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Goldsmith et al.

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(45) **Date of Patent: Sep. 23, 2025**

(54) **KINEMATICS OF A MECHANICAL END EFFECTOR**

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(73) Assignee: **FIGURE AI INC.**, San Jose, CA (US)

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(21) Appl. No.: **19/223,945**

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

Related U.S. Application Data

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(60) Provisional application No. 63/573,226, filed on Apr. 2, 2024, provisional application No. 63/561,315, filed on Mar. 5, 2024, provisional application No. 63/620,633, filed on Jan. 12, 2024, provisional application No. 63/617,762, filed on Jan. 4, 2024.

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B25J 15/00 (2006.01)
B25J 15/02 (2006.01)

(52) **U.S. Cl.**
CPC ***B25J 15/0009*** (2013.01); ***B25J 15/0213*** (2013.01)

(58) **Field of Classification Search**
CPC B25J 15/0009; B25J 15/0213
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,394,766	A	3/1995	Johnson
7,024,276	B2	4/2006	Ito
7,308,336	B2	12/2007	Takenaka
7,319,918	B2	1/2008	Takenaka
7,379,789	B2	5/2008	Takenaka
7,386,364	B2	6/2008	Mikami
7,664,569	B2	2/2010	Shimizu
7,864,159	B2	1/2011	Sweetser
8,511,964	B2	8/2013	Linn
8,660,695	B2	2/2014	De La Rosa Tames
8,770,749	B2	7/2014	Mccabe
9,134,547	B2	9/2015	Mccabe
9,205,556	B1	12/2015	Magnusson
9,205,560	B1	12/2015	Edsinger
9,346,165	B1	5/2016	Metzger

(Continued)

FOREIGN PATENT DOCUMENTS

CN	102357889	2/2012
CN	209615545	11/2019

(Continued)

OTHER PUBLICATIONS

International Search Report and Written Opinion for PCT/US2025/010425 dated May 7, 2025.

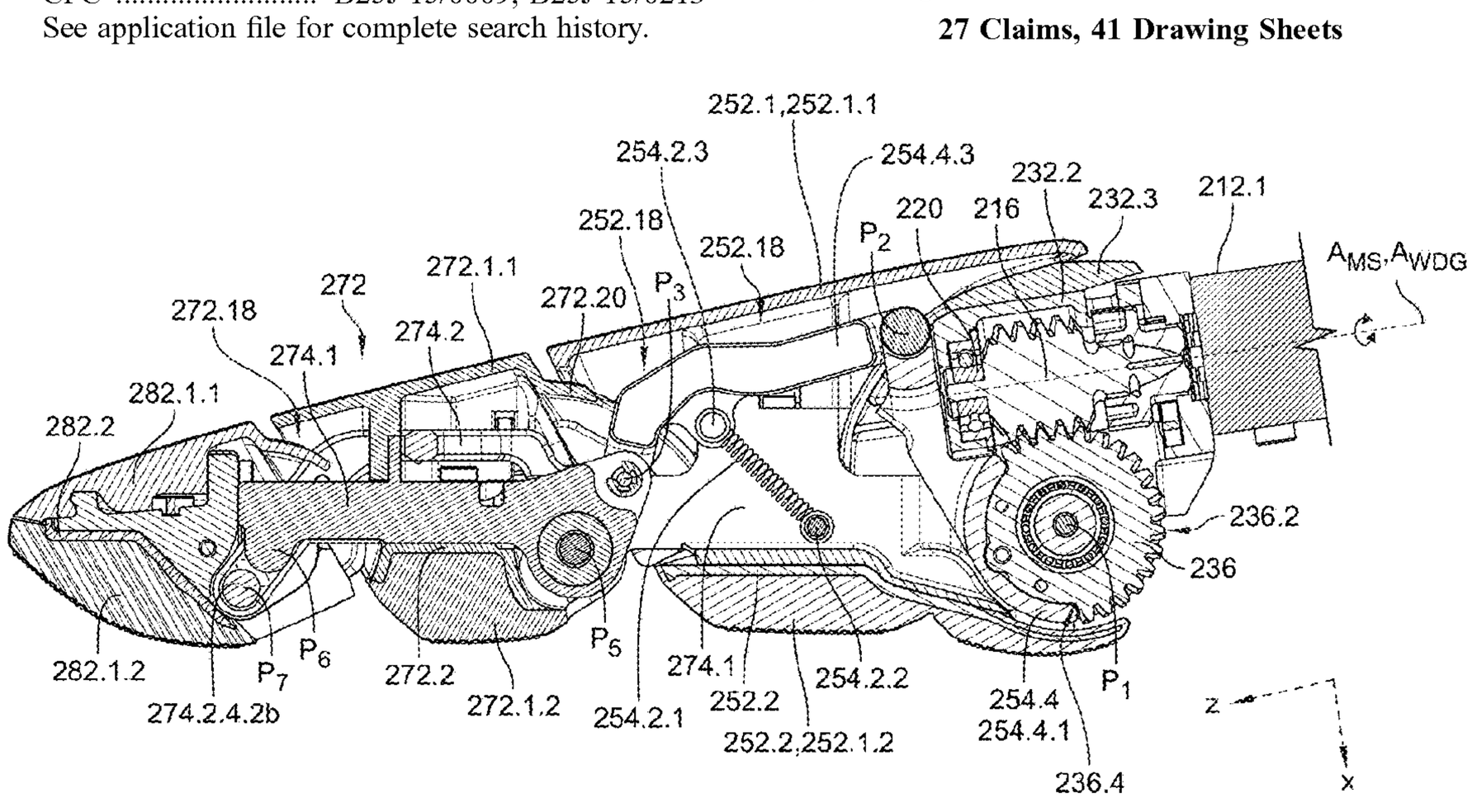
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Primary Examiner — Stephen A Vu

(57) **ABSTRACT**

A mechanical end effector for a humanoid robot includes a plurality of identical finger assemblies. Each of the finger assemblies is removably connected to a frame. Each of the finger assemblies is fully self-contained and operable independently of every other one of the finger assemblies and independently of every other component connected to the frame. Each of the finger assemblies includes a single electric motor and is configured to be fully operable using only the single electric motor.

27 Claims, 41 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

9,383,594	B2	7/2016	Mccabe
9,494,415	B2	11/2016	Sweetser
9,574,646	B1	2/2017	Edsinger
9,575,335	B1	2/2017	Mccabe
9,592,603	B2	3/2017	Hardouin
9,789,607	B1	10/2017	Whitman
9,789,612	B2	10/2017	Hoffman
9,796,078	B2	10/2017	Angle
9,821,466	B2	11/2017	Bingham
9,868,210	B1	1/2018	Whitman
9,910,297	B1	3/2018	Mccabe
9,992,474	B2	6/2018	Grunnet-Jepsen
10,007,994	B2	6/2018	Grunnet-Jepsen
10,018,256	B1	7/2018	Magnusson
10,189,158	B2	1/2019	Edsinger
10,203,209	B2	2/2019	Roumeliotis
10,310,362	B2	6/2019	Grunnet-Jepsen
10,349,245	B2	7/2019	Tokuchi
10,537,998	B2	1/2020	Salisbury
10,656,511	B2	5/2020	Grunnet-Jepsen
10,780,578	B2	9/2020	Blankespoor
10,890,921	B2	1/2021	Gillett
10,921,558	B2	2/2021	Yao
10,924,638	B2	2/2021	Swaminathan
10,946,528	B2	3/2021	Gupta
10,960,539	B1	3/2021	Kalakrishnan
11,180,205	B2	11/2021	Amino
11,188,821	B1	11/2021	Kalakrishnan
11,333,954	B2	5/2022	Bull
11,347,030	B2	5/2022	Yao
11,402,726	B2	8/2022	Bull
11,416,003	B2	8/2022	Whitman
11,435,745	B2	9/2022	Lee
11,498,223	B2	11/2022	Williams
11,546,504	B2	1/2023	Kim
11,554,484	B2	1/2023	Jung
11,599,009	B2	3/2023	Bull
11,600,010	B2	3/2023	Doutre
11,602,853	B2	3/2023	Stoianovici
11,686,884	B2	6/2023	Shinohara
11,707,852	B1	7/2023	Hurst
11,736,677	B2	8/2023	Grunnet-Jepsen
11,807,067	B2	11/2023	Mancini
11,833,680	B2	12/2023	Deits
11,850,738	B2	12/2023	Chernyak
11,851,120	B2	12/2023	Fay
11,999,423	B2	6/2024	Whitman
12,036,670	B2	7/2024	Geating
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12,070,863	B2	8/2024	Whitman
12,077,229	B2	9/2024	Whitman
12,097,626	B2	9/2024	Ikeda
12,122,044	B2	10/2024	Webb
12,134,181	B2	11/2024	Klingensmith
12,172,537	B2	12/2024	Gonano
12,214,497	B2	2/2025	Whitman
12,235,652	B2	2/2025	Whitman
12,240,117	B2	3/2025	Chebotar
12,251,831	B2	3/2025	Murphy
2004/0103740	A1	6/2004	Townsend et al.
2010/0280662	A1	11/2010	Abdallah
2013/0175816	A1	7/2013	Kawasaki
2014/0265401	A1	9/2014	Allen Demers et al.
2016/0052574	A1	2/2016	Khripin
2016/0064263	A1	3/2016	Hosek
2017/0075143	A1	3/2017	Saylor
2017/0106738	A1	4/2017	Gillett
2017/0299898	A1	10/2017	Gallina
2018/0104823	A1	4/2018	Kaku
2019/0025611	A1	1/2019	Saylor
2019/0105783	A1	4/2019	Al Moubayed
2019/0278079	A1	9/2019	Mccabe
2019/0329413	A1	10/2019	Johnson
2019/0337166	A1	11/2019	Keeney-Ritchie
2020/0009739	A1	1/2020	Moon
2020/0096792	A1	3/2020	Mccabe
2020/0330246	A1	10/2020	Tognetti et al.
2020/0409183	A1	12/2020	Saylor
2021/0387346	A1	12/2021	Gillett
2022/0388174	A1	12/2022	Stathis
2022/0390952	A1	12/2022	Yu
2022/0395974	A1	12/2022	Balasubramanian
2022/0410380	A1	12/2022	Lu
2023/0143315	A1	5/2023	Whitman
2023/0173683	A1	6/2023	Gomez
2023/0182296	A1	6/2023	Sermanet
2023/0347514	A1	11/2023	Xiao
2024/0003380	A1	1/2024	Vyas
2024/0181637	A1	6/2024	Gillett
2024/0217104	A1	7/2024	Neville
2024/0228191	A1	7/2024	Kumar
2024/0300109	A1	9/2024	Shaw
2025/0147517	A1	5/2025	Swilling

FOREIGN PATENT DOCUMENTS

CN	212287717	1/2021
CN	112959343	6/2021
CN	115503013	12/2022
CN	117047810	11/2023
GB	2472046	4/2013
GB	2496335	5/2013
KR	20180107353	10/2018
WO	2009030922	3/2009
WO	2019234706	12/2019
WO	2023107501	6/2023
WO	2023110778	6/2023
WO	2024058844	3/2024
WO	2024085904	4/2024
WO	2024112350	5/2024
WO	2024112351	5/2024
WO	2024123766	6/2024
WO	2024163992	8/2024
WO	2025019583	1/2025
WO	2025042802	2/2025
WO	2025072321	4/2025

OTHER PUBLICATIONS

Available online at https://youtu.be/YsdnsNjvwKo?si=bu2dXk8mQaL86C2M, at least as early as Aug. 23, 2023.

Available online at https://www.youtube.com/watch?v=q8ldbodRG14, at least as early as May 22, 2019.

Available online at https://youtu.be/GtPs_ygfaEA?si=7lv6MEFvFoaacKfa, at least as early as Aug. 15, 2023.

Available online at https://www.youtube.com/watch?v=G6JE7mNYz2A, at least as early as Oct. 17, 2024.

Available online at https://www.youtube.com/watch?v=FuNFr7V7KFQ, at least as early as Aug. 19, 2024.

Available online at https://www.youtube.com/watch?v=GzX1qOIO1bE, at least as early as May 13, 2024.

Available online at https://youtu.be/_MBd_XfXy9M?si=PbEHUJpRUFqaxS3J, at least as early as Jun. 26, 2023.

Available online at https://youtu.be/SHPxcRBIXNO?si=VbJqbK7jzUqtZGmn, at least as early as Sep. 26, 2023.

Available online at https://youtu.be/BvFxD-8AhJA?si=Vx1F4a76tbQDUX48, at least as early as Nov. 16, 2023.

Available online at https://www.youtube.com/watch?v=jWTWWuzB6Cg, at least as early as Aug. 27, 2024.

Available online at https://www.youtube.com/watch?v=B-ebMigAHzQ, at least as early as Sep. 30, 2024.

Available online at https://youtu.be/XiQkeWOFwmk?si=1qOPC8gXgmmGvXRT, at least as early as May 16, 2023.

Available online at https://youtu.be/cpraXaw7dyc?si=JvPaT6eMA18psrmU, at least as early as Dec. 13, 2023.

Available online at https://www.youtube.com/watch?v=DrNcXgoFv20, at least as early as Oct. 18, 2024.

Available online at https://youtu.be/BNSZ8Fwcd20?si=_YnVgjYblVuhASk1, at least as early as Oct. 27, 2023.

