assemblies of the fingers **22***a*-**22***d* may include one contact region **61.4.8**, the distal assemblies of the fingers **22***a*-**22***d* may also include one contact region **61.4.10**, the proximal assembly **450** of the thumb **40** may include one contact region **61.4.12**; the medial assembly **470** of the thumb **40** may include one contact region **61.4.14**, the distal assembly **480** of the thumb **40** may also include one contact region **61.4.16**. It should be understood that in other embodiments, the plurality of contact areas **61.4** may be omitted, or the number of regions contained in the plurality of contact areas **61.4** may be increased (e.g., between 18 and 100) or decreased (e.g., between 1 and 16).

[0166] In alternative embodiments, the number or density of bumps or projections **61.6** within each region may be increased or decreased. For example, areas that experience more frequent contact during grasping could have a higher density of projections compared to less-used areas. Further, the bumps or projections **61.6** may have different shapes within a single region or area or may be different between regions or areas. For example, said bumps or projections **61.6** could be conical, pyramidal, hemispherical, or have more complex geometries or be arranged in specific patterns, such as concentric circles or spirals, to optimize gripping for particular object shapes or sizes commonly encountered in the robot's intended applications to enhance gripping capabilities. The height of the bumps or projections **61.6** may be 0.01 mm to 2 mm, and preferably between 0.25 mm and 0.75 mm. Also, the height of the projections **61.6** may vary within a single contact region, creating a gradient effect that can adapt to objects of different sizes and textures. Moreover, the contact areas may incorporate: (i) active elements such as micro-pneumatic or micro-hydraulic systems that can dynamically adjust the height or stiffness of the projections based on feedback during grasping, or electroadhesive materials to allow for electrically-controlled adhesion to supplement mechanical gripping.

[0167] As best shown in FIGS. **27** and **28**, the housing assembly **60** of the thumb assembly **40** features a unique cross-sectional shape resembling an obround or discorectangle. This design choice for the outer surfaces **61**.**8**.**2**, **61**.**10**.**2** of the exterior top housing **61**.**8** and interior bottom housing **61**.**10** serves dual purposes. The rounded edges minimize the risk of unintended contact with surrounding objects, enhancing the thumb assembly's **40** ability to navigate complex environments. Simultaneously, the substantially flat surfaces optimize the thumb assembly's **40** grasping capabilities by maximizing the contact area with objects. When compared to the finger assemblies **22***a*-**22***d*, the thumb assembly **40** exhibits distinct characteristics that enhance its functionality. It possesses a larger contact surface with a predominantly flat configuration, interrupted only by strategically placed bumps or projections **61**.**6**. These features contribute to improved grip and tactile sensitivity. Additionally, the thumb assembly's **40** proportions differ from those of the fingers **22***a*-**22***d*, with its width more closely approximating its height. This results in a more rounded profile for the thumb assembly **40**, contrasting with the more elongated, oval shape of the fingers **22***a*-**22***d*. While alternative configurations could theoretically be implemented by swapping the designs of the thumb assembly **40** and finger assemblies **22***a*-**22***d*, such modifications could compromise the thumb assembly's **40** effectiveness. The current design maximizes the thumb assembly's contact surface area, which is helpful for its role in grasping and manipulating objects. Reducing this surface area by adopting a more finger-like configuration may diminish the thumb assembly's **40** utility in performing precise and powerful grips.

[0168] With reference, for example, to FIGS. **1**A-**13**, the end effector **10** comprises a thumb assembly **40**. The thumb assembly **40** is removably connected to the palm surface **61**.**2**.**2** of the end effector frame **61**.**2** using elongated fasteners and is replaceable (and in some embodiments, it may be hot-swappable with a replacement thumb assembly **40**). The replaceable aspect of the thumb assembly **40** eliminates the need for various structural elements, such as synthetic tendons, mechanical or articulation cables, pulleys, pneumatic or hydraulic cables, and other components that extend from the lower arm or wrist to the medial **470** or distal **480** sections of the thumb assembly **40**. This configuration ensures that at least a majority, if not all, of the components such as linkages, motors, PCBs, encoders, and other elements required to actuate the thumb assembly **40** are self-contained within the palm region **62** and/or the thumb assembly **40** and are not spread throughout the robot system. This setup is advantageous as it enhances serviceability, consequently reducing the overall cost of ownership and usage.

[0169] As shown in FIGS. **12** and **18**, the thumb motor plane P_{TM} is offset by an angle gamma γ from line L_1, wherein: (i) line L_1 is perpendicular to the sagittal plane P_S or the middle finger plane P_{22b} and intersects with the center point of the knuckle assembly of the middle finger **22***b*, and (ii) the angle gamma γ is usually at least 1 degree, preferably between 2 degrees and 12 degrees, and most preferably between 4 degrees and 6 degrees, and likely less than 16 degrees. In light of this configuration, the first and second motor shaft axes A_{MS1}, A_{MS2} are also offset by an angle gamma γ from line L_1, wherein: (i) line L_1 is perpendicular to the sagittal plane P_S or the middle finger plane P_{22b} and intersects with the center point of the knuckle assembly of the middle finger **22***b*, and (ii) the angle gamma y is usually at least 1 degree, preferably between 2 degrees and 12 degrees, and most preferably between 4 degrees and 6 degrees, and likely less than 16 degrees. Thus, the first and second motor shaft axes A_{MS1}, A_{MS2} are non-parallel with the sagittal plane P_S; thus, the first motor shaft axes A_{MS1} is oriented at a first acute angle relative to the sagittal plane P_S, and the second motor shaft axes A_{MS2} is oriented at a second acute angle relative to the sagittal plane P_S, and wherein the first acute angle is approximately equal to the second acute angle.

[0170] With reference, for example, to FIGS. **1**A, **3**, **4**, **9**, **11**, the end effector **10** comprises four finger assemblies **22***a*-**22***d* that are removably connected to the back surface **61**.**2**.**4** of the end effector frame **61**.**2** using elongated fasteners and are configured to operate independent of one another. As shown in the figures, each finger assembly **22***a*-**22***d* of the plurality of finger assemblies **22***a*-**22***d* includes a single finger motor assembly **210** and a metacarpophalangeal joint MCP, a proximal finger interphalangeal joint PIP, and a distal finger interphalangeal joint DIP. Additionally, each finger assembly **22***a*-**22***d* includes a proximal assembly **250**, a medial assembly **270**, and a distal assembly **280**. In some embodiments, the end effector **10** may include more or fewer than four finger assemblies. The finger assemblies **22***a*-**22***d* may be configured identically, which may allow for reducing the number of distinct components used to manufacture the finger assemblies **22***a*-**22***d*, and may enhance modularity, potentially reducing expense. The modular nature of the finger assemblies **22***a*-**22***d* may enable them to be easily replaceable and may enable hot-swapping of the finger assemblies in some cases. The modular and replaceable aspect of the finger assemblies **22***a*-**22***d* may eliminate the use of various structural elements, such as synthetic tendons or articulation cables, pulleys, pneumatic or hydraulic cables, and other components that extend from the lower arm or wrist to the medial or distal sections of the finger assemblies **20**. This configuration may allow components such as linkages, motors, PCBs, encoders, and other elements used to actuate each finger assembly **22***a*-**22***d* to be self-contained within the palm **62** and/or within each finger assembly **22***a*-**22***d* and not spread throughout the robot system. This setup may enhance serviceability, potentially reducing the overall cost of ownership and usage.

[0171] In other embodiments, it should be understood that finger assemblies **22***a*-**22***d* may not be identical. Instead, there may be two pairs of finger assemblies, wherein the finger assemblies contained in said pairs of finger assemblies are identical. In other words, there may be two unique types of finger assemblies contained in said end effector **10**, wherein there are two finger assemblies of a first type and two finger assemblies of a second type. For example, the pointer finger **22***a* and the small finger **22***d* may be the first type, while the middle finger **22***b* and the ring finger **22***c* may be the second type (while the middle and ring **22***b*, **22***c* are different from the pointer and small **22***a*, **22***d*). In another example, the pointer finger **22***a* and the middle finger **22***b* may be the first type, while the ring finger **22***c* and the small finger **22***d* may be the second type (while the ring and small **22***c*, **22***d* are different from the pointer and middle **22***a*, **22***b*).

In an additional embodiment, there may be two unique types of finger assemblies contained in said end effector **10**, wherein there are three finger assemblies of a first type and one finger assembly of a second type. For example, the pointer, middle, and ring fingers **22***a*-**22***c* may be of the first type and the small finger **22***d* may be of the second type. In another embodiment, there may be three unique types of finger assemblies contained in said end effector **10**, wherein there are two finger assemblies of a first type, one finger assembly of a second type, and one finger assembly of a third type. For example, the middle and ring fingers **22***b*, **22***c* may be the first type, the pointer finger **22***a* may be of the second type to allow for abduction, and the small finger may be of the third type **22***d* due to its size. In a further embodiment, all finger assemblies **22***a*-**22***d* may be unique. Finally, it should be understood that other combinations of finger assembly types are contemplated by this application, and the above examples are not intended to be limiting.

[0172] With reference, for example, to FIGS. **9**-**10**, each finger assembly **22***a*-**22***d* may be connected to the back surface **61**.**2**.**4** of the end effector frame **61**.**2**. Thus, the overall location of the finger assemblies **22***a*-**22***d* cannot move in the Y-Z plane relative to the frame **61**.**2**. Also, the finger assemblies **22***a*-**22***d* may be connected to the end effector frame **61**.**2** in a manner that ensures that their tips are not aligned with one another. In other words, each finger assembly **22***a*-**22***d* is: (i) angularly offset and horizontally offset to at least one other finger assembly **22***a*-**22***d* in the X-Y plane, and (ii) vertically offset to at least one other finger assembly **22***a*-**22***d* in the X-Z plane. This configuration of finger assemblies **22***a*-**22***d* enables each finger assembly **22***n* of the four finger assemblies **22***a*-**22***d* to be angularly offset along the X-Y plane and within the Y-Z plane with respect to every other finger assembly **22***n* of the four finger assemblies **22***a*-**22***d*. The fixed position of the finger assemblies **22***a*-**22***d* may reduce the complexities of building, using, maintaining, and repairing the end effector **10**.

[0173] As shown in FIG. **12**, the middle or third finger assembly **22***b* is positioned such that its sagittal plane P_S is oriented vertically on the page. Based on the position of the middle or third finger assembly **22***b*, it can be seen that the center (i.e., C_{22a}, C_{22c}, C_{22d}) of a knuckle assembly **230** of each of the pointer, ring, and small fingers **22***a*, **22***c*, and **22***d* are positioned: (i) slightly rearward from the line L_1 and the center C_{22b} of the knuckle assembly **230** of the middle finger **22***b* (see FIG. **12**), and (ii) are angled relative to the center C22*b* of the knuckle assembly **230** of the middle finger **22***b* (see FIG. **10**). This configuration also causes the fasteners (e.g., **61**.**30***a*-**61**.**30***d*, if these are the fasteners) that removably connect the finger assemblies **22***a*-**22***d* at respective points to the end effector frame **61**.**2** to be not co-linear. At best, two of the respective connection points may be co-linear, but all four points are not co-linear. However, all four respective connection points are aligned in the same Y-Z plane.

[0174] Exemplary positional relationships between components of a thumb assembly **40** shown in FIG. **20** are listed in Table 1. It should be understood that the dimensions, angles, ratios, and other values that can be derived therefrom that are disclosed in the figures and Tables 1-3 are important to ensure that the end effector **10** can move, grasp objects, and be used in the desired robot system. As such, the structures, features, dimensions, angles, ratios, and other values that can be derived therefrom of non-end effectors for robots and non-linkage based end effectors cannot be simply adopted or implemented into an end effector **10** without careful analysis and verification of the complex realities of designing, testing, manufacturing, training, and using the robot system with an end effector **10**. Theoretical designs that attempt to implement such modifications from non-end effectors for robots and non-linkage based end effectors are insufficient (and in some instances, woefully insufficient) because they amount to mere design exercises that are not tethered to the complex realities of successfully designing, testing, manufacturing, training, and using the robot system with an end effector **10**.

C. Thumb Assembly

[0175] With reference, for example, to FIGS. **3**-**33**, the thumb assembly **40** of the end effector **10** is comprised of: (i) a motor assembly **410**, (ii) a base joint assembly **430**, (iii) a proximal assembly **450**, (iv) a medial assembly **470**, and (v) a distal assembly **480**. Each of the base joint assembly **430**, the proximal assembly **450**, the medial assembly **470**, and the distal assembly **480** includes internal linkages (in combination, an internal linkage assembly) that can operate together to move the thumb assembly **40**. Each of these assemblies will be discussed in great detail below; however, additional information about said assemblies may be contained within U.S. Provisional Patent Applications Nos. 63/614,499, 63/617,762, 63/561,315, 63/573,226, 63/615,766, 63/620,633, all of which are incorporated herein by reference for any purpose.

a. Motor Assembly

[0176] As illustrated in FIGS. **9**, **10**, **12**, and **25**, the motor assembly **410** is designed to be releasably coupled to the palm surface **61**.**2**.**2** of the housing end effector frame **61**.**2**. This modular design allows for case of maintenance, replacement, and customization of the motor assembly **410** based on specific application requirements. The motor assembly **410** comprises the following components: (i) a first motor **412**, (ii) a first controller **414**, (iii) a first motor gear **416**, (iv) a second motor **418**, (v) a second controller **420**, and (vi) a second motor gear **422**. The first motor **412** and the second motor **418** are responsible for driving various degrees of freedom within the end effector **10**, enabling precise and dynamic control of the robotic hand's movements. These motors can be selected from a variety of types, including but not limited to: slotless brushless direct current (BLDC) motors, brushed DC motors, stepper motors, switched reluctance motors, permanent magnet synchronous motors, and servo motors. Each type of motor offers distinct advantages based on application needs, such as high torque output, precise positioning, or energy efficiency. It should be noted that the first motor **412** and the second motor **418** may either be identical in type and specifications or differ based on the specific functional requirements of the end effector **10**. In an example where the motors are different, the first motor **412** controlling flexion/extension could be a high-torque brushless DC motor, while the second motor **418** for abduction/adduction could be a stepper motor for precise positioning. Variations between the motors can include, but are not limited to, different torque outputs, transmission ratios, gear types, end stop configurations, or other operational characteristics. This flexibility allows for a highly customizable motor assembly **410** capable of accommodating a wide range of tasks and environments. The inclusion of first and second controllers, **414** and **420** respectively, ensures that the motors can be individually managed and optimized for performance. These controllers are configured to handle motor feedback, control signals, and power distribution, thereby enhancing the overall responsiveness and efficiency of the motor assembly **410**. Furthermore, the integration of the motor gears **416** and **422** allows for appropriate torque conversion and mechanical advantage, ensuring that the end effector **10** operates smoothly and with the necessary precision.

[0177] As illustrated in FIGS. **9-18** and **28**A-**31**B, the motor assembly **410** for the thumb assembly **40** is specifically designed to include only two motors, namely the first motor **412** and the second motor **418**. By restricting the number of motors to two, the end effector **10** adopts an underactuated configuration. In practical terms, this means that the thumb assembly **40** comprises four joints or degrees of freedom (DoF), with each of these four joints being controlled by only two motors. Breaking down the motor functionality further, the first motor **412** is responsible for controlling three degrees of freedom associated with flexion and extension of the thumb assembly **40**. Meanwhile, the second motor **418** is dedicated to managing one degree of freedom associated with abduction and adduction of the thumb assembly **40**. The decision to limit the thumb assembly **40** to two motors yields multiple advantages. Firstly, it simplifies the overall manufacturing process by reducing the number of components required, which in turn leads to fewer assembly steps and reduced production time. Secondly, the reduced motor count increases the durability of the end effector **10** by minimizing potential failure points, thereby enhancing the reliability of the thumb assembly **40** in various operational environments. Thirdly, this design approach enables the thumb assembly **40** to be modular, allowing for easier replacements, upgrades, or reconfigurations without the need for extensive redesigns. Lastly, the reduction in the number of motors significantly decreases both the cost and complexity of the control systems required to operate the thumb assembly **40**, making the end effector **10** more cost-effective and efficient for a wide range of applications. By optimizing the control of four joints with just two motors, the design achieves a robust yet simplified solution that meets the performance requirements of advanced robotic systems while minimizing unnecessary complexity.

[0178] The motor assembly **410** is an integral component of the thumb assembly **40** and is positioned directly within the hand structure of the robotic system, rather than being remotely located in another part of the robot. This design choice has several important implications for the overall functionality and performance of the thumb assembly **40**. While it may impose certain constraints on the size and dimensions of the robotic hand, particularly in terms of how compact the hand can be, it offers numerous advantages that enhance the utility and effectiveness of the end effector **10**. By incorporating the motor assembly **410** within the thumb assembly **40**, the need for extensive linkage mechanisms is significantly reduced. This simplification leads to fewer mechanical parts, which not only minimizes potential points of failure but also streamlines the manufacturing process and reduces maintenance requirements. The reduction in linkages also increases the modularity of the thumb assembly **40**, making it easier to swap out or upgrade individual components without requiring extensive modifications to the overall system. This modular design enhances the versatility of the thumb assembly **40**, allowing for greater adaptability across various tasks and environments. Additionally, with fewer external linkages and a more self-contained structure, the thumb assembly **40** can operate more effectively in confined spaces and interact more directly with objects in its surroundings. The integration of the motor assembly **410** within the thumb assembly **40** also contributes to the overall reliability of the system by reducing the number of external components and connections, the likelihood of mechanical failures or misalignments is minimized.

[0179] This reliability is further enhanced by the inclusion of the first controller **414**, which is specifically designed to manage the movements of the thumb assembly **40**. The first controller **414** is equipped with electronic controls that can be programmed to limit the rotation and movement of the thumb assembly **40**, ensuring that it operates within predefined parameters to avoid overextension or damage. The first controller **414** may also incorporate advanced feedback mechanisms, such as position sensors or torque sensors, to provide real-time data on the thumb's movements. This data can be used to optimize the thumb's performance, enabling precise and adaptive control based on the task at hand. Furthermore, the controller **414** can be configured to implement safety protocols, such as emergency stop functions or collision detection, to prevent accidental damage to the robot or its surroundings.

i. First Motor

[0180] As shown in FIGS. **30-31**B, the first motor **412** includes: (i) internal components (not shown), (ii) a digit or first motor housing **412.1**, (iii) a digit or first motor shaft **412.2**, and (iv) a motor gear bearing **412.3**. The internal components of the first motor **412** are designed to rotate the first motor shaft **412.2** about a first motor shaft axis A_{MS1}. To help ensure that the first motor shaft **412.2** rotates about the first motor shaft axis A_{MS1} at the desired speed, the internal components of the first motor **412** may include a transmission, gear reduction, or other components. Said transmission, gear reduction, or other component may include: a planetary gear system, a strain wave gear (e.g., harmonic drive), a cycloidal drive, a clutch mechanism, and/or an electromagnetic brake. In addition to altering the speed of the first motor shaft **412.2**, the transmission, gear reduction, or other component may prevent the first motor shaft **412.2** from making full revolutions (i.e., 360 degrees) around the first motor shaft axis A_{MS1}. This may be accomplished using mechanical hard stops that could be integrated into the gearbox. In some cases, it may be beneficial to physically limit the rotational movement of the first motor shaft **412.2** (as opposed to electronically limiting said rotation using programming or control methodologies) because it helps ensure that the thumb assembly **40** cannot be over-rotated. However, in other embodiments, the transmission, gear reduction, or other component may not prevent the first motor shaft **412.2** from making full revolutions (i.e., 360 degrees) around the first motor shaft axis A_{MS1}. In this embodiment, electronically limiting said rotation using programming or control methodologies may be used to help ensure that the thumb assembly **40** is not over-rotated. Alternatively, it may be desirable to allow the first motor shaft **412.2** to make full revolutions (i.e., 360 degrees) based on the gearing ratio.