(56) **References Cited**

OTHER PUBLICATIONS

Available online at https://youtu.be/SS3Ga2HQQ0s?si=Dwr3sJuCsOeUoSLj, at least as early as Nov. 20, 2023.
Available online at https://www.youtube.com/watch?v=iWC8rSjDywU, at least as early as Oct. 18, 2024.
Available online at https://youtu.be/sihlDeJ4Hmk?si=fJsKpvRFPzFejmS6, at least as early as Dec. 27, 2023.
Available online at https://www.youtube.com/watch?v=zkBnFPBV3f0, at least as early as Jul. 11, 2013.
Available online at https://www.youtube.com/watch?v=oXBYZxa25vc&t=1s, at least as early as Apr. 3, 2013.
Available online at https://www.youtube.com/watch?v=LBem19AmTT4, at least as early as Apr. 7, 2015.
Available online at https://www.youtube.com/watch?v=IE-YBaYjbqY, at least as early as Dec. 10, 2013.
Available online at https://www.youtube.com/watch?v=y-j4dixQQml&t=222s, at least as early as May 22, 2012.
Available online at https://www.youtube.com/watch?v=Bmglbk_Op64&t=1s, at least as early as Nov. 10, 2011.
Available online at https://www.youtube.com/watch?v=20GHG-R9eFI, at least as early as Mar. 6, 2023.
Available online at https://www.youtube.com/watch?v=bUrLuUxv9gE, at least as early as Aug. 30, 2024.
Available online at https://www.youtube.com/watch?v=-9EM5_VFIt8, at least as early as Apr. 16, 2024.
Available online at https://www.youtube.com/watch?v=29ECwExc-_M&t=2s, at least as early as Apr. 17, 2024.
Available online at https://www.youtube.com/watch?v=67CUudkjEG4, at least as early as Oct. 26, 2009.
Available online at https://www.youtube.com/watch?v=yBmatGQ0giY&t=1s, at least as early as Aug. 11, 2022.
Available online at https://www.youtube.com/watch?v=bdVrWxjK2vo, at least as early as Sep. 17, 2024.
Available online at https://www.youtube.com/watch?v=qw2y0kceAv0, at least as early as Oct. 15, 2024.
Available online at https://www.youtube.com/watch?v=B_I2k7MZEKg, at least as early as Jun. 30, 2024.
Available online at https://www.youtube.com/watch?v=CbA9wA9etGA, at least as early as Sep. 19, 2024.
Available online at https://www.youtube.com/watch?v=zLhA-RWBBYU, at least as early as Jul. 5, 2024.
Available online at https://www.youtube.com/watch?v=_mQJw8VhZ7w&t=111s, as least as early as Oct. 5, 2022.
Available online at https://www.youtube.com/watch?v=1fC7b2LjVW4, at least as early as Jul. 12, 2016.
Available online at https://www.youtube.com/watch?v=UPOLcE1vwA0, at least as early as Apr. 28, 2016.
Available online at https://www.youtube.com/watch?v=UBbk180ZbTc, at least as early as Oct. 14, 2024.
Available online at https://www.youtube.com/watch?v=UHe1zSQwep0, at least as early as Oct. 14, 2024.
Available online at https://www.youtube.com/watch?v=MCbGeC-kuBM, at least as early as Aug. 5, 2024.
Available online at https://www.youtube.com/watch?v=ujdK3yd2gHY, at least as early as Jul. 2, 2024.
Available online at https://www.youtube.com/watch?v=-HizP4UQvug, at least as early as Apr. 25, 2024.
Available online at https://www.youtube.com/watch?v=ioOkbUQqmZ0, at least as early as Nov. 9, 2022.
Available online at https://www.youtube.com/watch?v=zmqWU2dQKZ8, at least as early as Oct. 24, 2024.
Available online at https://www.youtube.com/watch?v=q8ldbodRG14, at least as early as Feb. 26, 2024.
Available online at https://www.youtube.com/watch?v=CUhuhleQNos, at least as early as May 22, 2019.
Available online at https://www.youtube.com/watch?v=dY57qnD_O7U, at least as early as Jul. 27, 2021.
Pateromichelakis et al., Head-eyes system and gaze analysis of the humanoid robot Romeo, 2014, IEEE, p. 1374-1379 (Year: 2014).
Jeung et al., Realization of human neck motion with novel robotic mechanism, 2016, IEEE, p. 482-486 (Year: 2016).
International Search Report for PCT/US2025/016930 dated Jun. 10, 2025.
Barker et al., Natural head movement for HRI with a muscular-skeletal head and neck robot, 2017, IEEE, p. 587-592 (Year: 2017).
Gao et al., Development of a low motion-noise humanoid neck: Statics analysis and experimental validation, 2010, IEEE, p. 1203-1208 (Year: 2010).
International Search Report for PCT/US2025/012544.
International Search Report for PCT/US2025/011450.
Keselman et al., "Intel RealSense stereoscopic depth cameras," in Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition Workshops, pp. 1-10, 2017.

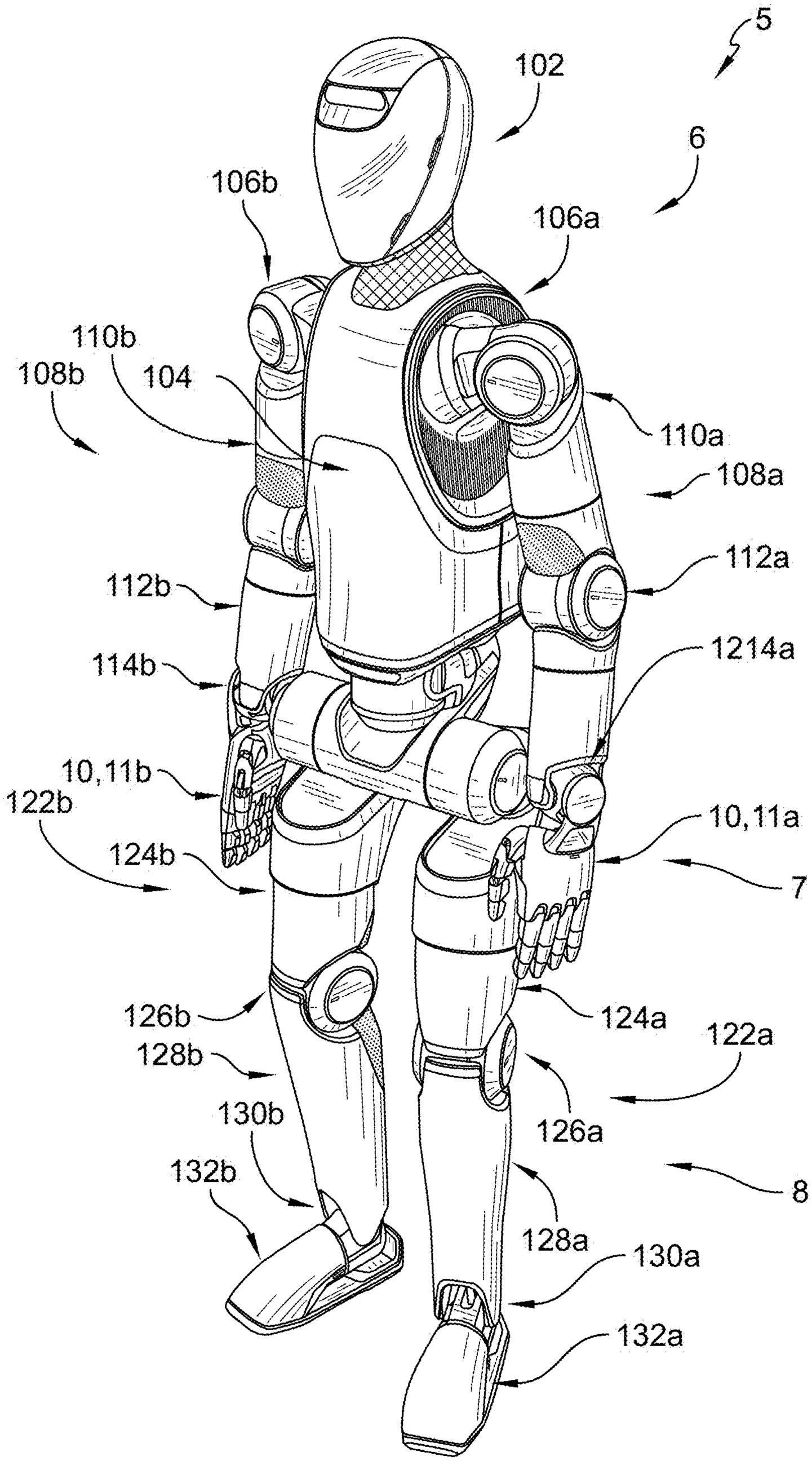

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102
6
106b
106a
110b
108b
104
110a
108a
112a
112b
1214a
114b
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122b
10,11a
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126a
130b
8
132b
128a
130a
132a