[0181] The first motor gear **416** extends past a frontal portion of the first motor housing **412.1** and: (i) includes an extent that is designed to receive the first motor shaft **412.2**

to enable said first motor gear **416** to be coupled to the first motor shaft **412.2**, and (ii) has helical or screw-like threads. Coupling said first motor gear **416** to the first motor shaft **412.2** enables the internal components of the first motor **412** to rotate the first motor shaft **412.2** around the first motor shaft axis A_{MS1}, wherein said rotation of the first motor shaft **412.2** around the first motor shaft axis A_{MS1} causes the first motor gear **416** to rotate about a first motor gear axis A_{MSG1}. The first motor shaft axis A_{MS1} and the first motor gear axis A_{MSG1} may be parallel, aligned, and coaxial. This coaxial arrangement may be achieved through precise machining and alignment of the motor shaft **412.2** and motor gear **416** during assembly. The motor housing **412.1** may include precision-machined bearing surfaces to support the motor shaft **412.2** and maintain its alignment. Additionally, the motor gear **416** may be manufactured with a precision-bored central opening that closely matches the diameter of the motor shaft **412.2**, allowing for a tight, coaxial fit when assembled. In some aspects, additional alignment features such as keyways or splines may be incorporated on the shaft **412.2** and gear **416** to ensure proper rotational alignment. The use of high-precision bearings at the interface between the motor shaft **412.2** and housing **412.1** may further contribute to maintaining the coaxial relationship between the shaft and gear axes. This configuration may also cause the first motor shaft axis A_{MS1} and the first motor gear axis A_{MSG1} to be parallel with (and potentially, coaxial with) the thumb motor plane P_{TM}. In some cases, the first motor shaft axis A_{MS1}, the first motor gear axis A_{MSG1}, and thumb motor plane P_{TM} may not be parallel, aligned, and/or coaxial. Instead, the first motor shaft axis A_{MS1} and the first motor gear axis A_{MSG1} may be perpendicular to one another, while the thumb motor plane P_{TM} may be parallel with the first motor shaft axis A_{MS1}.

[0182] As described above, the motor assembly **410** also includes a first motor gear bearing **412.3** that is designed to support the distal, rotating end of the first motor gear **416**. In alternative embodiments, the first motor gear bearing **412.3** may be omitted or integrally formed with the first motor gear **416**. It may also be understood that in alternative embodiments, the first motor shaft **412.2** and the first motor gear **416** may be integrally formed and/or sealed. As shown in FIGS. **30-31**B and discussed below, the first motor gear **416** is designed to be in geared engagement with an extent of the base joint assembly **430**, wherein this geared engagement enables the rotation of the first motor gear **416** to cause the thumb assembly **40** to move or curl.

ii. Second Motor

[0183] As shown in FIGS. **30-31**B, the second motor **418** includes: (i) internal components (not shown), (ii) a second or digit motor housing **418.1**, (iii) a second or digit motor shaft **418.2**, and (iv) a motor gear bearing **418.3**. The internal components of the second motor **418** are designed to rotate the second motor shaft **418.2** about a second motor shaft axis A_{MS2}. To help ensure that the second motor shaft **418.2** rotates about the second motor shaft axis A_{MS2} at the desired speed, the internal components of the second motor **418** may include a transmission, gear reduction, or other components. This transmission, gear reduction, or other component may include: a planetary gear system, a strain wave gear (e.g., harmonic drive), a cycloidal drive, a clutch mechanism, and/or an electromagnetic brake. In addition to altering the speed of the second motor shaft **418.2**, the transmission, gear reduction, or other component may prevent the second motor shaft **418.2** from making full revolutions (i.e., 360 degrees) around the second motor shaft axis A_{MS2}. This may be accomplished using mechanical hard stops that could be integrated into the gearbox. In some cases, it may be beneficial to physically limit the rotational movement of the second motor shaft **418.2** (as opposed to electronically limiting said rotation using programming or control methodologies) because it helps ensure that the thumb assembly **40** cannot be over-rotated. However, in other embodiments, the transmission, gear reduction, or other component may not prevent the second motor shaft **418.2** from making full revolutions (i.e., 360 degrees) around the second motor shaft axis A_{MS2}. In this embodiment, electronically limiting said rotation using programming or control methodologies may be used to help ensure that the thumb assembly **40** is not over-rotated. Alternatively, it may be desirable to allow the second motor shaft **418.2** to make full revolutions (i.e., 360 degrees) based on the gearing ratio.

[0184] As shown in the FIGS. **30-31**B, the second motor gear **422** extends past a frontal portion of the second motor housing **418.1** and: (i) includes an extent that is designed to receive the second motor shaft **418.2** to enable said second motor gear **422** to be coupled to the second motor shaft **418.2**, and (ii) has helical or screw-like threads. Coupling said second motor gear **422** to the second motor shaft **418.2** enables the internal components of the second motor **418** to rotate the second motor shaft **418.2** around the second motor shaft axis A_{MS2}, wherein said rotation of the second motor shaft **418.2** around the second motor shaft axis A_{MS2} causes the second motor gear **422** to rotate about a second motor gear axis A_{MSG2}. The second motor shaft axis A_{MS2} and the second motor gear axis A_{MSG2} may be parallel, aligned, and coaxial. This coaxial arrangement may be achieved through precise machining and alignment of the motor shaft **418.2** and motor gear **422** during assembly. The motor housing **418.1** may include precision-machined bearing surfaces to support the motor shaft **418.2** and maintain its alignment. Additionally, the motor gear **422** may be manufactured with a precision-bored central opening that closely matches the diameter of the motor shaft **418.2**, allowing for a tight, coaxial fit when assembled. In some aspects, additional alignment features such as keyways or splines may be incorporated on the shaft **418.2** and gear **422** to ensure proper rotational alignment. The use of high-precision bearings at the interface between the motor shaft **418.2** and housing **418.1** may further contribute to maintaining the coaxial relationship between the shaft and gear axes. This configuration also causes the second motor shaft axis A_{MS2} and the second motor gear axis A_{MSG2} to be parallel with (and potentially, coaxial with) the thumb motor plane P_{TM}. In some cases, the second motor shaft axis A_{MS2}, the second motor gear axis A_{MSG2}, and thumb motor plane P_{TM} may not be parallel, aligned, and coaxial. Instead, the second motor shaft axis A_{MS2} and the second motor gear axis A_{MSG2} may be perpendicular to one another, while the finger motor plane P_{FM} may be parallel with the second motor shaft axis A_{MS2}.

[0185] Also, as shown in FIGS. **30-31**B, the first motor shaft axis A_{MS1} is parallel, aligned, and positioned within the first motor gear plane P_{G1}, while the second motor shaft axis A_{MS2} is parallel, aligned, and positioned within the second motor gear plane P_{G2}. The first motor shaft axis A_{MS1} is parallel with the second motor shaft axis A_{MS2}, which causes the first motor gear plane P_{G1} to be parallel with the second motor gear plane P_{G2}. Likewise, the first motor gear axis

A_{MSG1} is parallel, aligned, and positioned within the first motor gear plane P_{G1}, while the second motor gear axis A_{MSG2} is parallel, aligned, and positioned within the second motor gear plane P_{G2}. Also, the first motor shaft axis A_{MS1} and the first motor gear axis A_{MSG1} are vertically aligned in a plane that is parallel with the Y-Z plane.

[0186] As described above, the motor assembly **410** also includes a second motor gear bearing **418.3** that is designed to support the distal, rotating end of the second motor gear **422**. In alternative embodiments, the second motor gear bearing **418.3** may be omitted or integrally formed with the second motor gear **422**. It may also be understood that in alternative embodiments, the second motor shaft **418.2** and the second motor gear **422** may be integrally formed and/or sealed. As shown in FIGS. **30-31**B and discussed below, the second motor gear **422** is designed to be in geared engagement with an extent of the base joint assembly **430**, wherein said geared engagement causes the thumb assembly **40** to move or rotate towards or away from the palm **62**.

b. Base Joint Assembly

[0187] The base joint assembly **430** is positioned forward of a majority of the motor assembly **410** and is configured to allow the thumb assembly **40** to move from: (i) the open, uncurled, or neutral position to the curled position, and (ii) the open, unrotated, or neutral position to the rotated position. In said curled and rotated position, an acute interior angle is formed between: (i) the right side **68** and an interior surface of the thumb assembly **40**, and (ii) the palm **62** and an interior surface of the thumb assembly **40**. The base joint assembly **430** is best shown in FIGS. **20-24**, **28**A-**28**D, **30**, and **31**A-**31**B and includes: (i) a carpometacarpal joint assembly **432**, (ii) carpometacarpal electronics **434**, and (iii) a carpometacarpal or base joint housing **436**.

i. Carpometacarpal Joint Assembly

[0188] The carpometacarpal joint assembly **432** includes: (i) a frame **432.1**, and (ii) a thumb drive assembly **432.2**, and wherein said carpometacarpal joint assembly **432** includes a first or vertical carpometacarpal joint assembly CMC_1. The frame **432.1** and the thumb drive assembly **432.2** are complex and important components of the thumb assembly **40**, whereby said assemblies **432.1**, **432.2** translate the movement of the motor assembly **410** to movements of the base joint assembly **430** and the digit assembly **408**. It should be understood that other assemblies, components, sub-components, and/or parts may be added, removed, combined into a fewer number of parts, or separated into additional parts. While some of the positional relationships are set forth below, it should be understood that additional relationships may be derived from the figures (as these assemblies, components, sub-components, and/or parts are shown as proportional to one another).

1. Thumb Frame

[0189] The thumb frame **432.1** includes two major components, wherein the first component is an upper frame member **432.1.2** and a second component is a lower frame member **432.1.4**. The upper frame member **432.1.2** is affixed to the end effector frame **61.2** and does not rotate, or move relative to the end effector frame **61.2**. The structure and affixed relationship of the upper frame member **432.1.2** and the end effector frame **61.2** enables said upper frame member **432.1.2** to secure the remaining components of the thumb assembly **40** within the end effector **10**. As such, the upper frame member **432.1.2** is made from a material with sufficient rigidity. Stated another way, the thumb frame **432.1** may be made from any material disclosed herein or known in the art that can achieve the desired task of supporting and securing components of the thumb assembly **40** to the frame **61.2**, including the same material as the frame **61.2**. In other embodiments, the thumb frame **432.1** may be integrally formed with other components (e.g., palm housing **60.1**) and as such be made from the same material as the other component.

[0190] As shown in FIG. **21**, the upper frame member **432.1.2** includes an upper opening **432.1.10** and a lower opening **432.1.12**. These openings allow for the insertion of the lower frame member **432.1.4** and the thumb drive assembly **432.2**. Additionally and as shown in the Figures, the upper frame member **432.1.2** is not a simple tube or cylinder, but instead includes internal walls that are configured to support and allow the lower frame member **432.1.4** and the thumb drive assembly **432.2** to rotate within said upper frame member **432.1.2**. It should be understood that the configuration and design of these internal walls may be changed or altered to accompany and/or support the lower frame member **432.1.4** and other components of the thumb assembly **40**.

[0191] The lower frame member **432.1.4** has a complex geometry that includes a first or upper portion **432.1.4.1** that is positioned above line L_F and a lower portion **432.1.4.2** that is positioned below line L_F, wherein line L_F is co-linear with a lower surface of the upper frame member **432.1.2**. This complex geometry of the lower frame member **432.1.4**: (i) allows it to interact with the carpometacarpal electronics **434**, (ii) includes the upper portion **432.1.4.1** to rotate within the internal walls of the upper frame member **432.1.2**, (iii) provides for carpometacarpal or base joint housing coupling points **432.1.4.6**, (iv) has a proximal link aperture **432.1.4.3** formed therein to allow for an interaction between a worm drive gear **432.2.2** and the worm wheel **454.4.1**, and (v) is designed to receive a bearing **432.2.16.8**. While one embodiment of said lower frame member **432.1.4** is shown in the Figures, it should be understood that other embodiments are contemplated by this disclosure.

2. Thumb Drive Assembly

[0192] As best shown in FIGS. **20-26**, the thumb drive assembly **432.2** is configured to translate the rotational motion from the motor assembly **410** to the carpometacarpal joint assembly **432** and the digit assembly **408**. Specifically, the thumb drive assembly **432.2** is in geared engagement with the first and second motor gears **416**, **422** and the worm wheel **454.4.1**. To do this, the gear assembly **432.3** is comprised of: (i) a worm drive gear **432.2.2**, (ii) a flexion gear **432.2.4**, (iii) an interposition gear **432.2.6**, (iv) a middle, digit adaptor, or flexion gear adaptor **432.2.10**, (v) a flexion gear coupler **432.2.12**, (vi) a drive shaft or flexion shaft **432.2.14**, and (vii) a flexion bearing assembly **432.2.16** that includes a plurality of bearings **432.2.16.2-432.2.16.8**. As discussed above and throughout this application, it should be understood that some of these components may be omitted, modified, replaced, and/or other parts may be added.

[0193] The flexion gear **432.2.4** is a toothed gear that is designed to be in geared engagement with the first motor gear **416**, such that it rotates in response to the rotation of the first motor **412** and generates a zero pivot point P_0. Specifically, the rotation of the first or digit motor shaft **412.2**

rotates the first motor gear **416**, and wherein the rotation of the first motor gear **416** rotates the flexion gear **432.2.4** about a flexion axis A_F. While the flexion axis A_F does not intersect the first motor shaft axis A_{MS1} or the first motor gear axis A_{MSG1}, said flexion axis A_F is perpendicular to both the first motor shaft axis A_{MS1} and the first motor gear axis A_{MSG1}. Based on this configuration, the center of the teeth of the flexion gear **432.2.4**, the first motor shaft axis A_{MS1} and the first motor gear axis A_{MSG1} are all positioned within the first motor gear plane P_{G1}. It should be understood that in an alternative embodiment, the flexion axis A_F may be parallel with the first motor shaft axis A_{MS1} and/or the first motor gear axis A_{MSG1}.

[0194] The flexion gear adaptor **432.2.10** is designed to couple the flexion gear **432.2.4** to the drive shaft or flexion shaft **432.2.14**. To accomplish this, the flexion gear adaptor **432.2.10** has a cone shaped configuration, wherein an outer extent of the cone is designed to be coupled to the flexion gear **432.2.4** and an inner extent of the cone is designed to receive an extent of the drive shaft or flexion shaft **432.2.14**. Once said drive shaft or flexion shaft **432.2.14** is positioned within the flexion gear adaptor **432.2.10**, the flexion coupler **432.2.12** is utilized to secure said flexion gear adaptor **432.2.10** to the drive shaft or flexion shaft **432.2.14**. As such, the flexion gear **432.2.4** is in geared engagement with the first motor gear **416**; the worm drive gear **432.2.2** is in geared engagement with the worm wheel **454.4.1**; and the drive shaft **432.2.14** is coupled to both the flexion gear **432.2.4** and the worm drive gear **432.2.2** via the flexion gear adaptor **432.2.10** and flexion gear coupler **432.2.12**.

[0195] The above described positional relationship allows for the rotation of the first motor shaft **412.2** about a first motor shaft axis A_{MS1} to cause the first motor gear **416** to rotate around the first motor gear axis A_{MSG1}, the rotation of the first motor gear **416** causes the flexion gear **432.2.4** to rotate about the flexion axis A_F, the rotation of the flexion gear **432.2.4** causes the flexion gear adaptor **432.2.10** to rotate, the rotation of the flexion gear adaptor **432.2.10** causes the flexion gear coupler **432.2.12** to rotate, and the rotation of the flexion gear coupler **432.2.12** causes the drive shaft or flexion shaft **432.2.14** to rotate about the drive shaft axis A_{DS}. The drive shaft axis A_{DS} is parallel, aligned, and coaxial with the flexion axis A_F. As such, the drive shaft axis A_{DS} does not intersect the first motor shaft axis A_{MS1} or the first motor gear axis A_{MSG1}, said drive shaft axis A_{DS} is perpendicular to both the first motor shaft axis A_{MS1} and the first motor gear axis A_{MSG1}. Based on this configuration, the drive shaft axis A_{DS} is also perpendicular to each of the following: (i) the flexion axis A_F, (ii) the first motor shaft axis A_{MS1}, (iii) the first motor gear axis A_{MSG1}, and (iv) the first motor gear plane P_{G1}.

[0196] To allow the drive shaft or flexion shaft **432.2.14** to rotate within the thumb frame **432.1**, the thumb drive assembly **432.2** utilizes a first portion of the flexion bearing assembly **432.2.16**. In particular, internal bearings **432.2.16.6**, **432.2.16.8** that are positioned between the internal wall of the lower frame member **432.1.4** and the drive shaft or flexion shaft **432.2.14** permit said drive shaft or flexion shaft **432.2.14** to rotate within said thumb frame **432.1**. Without this ability to rotate the drive shaft or flexion shaft **432.2.14** without rotating the thumb frame **432.1** is important because otherwise the movement of the first motor **412** would cause the digit assembly **408** to rotate towards or away from the palm. This is not desirable because it would significantly complicate the proper positioning of the thumb assembly **40** and would likely make certain positions impossible to reach or achieve. As such, this limitation would likely cause the end effector **10** to lack the human dexterity that is needed to complete fine and delicate tasks. Nevertheless, an alternative embodiment may couple the drive shaft or flexion shaft **432.2.14** to an extent of the thumb frame **432.1**, and wherein said coupling may be biased in a certain position (e.g., open). In this alternative embodiment, the second motor **418** may be omitted and the first motor **412** may drive the digit assembly **408** inward until it reaches a resistance point. Once said resistance point has been reached, the motor **412** may continue driving the drive shaft or flexion shaft **432.2.14** until the digit assembly **408** is fully curled around the object.

[0197] As described above, the rotation of the drive shaft or flexion shaft **432.2.14** to rotate about the drive shaft axis A_{DS}, causes the worm drive gear **432.2.2** to rotate about the worm drive gear axis A_{WDG}. The worm drive gear axis A_{WDG} is parallel, aligned, and coaxial with the flexion axis A_F and drive shaft axis A_{DS}. As such, the worm drive gear axis A_{WDG} does not intersect the first motor shaft axis A_{MS1} or the first motor gear axis A_{MSG1}, and the worm drive gear axis A_{WDG} is perpendicular to both the first motor shaft axis A_{MS1} and the first motor gear axis A_{MSG1}. Based on this configuration, the worm drive gear axis A_{WDG} is also perpendicular to the first motor gear plane P_{G1}. As will be discussed in greater detail below, the rotation of the worm drive gear **432.2.2** about the worm drive gear axis A_{WDG} causes the thumb assembly **40** to move about a second carpometacarpal joint axis A_{FC} (e.g., curl or uncurl).

[0198] Similar to how the rotation of the flexion gear **432.2.4** causes the digit assembly **408** to move (e.g., curl or uncurl), the rotation of the interposition gear **432.2.6** causes the base joint assembly **432** cause the base joint assembly **432** to rotate the digit assembly **408** towards or away from the palm region **62** and about a first carpometacarpal joint axis A_{SC}. To enable this rotational movement of the digit assembly **408**, the interposition gear **432.2.6** is affixed to the lower frame member **432.1.4** of the thumb frame **432.1**. Thus, the rotation of the interposition gear **432.2.6** about the interposition gear axis A_A causes the lower frame member **432.1.4** to rotate about a lower frame axis A_{LF}. The lower frame axis A_{LF} is parallel, aligned, and coaxial with the flexion axis A_F, drive shaft axis A_{DS}, and worm drive gear axis A_{WDG}. As such, the lower frame axis A_{LF} does not intersect the first motor shaft axis A_{MS1} or the first motor gear axis A_{MSG1}, and said lower frame axis A_{LF} is perpendicular to both the first motor shaft axis A_{MS1} and the first motor gear axis A_{MSG1}. Based on this configuration, the lower frame axis A_{LF} is also perpendicular to the first motor gear plane P_{G1}.

[0199] To further enable the smooth movement of the lower frame member **432.1.4** within the upper frame member **432.1.2**, the thumb drive assembly **432.2** utilizes a second portion of the flexion bearing assembly **432.2.16**. In particular, external bearings **432.2.16.2**, **432.2.16.4** are positioned between the internal wall of the upper frame member **432.1.2** and the internal walls of the lower frame member **432.1.4**. This ability to rotate the lower frame member **432.1.4** without curling/uncurling the digit assembly **408** is important because otherwise the movement of the second motor **418** would cause the digit assembly **408** to move/curl towards or away from the palm. This is not desirable because it would significantly complicate the proper positioning of the thumb assembly **40** and would likely make certain positions impossible to reach or achieve. As such, this limitation would likely cause the end effector **10** to lack the human dexterity that is needed to complete fine and delicate tasks.

[0200] In summary, the first motor **412** causes: (i) the first motor shaft **412.2** to rotate about a first motor shaft axis A_{MS1}, (ii) the rotation of the first motor shaft **412.2** causes the first motor gear **416** to rotate around the first motor gear axis A_{MSG1}, (iii) the rotation of the first motor gear **416** causes the flexion gear **432.2.4** to rotate about the flexion axis A_F, (iv) the rotation of the flexion gear **432.2.4** causes the flexion gear adaptor **432.2.10** to rotate, (v) the rotation of the flexion gear adaptor **432.2.10** causes the flexion gear coupler **432.2.12** to rotate, (vi) the rotation of the flexion gear coupler **432.2.12** causes the drive shaft or flexion shaft **432.2.14** to rotate about the drive shaft axis A_{DS}, (vii) the rotation of the drive shaft or flexion shaft **432.2.14** causes the worm drive gear **432.2.2** to rotate, (viii) the rotation of the worm drive gear **432.2.2** causes the worm wheel **454.4.1** to rotate, and (ix) the rotation of the worm wheel **454.4.1** causes the digit assembly **408** to curl/uncurl towards or away from the palm **62**.

[0201] Likewise, the second motor **418** causes: (i) the second motor shaft **418.2** to rotate about a second motor shaft axis A_{MS2}, (ii) the rotation of the second motor shaft **418.2** causes the second motor gear **422** to rotate around the second motor gear axis A_{MSG2}, (iii) the rotation of the second motor gear **422** causes the interposition gear **432.2.6** to rotate about the interposition gear axis A_A, (iv) the rotation of the interposition gear **432.2.6** causes the lower frame member **432.1.4** to rotate, (v) the rotation of the lower frame member **432.1.4** causes the digit assembly **408** to rotate towards or away from the palm region **62**. It should be understood that alternative embodiments are contemplated herein, wherein said alternatives include changing the position of the motors **412**, **418** (switching them, rotating them to be parallel or substantially parallel with the finger motors, placing them on the same side of the frame **61.2** as the finger motors, etc.).

ii. Carpometacarpal Electronics and Housing

[0202] The carpometacarpal electronics **434** may comprise a carpometacarpal encoder employing various sensing technologies, such as magnetic, optical, capacitive, or resistive systems, strategically positioned near the first carpometacarpal joint CMC_1. This encoder is configured to capture data related to the rotational movement of the joint CMC_1. Such data may be utilized by the robot system to generate a vector representation, such as a spatial embedding, that reflects the current state of the digit assembly **408** or the surrounding environment. In certain embodiments, the carpometacarpal electronics **434** may acquire data either upon receiving a specific command from the robot system or at regular intervals, ranging from high-frequency sampling (e.g., 500 times per second) to periodic updates (e.g., once per minute). The data provided by the carpometacarpal encoder may include precise information about the position and movement of the first carpometacarpal joint CMC_1, enabling fine-tuned control of the thumb assembly **40**.

[0203] In some implementations, the carpometacarpal encoder may integrate multiple sensing modalities, such as a combination of magnetic and optical sensing, to enhance redundancy and accuracy in detecting joint position. This multi-modal approach may enable reliable operation under diverse environmental conditions, such as variations in lighting, temperature, or magnetic interference. Furthermore, the carpometacarpal encoder may incorporate machine learning algorithms to facilitate adaptive calibration, improving accuracy over time by analyzing usage patterns. This adaptive capability may also allow the system to compensate for wear or minor misalignments that develop during prolonged operation. In addition to rotational data, the encoder may detect small translational movements or vibrations of the joint CMC_1. These additional data points could be used to identify early signs of mechanical wear or looseness in the joint assembly, enabling predictive maintenance and extended system longevity. For enhanced precision, the encoder may employ a high-resolution absolute encoding scheme, which provides accurate positional data immediately after power-up without necessitating a homing sequence. This feature could significantly reduce initialization time for the thumb assembly **40**.

[0204] To optimize data handling, the carpometacarpal electronics **434** may incorporate local data buffering and preprocessing functionalities. This design may allow high-frequency sampling and real-time filtering of joint position data, transmitting only significant state changes to the primary robot control system. Such an approach could reduce communication bandwidth requirements while maintaining system responsiveness. Additionally, the encoder system may be engineered for ultra-low power consumption, with the potential to harvest energy from the mechanical movements of the joint itself. This energy-efficient design could extend operational duration and decrease dependence on external power sources, enhancing the overall autonomy of the sensing system.

[0205] The base joint or carpometacarpal joint housing assembly **436** is designed to protect a lower extent of the thumb assembly **40** and enable a substantially smooth transition from the interior bottom housing **61.10** of the palm housing **60.1**. Thus, a base gap G_1 is formed between a bottom edge **60.1.1** of the palm housing **60.1** and an upper edge **436.10** of the base joint or carpometacarpal joint housing assembly **436**. Said design of the palm housing **60.1** and the base joint or carpometacarpal joint housing assembly **436** minimizes the base gap G_1 that is formed between these two structures **60.1**, **436.10**. Said minimization of the base gap G_1 provides a substantial benefit over conventional end effectors **10** that include a large gap between the palm and the thumb because it: (i) minimizes the chance or probability that a glove or external covering can be caught or pinched between these housings/assemblies, (ii) provides better protection of the internal components of the thumb assembly **40**, and (iii) helps seal the interworking of the thumb assembly **40** from the environment.

[0206] Additionally, the configuration of the base joint or carpometacarpal joint housing assembly **436** is significantly different from a conventional boot or flexible member, which are typically stretched between the thumb assembly **40** and the inner palm surface S_P of the palm housing **60.1**. The differences include the following key factors: (i) the housing assembly **436** is not engineered to be substantially flexible; rather, it is designed to be substantially rigid, providing enhanced stability and durability, (ii) the entire housing **436** is intended to rotate in coordination with the thumb assembly **40**, (iii) a portion of the housing **436** is not directly coupled to the palm housing **60.1**, allowing for improved articulation and independent movement of the housing assembly **436**, and (iv) while the base gap G_1 is minimized, said base gap G_1 remains between the palm housing **60.1** and the housing **436**, which accommodates the necessary movement without causing friction or restricting motion. These distinctive features afford the housing **436** substantial advantages over a conventional boot design. Specifically, the disclosed housing **436** design: (i) does not obstruct or interfere with the contact between the end effector **10** and the object with which the end effector **10** is interacting, ensuring optimal performance and precision, (ii) is resistant to tearing or rapid degradation, even when the end effector **10** encounters sharp objects such as sheet metal, and (iii) additional benefits, which will be apparent to those skilled in the art, can be derived from these design elements as disclosed herein.

[0207] The base joint or carpometacarpal joint housing assembly **436** has an overall shape that is similar to a checkmark or tick and includes: (i) an interior, upper member **436.1**, (ii) an exterior, upper member **436.2**, and (iii) a lower member **436.3**. Each of the members **436.1**, **436.2**, **436.3** include interior mounting projections **436.10** that extend inward and are designed to be coupled to the thumb frame **432.1** (and specifically, the carpometacarpal or base joint housing coupling points **432.1.4.6**) using elongated mechanical fasteners. It should be understood that alternative coupling means are contemplated by this disclosure, including snaps, press-fit, other mechanical interacting structures, and/or any other known method of mechanical coupling. Further, it should be understood that the number of members contained within the housing assembly **436** may increase or decrease depending on the needs and configuration of said thumb drive assembly **432.2**.

[0208] As shown in FIGS. **20-24**, the base joint or carpometacarpal joint housing assembly **436** is configured to surround or at least substantially surround a portion of: (i) the lower frame member **432.1.4**, (ii) the worm drive gear **432.2.2**, and (iii) the proximal link assembly **454**. To surround or at least substantially surround the above components, the base joint or carpometacarpal joint housing assembly **436** forms a base joint receiver **432.20**. The base joint receiver **432.20** is designed to receive: (i) an extent of the proximal assembly **450** (namely, a rear extent of the proximal housing assembly **452**), when the thumb assembly **40** is in the open, uncurled, or neutral position, and (ii) a lesser extent of, or none of, the proximal assembly **450** (namely, the rear extent of the proximal housing assembly **452**), when the thumb assembly **40** is in the closed, curled, or inwardly rotated position. In other words, the base joint housing assembly **436** overlies: (i) an extent of the proximal housing assembly **452** when the thumb assembly **40** is in the open, uncurled, or neutral position, and (ii) none of the proximal housing assembly **452** when the thumb assembly **40** is in the closed, curled, or inwardly rotated position. Stated another way, the percentage of the proximal housing assembly **452** (namely, the rear extent of the proximal housing assembly **452**) that is positioned within the base joint housing assembly **436** is reduced when the thumb assembly **40** moves from the open, uncurled, or neutral position to the closed, curled, or inwardly rotated position. By enabling at least a minimal extent of the proximal housing assembly **452** to be positioned within or adjacent to the base joint housing assembly **436**, the gap G_2 formed between the assemblies **436** and **452** is minimized, and wherein said minimization of said gap G_2 is beneficial because it minimizes the chance or probability that a glove or external covering can be caught or pinched between these assemblies.

a. Proximal Assembly

[0209] The proximal assembly **450** is positioned between the base joint assembly **430** and the medial assembly **470** and is the first portion of the thumb assembly **40** that is configured to move relative to the housing frame **61.2** and the palm **62** in response to actuation of the first motor **412** and worm drive gear **432.2.2**. The proximal assembly **450** includes: (i) a proximal housing assembly **452**, (ii) a proximal link assembly **454**, and (iii) the worm wheel interface **456**.

i. Proximal Housing Assembly

[0210] As shown in FIGS. **20-24** and **35-37**, the proximal housing assembly **452** is designed to substantially surround a majority of the other components of the proximal assembly **450**. To achieve this, the proximal housing assembly **452** forms an internal proximal recess **452.18**. Unlike the finger assemblies **22*a*-22*d***, the internal proximal recess **452.18** is not designed to receive an extent of the medial assembly **470** (namely, the medial tongue) when the thumb assembly **40** is in the open, uncurled, or neutral position. Instead, an extent of said proximal housing assembly **452** is designed to be positioned near or adjacent to the medial housing **472**. This configuration helps ensure that the gap G_3 formed between the assemblies **450** and **470** is minimized, and wherein said minimization of said gap G_3 is beneficial because it minimizes the chance or probability that a glove or external covering can be caught or pinched between these assemblies **450**, **470**.

[0211] In an alternative embodiment, the proximal housing assembly **452** may be configured to overlie: (i) a substantial extent of a medial tongue when the thumb assembly **40** is in the open, uncurled, or neutral position, and (ii) a minor extent of, or none of, the medial tongue when the thumb assembly **40** is in the closed, curled, or inwardly rotated position. Stated another way, the percentage of the medial assembly **470** (namely, the medial tongue) that is positioned within the proximal housing assembly **452** is reduced when the thumb assembly **40** moves from the open, uncurled, or neutral position to the closed, curled, or inwardly rotated position. This configuration may further minimize the size of gap G_3, which may further minimize the chance or probability that a glove or external covering can be caught or pinched between these assemblies **450**, **470**.

[0212] As shown in FIGS. **20-24** and **35-37**, the proximal housing assembly **452** specifically includes: (i) a proximal jacket assembly **452.1** with a top member **452.1.1** and a bottom member **452.1.2**, and (ii) a proximal bottom casing assembly **452.2**. While the bottom member **452.1.2** is in direct contact with and underlies the proximal bottom casing assembly **452.2**, the thumb assembly **40** lacks a proximal top casing assembly that is in direct contact with the top member **452.1.1**. This design is advantageous because the proximal bottom casing assembly **452.2** provides the bottom member **452.1.2** with additional rigidity, which enables said bottom member **452.1.2** to be made from a softer, easier-to-form, and potentially less durable material, thereby increasing the gripping capability of the end effector **10**. In contrast, the top member **452.1.1** does not need to include a softer, easier-to-form, and potentially less durable material because said top member **452.1.1** is not designed to come into regular contact with objects. Additionally, even if the materials of the proximal bottom casing assembly **452.2** and the bottom member **452.1.2** are the same, it may be desirable to form these components as two separate components to facilitate replaceability without exposing an inner extent of the thumb assembly **40**. Another way of describing this beneficial configuration includes the fact that the proximal jacket assembly **452.1** is configured to provide the primary external shape of the thumb assembly **40**, while the proximal casing assembly **452.2** is configured to protect the internal workings of said thumb assembly **40**. Nevertheless, it should be understood that in an alternative embodiment, the bottom member **452.1.2** and the proximal bottom casing assembly **452.2** may be integrally formed as a single structure.

[0213] As best shown in FIGS. **11-12**, **20-24**, and **35-37**, the top member **452.1.1** of the proximal jacket assembly **452.1** includes an exterior surface back with a curvilinear extent in a first direction (namely, across the width of the thumb assembly **40**), and the bottom member **452.1.2** of the proximal jacket assembly **452.1** includes an exterior palm surface **61.2.2** with a curvilinear extent in the first direction (namely, across the width of the thumb assembly **40**) and a second direction (namely, across the length of the thumb assembly **40**). The curvilinear extent in the first direction helps ensure that the thumb assembly **40** has rounded edges to help with grasping objects, while the curvilinear extent in the second direction helps ensure that the thumb assembly **40** can curl inward. As discussed above, the proximal housing assembly **452** may be: (i) made from the same materials as the housing assembly **60**, (ii) made from material that differs from the materials used in the housing assembly **60**, and/or (iii) may include silicon, plastic (e.g., may include a polymer composition), carbon composite, or metal, a combination of these materials, any other material disclosed herein, and/or any other suitable material. Alternatively, the proximal housing assembly **452** may include additional components or layers (e.g., between three and an nth layer).

iii. Proximal Link Assembly

[0214] As shown in FIGS. **20-24** and **35-54**, the proximal link assembly **454** includes: (i) a primary or main proximal link or first bar **454.1**, (ii) a coupling link **454.2**, (iii) a medial assembly coupler **454.3**, and (iv) a proximal drive link assembly **454.4**. The proximal link assembly **454** is involved with all movements of the thumb assembly **40**, wherein its angular position can be altered based on the curling of an extent of the assembly **40** and its rotational position can be altered based on rotating the assembly **40**. In other words, at least one aspect of the proximal link assembly **454** must move in some aspect to cause any portion of the thumb assembly **40** to move. As discussed above, this disclosure is in contrast to conventional end effectors and/or conventional fingers. This configuration is beneficial because it reduces complexities, components, cost, and weight, while increasing reliability.

1. Main Proximal Link

[0215] The primary or main proximal link or first bar **454.1** is best shown in FIGS. **20-24**, **34-40**, and **48-50**. The main proximal link **454.1** includes: (i) first and second frame members **454.1.1***a*, **454.1.1***b*, (ii) a proximal link bridge **454.1.2**, and (iii) a proximal link recess **454.1.3**. The first and second frame members **454.1.1***a*, **454.1.1***b* are comprised of: (i) a first proximal link segment **454.1.1.1***a*, **454.1.1.1***b* that extends from a rearmost extent of the main proximal link **454.1** to a first proximal link plane P_{L1}, (ii) a second proximal link segment **454.1.1.2***a*, **454.1.1.2***b* that extends from the first proximal link plane P_{L1} to a second proximal link plane P_{L2}, and (iii) a third proximal link segment **454.1.1.3***a*, **454.1.1.3***b* that extends forward from the second proximal link plane P_{L2} to the forward most extent of the main proximal link **454.1**.

[0216] As shown in FIG. **50**, the second left and right segments **454.1.1.2***a*, **454.1.1.2***b* taper inward as they extend from plane P_{L1} to plane P_{L2}, which reduces the overall width of the link **454.1**. The reduction in width is beneficial because it allows for a reduction in the width of the thumb assembly **40** to aid in gripping objects. It should be understood that in other embodiments, the taper may be more significant or may be eliminated. Also, as shown in FIG. **54**, first right and left segments **454.1.1.1***a*, **454.1.1.1***b* are substantially parallel with one another, but are not aligned with the third right and left segments **454.1.1.3***a*, **454.1.1.3***b*. In other embodiments, said first and third left and right segments **454.1.1.1***a*, **454.1.1.1***b*, **454.1.1.3***a*, **454.1.1.3***b* may not be substantially parallel with one another and/or may be substantially aligned with other components of the main proximal link **454.1**.

[0217] As shown in FIGS. **48-51**, the first proximal link segment **454.1.1.1** includes a second joint or carpometacarpal joint CMC_2 with a carpometacarpal joint coupler **454.1.1.1.1** having an axle aperture **454.1.1.1.1.1** and a stopping projection **454.1.1.1.1.2**. The axle aperture **454.1.1.1.1.1** of the carpometacarpal joint coupler **454.1.1.1.1** is circular and is designed to receive an extent of the worm wheel assembly **456** (which will be discussed later). It should be understood that non-circular configurations of the axle aperture **454.1.1.1.1** are contemplated by this disclosure (e.g., tear-drop). Referring to FIG. **51**, the stopping projection **454.1.1.1.1.2** is positioned in a lower extent of the first proximal link segment **454.1.1.1**. When the proximal assembly **450** is in the curled position, a second limiting interface region **454.1.1.1.1.2.1** of the stopping projection **454.1.1.1.1.2** is designed to interact with an extent of the joint frame member **432.1**. It should be understood that the above described interface region **454.1.1.1.1.2.1** may not make contact with the described adjacent structures. Instead, a gap may be present between these structures regardless of the state of the thumb assembly **40**.