FIG. 1A

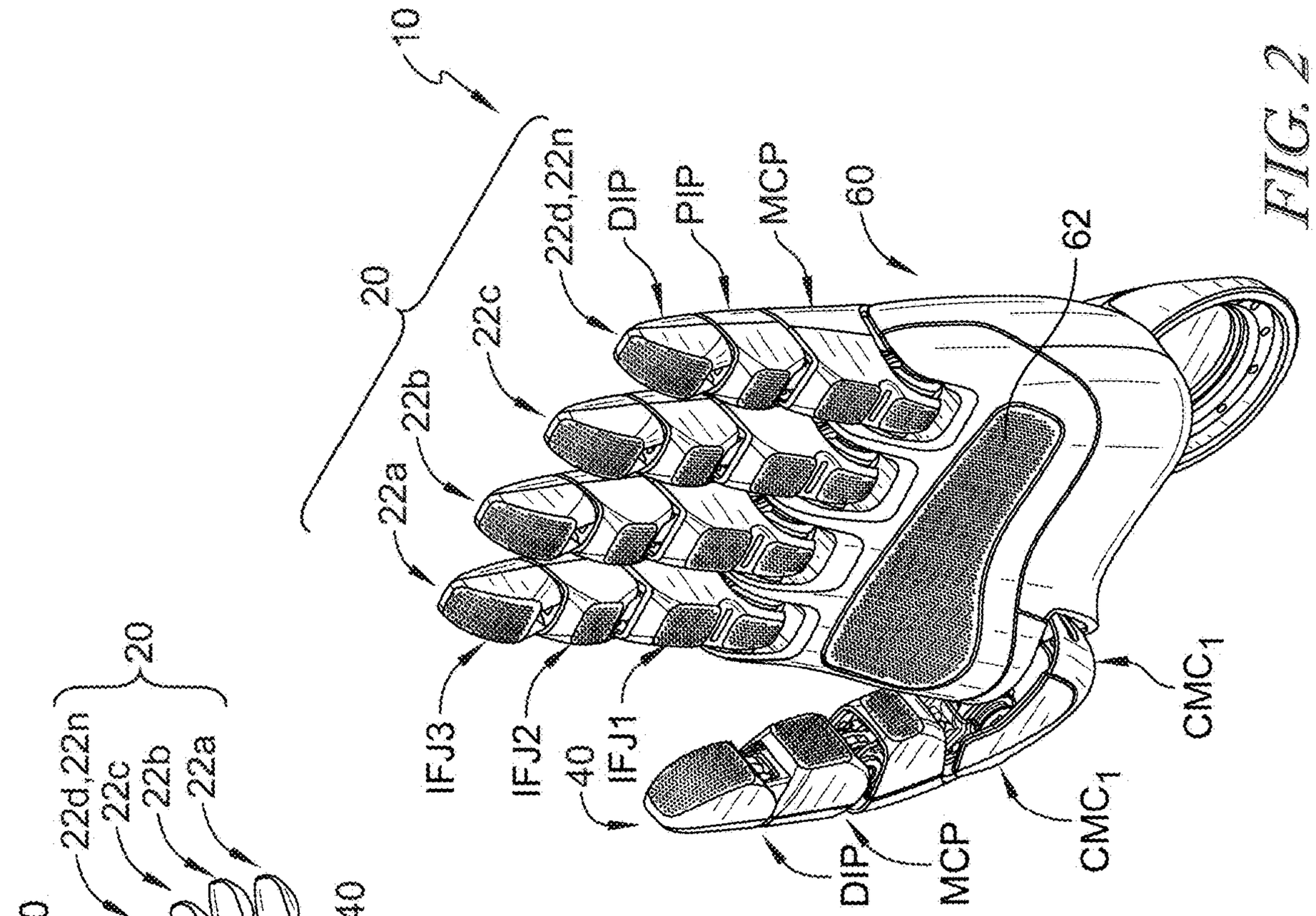

10
20
22d,22n
22c
22b
22a
DIP
PIP
MCP
60
62
IFJ3
IFJ2
IFJ1
40
CMC1
CMC1
DIP
MCP

FIG. 2

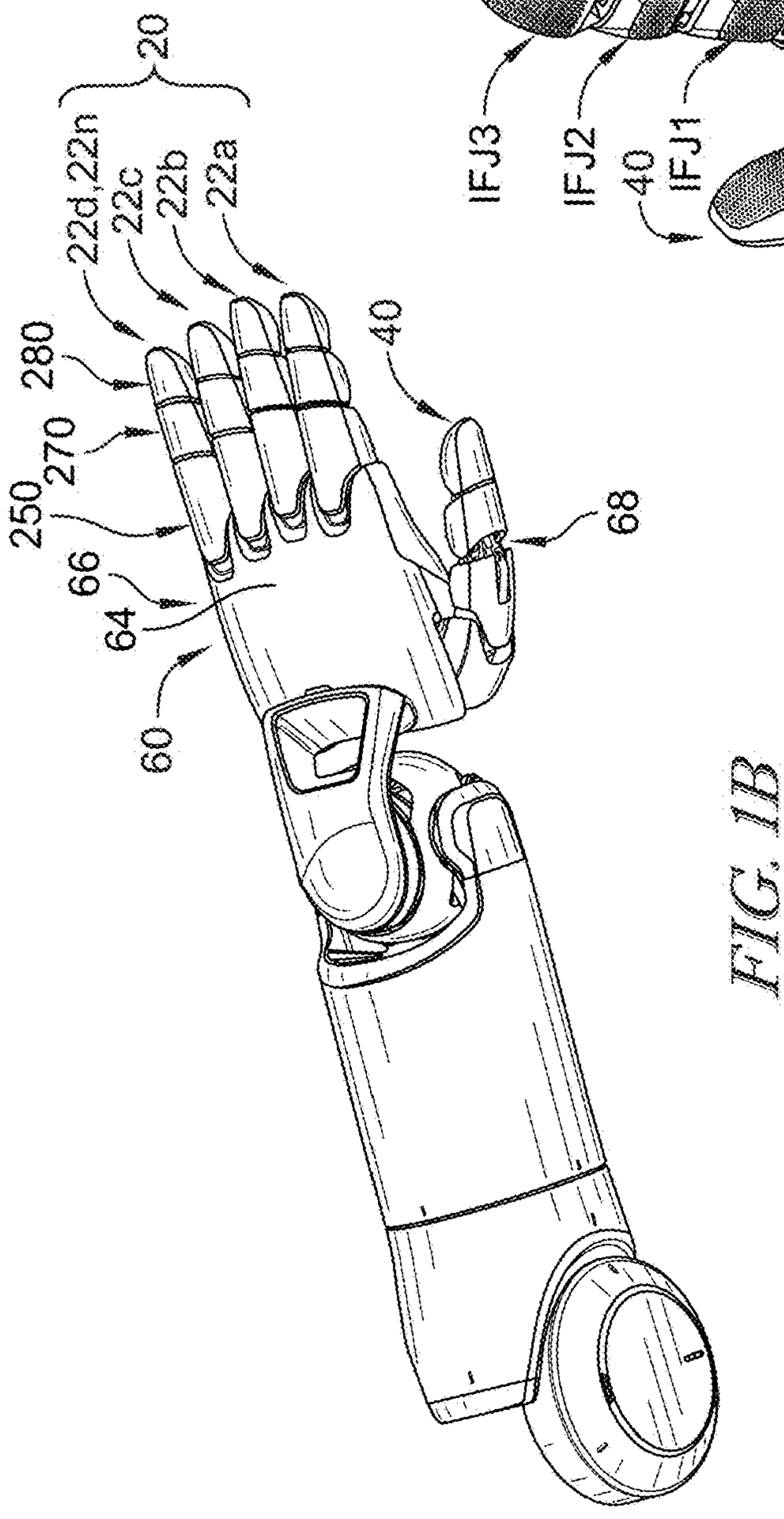

20
22d,22n
22c
22b
22a
280
270
250
66
64
60
40
68

FIG. 1B

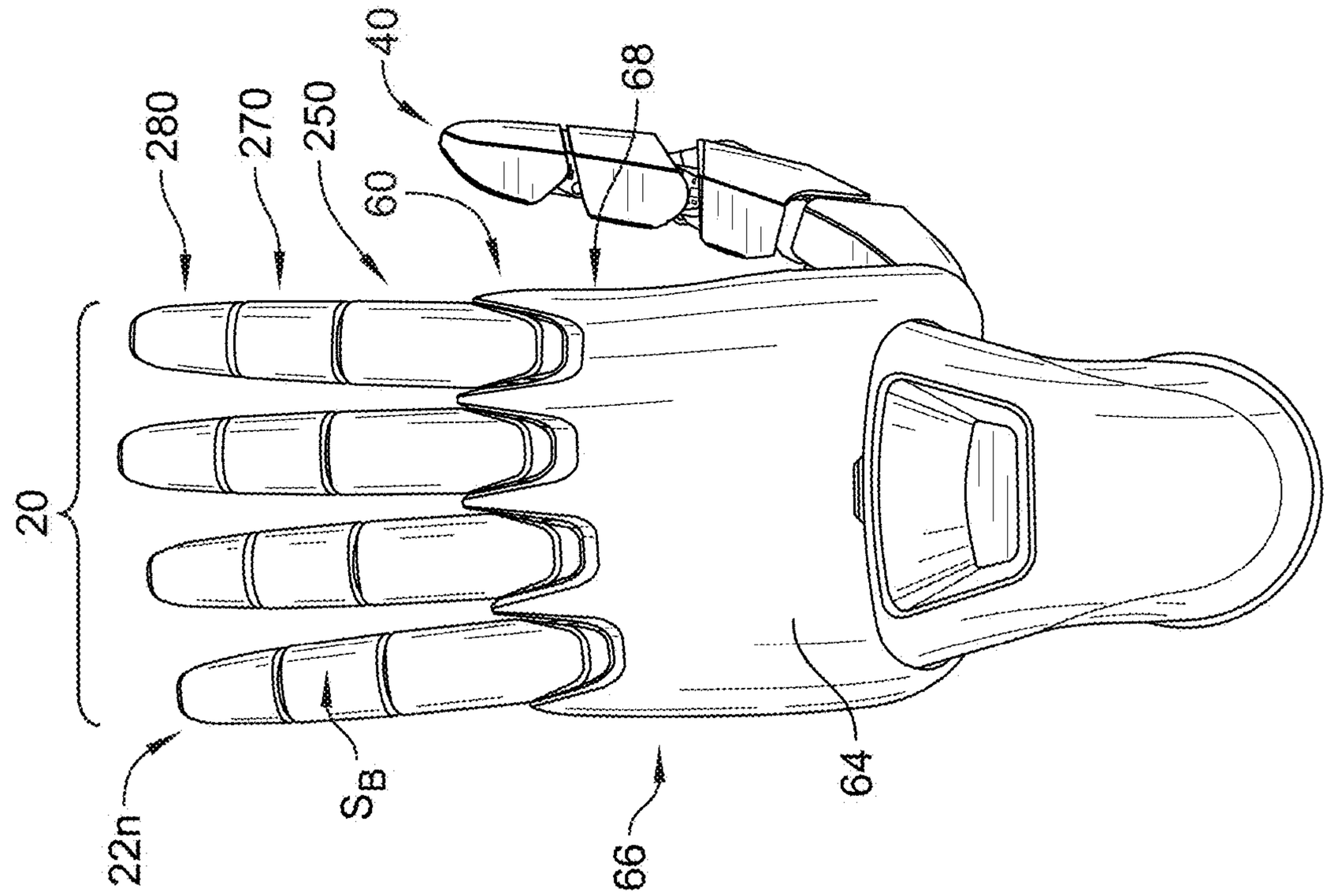

280
270
250
40
68
60
20
22n
S_B
66
64

FIG. 4

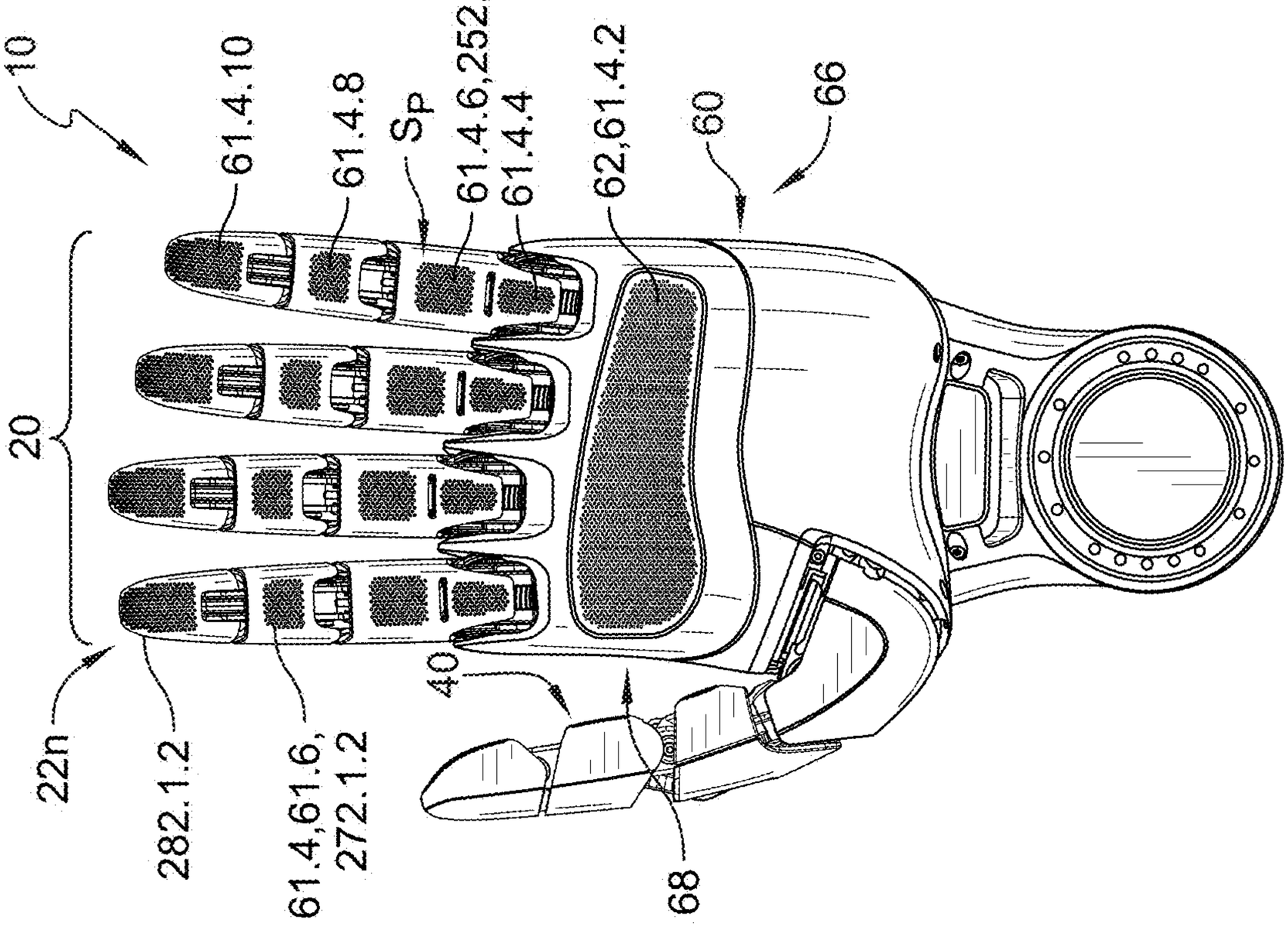

10
61.4.10
61.4.8
S_P
61.4.6,252.1.2
61.4.4
62,61.4.2
60
66
20
22n
282.1.2
61.4.61.6,
272.1.2
40
68

FIG. 3

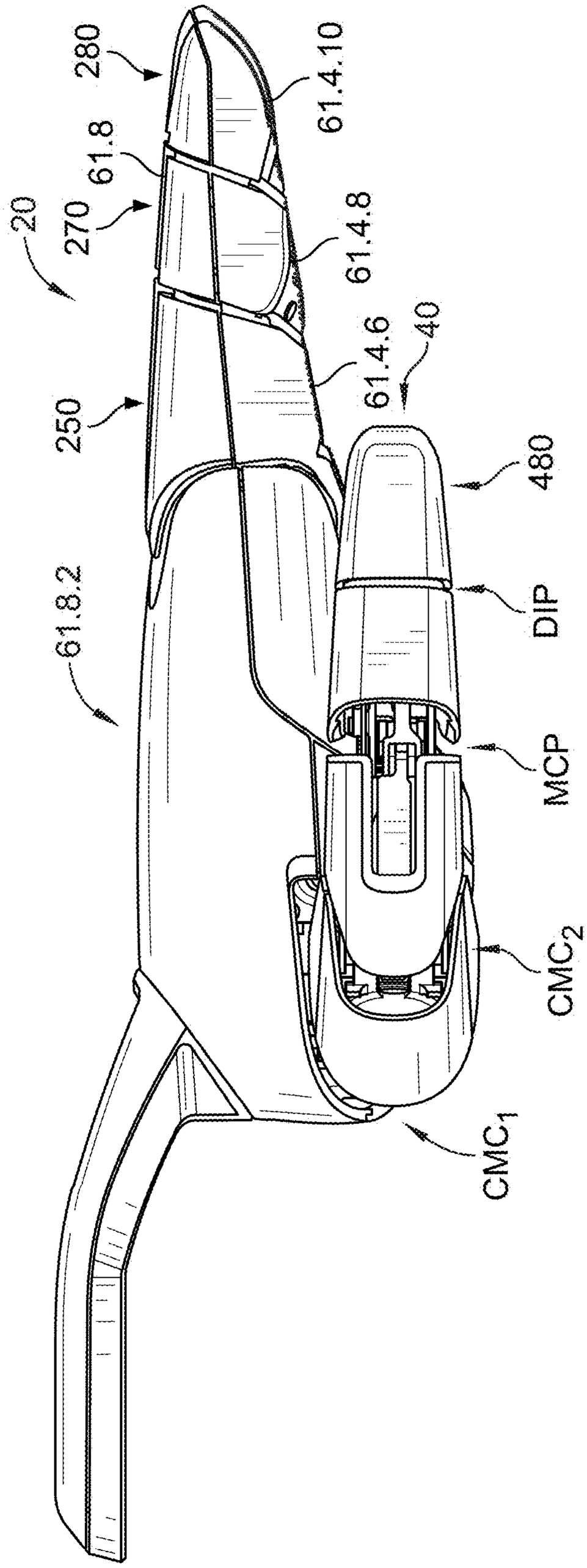

280
61.4.10
61.8
20
270
61.4.8
61.4.6
40
250
480
61.8.2
DIP
MCP
CMC_2
CMC_1

FIG. 5

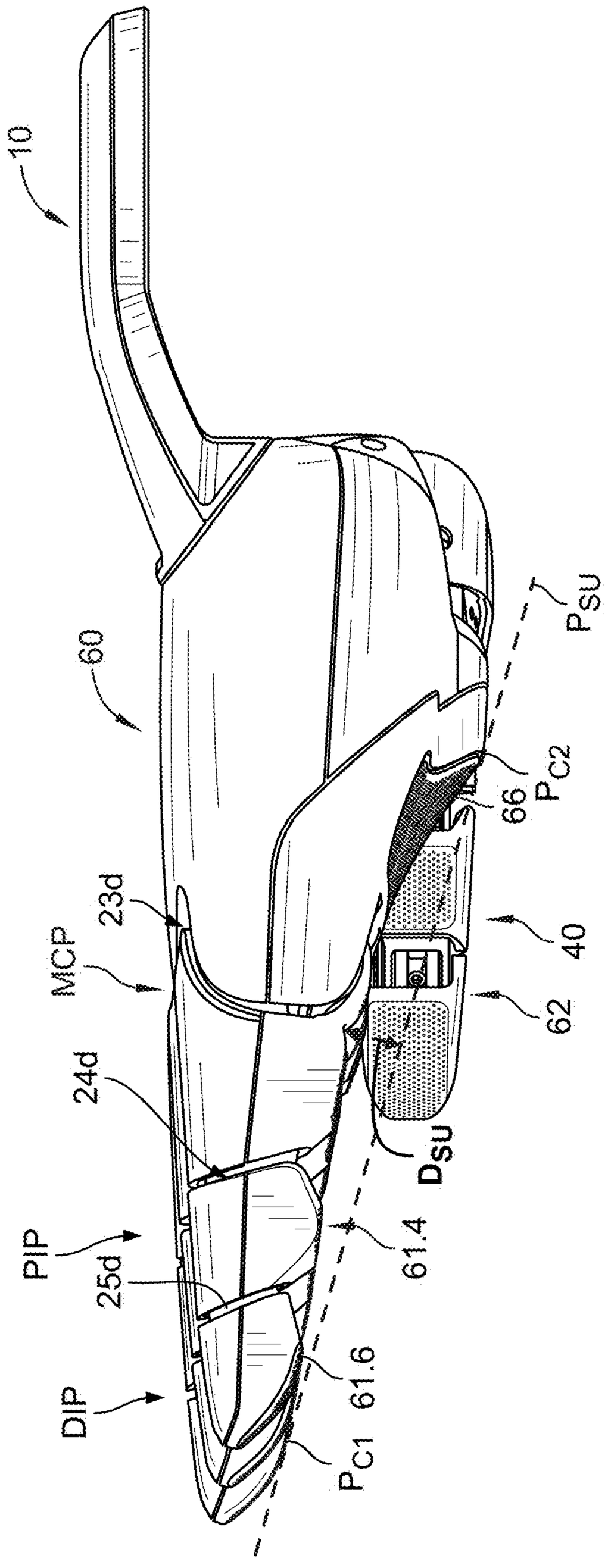


FIG. 6

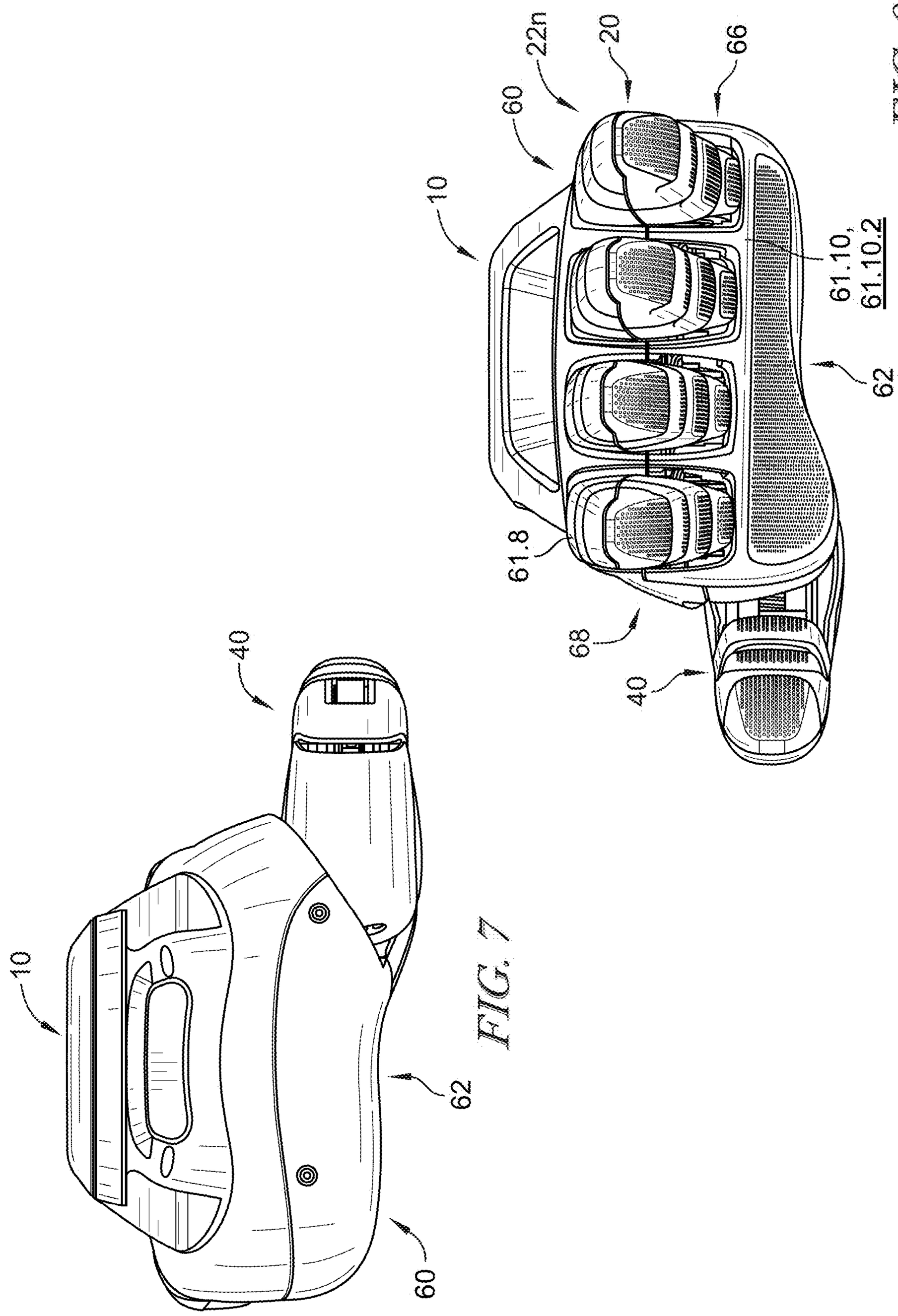


FIG. 8

FIG. 7

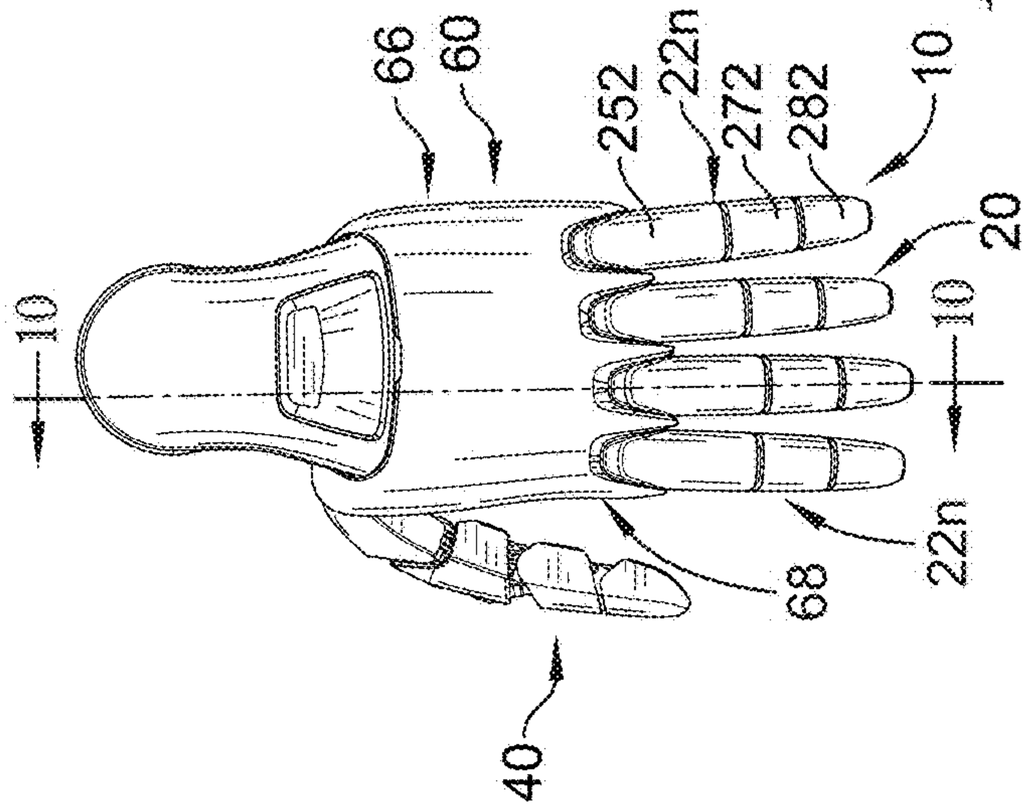

10
66
60
252
22n
272
282
10
20
10
22n
68
40

FIG. 9

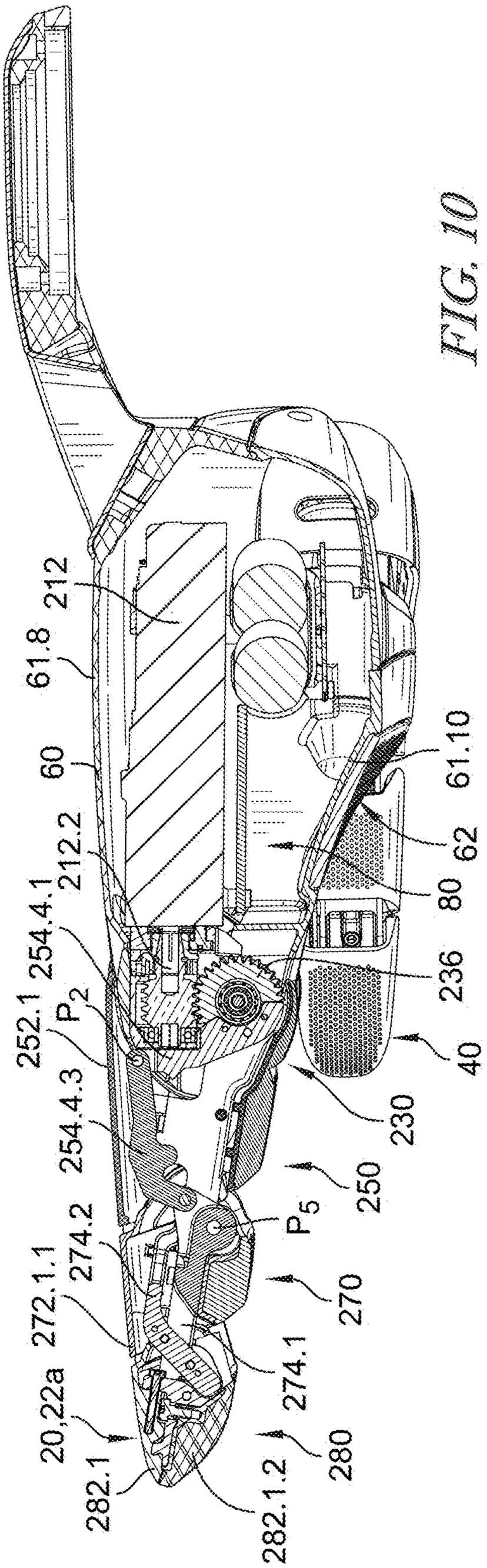

212
61.8
60
61.10
62
212.2
80
254.4.1
236
252.1
P2
40
254.4.3
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P5
250
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272.1.1
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274.1
20,22a
282.1
280
282.1.2