[0218] As shown in FIGS. **48-51**, the second proximal link segment **454.1.1.2** is not aligned with either the first or third segments **454.1.1.1**, **454.1.1.3** and includes: (i) elongated ribs **454.1.1.2.1** that extend from a side of the proximal frame member **454.1.1***a*, **454.1.1***b*, (ii) a second set of housing mounting projections **454.1.1.2.2**, wherein the first set of housing mounting projections **454.1.1.1.2** were a component of the first proximal link segment **454.1.1.1**. The housing mounting projections **454.1.1.1.2**, **454.1.1.2.2** are configured to couple the proximal jacket assembly **452.1** to the proximal link assembly **454**. Other methods of coupling said assemblies **452.1**, **454** to one another are contemplated by this disclosure, including clips, press- fits, or other mechanical coupling means.

[0219] Like the frame members **454.1.1***a*, **454.1.1***b* of the first segment **454.1.1.1**, the frame members **454.1.1***a*, **454.1.1***b* of the third segment **454.1.1.3** are substantially parallel to one another. Additionally, the third proximal link segment **454.1.1.3** also includes: (i) a medial assembly opening

454.1.1.3.1 configured to receive a securement means that couples the main proximal link **454.1** to the jumper **454.4.4** of the proximal drive link assembly **454.4** to form a fourth pivot point P_4, and (ii) a medial assembly recess **454.1.1.3.2** to ensure that the securement means does not interfere with the movement of any of the links contained within the thumb assembly **40**. It should be understood that the securement means is contemplated by this disclosure, including any mechanical coupler (e.g., pin and clip). Also, the medial assembly recess **454.1.1.3.2** may be omitted or the nesting of components may be altered in other embodiments.

[0220] As shown in FIGS. **37**, **38**, **40**, **49**, and **50**, the proximal bridge **454.1.2** extends between an extent of the first and second proximal frame members **454.1.1***a*, **454.1.1***b*. Thus, a U-shaped member with a proximal link recess **454.1.3** is formed from the combination of the proximal bridge **454.1.2** and the proximal frame members **454.1.1***a*, **454.1.1***b*. This proximal link recess **454.1.3** is designed to receive different extents of the coupling link **454.2** and proximal drive link assembly **454.4** depending on the position of the thumb assembly **40**. The proximal bridge **454.1.2** also includes a third limiting interface region **454.1.2.1** designed to interact with the first limiting interface region **432.1.2.1** of the upper frame member **432.1.2** when the thumb assembly **40** is fully curled. Modifications to the location and configuration of the interface regions **432.1.2.1**, **454.1.2.1** are contemplated by this disclosure.

2. Coupling Link

[0221] As shown in FIGS. **37**, **38**, and **52-54**, the coupling link or fourth bar **454.2** secures the frame **432.1** of the base joint assembly **430** to the biasing assembly **474.4** of the medial link assembly **474**. As such, the coupling link or fourth bar **454.2** includes a first end that is pivotally coupled at a second pivot point P_2 to said thumb frame **432.1** and a second end that is pivotally coupled at a third pivot point P_3 to said Y-link **474.3**. Thus, the second and third pivot points are P_2, P_3. The coupling link **454.2** is comprised of left and right portions **454.2.1***a*, **454.2.1***b*, which when assembled allow the coupling link **454.2** to include: (i) frame projections **454.2.2***a*, **454.2.2***b* that are configured to be received by an extent of the frame **432.1**, (ii) a link assembly recess **454.2.3**, which is configured to receive an extent of the proximal drive link assembly **454.4** when said thumb assembly **40** is in the curled position, (iii) a Y-link opening **454.2.4** and a Y-link recess **454.2.5**, both of which are configured to allow said coupling link **454.2** to interact with the Y-link **474.3** of the medial link assembly **474**. This configuration also ensures that the coupling link or fourth bar **454.2** is supported on two sides of a plane that bisects the length of the thumb assembly **40**. It should be understood that in other embodiments, the coupling link **454.2** may be combined with other links or may be omitted.

3. Proximal Drive Link Assembly

[0222] As shown in FIGS. **34-47**, the proximal drive link assembly **454.4** includes: (i) a worm wheel **454.4.1**, (ii) a worm wheel coupler **454.4.2**, (iii) a worm drive link or second bar **454.4.3**, and (iv) a jumper or third bar **454.4.4**. The worm wheel **454.4.1** is a semi-circular toothed gear that is designed to be in geared engagement with the worm drive gear **432.2.2** and is configured to facilitate the movement of the thumb assembly **40** from an uncurled position to a curled position. In particular, the worm wheel **454.4.1** includes: (i) a toothed section that includes 18 teeth that encircle 220 degrees of the worm wheel **454.4.1**, (ii) a recessed portion **454.4.1.1** that is designed to receive an extent of the worm wheel coupler **454.4.2**, and (iii) a central bearing opening **454.4.1.2** that is designed to receive first and second worm bearings **456.2***a*, **456.2***b* (as discussed below). The worm wheel **454.4.1** is designed to rotate about a worm wheel axis A_{ww}, wherein the worm wheel axis A_{ww} is located at the center of the central bearing opening **454.4.1.2** and the first pivot point P_1. It should be understood that in other embodiments, the worm wheel **454.4.1** may include additional teeth (e.g., between 19 and 50) or fewer teeth (e.g., between 5 and 17). Additionally, the toothed section **454.4.1** may span more than **220** degrees (e.g., between 221 and 300 degrees) or span less than 220 degrees (e.g., between 100 and 119 degrees).

[0223] The worm wheel coupler **454.4.2** includes a worm drive link opening **454.4.2.2** that is designed to couple said worm wheel **454.4.1**, via the worm wheel coupler **454.4.2**, to the worm drive link or second bar **454.4.3**. Further, the worm wheel coupler **454.4.2** includes other features that permit the transfer of energy from the worm wheel **454.4.1** to the assemblies **480**, **470** of the thumb assembly **40**. For example, said worm wheel **454.4.1** includes a recess that is positioned adjacent to the worm wheel interface region **454.4.1.3** and is configured to ensure that a coupler does not interfere with the movement of the worm wheel assembly **456**. However, it should be understood that the recess may be omitted in other embodiments and/or said worm wheel **454.4.1** may be sealed within the motor assembly **410**.

[0224] The worm drive link **454.4.3** includes: (i) a wheel coupler opening **454.4.3.1** that is configured to receive a coupler designed to pivotally secure said worm drive link **454.4.3** to the worm wheel coupler **454.4.2** at the fourth pivot point P_4, and (ii) a proximal drive link opening **454.4.3.2** that is configured to receive a coupler designed to pivotally secure said worm drive link **454.4.3** to the jumper **454.4.4** and the medial drive link **474.2** at the fifth pivot point P_5. Duc to the worm drive link's **454.4.3** design and as shown in FIGS. **21** and **24**, an extent of the link is designed to move from outside of the primary or main proximal link or first bar **454.1** to within said primary or main proximal link or first bar **454.1**. As such, the fourth and fifth pivot points P_4, P_5 are not fixed and thus are configured to move in response to the movement of the digit assembly **408**.

[0225] Said jumper **454.4.4** includes: (i) a proximal drive link opening **454.4.4.1** that is configured to receive a coupler designed to secure said jumper **454.4.4** to the worm drive link **454.4.3** and the medial drive link **474.2** (at pivot point P5), and (ii) a main link opening **454.4.4.2** that is configured to receive a coupler designed to secure said jumper **454.4.4** to the main proximal link **454.1**. The combination of these links (worm wheel coupler **454.4.2**, worm drive link **454.4.3**, jumper **454.4.4**) enables the transfer of the movement from the worm wheel **454.4.1** to the medial assembly **470**. Due to this transfer of movement, the angles formed between the following links change depending on the position of the digit assembly **408**: (i) the worm wheel coupler **454.4.2** and the worm drive link **454.4.3**, (ii) the worm drive link **454.4.3** and jumper **454.4.4**, (iii) the jumper **454.4.4** and the medial drive link **474.2**, and (iv) the worm drive link **454.4.3** and the medial drive link **474.2**.

iv. Worm Wheel Assembly

[0226] The worm wheel assembly **456** includes first and second worm locking members **456.1***a*, **456.1***b*, along with first and second worm bearings **456.2***a*, **456.2***b*. The worm wheel assembly **456** utilizes the configuration of the locking members **456.1***a*, **456.1***b* and bearings **456.2***a*, **456.2***b* to allow the main proximal link **454.1** to remain in a fixed position once it has come into contact with a resistance point/surface, while the motor assembly **410** continues to drive the proximal drive link assembly **454.4** (causing movement of the medial and distal assemblies **470**, **480**). In other words, the bearings **456.2***a*, **456.2***b* allow the main proximal link **454.1** to stop rotating even when the worm wheel **454.4.1** continues to rotate. This continued rotation of the worm wheel **454.4.1** enables the thumb assembly **40** to move the biasing member **474.4.1** from the first or collapsed position to a second or extended position, which enables the medial and distal assemblies **470**, **480** to continue curling about said object. It should be understood that without this slippage between the main proximal link **454.1** and the worm wheel **454.4.1**, the thumb assembly **40** could not rotate the medial and distal assemblies **470**, **480** once the proximal assembly **450** came into contact with a resistance point/surface.

b. Medial Assembly

[0227] The medial assembly **470** is positioned between the proximal assembly **450** and the distal assembly **480** and is the second portion of the thumb assembly **40** configured to move relative to the palm **62**. The medial assembly **470** includes: (i) a medial housing assembly **472**, and (ii) a medial link assembly **474**.

i. Medial Housing Assembly

[0228] As shown in FIGS. **20-24** and **55-67**, the medial housing assembly **472** is designed to substantially surround a majority of the other components of the medial assembly **470**. To achieve this, the medial housing assembly **472** forms an internal medial recess **472.18**. The internal medial recess **472.18** is designed not only to surround components of the medial assembly **470**, but is also designed to receive: (i) an extent of the distal assembly **480** (namely, a distal tongue **482.20**), when the thumb assembly **40** is in the open, uncurled, or neutral position, and (ii) a lesser extent of, or none of, the distal assembly **480** (namely, the distal tongue **482.20**), when the thumb assembly **40** is in the closed, curled, or inwardly rotated position. In other words, the medial housing assembly **472** overlies: (i) a substantial extent of the distal tongue **482.20** when the thumb assembly **40** is in the open, uncurled, or neutral position, and (ii) a minor extent of, or none of, the distal tongue **482.20** when the thumb assembly **40** is in the closed, curled, or inwardly rotated position. Stated another way, the percentage of the distal assembly **480** (namely, the distal tongue **482.20**) that is positioned within the medial housing assembly **472** is reduced when the thumb assembly **40** moves from the open, uncurled, or neutral position to the closed, curled, or inwardly rotated position. By enabling at least a minimal extent of the distal assembly **480** (namely, the distal tongue **482.20**) to be positioned within or adjacent to the medial assembly **470**, the gap G_4 formed between the assemblies **470** and **480** is minimized, and wherein said minimization of said gap G_4 is beneficial because it minimizes the chance or probability that a glove or external covering can be caught or pinched between these assemblies.

[0229] As shown in FIGS. **20-24** and **55-57**, the medial housing assembly **472** specifically includes: (i) a medial jacket assembly **472.1** with a top member **472.1.1** and a bottom member **472.1.2**, and (ii) a medial bottom casing assembly **472.2**. While the bottom member **472.1.2** is in direct contact with and underlies the medial bottom casing assembly **472.2**, the thumb assembly **40** lacks a medial top casing assembly that is in direct contact with the top member **472.1.1**. This design is advantageous because the medial bottom casing assembly **472.2** provides the bottom member **472.1.2** with additional rigidity, which enables said bottom member **472.1.2** to be made from a softer, easier-to-form, and potentially less durable material, thereby increasing the gripping capability of the end effector **10**. In contrast, the top member **472.1.1** does not need to include a softer, easier-to-form, and potentially less durable material because said top member **472.1.1** is not designed to come into regular contact with objects. Additionally, even if the materials of the medial bottom casing assembly **472.2** and the bottom member **472.1.2** are the same, it may be desirable to form these components as two separate components to facilitate replaceability without exposing an inner extent of the thumb assembly **40**. Another way of describing this beneficial configuration includes the fact that the medial jacket assembly **472.1** is configured to provide the primary external shape of the thumb assembly **40**, while the medial casing assembly **472.2** is configured to protect the medial PCB **476** and provide a spacer between the medial link assembly **474** and the medial jacket assembly **472.1**. Nevertheless, it should be understood that in an alternative embodiment, the bottom member **472.1.2** and the medial bottom casing assembly **472.2** may be integrally formed as a single structure.

[0230] As best shown in FIGS. **20-24**, the top member **472.1.1** of the medial jacket assembly **472. 1** includes an exterior surface back with a curvilinear extent in a first direction (namely, across the width of the thumb assembly **40**), and the bottom member **472.1.2** of the medial jacket assembly **472.1** includes an exterior palm surface that has a curvilinear extent in the first direction (namely, across the width of the thumb assembly **40**) and a second direction (namely, across the length of the thumb assembly **40**). The curvilinear extent in the first direction helps ensure that the thumb assembly **40** has rounded edges to help with grasping objects, while the curvilinear extent in the second direction helps ensure that the finger can curl inward.

[0231] As discussed above, the medial housing assembly **472** may be: (i) made from the same materials as the housing assembly **60**, (ii) made from materials that differ from the materials used in the housing assembly **60**, and/or (iii) may include silicon, plastic (e.g., may include a polymer composition), carbon composite, or metal, a combination of these materials, and/or any other known material used in robot systems. Alternatively, the medial housing assembly **472** may include additional components or layers (e.g., between three and an nth layer). It should also be understood that in alternative embodiments the medial jacket assembly **472.1** and the medial casing assembly **472.2** may be combined into a single component and/or additional exterior members may be added to the end effector **10**/thumb assembly **40**.

ii. Medial PCB

[0232] The medial PCB **476** may include a first thumb encoder (e.g., magnetic, optical, capacitive, resistive, etc.) that is positioned adjacent to the first interphalangeal joint and configured to collect first interphalangeal joint data and a second thumb encoder (e.g., magnetic, optical, capacitive, resistive, etc.) that is positioned adjacent to the second interphalangeal joint and configured to collect second interphalangeal joint data. The first interphalangeal joint data and the second interphalangeal joint data are a part of curl data. This curl data may be used by the robot system to generate a vector representation (e.g., a spatial embedding) indicating the state of the proximal, medial, and distal assemblies **450**, **470**, **480** or the environment around these assemblies **450**, **470**, **480**. The encoder of the medial PCB **476** may collect data upon a specific command from the robot system or periodically (e.g., between **500** times per second to once every minute). It should be understood that the robot system's knowledge of the position of the proximal, medial, and distal assemblies **450**, **470**, **480** is highly desirable because said robot system may lack other sensors that a conventional robot system utilizes and/or relies on to grasp or manipulate objects. In particular, said end effector **10** (including the finger assemblies **22***a*-**22***d* and the thumb assembly **40**) may lack pressure sensors that are heavily relied upon in conventional end effectors and instead merely rely on determining the size and position of objects and the knowledge of the position of components contained in the end effector **10**.

[0233] In some implementations, the first and second thumb encoders may integrate multiple sensing modalities, such as a combination of magnetic and optical sensing, to enhance redundancy and accuracy in detecting joint position. This multi-modal approach may enable reliable operation under diverse environmental conditions, such as variations in lighting, temperature, or magnetic interference. Furthermore, the first and second thumb encoders may incorporate machine learning algorithms to facilitate adaptive calibration, improving accuracy over time by analyzing usage patterns. This adaptive capability may also allow the system to compensate for wear or minor misalignments that develop during prolonged operation. In addition to rotational data, the first and second thumb encoders may detect small translational movements or vibrations of the joint. These additional data points could be used to identify early signs of mechanical wear or looseness in the joint assembly, enabling predictive maintenance and extended system longevity. For enhanced precision, the first and second thumb encoders may employ a high-resolution absolute encoding scheme, which provides accurate positional data immediately after power-up without necessitating a homing sequence. This feature could significantly reduce initialization time for the thumb assembly **40**.

[0234] To optimize data handling, the first and second thumb encoders may incorporate local data buffering and preprocessing functionalities. This design may allow high-frequency sampling and real-time filtering of joint position data, transmitting only significant state changes to the primary robot control system. Such an approach could reduce communication bandwidth requirements while maintaining system responsiveness. Additionally, the first and second thumb encoders may be engineered for ultra-low power consumption, with the potential to harvest energy from the mechanical movements of the joint itself. This energy-efficient design could extend operational duration and decrease dependence on external power sources, enhancing the overall autonomy of the sensing system.

iii. Medial Link Assembly

[0235] As shown in FIGS. **58**-**67**, the medial link assembly **474** includes: (i) a primary or main medial link or fifth bar **474.1**, (ii) a medial drive link or sixth bar **474.2**, (iii) a Y-link or seventh bar **474.3**, and (iv) a biasing assembly **474.4**. The medial link assembly **474** is involved with a majority of the movements of the thumb assembly **40**. While the proximal assembly **450** could move without causing a positional change between said proximal assembly **450** and the medial assembly **470**, the distal assembly **480** cannot move without causing a positional change between said distal assembly **480** and the medial assembly **470**. Because most movements of the end effector **10** involve movement of the medial assembly **470** relative to the proximal assembly **450** and/or distal assembly **480**, said medial assembly **470** is involved with a majority of the movements of the thumb assembly **40**. As discussed above, this is in contrast to conventional end effectors and/or conventional fingers and is beneficial because it reduces complexities, reduces components, and increases reliability. many other benefits are obvious to one of skill in the art.

1. Main Medial Link

[0236] The primary or main medial link or fifth bar **474.1** is best shown in FIGS. **58**-**64**. The main medial link **474.1** includes: (i) left and right medial frame members **474.1.1***a*, **474.1.1***b*, (ii) a medial link bridge **474.1.2**, and (iii) a medial link recess **474.1.3**. The left and right medial frame members **474.1.1***a*, **474.1.1***b* include: (i) first interphalangeal joint openings **474.1.1.1***a*, **474.1.1.1***b*, (ii) second interphalangeal joint openings **474.1.1.2***a*, **474.1.1.2***b*, (iii) PCB projections **474.1.1.3** configured to allow the PCB **476** to be offset from the frame member **474.1.1***b*, and (iv) housing mounting projections **474.1.1.4** that are configured to couple the medial housing assembly **472** to the main medial link **474.1**. As shown in the Figures, the first end of the primary or main medial link or fifth bar **474.1** is pivotally coupled to the primary or main proximal link or first bar **454.1** at the sixth pivot point P_6 and at the first interphalangeal joint FIP or MCP. A second end of the primary or main medial link or fifth bar **474.1** is pivotally coupled to the primary or main distal link or eighth bar **484.1** at the seventh pivot point P_7 and at the second interphalangeal joint SIP or DIP. It should be understood that the first end of the primary or main medial link or fifth bar **474.1** includes the first interphalangeal joint openings **474.1.1.1***a*, **474.1.1.1***b*, while the second end of the primary or main medial link or fifth bar **474.1** includes the second interphalangeal joint openings **474.1.1.2***a*, **474.1.1.2***b*. It should be understood that this disclosure contemplates omitting one or more of these components or altering their configuration.