FIG. 10

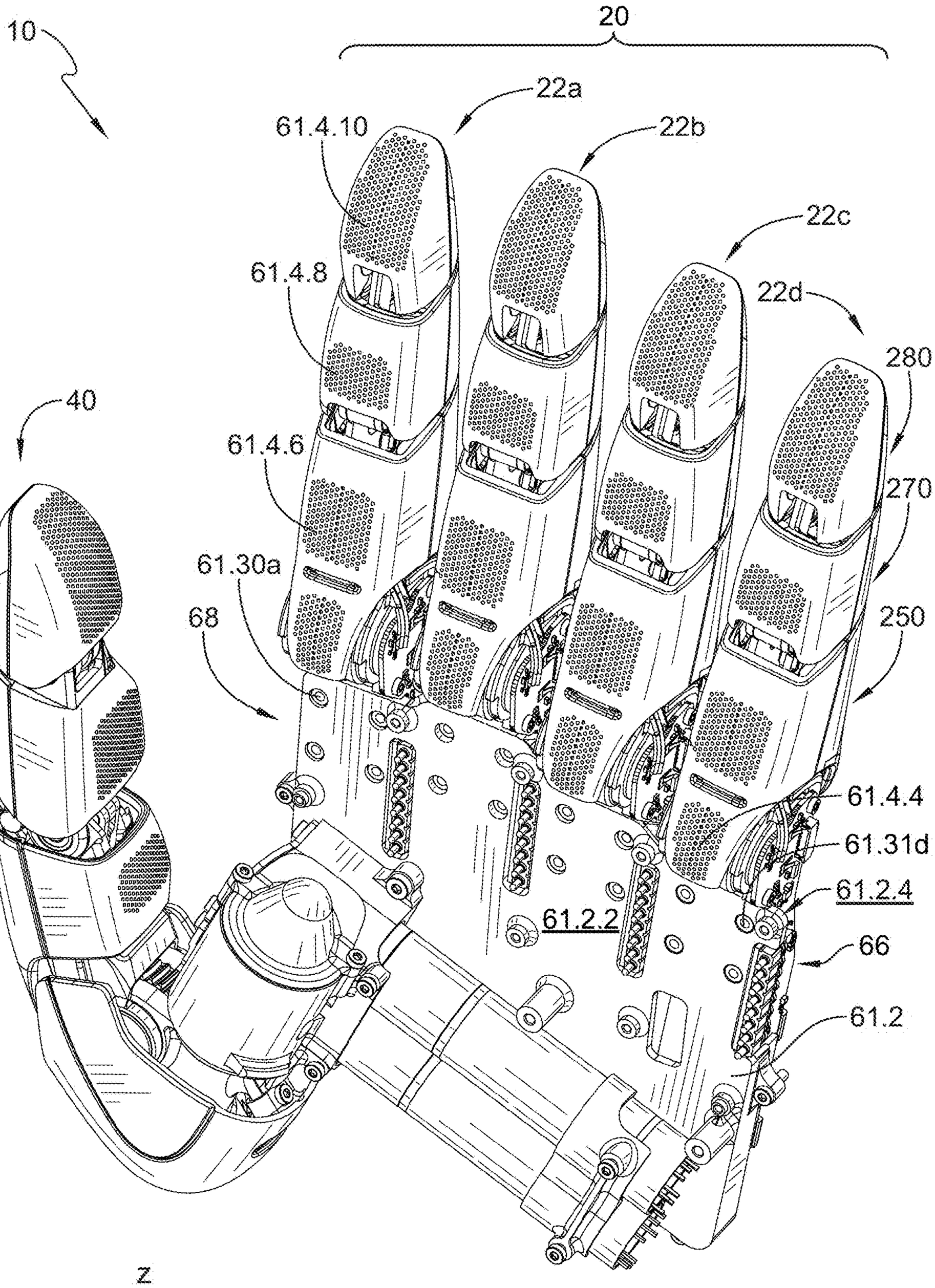

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22a
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22b
22c
61.4.8
22d
280
40
61.4.6
270
61.30a
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250
61.4.4
61.31d
61.2.4
61.2.2
66
61.2
z
y
x

FIG. 11

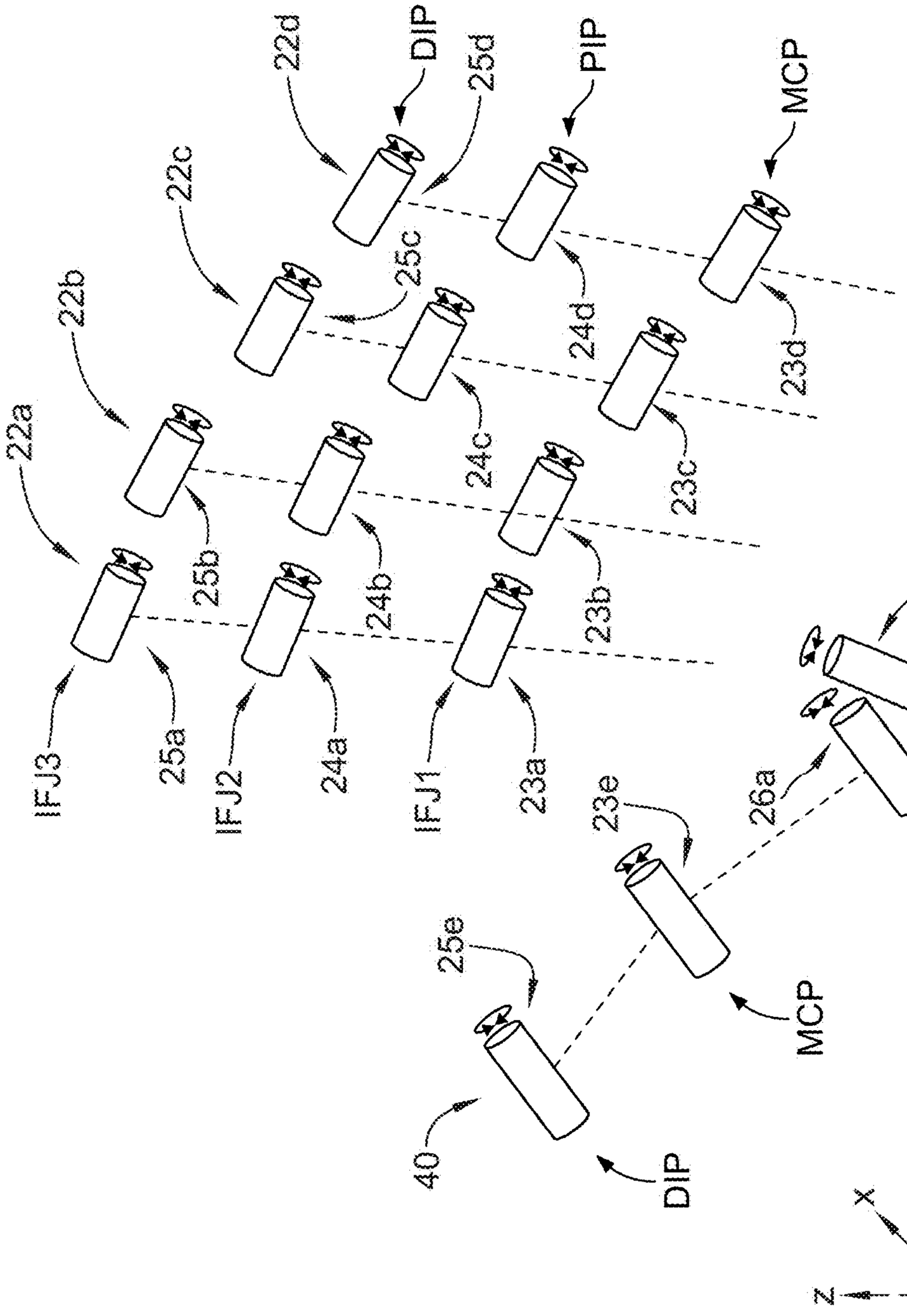

22d
DIP
25d
PIP
MCP
22c
22b
22a
25c
24d
24c
23d
23c
25b
24b
23b
IFJ3
25a
IFJ2
24a
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DIP
MCP
z
x
y

FIG. 12

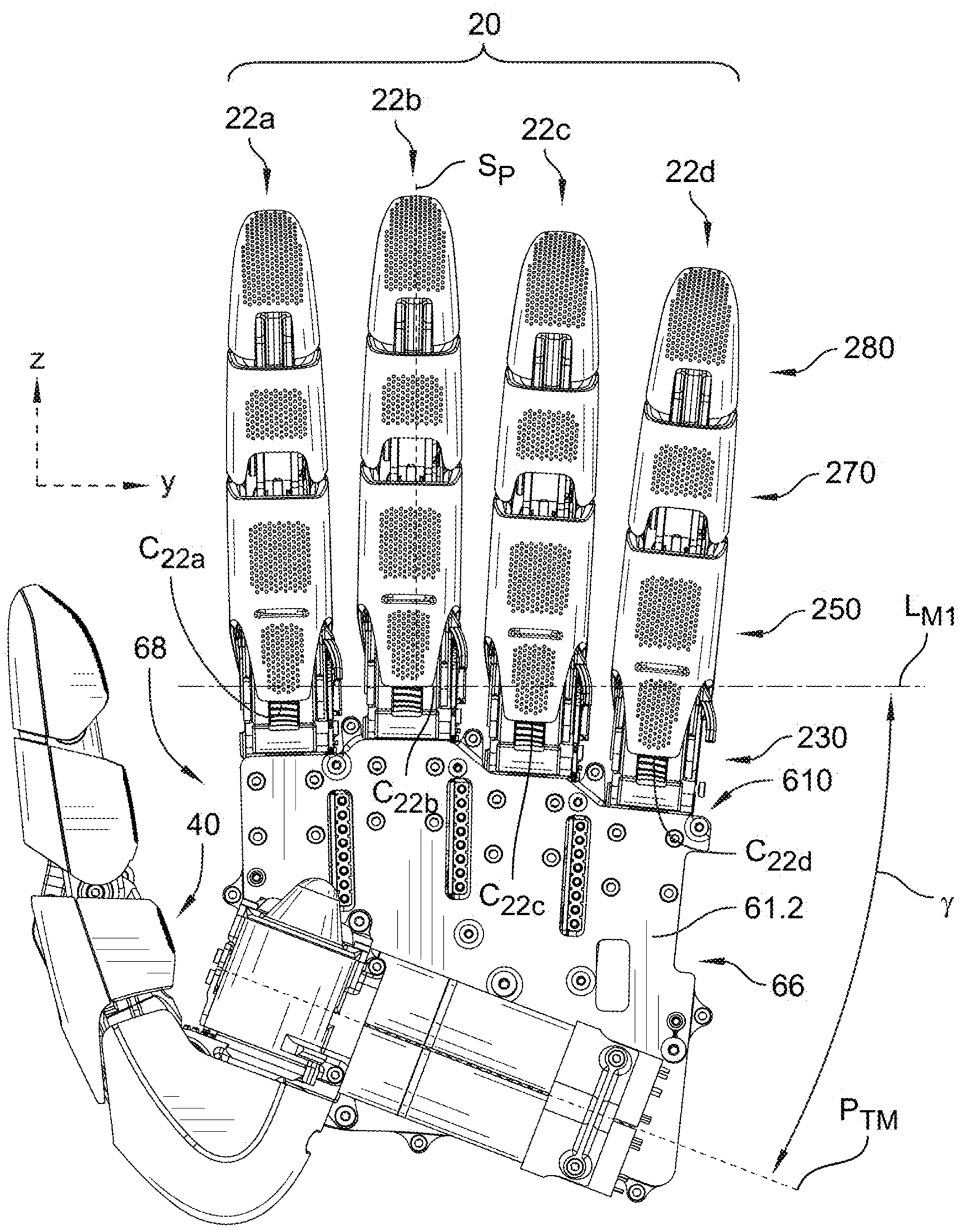

20
22a
22b
22c
22d
S_P
z
y
280
270
C_{22a}
250
L_{M1}
68
230
610
C_{22b}
40
C_{22d}
C_{22c}
61.2
γ
66
P_{TM}