[0237] The left and right medial frame members **474.1.1***a*, **474.1.1***b* are coupled to one another via a medial link bridge **474.1.2**. The combination of the left and right medial frame members **474.1.1***a*, **474.1.1***b* and the medial link bridge **474.1.2** forms a U-shaped member. the U-shaped member includes a medial link recess **474.1.3**. This medial link recess **474.1.3** is configured to receive an extent of the medial link assembly **474**, wherein the position of various components in the medial link assembly **474** may move or shift when the position of the thumb assembly **40** is altered. It should be understood that in other embodiments the medial link bridge **474.1.2** may be omitted, and the frame members **474.1.1***a*, **474.1.1***b* may be connected via a first interphalangeal joint assembly **474.5** and a second interphalangeal joint assembly **474.6**. Additionally, as shown in the Figures, an extent of the main proximal link **454.1** is positioned within the main medial link **474.1**. Specifically, the main medial link **474.1** overlies the medial assembly recess **474.1.1.3.2** of the first and second proximal frame members **454.1.1***a*, **454.1.1***b*. This interlocking nature of the disclosed end effector **10** increases the reliability of said robot system.

[0238] A bushing **474.5.1**, an axle **474.5.2**, and a washer **474.5.3** form the first interphalangeal joint assembly **474.5** and wherein an extent of said first interphalangeal joint assembly **474.5** is positioned within the first interphalangeal joint openings **474.1.1.1***a*, **474.1.1.1***b* and extends between the first and second medial frame members **474.1.1***a*, **474.1.1***b*. Meanwhile, a bushing **474.6.1**, an axle **474.6.2**, and a washer **474.6.3** form the second interphalangeal joint assembly **474.6** and wherein an extent of said second interphalangeal joint assembly **474.6** is positioned within the second interphalangeal joint openings **474.1.1.2***a*, **474.1.1.2***b* and extends between the first and second medial frame members **474.1.1***a*, **474.1.1***b*. The combination of the first interphalangeal joint assembly **474.5** and the first interphalangeal joint openings **474.1.1.1***a*, **474.1.1.1***b* forms the sixth pivot point P_6, while the combination of the second interphalangeal joint assembly **474.6** and the second interphalangeal joint openings **474.1.1.2***a*, **474.1.1.2***b* forms the seventh pivot point P_7.

2. Medial Drive Link and Biasing Assembly

[0239] The medial drive link, or sixth bar **474.2**, is best shown in FIGS. **20-24**, **58-59**, and **65-67**. The medial drive link **474.2** includes: (i) a proximal drive link yoke **474.2.1**, (ii) an elongated segment **474.2.2**, and (iii) a distal link opening **474.2.3**. The proximal drive link yoke **474.2.1** is designed to receive an extent of both: (i) the worm drive link **454.4.3**, and (ii) the jumper **454.4.4**. After the yoke **474.2.1** receives both the worm drive link **454.4.3** and the jumper **454.4.4**, a securement means is inserted into an extent of the proximal drive link opening **454.4.4.1** of the jumper, the main link opening **454.4.4.2** of the jumper, and the proximal drive link opening **454.4.3.2** of the worm drive link **454.4.3**. The coupling of these three linkages: medial drive link **474.2**, worm drive link **454.4.3**, and jumper **454.4.4** creates a fifth pivot point P_5 after a securement means is inserted into each of these openings. Additionally, the coupling of the distal assembly **480** to the medial drive link **474.2** by inserting a securement means within the distal link opening **474.2.3** forms an eighth pivot point P_8.

[0240] It should be understood that both of the disclosed securement means should be sufficiently rigid to withstand the movement and torque of the motors **412**, **418**. However, in other embodiments, the disclosed interlocking or nesting of these components may be omitted and/or the coupling of three separate bars at a single central point may be altered. For example, the medial drive link **474.2** may be coupled to one extent of the jumper **454.4.4** on a single side, and the jumper **454.4.4** may be coupled to the worm drive link **454.4.3** on the opposite side of the jumper **454.4.4** at an alternative location that is different from the location where the medial drive link **474.2** is coupled.

[0241] A biasing projection **474.2.2.1** extends outward and depends from the elongated segment **474.2.2** of medial drive link **474.2** and is designed to receive an extent of the biasing assembly **474.4**. It should be understood that said biasing projection **474.2.2.1** may be coupled to other members (e.g., main medial link **474.1**) in other embodiments. Said biasing assembly **474.4** is best shown in FIGS. **21**, **24**, **57**, **60**, and **66-67**, wherein the biasing assembly **474.4** includes the biasing member **474.4.1** and a biasing coupler **474.4.2**. The biasing coupler **474.4.2** is configured to be positioned within a biasing assembly opening **474.3.3** of the Y-link **474.3**, which enables said biasing member **474.4.1** to be positioned within a biasing assembly receiver **474.3.4** of said Y-link **474.3**. The biasing member **474.4.1** may be a spring or any other known member (e.g., magnet, torsion bar, elastically deformable members, leaf spring, shape memory alloys, etc.) that can provide a biasing force on an extent of the thumb assembly **40** to control the order of closure/collapse of the components contained in said thumb assembly **40**. In particular, when the thumb assembly **40** moves from the open, uncurled, or neutral position to the curled position, the biasing member **474.4.1** moves from a first or collapsed position with a length L_1 to a second or extended position with a length L_2. In the first or collapsed position, the biasing member **474.4.1** exerts a first biasing force F_1 that is less than a second biasing force F_2 that is exerted in the second or extended position. The biasing member **474.4.1** is designed to prevent the medial or distal assemblies **470**, **480** from curling before the proximal housing **452** has come into contact with a resistance point (e.g., an object). Once the proximal housing **452** has come into contact with a resistance point (e.g., an object), the main proximal link **454.1** and the proximal housing **452** stop moving. However, the motor assembly **410** can continue driving the worm drive gear **432.2.2** in a first direction, which turns the worm wheel **454.4.1**, thereby causing the worm drive link **454.4.3** and the jumper **454.4.4** proximal drive link **454.4.3** to move into the proximal link recess **454.1.3** and rotation about the worm wheel axis A_{ww}. This forces the biasing member **474.4.1** to expand from its original state, and therefore forces the medial and distal assemblies **470**, **480** to curl inwards. The thumb assembly **40** can uncurl or return to its original position if the motor assembly **410** drives the worm drive gear **432.2.2** in a second direction, which turns the worm wheel **454.4.1**, thereby causing the worm drive link **454.4.3** and the jumper **454.4.4** to move out of the proximal link recess **454.1.3**. This forces the medial and distal assemblies **470**, **480** to uncurl, therefore allowing the biasing member **474.4.1** to return to its original state, and consequently allowing the main proximal link **454.1** and the proximal housing **452** to return to their original position. It should be understood that other biasing members, structures, assemblies, or components may be used instead of the spring shown in the figures, and in certain embodiments, the biasing assembly **474.4** may be eliminated.

3. Y-Link

[0242] As best shown in FIGS. **52-54**, the Y-link or seventh bar **474.3** is primarily configured to be coupled to an extent of the biasing assembly **474.4** and the main medial link **474.1**. To accomplish this, the Y-link **474.3** includes: (i) a coupling link opening **474.3.1**, (ii) a securement opening **474.3.2**, (iii) a biasing assembly opening **474.3.3**, and (iv) a biasing assembly receiver **474.3.4**. The coupling link opening **474.3.1** is designed to receive a securement member (e.g., pin) that extends through the Y-link opening **454.2.4** of the coupling link **454.2**, thereby pivotally coupling said Y-link **474.3** to the coupling link **454.2** at the third pivot point P_3. While the third pivot point P_3 is formed at the center of the coupling link opening **474.3.1**, a pivot point is not formed at the center of the securement opening **474.3.2**. Instead, the securement opening **474.3.2** is configured to receive an extent of a fastener (e.g., screw) to couple said Y-link **474.3** to an extent of the main medial link **474.1**. Based on this configuration, it should be understood that the Y-link **474.3** may be eliminated in certain embodiments. In these embodiments, the attributes of the Y-link **474.3** may be incorporated into the main medial link **474.1**. As described in greater detail below, the frontal end of the Y-Link that includes the biasing assembly opening **474.3.3** is designed to receive an extent of the biasing member **474.4.1**, and wherein said biasing member **474.4.1** is secured to the Y-Link via insertion of biasing coupler **474.4.2** through both an extent of the biasing member **474.4.1** and the biasing assembly receiver **474.3.4**. It should be understood that in other embodiments, the biasing member **474.4.1** may be integrally formed with the Y-link **474.3**, and thus, various structures described herein may be omitted or modified.

c. Distal Assembly

[0243] The distal assembly **480** is positioned forward of the medial assembly **470** and is the third portion of the thumb assembly **40** configured to move relative to the palm **62**. The distal assembly **480** includes: (i) a distal housing assembly **482**, and (ii) a distal link assembly **484**.

i. Distal Housing Assembly

[0244] As shown in FIGS. **20-24** and **68-76**, the distal housing assembly **482** is designed to substantially surround a majority of the other components of the distal assembly **480**. To achieve this, the distal housing assembly **482** forms an internal distal recess **482.18** and specifically includes: (i) a distal jacket assembly **482.1** with a top member **482.1.1** and a bottom member **482.1.2**, and (ii) a distal bottom casing assembly **482.2**. While the bottom member **482.1.2** is in direct contact with and underlies the distal bottom casing assembly **482.2**, the thumb assembly **40** lacks a distal top casing assembly that is in direct contact with the top member **482.1.1**. This design is advantageous because the distal bottom casing assembly **482.2** provides the bottom member **482.1.2** with additional rigidity, which enables said bottom member **482.1.2** to be made from a softer, easier-to-form, and potentially less durable material, thereby increasing the gripping capability of the end effector **10**. In contrast, the top member **482.1.1** does not need to include a softer, easier-to-form, and potentially less durable material because said top member **482.1.1** is not designed to come into regular contact with objects. Additionally, even if the materials of the distal bottom casing assembly **482.2** and the bottom member **482.1.2** are the same, it may be desirable to form these components as two separate components to facilitate replaceability without exposing an inner extent of the thumb assembly **40**. Another way of describing this beneficial configuration includes the fact that the distal jacket assembly **482.1** is configured to provide the primary external shape of the thumb assembly **40**, while the distal casing assembly **482.2** is configured to protect the distal link assembly **484**. Nevertheless, it should be understood that in an alternative embodiment, the bottom member **482.1.2** and the distal bottom casing assembly **482.2** may be integrally formed as a single structure.

[0245] As best shown in FIGS. **20-24**, the top member **482.1.1** of the distal jacket assembly **482.1** includes an exterior surface back with a curvilinear extent in a first direction (namely, across the width of the thumb assembly **40**). the bottom member **482.1.2** of the distal jacket assembly **482.1** includes an exterior palm surface that has a curvilinear extent in the first direction (namely, across the width of the thumb assembly **40**) and a second direction (namely, across the length of the thumb assembly **40**). The curvilinear extent in the first direction helps ensure that the thumb assembly **40** has rounded edges to help with grasping objects, while the curvilinear extent in the second direction helps ensure that the finger can curl inward. Additionally and as discussed above, the top member **482.1.1** of the distal jacket assembly **482.1** includes a rearward extending distal tongue **482.20**. The distal tongue **482.20** has an arched shape with a curvilinear rear surface **482.20.2**, wherein the width of said distal tongue **482.20** is reduced from a first or front width to a second or rear width. As such, the distal tongue **482.20** includes curvilinear extents in at least two directions. As discussed above, the distal tongue **482.20** is designed to be positioned within or adjacent to the medial housing assembly **472** and configured to minimize the gap G_4 that is formed between assemblies **470** and **480**. It should be understood that in an alternative embodiment, the distal tongue **482.20** may be omitted.

[0246] As discussed above, the distal housing assembly **482** may be: (i) made from the same materials as the housing assembly **60**, (ii) made from materials that differ from the materials used in the housing assembly **60**, and/or (iii) may include silicon, plastic (e.g., may include a polymer composition), carbon composite, or metal, a combination of these materials, and/or any other known material used in robot systems. Alternatively, the distal housing assembly **482** may include additional components or layers (e.g., between three and an nth layer). It should also be understood that in alternative embodiments the distal jacket assembly **482.1** and the distal casing assembly **482.2** may be combined into a single component and/or additional exterior members may be added to the end effector **10**/thumb assembly **40**.

v. Distal Link Assembly

[0247] As shown in FIGS. **20-24** and **68-76**, the distal link assembly **484** includes a mounting tip **486** and a primary or main distal link or eighth bar **484.1** having: (i) an interphalangeal opening **484.1.1**, (ii) a coupler recess **484.1.2**, (iii) a medial drive link opening **484.1.3**, (iv) limiting projections **484.1.4** with a fourth limiting interface region **484.1.4.1**, and (v) a tip projection **484.1.5** with a tip opening **484.1.5.1**. The distal link assembly **484** is involved in the least number of movements of the thumb assembly **40** compared to the number of movements involving the proximal and medial assemblies **450**, **470**. As discussed above, this is in contrast to conventional end effectors and/or conventional fingers and is beneficial because it reduces complexities, reduces components, and increases reliability. It may have other benefits that are obvious to one of skill in the art.

[0248] The interphalangeal opening **484.1.1** is configured to receive a securement means that couples said main distal link **484.1** to the main medial link **474.1** to form the seventh pivot point P_7. The coupler recess **484.1.2** is formed near the interphalangeal opening **484.1.1** and is designed to have the medial drive link opening **484.1.3** positioned therein to help ensure that the securement means that couples the medial drive link **474.2** to the main distal link **484.1** does not interfere with other parts or components of the thumb assembly **40**. Finally, the limiting projections **484.1.4** with the fourth limiting interface region **484.1.4.1** are designed to interact with an extent of the main medial link **474.1** to help ensure that the distal assembly **480** does not over-curl or move backward (e.g., away from the palm **62**).

B. Kinematics of the End Effector

[0249] As best shown in FIGS. **9**, **10** and **12**, the disclosed end effector **10** includes: (i) at least one, and preferably five, metacarpophalangeal (MCP) joints **23***a*-**23***e*, (ii) at least one, and preferably four, proximal interphalangeal (PIP) joints **24***a*-**24***d*, (iii) at least one, and preferably five, distal interphalangeal (DIP) joints **25***a*-**25***e*, and (iv) at least one, preferably two, carpometacarpal (CMC) joints **26***a*, **26***b*. As shown in these Figures, each finger assembly **22***a*-**22***d* includes: (i) an MCP joint **23***a*-**23***d* or a first joint (FFJ**1**, MFJ**1**, RFJ**1**, LFJ**1**), (ii) a PIP joint **24***a*-**24***d* or a second joint (FFJ**2**, MFJ**2**, RFJ**2**, LFJ**2**), and (iii) a DIP joint **25***a*-**25***d* or a third joint (FFJ**3**, MFJ**3**, RFJ**3**, LFJ**3**). The inclusion of these three joints **23***a*-**23***d*, **24***a*-**24***d*, **25***a*-**25***d* allows each finger assembly **22***a*-**22***d* to have three degrees of freedom, while being driven by a single integrated motor **212**. As shown in these Figures, the thumb assembly **40** includes: (i) a second CMC joint **26***a* or a first joint (THJ**1**), (ii) a first CMC joint **26***b* or a second joint (THJ**2**), (iii) a FIP or MCP joint **23***e* or a third joint (THJ**3**), and (iv) a DIP joint **25***e* or a fourth joint (THJ**4**). The inclusion of these four joints, **26***a*, **26***b*, **23***e*, **25***e* allows the thumb assembly **40** to have four degrees of freedom, while being driven by two integrated motors **412**, **418**. As such, the disclosed end effector **10** has at least 12 degrees of freedom, and preferably 16 degrees of freedom, and utilizes at least four, and preferably six, integrated motors (four finger motors **212**. two thumb motors **412**. **418**). Accordingly, the end effector **10** has approximately 2.66 (16 DoF/6 motors) degrees of freedom per motor.

[0250] The first CMC_1 joint **26***b* is defined as having a rotational pivot point Po of the gear assembly **432.3** of the carpometacarpal joint assembly **432** (e.g. FIGS. **120**-**139**), wherein the first CMC_1 joint **26***b* allows for adduction and abduction. The first CMC_1 joint **26***b* allows for rotation of the thumb assembly **40** in a plane, regardless of flexion position, and has a range of motion that is between 80° and 160°, preferably between 100° and 145°, and most preferably between 110° and 150°. To provide the range of motion associated with the first CMC_1 joint **26***b*, the internal angles range from 48° to 228°. The first CMC_1 joint **26***b* is: (i) positioned adjacent to the second CMC_2 joint **26***a*, (ii) has an axis A_{SC} that is substantially orthogonal to an axis A_{FC} of the second CMC_2 joint **26***a*.

[0251] The second CMC_2 joint **26***a* is defined between a lower extent of the motor assembly **410** and the First Link Plane L_1 (i.e., the plane that extends from the first pivot point P_1 to the sixth pivot point P_6) and has a range of motion that is between 35° and 65°, preferably between 40° and 60°, and most preferably between 45° and 55°. To provide the range of motion associated with the second CMC_2 joint **26***a*, the internal angles range from 12° in the first configuration C_1 to 78° in configurations C_4-C_7. It should be understood that the internal angle that extends from the lower extent of the motor assembly **410** to the contact pad/internal surface of the proximal assembly **450** ranges from 13° to 79°. As such, the internal angle has a range of motion that is between 37° and 60° and most preferably between 40° and 55°. The axis A_{FC} of the second CMC_2 joint **26***a* is orthogonal to the A_{SC} of the first CMC_1 joint **26***b* for movement of the proximal assembly **450** of the thumb assembly **40**. The proximal assembly **450** can rotate about the second CMC_2 joint **26***a* such that movement is in the same plane as the medial and distal assemblies **470**, **480** about the MCP and DIP joints **23***e*, **25***e* to flex or extend thumb assembly **40**. The range of motion of the first CMC_1 joint **26***b* is greater than second CMC_2 joint **26***a*.

[0252] The MCP joint **23***e* is defined between the First Link Plane L_1 and the Second Link Plane L_2 (i.e., the plane that extends from the sixth pivot point Pe to the seventh pivot point P_7) and has a range of motion that is between 55° and 90°, preferably between 60° and 85°, and most preferably between 65° and 80°. To provide the range of motion associated with the MCP joint **23***e*, the internal angle ranges from 241° in the configuration C_1 104° in configurations C_4-C_7. It should be understood that the contact pad/internal surface of the proximal assembly **450** to the contact pad/internal surface of the medial assembly **470** ranges from 106° to 246°. As such, the internal angle has a range of motion that is between 55° and 87° and most preferably between 60° and 80°.

[0253] The DIP joint **25***e* is defined between the Second Link Plane L_2 and the Third Link Plane L_3 (i.e., the plane that extends from the eighth pivot point P_8 to the forward most point of the finger FP) and has a range of motion that is between 35° and 57°, preferably between 40° and 55°, and most preferably between 43° and 52°. To provide the range of motion associated with the DIP joint **25***e*, the internal angles ranges from 231° in the first configuration C_1 117° in the seventh configuration C_7. It should be understood that the contact pad/internal surface of the medial assembly **470** to the contact pad/internal surface of the distal assembly **480** ranges from 106° to 214°. As such, the internal angle has a range of motion that is between 35° and 55° and most preferably between 40° and 50°. In summary, the CMC_1 joint **26***b* has the largest range of motion, then the MCP joint **23***e*, then the CMC_2 joint **26***a*, and the DIP joint **25***e* has the smallest range of motion. Additionally, the largest angle is formed between the MCP joint **23***e*, then the DIP joint **25***e*, then the CMC_1 joint **26***b*, and the CMC_2 joint **26***a* has the smallest angle.

a. Scenario 1: FIGS. **38**-**79**

[0254] The thumb assembly **40** moves from the first configuration C_1 until it reaches the seventh configuration C_7, for example as shown in FIGS. **38**-**58**. During the movement between these configurations C_1-C_7, the thumb assembly **40** curls fully from an open, uncurled and unrotated, or neutral state without obstruction. In other words, the thumb assembly **40** is free to move, without being stopped or interrupted from: (i) the open, uncurled, hyperextended, or neutral state, to (ii) a point where the proximal, medial and distal assemblies are at a maximum flexion position or the thumb assembly **40** is in a fully curled or flexed state. In order for this movement to occur, the first motor **412** causes: (i) the first motor shaft **412.2** to rotate about a first motor shaft axis A_{MS1}, (ii) the rotation of the first motor shaft **412.2** causes the first motor gear **416** to rotate around the first motor gear axis A_{MSG1}, (iii) the rotation of the first motor gear **416** causes the flexion gear **432.2.4** to rotate about the flexion axis A_F, (iv) the rotation of the flexion gear **432.2.4** causes the flexion gear adaptor **432.2.10** to rotate, (v) the rotation of the flexion gear adaptor **432.2.10** causes the flexion gear coupler **432.2.12** to rotate, (vi) the rotation of the flexion gear coupler **432.2.12** causes the drive shaft or flexion shaft **432.2.14** to rotate about the drive shaft axis A_{DS}, (vii) the rotation of the drive shaft or flexion shaft **432.2.14** causes the worm drive gear **432.2.2** to rotate, (viii) the rotation of the worm drive gear **432.2.2** causes the worm wheel **454.4.1** to rotate about the worm wheel axis A_{ww}, and (ix) the rotation of the worm wheel **454.4.1** causes the worm wheel coupler **454.4.2** to rotate about the worm wheel axis A_{ww}. the rotation of the worm wheel coupler **454.4.2** causes the fourth pivot point P_4 to shift forward or towards the distal assembly **480**. This forward shift causes the worm drive link or second bar **454.4.3** to shift forward or towards the distal assembly **480** and pivot about the fifth pivot point P_5, wherein this movement causes the medial drive link or sixth bar **474.2** to also shift forward or towards the distal assembly **480**, pivot about the fifth pivot point Ps, and its other end forms P_8 with distal link. and can cause the biasing assembly **474.4** to deform. Finally, the movement of the medial drive link or sixth bar **474.2** causes the distal assembly **480** to rotate about the eighth pivot point P_8.

[0255] FIG. **59** is a schematic that shows the movement of the sixth pivot point P_6 (i.e., from the second location L_{2P6} to the fifth location L_{5P6}), the eighth pivot point P_8 sixth location L_{6P8} to the ninth location L_{9P8}), the end point of the thumb assembly **40** (i.e., from the tenth location L_{10PE1} to the sixteenth location L_{16P5}), the First Link Plane L_1, the Second Link Plane L_2, and the Third Link Plane L_3 caused by the movement of the thumb assembly **40** from the first configuration C_1 to the seventh configuration C_7. As shown in this schematic, movement of said thumb assembly **40** from the first configuration C_1 to the seventh configuration C_7 causes the sixth pivot point P_6 to move along a first curvilinear path CU_1, the eighth pivot point P_8 to move along a second curvilinear path CU_2, and the end point of the thumb assembly **40** to move along a third curvilinear path CU_3, wherein the first, second, or third curvilinear paths are not equal to one another. It can also be seen that the Second Link Plane L_2 and the Third Link Plane L_3 do not move relative to one another before the thumb assembly **40** moves to the fifth configuration C_5. Further, it can be seen that the First Link Plane L_1 and Second Link Plane L_2 do not move relative to one another after the thumb assembly **40** has reached the fourth configuration C_4.

[0256] As will be discussed in greater detail below, FIG. **60** is a schematic that shows the movement of each of the eight pivot points that are caused by the movement of the thumb assembly **40** from the first configuration C_1 to the seventh configuration C_7. Each pivot point is labeled X.Y, wherein X is the configuration of the thumb assembly and Y is the number of the pivot point. For example, **4.2** indicates the location of the second pivot point P**2** when the thumb assembly **40** is in the fourth configuration C_4. As shown in this schematic, movement of the thumb assembly **40** from the first configuration C_1 to the seventh configuration C_7 causes the seventh pivot point P_7 to rotate around the sixth pivot point P_6, all pivot points to rotate around the first pivot point P_1, and other information that is discernible by one of skill in the art based on their review of the figures in this application, including FIG. **60**.

[0257] FIGS. **1-40** and **61-71** show the thumb assembly **40** in the first configuration C_1, wherein: (i) the proximal assembly **450** is offset from being parallel with the motor **412** by between 12° and 17°, and (ii) the proximal, medial, and distal assemblies **450**, **470**, **480** are in an open and original, uncurled and unrotated, or neutral state. In this first configuration C_1, the thumb assembly **40** is in the best position to start or begin to start the procedure for grasping an item due to the fact it is in hyperextension or near hyperextension.

[0258] FIGS. **41-43** and **72-73** show the thumb assembly **40** in a second configuration C_2, wherein: (i) the proximal assembly **450** is offset from being parallel with the motor **412** by between 24° and 36°, (ii) the medial assembly **470** is in a partially curled state, (iii) the distal assembly **480** is in the neutral state, and (iv) the contact pads of the medial assembly **470** and the distal assembly **480** are substantially aligned with one another. The movement of the proximal assembly **450** causes angular movement or change between the proximal and medial assemblies **450**, **470**. This is in contrast to the disclosed finger assemblies **22***a*-**22***d*, wherein movement of the proximal assembly **250** does not cause angular movement or change between the proximal and medial assemblies **250**, **270**. Stated in another way, rotational movement of the proximal assembly **450** around pivot point P_1 changes the angle formed at the MCP joint **23***e*, and rotational movement of the proximal assembly **250** around its pivot point P_1 does not change the angle formed at the MCP joint **24***a*-**24***e*. In comparing FIGS. **38-40** and FIGS. **41-43**, the movement from the first configuration C_1 to the second configuration C_2 has caused the proximal assembly **450** to revolve around the first pivot point P_1 by approximately 12° to 19° and the medial assembly **470** to revolve around the sixth pivot point P_6 by approximately 11° to 16°.

[0259] FIGS. **44-46** show the thumb assembly **40** in a third configuration C_3, wherein: (i) the proximal assembly **450** is offset from being parallel with the motor **412** by between 36° and 54°, (ii) the medial assembly **470** is in a partially curled state, (iii) the distal assembly **480** is in the neutral state, and (iv) the contact pads of the medial assembly **470** and the distal assembly **480** are substantially aligned with one another. In comparing FIGS. **41-43** and FIGS. **44-46**, the movement from the second configuration C_2 to the third configuration C_3 has caused the proximal assembly **450** to revolve around the first pivot point P_1 by approximately 12° to 18° and the medial assembly **470** to revolve around the sixth pivot point P_6 by approximately 18° to 28°. Movement from the second configuration C_2 to the third configuration C_3 illustrates that the medial assembly **470** may revolve around the sixth pivot point P_6 faster than the proximal assembly **450** revolves around the first pivot point Pt.

[0260] FIGS. **47-49** and **74-75** show the thumb assembly **40** in a fourth configuration C_4, wherein: (i) the proximal assembly **450** is offset from being parallel with the motor **412** by between 52° and 78°, (ii) the medial assembly **470** is in a partially curled state, (iii) the distal assembly **480** is in the neutral state, and (iv) the contact pads of the medial assembly **470** and the distal assembly **480** are substantially aligned with one another. As discussed below, the proximal and medial assemblies **450**, **470** are at maximum flexion positions in configurations four through seven C_4-C_7. In comparing FIGS. **44-46** and FIGS. **47-49**, the movement from the third configuration C_3 to the fourth configuration Ca has caused the proximal assembly **450** to revolve around the first pivot point P_1 by approximately 16° to 24° and the medial assembly **470** to revolve around the sixth pivot point P_6 by approximately 28° to 41°. At this fourth configuration C_4, the third limiting interface region **454.1.2.1** of the primary proximal link **454.1** has come into contact with the frame **432.1** of the carpometacarpal joint assembly **432**, which in turn has limited the revolution of the proximal assembly **450** around the first pivot point P_1. Because of the interaction between an extent (i.e., third limiting interface region **454.1.2.1**) of the proximal assembly **450** and the resistance surface/point (i.e., frame **432.1**), movement beyond the fourth configuration C_4 will: (i) not allow the proximal or medial assemblies **450**, **470** to curl or revolve inward, and (ii) cause engagement between the primary proximal link **454.1** and the worm bearings **456.2** to allow the thumb assembly **40** to continue bending or curling towards the palm **62**. Without utilization of the worm bearings **456.2**, the thumb assembly **40** could not continue bending or curling towards the palm **62** (i.e., the thumb assembly **40** would be locked out). It should be understood that in other embodiments, the frame assembly **432.1** may be modified to allow the proximal assembly **450** to: (i) further revolve around the first pivot point P_1 by another 10° to 40°, or (ii) revolve a smaller amount around said first pivot point P_1 by another 10° to 40°.

[0261] As discussed above, the movement from the fourth configuration C_4 to the fifth configuration C_5 causes: (i) the proximal housing assembly **452** and medial assembly **470** to remain frozen in its position, and (ii) the distal assembly **480** to start moving around an additional pivot point (i.e., eighth pivot point P_8). It should be understood from reviewing the Figures of this Application, that while the proximal and medial housing assemblies **452**, **472** may be frozen in position, other components (e.g., biasing assembly **474.4**, the proximal drive link assembly **454.4**, medial link assembly **474**) can continue to move or are not frozen. Without permitting the movement of these other components, the motor **412** could not continue driving the closure of the thumb assembly **40** once the proximal and medial assemblies **450**, **470** come into contact with a resistant surface/point. It should be understood that additional or fewer components of the thumb assembly **40** may not be permitted to move once said thumb assembly **40** reaches the fourth configuration C_4.

[0262] FIGS. **50-52** show the thumb assembly **40** in a fifth configuration C_5, wherein: (i) the proximal and medial assemblies **450**, **470** are in contact with a resistance point/surface, and (ii) the distal assembly **480** is in a partially curled state, wherein none of the assemblies **450**, **470**, **480** are substantially aligned. In said fifth configuration C_5, the proximal and medial assemblies **450**, **470** are at a maximum flexion position and the distal assembly **480** is in a partially curled state. In comparing FIGS. **47-49** and FIGS. **50-52**, the movement from the fourth configuration C_4 to the fifth configuration C_5 has caused the distal assembly **480** to revolve around the eighth pivot point P_8 by approximately 12° to 18°, which causes the fourth limiting interface region **484.1.4.1** to move from being in contact with a lower extent of the medial assembly **470**.

[0263] FIGS. **53-55** and **76-77** show the thumb assembly **40** in a sixth configuration C_6, wherein: (i) the proximal assembly **450** is in contact with a resistance point/surface, and (ii) the proximal, medial, and distal assemblies **450**, **470**, **480** are in a second state, wherein none of the assemblies **450**, **470**, **480** are substantially aligned. In said sixth configuration C_6, the proximal and medial assemblies **450**, **470** are at the maximum flexion position and the distal assembly **480** is in a partially curled state. In comparing FIGS. **50-52** and FIGS. **53-55**, the movement from the fifth configuration C_5 to the sixth configuration C_6 has caused the distal assembly **480** to revolve around the eighth pivot point P_8 by approximately 12° to 18°.

[0264] FIGS. **56-58** and **78-79** show the thumb assembly **40** in a seventh configuration C_7, wherein: (i) the proximal and medial assemblies **450**, **470** are in contact with a resistance point/surface, (ii) the proximal, medial, and distal assemblies **450**, **470**, **480** are in a second state, wherein none of the assemblies **450**, **470**, **480** are substantially aligned, and (iii) the proximal, medial and distal assemblies are at maximum flexion position or the thumb assembly **40** is in a fully curled state. In comparing FIGS. **53-55** and FIGS. **56-58**, the movement from the sixth configuration C_6 to the seventh configuration C_7 has caused the distal assembly **480** to further revolve around the eighth pivot point P_8 by approximately 12° to 18°. The revolution around the eighth pivot point P_8 is stopped when an upper extent of the limiting projections **484.1.4** comes into contact with an upper surface of the medial assembly **470**. Overall, the quicker revolution of the medial assembly **470** around the sixth pivot point **P6** in comparison to the revolution of the proximal assembly **450** around the first pivot point P_1 is desirable because the range of motion of the MCP joint **23*e*** is larger than the range of motion of the DIP joint **25*e***.

b. Scenario 2: FIGS. **80-98**

[0265] The thumb assembly **40** moves from the first configuration C_1 to configurations eight through eleven (C_8-C_{11}). FIGS. **80-82** show the thumb assembly **40** in an open and original, uncurled and unrotated, or neutral state. During the movement, the thumb assembly **40** starts to curl, but the proximal assembly **450** comes into contact with a first object O_1 before the proximal assembly **450** or medial assembly **470** can be fully curled inward (i.e., allow contact between the third limiting interface region **454.1.2.1** and the first limiting interface region **432.1.2.1**). In other words, the movement of the proximal assembly **450** is not independent of the medial assembly **470**; thus the medial assembly **470** also stops before it can be fully curled inward. Stated another way, the CMC_2 joint **26*a*** and the MCP joint **23*e*** are linked together to allow the thumb assembly **40** to be underactuated. In operation, once the proximal assembly **450** or the medial assembly **470** comes into contact with a resistance point/surface (i.e., an object O_1 or the third limiting interface region **454.1.2.1** contacts an extent of the frame **432.1**), the dependent distal assembly **480** starts moving or curling inward towards the palm **62**.

[0266] Once the proximal assembly **450** comes into contact with the object O_1, the distal assembly **480** starts to curl inward. While curling inward, the distal assembly **480** comes into contact with a second object O_2. In other words, by positioning the object O_1 in a location that impedes proximal/medial curl, the thumb assembly **40** cannot maximize the range of movement of each joint contained in the thumb assembly **40** if a second object O2 further impedes distal curl. FIGS. **83-85** and **95-96** show the thumb assembly **40** in an eighth configuration C_8, wherein: (i) the proximal assembly **450** is in contact with a resistance point/surface (i.e., the first object O_1), and (ii) the medial and distal assemblies **470**, **480** are substantially aligned. In these Figures,: (i) proximal assembly **450** revolved about the first pivot point P_1 by approximately 20° to 31°, (ii) the medial assembly **470** revolved around the sixth pivot point P_6 by approximately 23° to 34°, and (iii) the distal assembly **480** remains in a neutral state. In the eighth through tenth configurations C_8-C_{10}, the proximal and medial assemblies remain in partially curled states, while the distal assembly **480** continues to move about the eighth pivot point P_8 to a maximum flexion position or the thumb assembly **40** is in a fully curled state about the object O_1 (and potentially O_2).

[0267] For sake of brevity, movement from configuration eight to nine (C**8** to C**9**) and from configuration nine to ten (C_9 to C_{10}) will not be discussed due to the fact that these movements are similar, if not the same as, the movements that the thumb assembly **40** undergoes when moving from the fourth to fifth (C_4 to C_5) and from fifth to sixth (C**5** to C_6) configurations. However, it should be noted that the angles formed between the components in configurations nine (C_9) and ten (C_{10}) are slightly different from the angles formed between the components in configurations fifth (C_5) and sixth (C_6). In particular, the ninth configuration C_9 positions: (i) the proximal and medial assemblies **450**, **470** are positioned with relationships between those discussed in connection with the second and third configurations (C_2, C_3), and (ii) the distal assembly **480** is positioned with relationships between those discussed in connection with the fifth and sixth configurations (C_5, C_6). While the tenth configuration C_{10} positions: (i) the proximal and medial assemblies **450**, **470** are positioned with relationships between those discussed in connection with the second and third configurations (C_2, C_3), and (ii) the distal assembly **480** is positioned with relationships between those discussed in connection with the fourth and fifth configurations (C_4, C_5). Finally, due to the fact the distal assembly **480** came into contact with a second object O_2, the distal assembly **480** was not able to move from a partially curled state into the fully curled state. Accordingly, the angles set forth in the eleventh configuration C**11** do not match the angles disclosed in the seventh configuration C_7. In particular, the positional relationships in C_{11} are: (i) the proximal and medial assemblies **450**, **470** are positioned with relationships between those discussed in connection with the second and third configurations (C_2, C_3), and (ii) the distal assembly **480** is positioned with relationships between those discussed in connection with the sixth and seventh configurations (C_6, C_7).

c. Scenario 3: FIGS. **99-106**

[0268] The thumb assembly **40** moves from the first configuration C_1 to the twelfth configuration C_{12}. FIGS. **99-101** show the thumb assembly **40** in an open and original, uncurled and unrotated, or neutral state. During the movement, the thumb assembly **40** starts to curl, but the distal assembly **480** comes into contact with an object. Contact between the object and the distal assembly **480** prevents the thumb assembly **40** from being fully curled inward. In other words, by positioning the object in the disclosed locations, the thumb assembly **40** cannot maximize the range of movement of each joint contained in said thumb assembly **40**. In fact, said contact between the object and the distal assembly **480** locks the thumb assembly **40** in position. Stated another way, said contact prevents the thumb assembly **40** from curling around the object. If this scenario happens while the end effector **10** is in use, said system will typically move the object due to compliance in the overall environment, or the robot will try to reposition the thumb assembly **40** within the environment.

[0269] FIGS. **102-106** show the thumb assembly **40** in the twelfth configuration C_{12}, wherein: (i) the distal assembly **480** is in contact with a resistance point/surface (i.e., the object), and (ii) the proximal, medial, and distal assemblies **450**, **470**, **480** are in a second state, wherein none of the assemblies **450**, **470**, **480** are substantially aligned. In said twelfth configuration C_{12}, none of the assemblies **450**, **470**, **480** are at a minimum or maximum flexion position. In these Figures: (i) the proximal assembly **450** revolved about the first pivot point P_1 by approximately 32° to 49°, and (ii) the medial assembly **470** revolved around the sixth pivot point P_6 by approximately 43° to 64°. It should be noted that the twelfth configuration C_{12} is not the same as any of the first through the eleventh configurations C_1-C_{11} because the rotation of the components is slightly different. In particular, the positional relationships between: (i) the medial and distal assemblies **470**, **480** are positioned with relationships between those discussed in connection with the eighth and ninth configurations (C_8, C_9).

d. Scenario 4: FIGS. **107-119**

[0270] The thumb assembly **40** moves from the first configuration C_1 to configurations thirteen and fourteen (C_{13}, C_{14}). FIGS. **107-109** show the thumb assembly **40** in an open and original, uncurled and unrotated, or neutral state. During the movement, the thumb assembly **40** starts to curl, but the medial assembly **470** comes into contact with an object before the proximal and medial assemblies **450**, **470** can be fully curled inward (i.e., allow contact between the third limiting interface region **454**.**1**.**2**.**1** and the frame **432**.**1**). In other words, by positioning the object in a fifth location, the thumb assembly **40** cannot maximize the range of movement of either the proximal or medial assemblies **450**, **470**. This contact between the object and the medial assembly **470** stops the proximal and medial assemblies **450**, **470**; however, the distal assembly **480** can continue movement.