FIG. 13

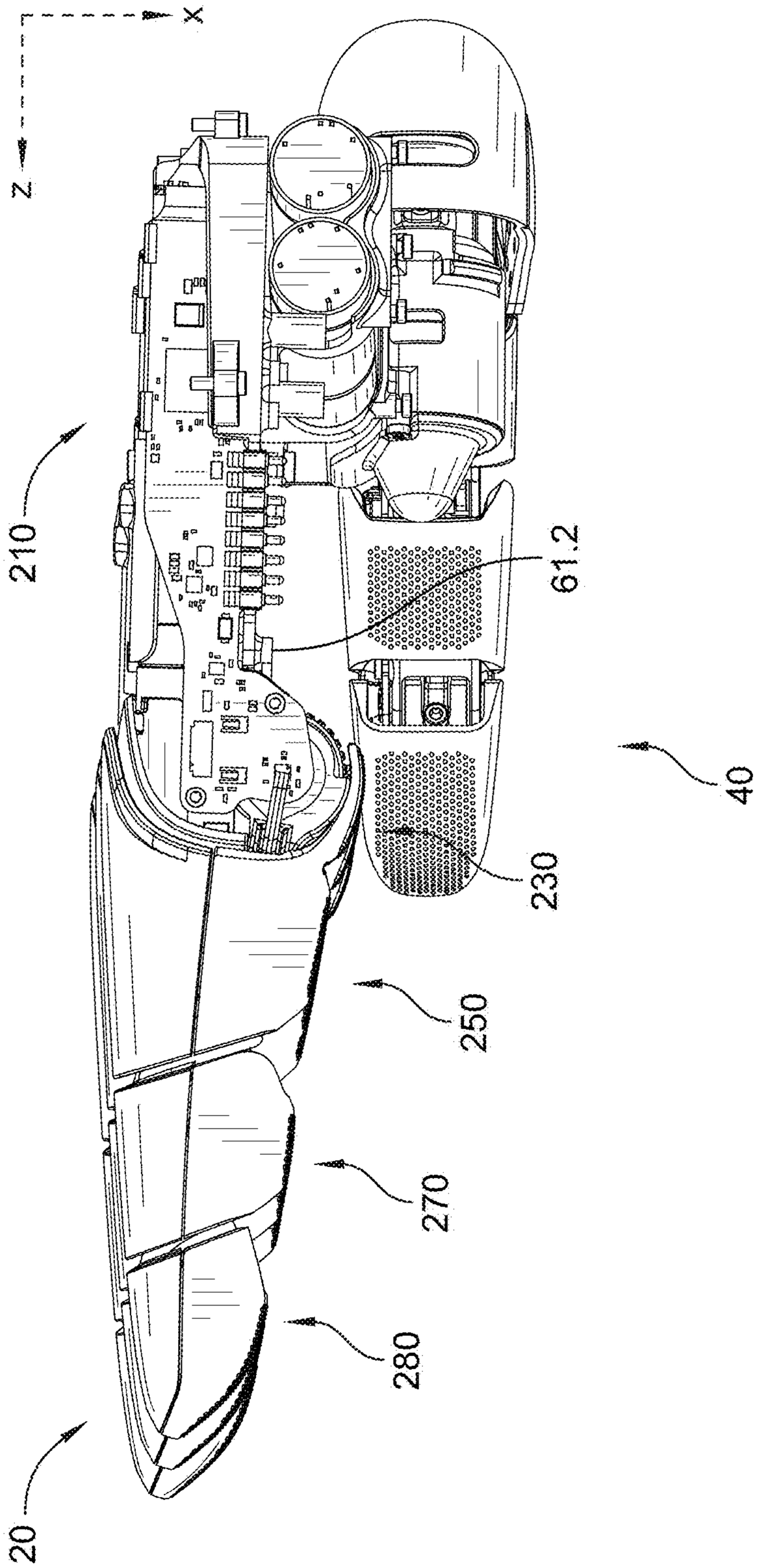


FIG. 14

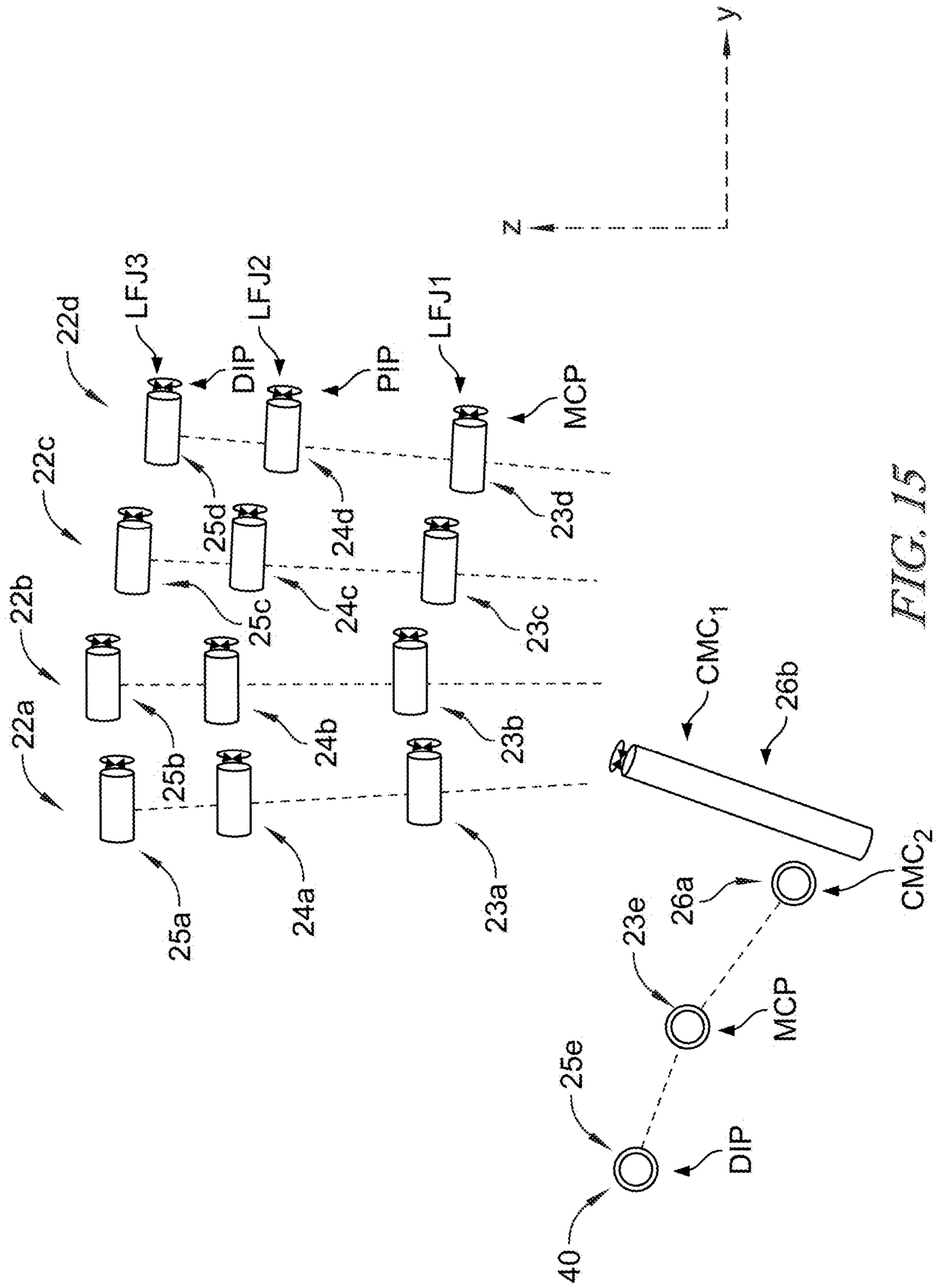

y
N
LFJ2
LFJ1
22d
DIP
PIP
MCP
22c
25d
24d
23d
22b
25c
24c
23c
22a
25b
24b
23b
25a
24a
23a
CMC1
26b
23e
26a
CMC2
MCP
25e
DIP
40

FIG. 15

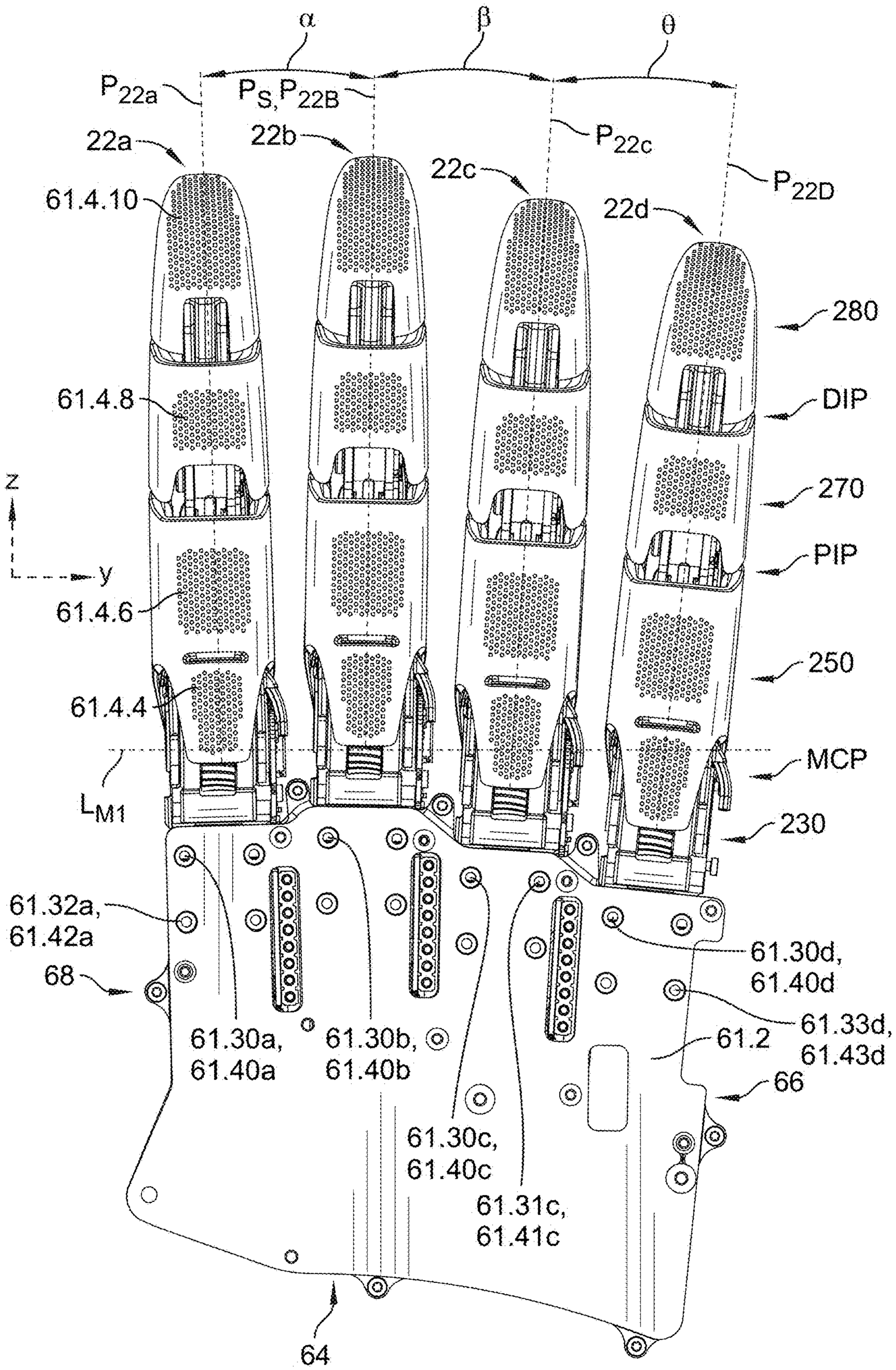

α
β
θ
P22a
PS, P22B
P22c
P22D
22a
22b
22c
22d
61.4.10
280
61.4.8
DIP
z
270
y
PIP
61.4.6
250
61.4.4
MCP
LM1
230
61.32a,
61.42a
61.30d,
61.40d
68
61.33d,
61.43d
61.2
66
61.30a,
61.40a
61.30b,
61.40b
61.30c,
61.40c
61.31c,
61.41c
64

FIG. 16

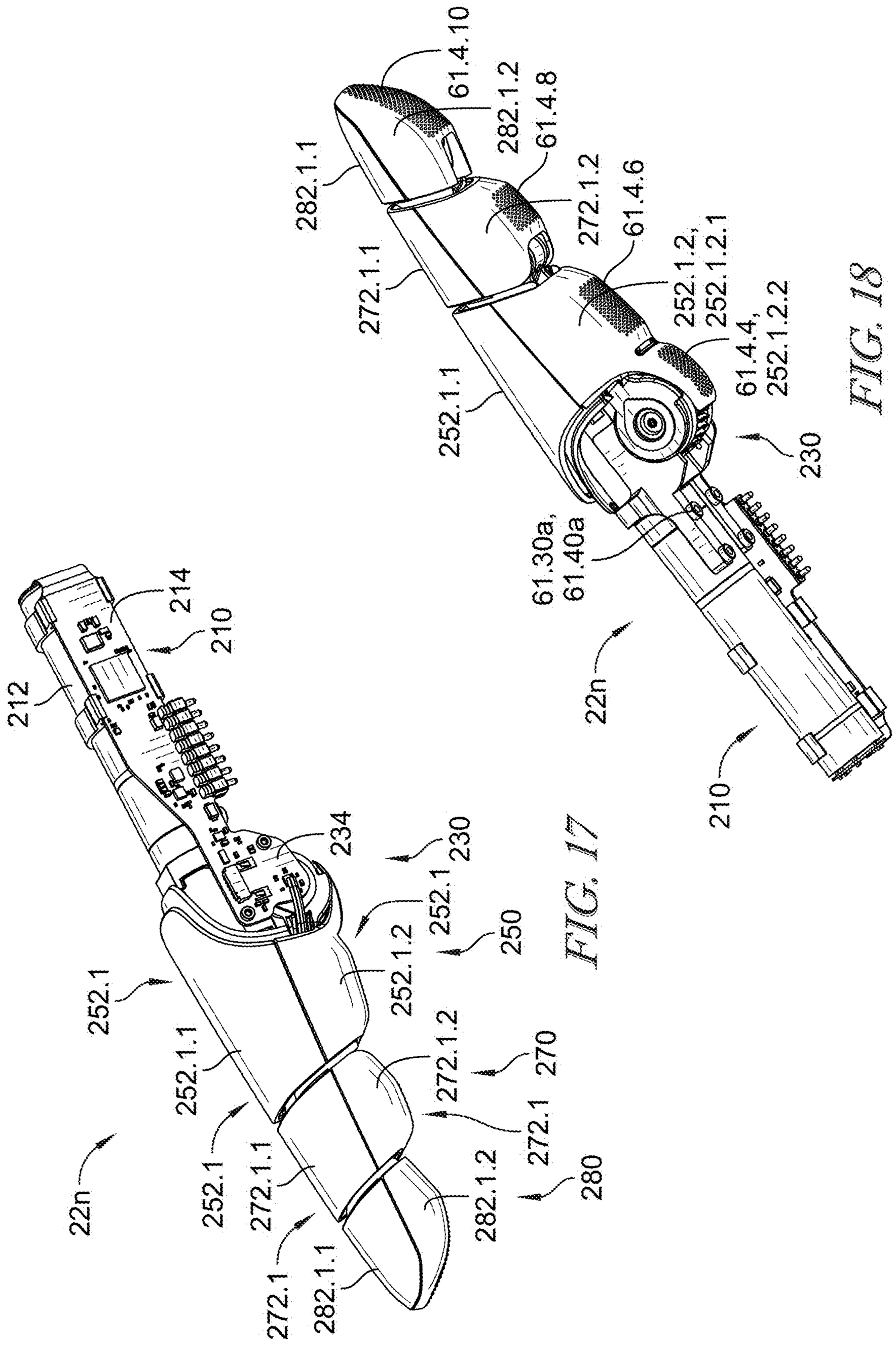

61.4.10
282.1.2
61.4.8
282.1.1
272.1.2
61.4.6
272.1.1
252.1.2,
252.1.2.1
61.4.4,
252.1.2.2
252.1.1
230
61.30a,
61.40a
22n
210
214
210
212
234
230
252.1
250
252.1.2
252.1
252.1.1
272.1.2
270
272.1
252.1
272.1.1
272.1
282.1.2
280
22n
282.1.1