[0271] FIGS. **110-112** and **116-117** show the thumb assembly **40** in the thirteenth configuration C_{13}, wherein: (i) the medial assembly **470** is in contact with a resistance point/surface (i.e., the object), (ii) the proximal and medial assemblies **450**, **470** are in a partially curled state, and (iii) the distal assembly **480** is in a neutral state. In FIGS. **110-112** and **116-117**: (i) the proximal assembly **450** revolved about the first pivot point P_1 by approximately 8° to 12°, (ii) the medial assembly **470** revolved about the sixth pivot point P_6 by approximately 7° to 9°, and (iii) the distal assembly **480** has not revolved around the eighth pivot point P_8. It should be noted that the thirteenth configuration C_{13} is not the same as any of the first through the twelfth configurations C_1-C_{12} because the rotation of the components is slightly different.

[0272] FIGS. **113-115** and **118-119** show the thumb assembly **40** in the fourteenth configuration C_{14}, wherein: (i) the medial assembly **470** is in contact with a resistance point/surface (i.e., the object), (ii) the proximal and medial assemblies **450**, **470** are in a partially curled state, and (iii) the distal assembly **480** is in a maximum flexion position. In the fourteenth configuration C_{14}, neither the proximal assembly **450** nor the medial assembly **470** are at minimum or maximum flexion position. In FIGS. **118-119**: (i) the proximal and medial assemblies **450**, **470** remain in the same position as the thirteenth configuration C_{13}, and (ii) the distal assembly **480** revolved about the eighth pivot point P_8 by approximately 37° to 56°. It should be noted that the fourteenth configuration C_{14} is not the same as any of the first through the thirteenth configurations C_1-C_{13} because the rotation of the components is different.

e. Scenario 5: FIGS. **120-139**

[0273] The thumb assembly **40** rotates about the first CMC_1 joint **26***b* allowing full inward rotation of the proximal, medial, and distal assemblies **450**, **470**, **480** towards the palm **62**. In other words, the thumb assembly **40** can move from: (i) the unrotated state in the first configuration C_1 to (ii) to a fully rotated state in a seventeenth configuration C_{17}. To accomplish this, the second motor **418** moves the second motor drive gear **422**, which interacts with the interposition gear **432.2.6** (as described above). FIGS. **120-139** illustrate the progression of movement from the first configuration C_1 to the seventeenth configuration C_{17} while the proximal, medial, and distal assemblies **450**, **470**, **480** remain in an uncurled state. The angle of rotation about rotational pivot point ranges from about 228° in the first configuration C_1 to about 48° in the seventeenth configuration C_{17}.

[0274] FIGS. **120** and **124** show the thumb assembly **40** in the first configuration C_1, with an angle of about 228°. In FIGS. **121**, **125**, and **128-131**, the thumb assembly **40** is in a fifteenth configuration C_{15}, where an internal angle of about 160° is formed between an inner surface and the palm **62**. In FIGS. **122**, **126**, and **132-135**, the thumb assembly **40** is in a sixteenth configuration C_{16}, where an internal angle of about 125° is formed between an inner surface and the palm **62**. In FIGS. **123**, **127**, and **136-139**, the thumb assembly **40** is in the seventeenth configuration C_{17}, where an internal angle of about 48° is formed between an inner surface and the palm **62**.

[0275] As discussed above, the first motor **412** drives the drive shaft **432.2.14** via the gears (i.e., flexion gear **432.2.4**, first motor gear **416**) and cap (flexion gear coupler **432.2.12** or adaptor **432.2.10**) Additionally, the second motor **418** drives the anterposition gear **432.2.6**, which in turn rotates an extent of the thumb frame **432.1** (specifically, the lower frame member **432.1.4**). Due to the configuration of the gear (interposition gear **432.2.6**), frame (thumb frame **432.1**), and axle (drive shaft/flexion shaft **432.2.14**), movement of the second motor **418** also moves the axle **432.2.14**. The movement of the axle **432.2.14** by the second motor **418** causes the worm drive gear **432.2.2** to move the worm wheel **454.4.1**, which causes flexion of the thumb assembly **40**. In other words, when the thumb assembly **40** is rotated inward or towards the palm **62** during adduction the thumb assembly **40** also undergoes slight flexion or curling. Likewise, when the thumb assembly **40** is rotated outward or away from the palm **62** during abduction, the thumb assembly **40** also undergoes slight extension. Stated another way, there is a degree of coupling between the second CMC_2 joint **26** and the first CMC_1 joint **26***b*. To adjust for this coupling, the robot can compensate for this slight degree utilizing software. In other embodiments, the configuration of the gear (anterposition gear **432.2.6**), frame (thumb frame **432.1**), and axle (drive shaft/flexion shaft **432.2.14**) may be altered such that there is no coupling between the first CMC_1 joint **26** and the second CMC_2 joint **26***b*. In this alternative embodiment, there will be no flexion or extension of the thumb assembly **40** when the assembly **40** undergoes adduction or abduction. Although the figures illustrate the thumb assembly **40** in a neutral state as an example to show the rotational movement, the same rotational movement can be applied to the thumb assembly **40** in various states of flex or extension where the proximal, medial, and distal assemblies **450**, **470**, **480** are uncurled, partially curled, or fully curled.

C. Configurations, Planes, Pivot Points, Angles, and Distances

TABLE 1

P_S, P_{22b}	Sagittal Plane or Middle Finger Plane
P_{TM}	Thumb Motor Plane
P_{SU}	Surface Plane
P_{S1}	First Section Plane
P_{S2}	Second Section Plane

TABLE 2

P_0	Zero Pivot Point - Fixed
P_1	First Pivot Point - Fixed
P_2	Second Pivot Point - Fixed
P_3	Third Pivot Point - Fixed
P_4	Fourth Pivot Point - Not Fixed
P_5	Fifth Pivot Point - Not Fixed
P_6	Sixth Pivot Point - Fixed
P_7	Seventh Pivot Point - Not Fixed
P_8	Eighth Pivot - Fixed

TABLE 3

C_1	First Configuration
C_2	Second Configuration
C_3	Third Configuration
C_4	Fourth Configuration
C_5	Fifth Configuration
C_6	Sixth Configuration
C_7	Seventh Configuration
C_8	Eighth Configuration
C_9	Ninth Configuration
C_{10}	Tenth Configuration
C_{11}	Eleventh Configuration
C_{12}	Twelfth Configuration
C_{13}	Thirteenth Configuration
C_{14}	Fourteenth Configuration

TABLE 4

L_1	First Link Plane	Extends Between P_1 and P_6
L_2	Second Link Plane	Extends Between P_6 and P_8
L_3	Third Link Plane	Extends Between P_8 and FP
L_4	Fourth Link Plane	Extends Between P_5 and P_7
L_5	Fifth Link Plane	Extends Between P_3 and CB1
L_6	Sixth Link Plane	Extends Between P_2 and P_3
L_7	Seventh Link Plane	Extends Between P_1 and P_4
L_8	Eighth Link Plane	Extends Between P_4 and P_5
L_9	Ninth Link Plane	Extends Between P_5 and P_6

TABLE 5

1.1 First Configuration, First Pivot Point	4.2 Fourth Configuration, Second Pivot Point
2.1 Second Configuration, First Pivot Point	5.2 Fifth Configuration, Second Pivot Point
3.1 Third Configuration, First Pivot Point	6.2 Sixth Configuration, Second Pivot Point
4.1 Fourth Configuration, First Pivot Point	7.2 Seventh Configuration, Second Pivot Point
5.1 Fifth Configuration, First Pivot Point	1.3 First Configuration, Third Pivot Point
6.1 Sixth Configuration, First Pivot Point	2.3 Second Configuration, Third Pivot Point

TABLE 5-continued

7.1 Seventh Configuration, First Pivot Point	3.3 Third Configuration, Third Pivot Point
1.2 First Configuration, Second Pivot Point	4.3 Fourth Configuration, Third Pivot Point
2.2 Second Configuration, Second Pivot Point	5.3 Fifth Configuration, Third Pivot Point
3.2 Third Configuration, Second Pivot Point	6.3 Sixth Configuration, Third Pivot Point
7.3 Seventh Configuration, Third Pivot Point	5.6 Fifth Configuration, Sixth Pivot Point
1.4 First Configuration, Fourth Pivot Point	6.6 Sixth Configuration, Sixth Pivot Point
2.4 Second Configuration, Fourth Pivot Point	7.6 Seventh Configuration, Sixth Pivot Point
3.4 Third Configuration, Fourth Pivot Point	1.7 First Configuration, Seventh Pivot Point
4.4 Fourth Configuration, Fourth Pivot Point	2.7 Second Configuration, Seventh Pivot Point
5.4 Fifth Configuration, Fourth Pivot Point	3.7 Third Configuration, Seventh Pivot Point
6.4 Sixth Configuration, Fourth Pivot Point	4.7 Fourth Configuration, Seventh Pivot Point
7.4 Seventh Configuration, Fourth Pivot Point	5.7 Fifth Configuration, Seventh Pivot Point
1.5 First Configuration, Fifth Pivot Point	6.7 Sixth Configuration, Seventh Pivot Point
2.5 Second Configuration, Fifth Pivot Point	7.7 Seventh Configuration, Seventh Pivot Point
3.5 Third Configuration, Fifth Pivot Point	1.8 First Configuration, Eighth Pivot Point
4.5 Fourth Configuration, Fifth Pivot Point	2.8 Second Configuration, Eighth Pivot Point
5.5 Fifth Configuration, Fifth Pivot Point	3.8 Third Configuration, Eighth Pivot Point
6.5 Sixth Configuration, Fifth Pivot Point	4.8 Fourth Configuration, Eighth Pivot Point
7.5 Seventh Configuration, Fifth Pivot Point	5.8 Fifth Configuration, Eighth Pivot Point
1.6 First Configuration, Sixth Pivot Point	6.8 Sixth Configuration, Eighth Pivot Point
2.6 Second Configuration, Sixth Pivot Point	7.8 Seventh Configuration, Eighth Pivot Point
3.6 Third Configuration, Sixth Pivot Point	
4.6 Fourth Configuration, Sixth Pivot Point	

TABLE 6

Configuration 1			Configuration 2		
Angle	Lower Bound	Upper Bound	Angle	Lower Bound	Upper Bound
A56	142°	214°	A62	142°	213°
A57	164°	246°	A63	153°	229°
A58	13°	19°	A64	25°	38°
A59	154°	231°	A65	153°	229°
A60	161°	241°	A66	150°	225°
A61	12°	17°	A67	24°	36°
Configuration 4			**Configuration 6**		
Angle	Lower Bound	Upper Bound	Angle	Lower Bound	Upper Bound
A74	142°	213°	A86	118°	178°
A75	106°	159°	A87	106°	159°
A76	53°	79°	A88	53°	79°
A77	152°	228°	A89	129°	193°
A78	104°	156°	A90	104°	155°
A79	52°	78°	A91	52°	78°
Configuration 7			**Configuration 8**		
Angle	Lower Bound	Upper Bound	Angle	Lower Bound	Upper Bound
A92	106°	160°	A98	142°	213°
A93	106°	159°	A99	141°	211°
A94	53°	79°	A100	33°	49°
A95	117°	175°	A101	152°	228°
A96	104°	155°	A102	138°	207°
A97	52°	78°	A103	32°	48°
Configuration 11			**Configuration 12**		
Angle	Lower Bound	Upper Bound	Angle	Lower Bound	Upper Bound
A116	113°	169°	A122	142°	213°
A117	141°	211°	A123	121°	181°
A118	33°	49°	A124	45°	67°
A119	122°	183°	A125	151°	227°
A120	138°	207°	A126	118°	177°
A121	32°	48°	A127	44°	66°

TABLE 6-continued

Configuration 13			Configuration 14		
Angle	Lower Bound	Upper Bound	Angle	Lower Bound	Upper Bound
A128	142°	214°	A134	106°	159°
A129	158°	236°	A135	158°	236°
A130	21°	31°	A136	21°	31°
A131	153°	230°	A137	117°	175°
A132	154°	232°	A138	155°	232°
A133	20°	29°	A139	20°	29°

TABLE 7

Angle	Lower Bound	Upper Bound	Preferred Lower Bound	Preferred Upper Bound
λ1	66.0°	154.0°	88.0°	132.0°
λ2	30.4°	70.9°	40.5°	60.8°
λ3	43.6°	101.8°	58.2°	87.3°
λ4	28.9°	67.4°	38.5°	57.8°
λ5	43.3°	101.1°	57.8°	86.7°
A15	3.8°	8.8°	5.0°	7.5°
A16	33.6°	78.5°	44.8°	67.2°
A17	5.8°	13.6°	7.8°	11.7°
A18	37.4°	87.3°	49.9°	74.8°
A19	42.8°	99.8°	57.0°	85.6°
A20	1.7°	3.9°	2.3°	3.4°
A21	80.3°	187.4°	107.1°	160.7°
A22	46.7°	109.0°	62.3°	93.4°
A23	46.4°	108.2°	61.8°	92.8°
A24	72.7°	169.6°	96.9°	145.4°
A25	96.9°	226.2°	129.2°	193.9°
A26	3.5°	8.2°	4.7°	7.1°
A27	10.9°	25.4°	14.5°	21.7°
A28	14.9°	34.8°	19.9°	29.8°
A29	2.9°	6.8°	3.9°	5.8°
A30	57.8°	135.0°	77.1°	115.7°
A31	42.9°	100.2°	57.3°	85.9°
A32	39.1°	91.2°	52.1°	78.2°
A33	5.4°	12.6°	7.2°	10.8°
A34	44.5°	103.8°	59.3°	88.9°
A35	54.0°	126.0°	72.0°	108.0°

TABLE 8

Distance	Lower Bound	Upper Bound	Preferred Lower Bound	Preferred Upper Bound
D30	13.5	31.5	18	27
D31	18.5	42.5	24.5	36.5
D32	20.5	47.5	27	40.5
D33	7	16.5	9.5	14
D34	6	14.5	8	12.5
D35	1.5	3	1.5	2.5
D36	5.5	13	7.5	11.5
D37	6.5	15	8.5	13
D38	5	11.5	6.5	10
D39	4	10	5.5	8.5
D40	0.5	1.5	1	1.5
D41	1	2.5	1.5	2
D42	8.5	19.5	11	16.5
D43	2.5	6	3.5	5.5
D44	4	9	5	7.5
D45	7	16.5	9.5	14
D46	11.5	27	15.5	23.5
D47	12	27.5	16	23.5
D48	14	32.5	18.5	27.5
D49	6	14	8	12
D50	17.5	40.5	23	35
D51	5.5	13	7.5	11
D52	18.5	42.5	24.5	36.5
D53	21.5	49.5	28.5	42.5

TABLE 8-continued

Distance	Lower Bound	Upper Bound	Preferred Lower Bound	Preferred Upper Bound
D54	20.5	48	27.5	41
D55	7	17	9.5	14.5

D. Industrial Application

[0276] While the disclosure shows illustrative embodiments of a robot (in particular, a humanoid robot), it should be understood that embodiments are designed to be examples of the principles of the disclosed assemblies, methods and systems, and are not intended to limit the broad aspects of the disclosed concepts to the embodiments illustrated. As will be realized, the disclosed robot, and its functionality and methods of operation, are capable of other and different configurations and several details are capable of being modified all without departing from the scope of the disclosed methods and systems. For example, one or more of the disclosed embodiments, in part or whole, may be combined with a disclosed assembly, method and system. As such, one or more steps from the diagrams or components in the Figures may be selectively omitted and/or combined consistent with the disclosed assemblies, methods and systems. For example, end effector **10** may lack traditional sensors (e.g., pressure, force, etc.) found in a conventional end effector **10**. Additionally, those skilled in the art would recognize that many features of the implementation can be grouped together, split apart, reorganized, removed, or duplicated. Further, one or more steps from the arrangement of components may be omitted or performed in a different order. Accordingly, the drawings, diagrams, and detailed description are to be regarded as illustrative in nature, not restrictive or limiting, of the said humanoid robot.

[0277] While the above-described robot is designed as a head for use with a general-purpose humanoid robot, it should be understood that its assemblies, components, learning capabilities, and/or kinematic capabilities may be used with other robots. Examples of other robots include: articulated robot (e.g., an arm having two, six, or ten degrees of freedom, etc.), a cartesian robot (e.g., rectilinear or gantry robots, robots having three prismatic joints, etc.), Selective Compliance Assembly Robot Arm (SCARA) robots (e.g., with a donut shaped work envelope, with two parallel joints that provide compliance in one selected plane, with rotary shafts positioned vertically, with an end effector attached to an arm, etc.), delta robots (e.g., parallel link robots with parallel joint linkages connected with a common base, having direct control of each joint over the end effector, which may be used for pick-and-place or product transfer applications, etc.), polar robots (e.g., with a twisting joint connecting the arm with the base and a combination of two rotary joints and one linear joint connecting the links, having a centrally pivoting shaft and an extendable rotating arm, spherical robots, etc.), cylindrical robots (e.g., with at least one rotary joint at the base and at least one prismatic joint connecting the links, with a pivoting shaft and extendable arm that moves vertically and by sliding, with a cylindrical configuration that offers vertical and horizontal linear movement along with rotary movement about the vertical axis, etc.), self-driving car, a kitchen appliance, construction equipment, or a variety of other types of robot systems. The robot system may include one or more sensors (e.g., cameras, temperature, pressure, force, inductive or capacitive touch), motors (e.g., servo motors and stepper motors), actuators, biasing members, encoders, housing, or any other component known in the art that is used in connection with robot systems. Likewise, the robot system may omit one or more sensors (e.g., cameras, temperature, pressure, force, inductive or capacitive touch), motors (e.g., servo motors and stepper motors), actuators, biasing members, encoders, housing, or any other component known in the art that is used in connection with robot systems.

[0278] In other embodiments, other configurations and/or components may be utilized. For example, the end effector **10** may include one or more tactile sensor assemblies. The tactile sensor assembly may measure the load experienced on the finger assemblies of the end effector using a strain gauge or arrays of strain gauges. The strain gauges may measure strain, which may be used to determine the force, stress, torque, pressure, deflection, etc. experienced on the finger assemblies. The feedback provided by these tactile sensor assemblies embedded in the end effector (finger assemblies) can be combined with data from the encoders, torque sensors and/or other sensors that are positioned adjacent to or configured to obtain information from each joint. This combination of feedback, data, and/or information can be used to control the actuation of the finger assemblies, potentially enabling the robot to perform complex manipulations that require delicate touch. While the tactile sensor assemblies may be primarily designed to be embedded in the distal assembly of the finger assemblies, it should be understood that: (i) the tactile sensor assemblies may be positioned at any location in the end effector (e.g., palm, finger, thumb), (ii) may not be embedded in the assembly; instead, may be integrally formed therewith or directly secured to an outer extent of said assembly, (iii) may be formed in a layer or external covering (e.g., textile assembly—namely, a glove) that is positioned on top of or over said assembly, and/or (iv) a combination of any one of the described options. Examples of possible combinations include: (i) a portion of the tactile sensor assembly positioned in the textile assembly (e.g., glove) and a portion of the tactile sensor assembly embedded within the end effector, (ii) a portion of the tactile sensor assembly secured to the exterior of the housing of said end effector and a portion of the tactile sensor assembly embedded within the end effector, (iii) a portion of the tactile sensor assembly positioned in the textile assembly (e.g., glove), a portion of the tactile sensor assembly secured to the exterior of the housing of said end effector, and a portion of the tactile sensor assembly embedded within the end effector, (iv) a portion of the tactile sensor assembly positioned in the textile assembly (e.g., glove), a portion of the tactile sensor assembly integrally formed with the exterior of the housing of said end effector, and a portion of the tactile sensor assembly embedded within the end effector, and/or (v) any combination of hybrid thereof.

[0279] The strain gauges included in the tactile sensor assemblies may be any type of strain gauge including: (i) linear strain gauges, (ii) double linear strain gauges, (iii) shear or torsional strain gauges, (iv) rosette strain gauges (T (or Tee) shaped, rectangular shaped, delta shaped, stacked), (v) diaphragm strain gauges, (vi) biaxial strain gauges, (vii) bi-directional strain gauges, (viii) stacked strain gauges, (ix) cross strain gauges, (x) double shear, (xi) circular, (xii) any hybrid or combination thereof, and/or (xi) any other suitable strain gauge type that is known to one of skill in the art. The strain gauges may be arranged in different configurations including: (i) quarter-bridge configurations, (ii) half-bridge configurations, and/or (iii) full-bridge configurations. The strain gauges may also be foil strain gauges, semiconductor strain gauges, thin-film strain gauges, ink based strain gauges, thick-film strain gauges, optical, nano composite, and/or any combination or hybrid thereof. Further, the strain gauges may be directly integrated into the housings (interior or exterior), coupled to said housings (interior or exterior) after the housing is manufactured, coupled to another structure (e.g., bridge, spring, etc.) positioned within the housing, integrated into or coupled to the motor or motor housing, positioned between housings, and/or any other known configuration or combination thereof.

[0280] The foil strain gauges may be made from or include: (i) foils that may be or may include constantan (copper-nickel alloy) karma (nickel-chromium alloy) isoclastic (nickel-iron alloy) evanohm (nickel-chromium alloy) nichrome v (nickel-chromium alloy), and (ii) carrier that may be or may include polyimide film, epoxy or phenolic resin, glass-fiber reinforced epoxy, ceramic backing, and/or polyurethane. Finally, the strain gauges may be any gauge that meets, uses, and/or was tested with at least one of the flowing standards: ASTM E251-13 (2018), Standard Test Methods for Performance Characteristics of Metallic Bonded Resistance Strain Gages, ASTM International, ISO 376:2011, Metallic materials—Calibration of force-proving instruments used for the verification of uniaxial testing machines, ISO 9513:2012, Metallic materials—Calibration of extensometer systems used in uniaxial testing, VDI/VDE 2635 Blatt 2, Experimental structural analysis—Recommendation on the implementation of strain measurements at high temperatures, IEC 61298-3:1998, Process measurement and control devices—General methods and procedures for evaluating performance—Part 3: Tests for the effects of influence quantities, DIN 51301, which is hereby incorporated by reference for all purposes. The strain gauges may be used in combination with other sensors in the sensing assembly or at alternate locations in the robot. Other sensors or technology that may replace or be added to the tactile sensor assembles are discussed below.

[0281] It should be understood that other sensors and/or technology may be used instead of or in combination with the sensor assemblies discussed above. Other strain gauge technology that may be used includes: (i) mems-based strain gauges, (ii) nanocomposite strain gauges, (iii) thin-film or thick-film strain gauges (e.g., C4A Series or EA Series from Vishay Precision Group, RF9 Series or Y Series from Hottinger Brüel & Kjær, KFG Series or KFR Series from Kyowa Electronic Instruments, TFSG Series from BCM

Sensor Technologies, SGT Series or KFH Series from Omega Engineering, ELF Series or EPL Series from Meggitt Sensing Systems, or any other known manufacture), (iv) inductive strain gauges, (v) capacitive strain gauges, (vi) piezoelectric strain gauges, (vii) optical fiber strain gauges, (viii) semiconductor strain gauges, and/or (ix) a hybrid or combination thereof. The strain gauges may provide measurements with high accuracy, but may lack high resolution. The additional sensors used in combination with the strain gauges in the sensor assembly may help provide a higher resolution. Alternative or additional sensors/technology may include photodiodes, Hall Effect sensors, capacitive sensors, piezoelectric sensors, piezoresistive sensors, optical sensors, force-sensitive resistors (FSRs), magnetic sensors, inductive sensors, micro-electro-mechanical systems (MEMS) sensors, dielectric elastomer sensors, quantum tunneling composite (QTC) sensors, fiber Bragg grating sensors, ultrasonic sensors, thermal sensors, electroactive polymers, triboelectric nanogenerators (TENGs), linear variable differential transformers (LVDTs), flex sensors, acoustic emission sensors, resistive touch sensors, proximity sensors, hydrogel-based sensors, smart skin technologies, magnetoelastic sensors, capacitive micromachined ultrasonic transducers (CMUTs), pressure-sensitive adhesives, electromagnetic acoustic transducers (EMATs), photonic crystal sensors, laser doppler vibrometers, electrical impedance tomography sensors, graphene-based sensors, nanowire sensors, electronic skin (e-skin) sensors, carbon nanotube-based sensors, barometric pressure sensors, eddy current sensors, microfluidic tactile sensors, nanogenerators, stretchable electronic sensors, force torque sensors, rheological sensors, haptic feedback sensors, polymer nanofiber sensors, ionic liquid-based sensors, thermocouple sensors, touch-sensitive field-effect transistors, terahertz radiation sensors, radar sensors, LIDAR sensors, infrared touch sensors, humidity sensors, mechanical limit switches, pressure mapping sensors, distributed fiber optic sensors, magnetostrictive sensors, optoelectronic sensors, surface acoustic wave (SAW) sensors, capaciflectance sensors, tribo-skin sensors, spintronic sensors, photonic touch sensors, acoustic resonant sensors, and capacitive tomography sensors, or any other suitable technology that is known to one of skill in the art.

[0282] In other embodiments, other configurations and/or components may be utilized. As is known in the data processing and communications arts, a general-purpose computer typically comprises a central processor or other processing device, an internal communication bus, various types of memory or storage media (RAM, ROM, EEPROM, cache memory, disk drives etc.) for code and data storage, and one or more network interface cards or ports for communication purposes. The software functionalities involve programming, including executable code as well as associated stored data. The software code is executable by the general-purpose computer. In operation, the code is stored within the general-purpose computer platform. At other times, however, the software may be stored at other locations and/or transported for loading into the appropriate general-purpose computer system.

[0283] A server, for example, includes a data communication interface for packet data communication. The server also includes a central processing unit (CPU), in the form of one or more processors, for executing program instructions. The server platform typically includes an internal communication bus, program storage and data storage for various data files to be processed and/or communicated by the server, although the server often receives programming and data via network communications. The hardware elements, operating systems and programming languages of such servers are conventional in nature, and it is presumed that those skilled in the art are adequately familiar therewith. The server functions may be implemented in a distributed fashion on a number of similar platforms, to distribute the processing load.

[0284] Hence, aspects of the disclosed methods and systems outlined above may be embodied in programming. Program aspects of the technology may be thought of as "products" or "articles of manufacture" typically in the form of executable code and/or associated data that is carried on or embodied in a type of machine-readable medium. "Storage" type media includes any or all of the tangible memory of the computers, processors or the like, or associated modules thereof, such as various semiconductor memories, tape drives, disk drives and the like, which may provide non-transitory storage at any time for the software programming. All or portions of the software may at times be communicated through the Internet or various other telecommunication networks. Thus, another type of media that may bear the software elements includes optical, electrical and electromagnetic waves, such as used across physical interfaces between local devices, through wired and optical landline networks and over various air-links. The physical elements that carry such waves, such as wired or wireless links, optical links or the like, also may be considered as media bearing the software. As used herein, unless restricted to non-transitory, tangible "storage" media, terms such as computer or machine "readable medium" refer to any medium that participates in providing instructions to a processor for execution.

[0285] A machine-readable medium may take many forms, including but not limited to, a tangible storage medium, a carrier wave medium or physical transmission medium. Non-volatile storage media include, for example, optical or magnetic disks, such as any of the storage devices in any computer(s) or the like, such as may be used to implement the disclosed methods and systems. Volatile storage media include dynamic memory, such as the main memory of such a computer platform. Tangible transmission media include coaxial cables, copper wire and fiber optics, including the wires that comprise a bus within a computer system. Carrier-wave transmission media can take the form of electric or electromagnetic signals, or acoustic or light waves such as those generated during radio frequency (RF) and infrared (IR) data communications. Common forms of computer-readable media therefore include for example: a floppy disk, a flexible disk, hard disk, magnetic tape, any other magnetic medium, a CD-ROM, DVD or DVD-ROM, any other optical medium, punch cards, paper tape, any other physical storage medium with patterns of holes, a RAM, a PROM and EPROM, a FLASH-EPROM, any other memory chip or cartridge, a carrier wave transporting data or instructions, cables or links transporting such a carrier wave, or any other medium from which a computer can read programming code and/or data. Many of these forms of computer readable media may be involved in carrying one or more sequences of one or more instructions to a processor for execution.

[0286] It is to be understood that the invention is not limited to the exact details of construction, operation, exact materials or embodiments shown and described, as obvious modifications and equivalents will be apparent to one skilled in the art. While the specific embodiments have been illustrated and described, numerous modifications come to mind without significantly departing from the spirit of the invention, and the scope of protection is only limited by the scope of the accompanying Claims. It should also be understood that substantially utilized herein means a deviation less than 15% and preferably less than 5%. It should also be understood that other configuration or arrangements of the above-described components is contemplated by this Application. Moreover, the description provided in the background section should not be assumed to be prior art merely because it is mentioned in or associated with the background section. The background section may include information that describes one or more aspects of the subject of the technology. Finally, the mere fact that something is described as conventional does not mean that the Applicant admits it is prior art.

[0287] In this Application, to the extent any U.S. patents, U.S. patent applications, or other materials (e.g., articles) have been incorporated by reference, the text of such materials is only incorporated by reference to the extent that they do not conflict with materials, statements and drawings set forth herein. In the event of such conflict, the text of the present document controls, and terms in this document should not be given a narrower reading in virtue of the way in which those terms are used in other materials incorporated by reference. It should also be understood that structures and/or features not directly associated with a robot cannot be adopted or implemented into the disclosed humanoid robot without careful analysis and verification of the complex realities of designing, testing, manufacturing, and certifying a robot for completion of usable work nearby and/or around humans. Theoretical designs that attempt to implement such modifications from non-robotic structures and/or features are insufficient (and in some instances, woefully insufficient) because they amount to mere design exercises that are not tethered to the complex realities of successfully designing, manufacturing and testing a robot.

1. A thumb assembly for an underactuated end effector for a humanoid robot, the thumb assembly comprising:
- a frame;
- a sagittal plane;
- a motor assembly removably coupled to the frame and including both a first motor and a second motor;
- a base joint assembly coupled to the frame and comprising:
  - a flexion gear configured to be driven by the first motor, and wherein the first motor has a first motor shaft that is oriented at a first acute angle relative to the sagittal plane;
  - an interposition gear configured to be driven by the second motor, and wherein the second motor has a second motor shaft that is oriented at a second acute angle relative to the sagittal plane, and wherein the first acute angle is approximately equal to the second acute angle;
  - a first carpometacarpal joint formed between an extent of the base joint assembly and a digit assembly, and wherein movement of the interposition gear using the second motor causes the digit assembly to rotate about a first carpometacarpal joint axis of the first carpometacarpal joint; and
- the digit assembly coupled to the base joint assembly and comprising:
  - a proximal assembly;
  - a second carpometacarpal joint pivotably coupling the proximal assembly to an extent of the base joint assembly, and wherein movement of the flexion gear using the first motor causes the digit assembly to rotate about a second carpometacarpal joint axis of the second carpometacarpal joint;
  - a proximal interphalangeal joint pivotably coupling the proximal assembly to a medial assembly; and
  - a distal interphalangeal joint pivotably coupling the medial assembly to a distal assembly.

2. The thumb assembly of claim **1**, further comprising a carpometacarpal joint housing assembly configured to rotate in response to rotation of the interposition gear.

3. The thumb assembly of claim **2**, wherein the carpometacarpal joint housing assembly includes an upper edge that is positioned proximate to a lower extent of a palm housing, and wherein said palm housing overlies an extent of the motor assembly.

4. The thumb assembly of claim **1**, the thumb assembly further comprising:
- a carpometacarpal joint housing assembly having a base joint receiver; and
- a proximal housing assembly including a rear extent that is positioned within the base joint receiver when the thumb assembly is in an uncurled position, and wherein said rear extent of the proximal housing assembly is not positioned within the base joint receiver when the thumb assembly is in a curled position.

5. The thumb assembly of claim **1**, wherein the proximal interphalangeal joint has a range of motion between 55 and 90 degrees.

6. The thumb assembly of claim **1**, wherein the distal interphalangeal joint has a range of motion between 35 and 57 degrees.

7. The thumb assembly of claim **1**, wherein the first carpometacarpal joint has a range of motion between 80 and 160 degrees, and the second carpometacarpal joint has a range of motion between 35 and 65 degrees.

8. The thumb assembly of claim **1**, further comprising a rotation encoder positioned proximate the first carpometacarpal joint and configured to collect data related to rotation of the first carpometacarpal joint.

9. The thumb assembly of claim **1**, wherein the thumb assembly is covered by a textile covering.

10. A thumb assembly for an underactuated end effector for a humanoid robot, the thumb assembly comprising:
- a frame;
- a motor assembly removably coupled to the frame and including both a first motor and a second motor;
- a base joint assembly coupled to the frame and comprising:
  - a flexion gear configured to be driven by the first motor;
  - an interposition gear configured to be driven by the second motor;
  - a first carpometacarpal joint formed between an extent of the base joint assembly and a digit assembly, and wherein movement of the interposition gear using the second motor causes the digit assembly to rotate about a first carpometacarpal joint axis of the first carpometacarpal joint;

a carpometacarpal joint housing assembly configured to rotate in response to rotation of the interposition gear; and

the digit assembly coupled to the base joint assembly and comprising:

a proximal assembly;

a second carpometacarpal joint pivotably coupling the proximal assembly to an extent of the base joint assembly, and wherein movement of the flexion gear using the first motor causes the digit assembly to rotate about a second carpometacarpal joint axis of the second carpometacarpal joint;

a proximal interphalangeal joint pivotably coupling the proximal assembly to a medial assembly; and

a distal interphalangeal joint pivotably coupling the medial assembly to a distal assembly.

11. The thumb assembly of claim **10**, wherein:

the first motor includes a first motor shaft that is rotatable about a first motor shaft axis;

the second motor includes a second motor shaft that is rotatable about a second motor shaft axis; and

the first motor shaft axis is oriented substantially parallel to the second motor shaft axis.

12. The thumb assembly of claim **10**, the thumb assembly further comprising:

a proximal housing assembly including a rear extent that is positioned within the base joint receiver when the thumb assembly is in an uncurled position, and wherein said rear extent of the proximal housing assembly is not positioned within the base joint receiver when the thumb assembly is in a curled position, and

wherein the carpometacarpal joint housing assembly has a base joint receiver; and.

13. The thumb assembly of claim **10**, further comprising: (i) a first encoder positioned proximate to the proximal interphalangeal joint and configured to collect data related to rotation of the proximal interphalangeal joint, and (ii) a second encoder positioned proximate to the distal interphalangeal joint and configured to collect data related to rotation of the distal interphalangeal joint.

14. The thumb assembly of claim **10**, wherein the thumb assembly is covered by a textile covering.

15. The thumb assembly of claim **10**, wherein the frame includes a palm region, and wherein the first motor and the second motor are at least partially located within the palm region of the frame.

16. The thumb assembly of claim **10**, wherein the flexion gear is rotatable about a flexion axis, and wherein the flexion axis is oriented perpendicular to a first motor shaft axis of the first motor.

17. The thumb assembly of claim **10**, wherein the thumb assembly further comprises both a biasing member coupled to an extent of the proximal assembly and an extent of the medial assembly, and wherein the biasing member is configured to bias the medial assembly toward an uncurled position.

18. An end effector for a humanoid robot, the end effector comprising:

a frame;

a plurality of finger assemblies connected to the frame, each finger assembly of the plurality of finger assemblies comprising:

a metacarpophalangeal joint;

a proximal finger interphalangeal joint;

a distal finger interphalangeal joint; and

a thumb assembly removably connected to the frame, the thumb assembly comprising:

a first carpometacarpal joint;

a second carpometacarpal joint;

a metacarpophalangeal joint;

an interphalangeal joint;

a carpometacarpal joint housing assembly having a base joint receiver;

a proximal housing assembly including a rear extent that is positioned within the base joint receiver when the thumb assembly is in an uncurled position, wherein said rear extent of the proximal housing assembly is positioned external to the base joint receiver when the thumb assembly is in a curled position;

a carpometacarpal encoder positioned proximate to the first carpometacarpal joint and configured to collect data concerning rotation of the first carpometacarpal joint;

a first thumb encoder positioned proximate to the metacarpophalangeal joint and configured to collect data concerning rotation of the metacarpophalangeal joint; and

a second thumb encoder positioned proximate the interphalangeal joint and configured to collect data concerning rotation of the interphalangeal joint, and wherein the first thumb encoder and second thumb encoder are positioned adjacent to a main medial link of the thumb assembly.

19. The end effector of claim **18**, wherein the thumb assembly further comprises: (i) a first motor gear, (ii) a worm wheel configured to facilitate movement of the thumb assembly between an uncurled position and a curled position, and (iii) a thumb drive assembly in geared engagement with the first motor gear and the worm wheel.

20. The end effector of claim **19**, wherein the thumb drive assembly further includes: (i) a flexion gear in geared engagement with the first motor gear, (ii) a worm drive gear in geared engagement with the worm wheel, and (iii) a drive shaft coupled to both the flexion gear and the worm drive gear.

21. The end effector of claim **18**, wherein the frame includes a palm region, and wherein the first motor and the second motor are at least partially located within the palm region of the frame.

22. The end effector of claim **18**, wherein the thumb assembly is configured to covered by a textile covering.

23. The end effector of claim **18**, wherein the end effector has at least **2.66** degrees of freedom per motor.

24. The end effector of claim **18**, further comprising a carpometacarpal joint housing assembly configured to rotate in response to rotation of an interposition gear.

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