FIG. 17

FIG. 18

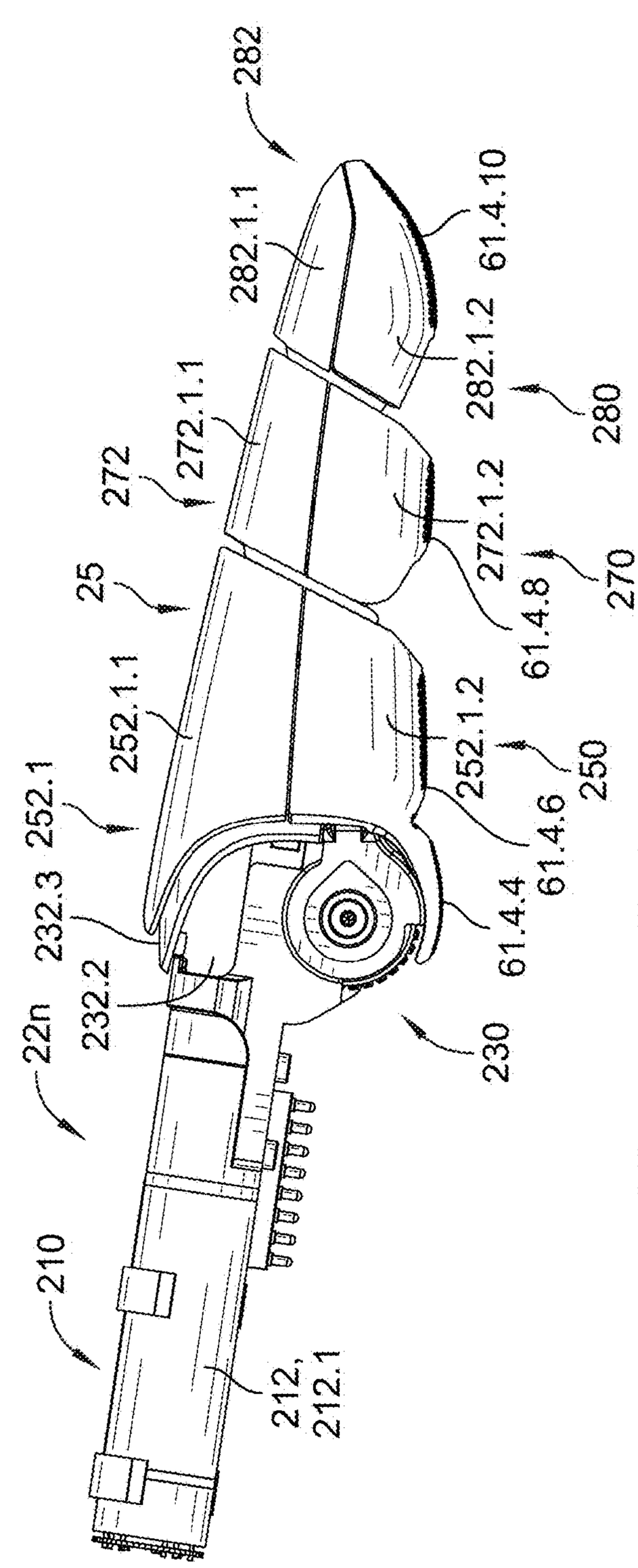


FIG. 19

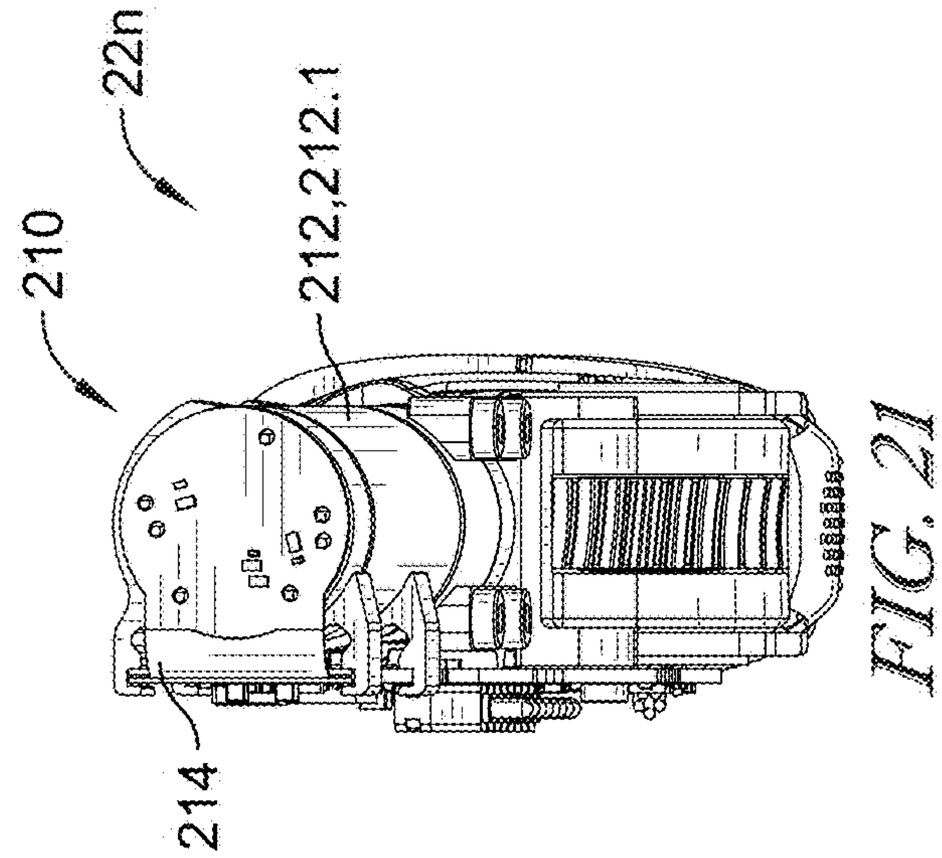


FIG. 21

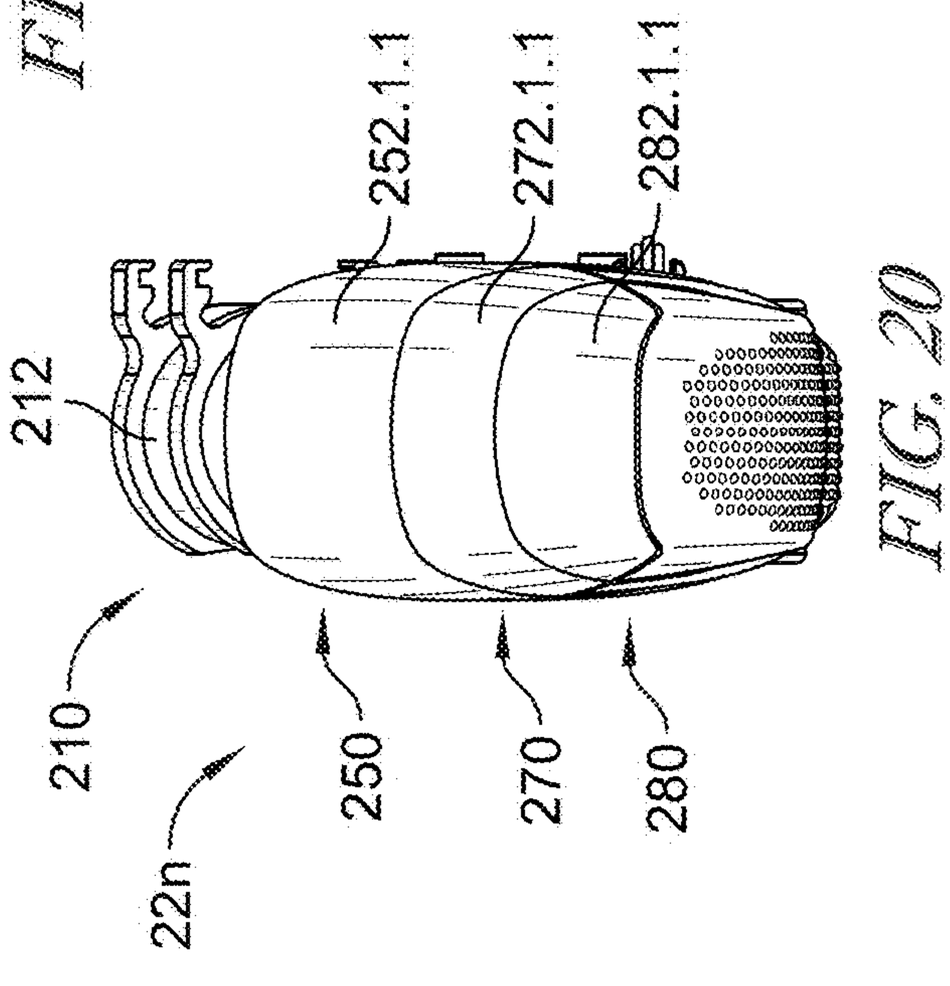


FIG. 20

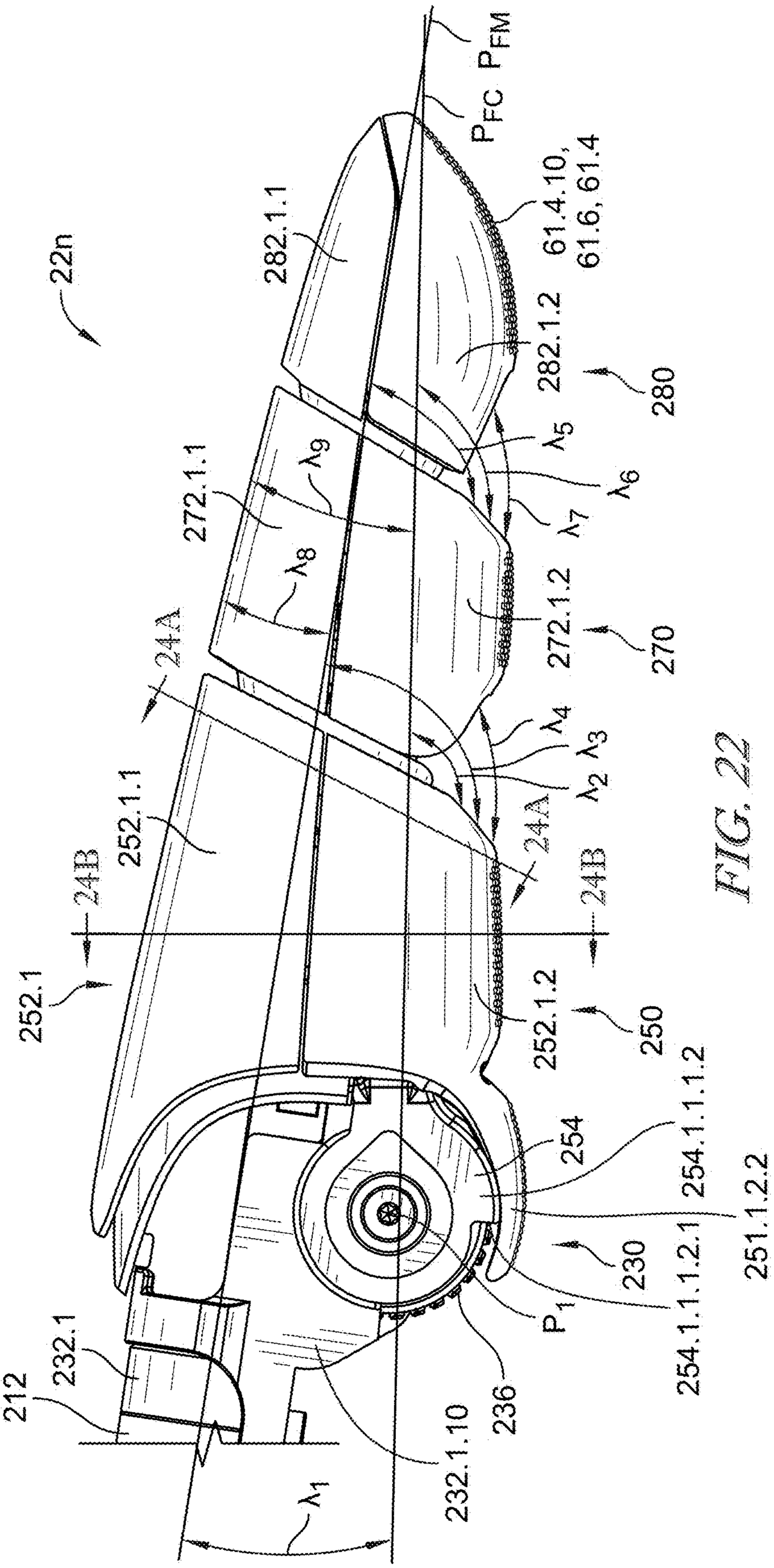

22n
282.1.1
P_{FM}
P_{FC}
61.4.10, 61.6, 61.4
282.1.2
280
λ_5
λ_6
λ_7
λ_8
λ_9
272.1.1
272.1.2
270
24A
24B
252.1.1
252.1.2
250
λ_2 λ_3 λ_4
254
254.1.1.1.1.2
254.1.1.1.2.1
251.1.2.2
230
P_1
212
232.1
232.1.10
236
λ_1

FIG. 22

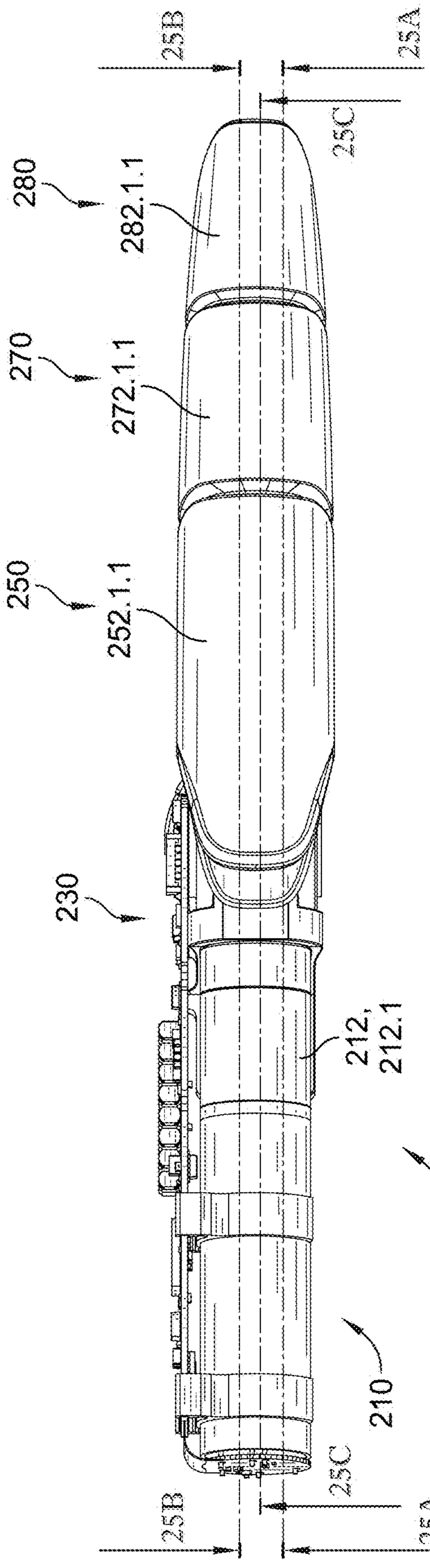

25B
25A
25C
280
282.1.1
270
272.1.1
250
252.1.1
230
212,
212.1
22n
210
25C
25B
25A

FIG. 23

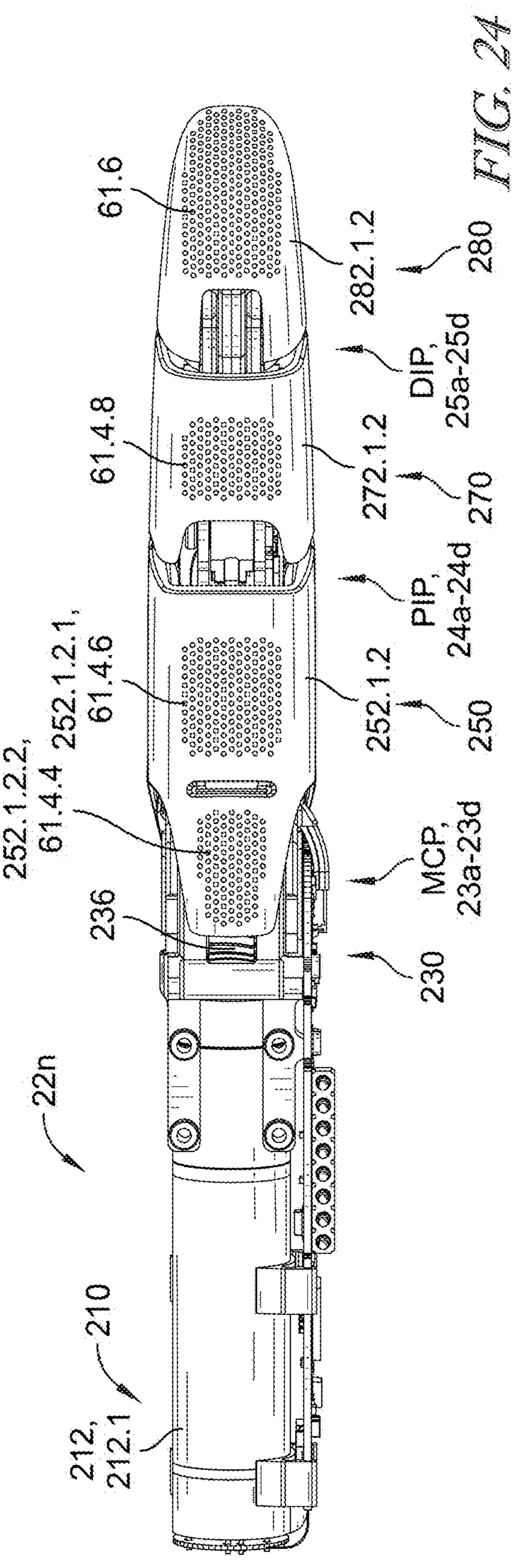

61.6
282.1.2
280
61.4.8
272.1.2
DIP,
25a-25d
270
252.1.2.2,
61.4.4
252.1.2.1,
61.4.6
PIP,
24a-24d
252.1.2
250
236
MCP,
23a-23d
230
22n
212,
212.1
210

FIG. 24

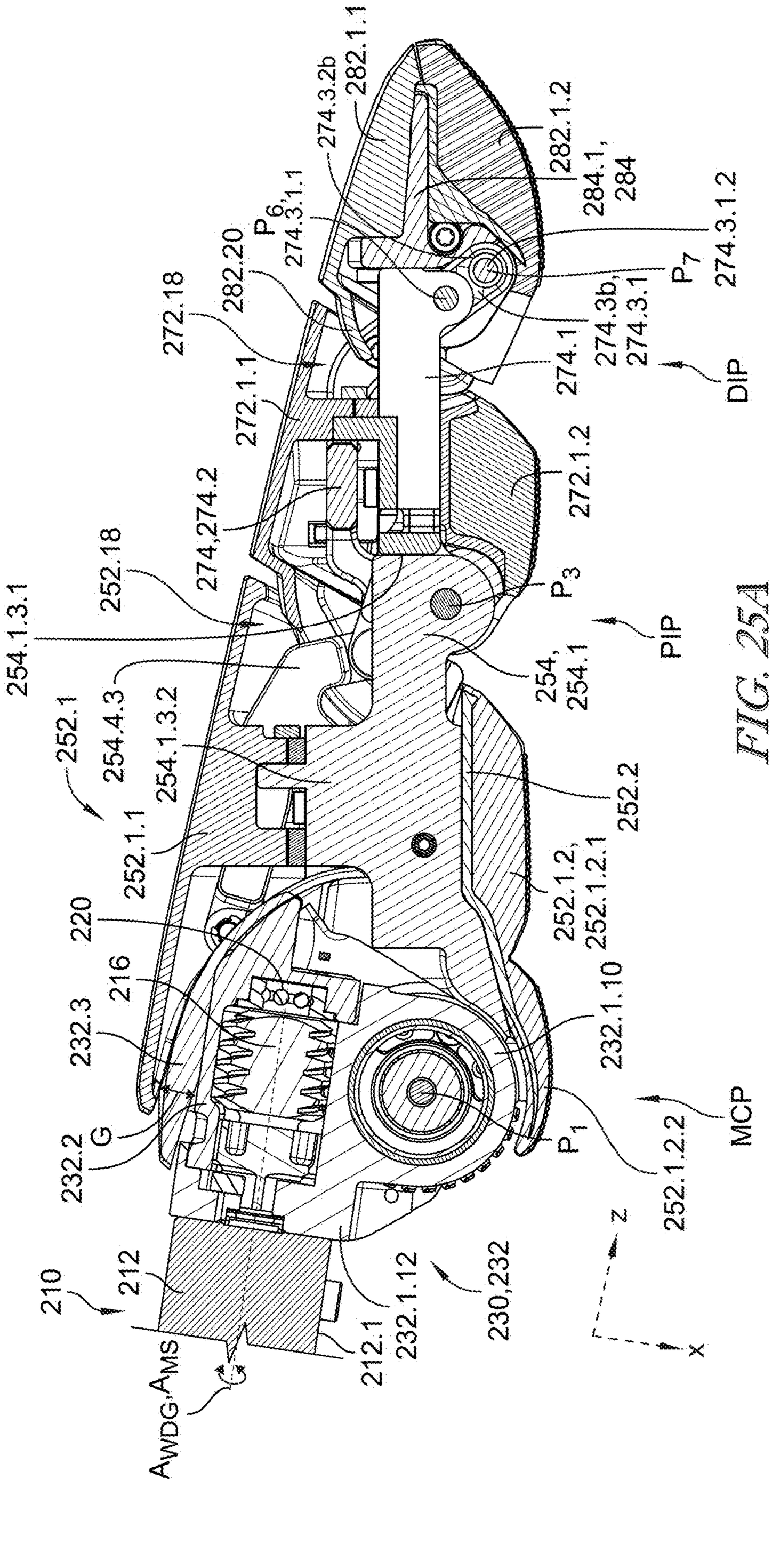

272.18
282.20
P6,
274.3.1.1
274.3.2b
282.1.1
282.1.2
284.1,
284
P7
274.3.1.2
274.3b,
274.3.1
272.1.1
274,274.2
272.1.2
DIP
PIP
P3
254.1.3.1
252.18
252.1
254.4.3
254.1.3.2
252.1.1
254,
254.1
252.2
252.1.2,
252.1.2.1
220
216
232.3
232.2
G
P1
232.1.10
252.1.2.2
MCP
210
212
212.1
232.1.12
230,232
AWDG,AMS
z
x

FIG. 25A

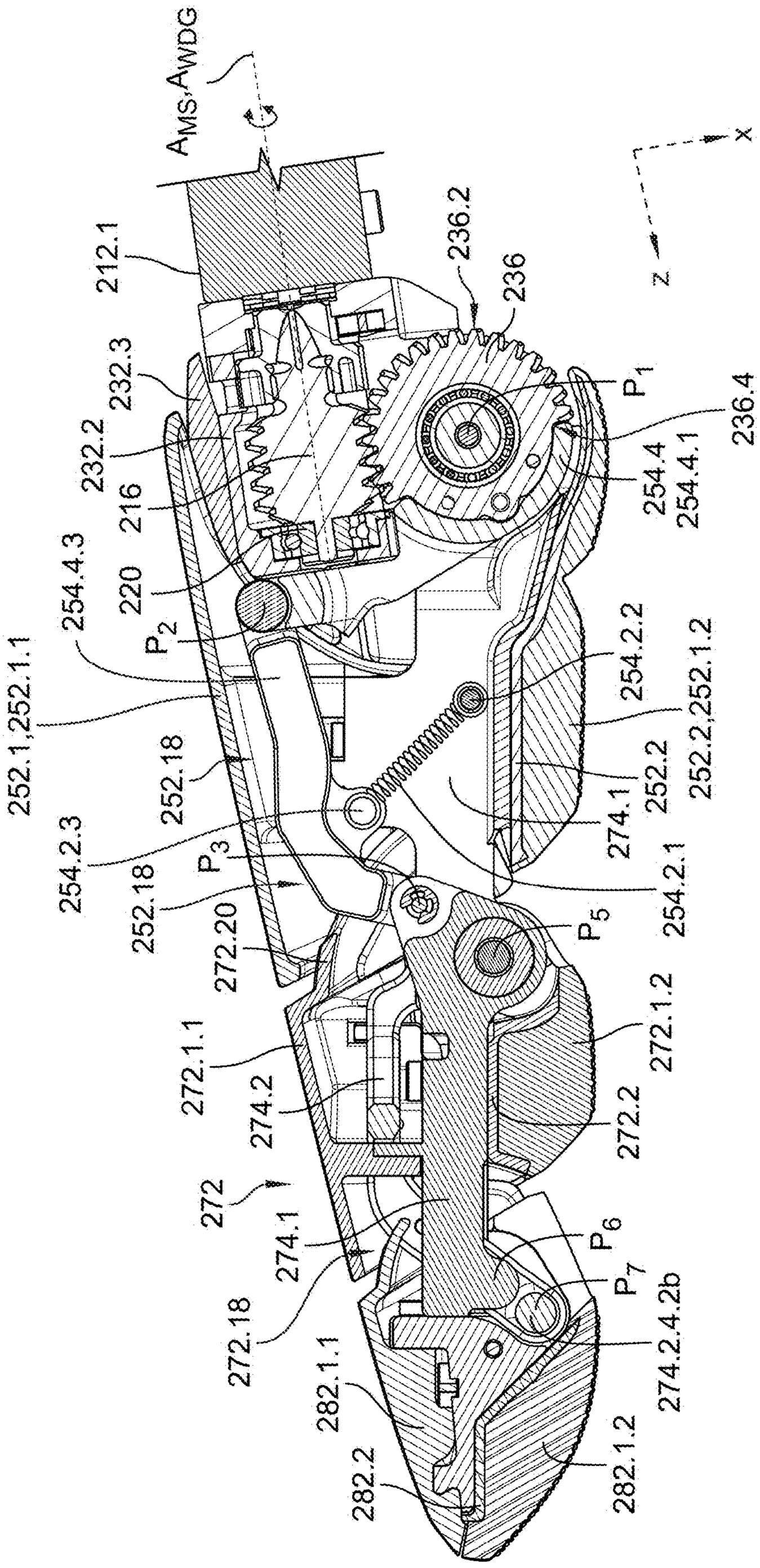

A_{MS},A_{WDG}
212.1
236.2
236
232.3
232.2
216
220
254.4.3
P_2
252.1,252.1.1
254.2.3
252.18
P_3
252.18
272.20
272.1.1
274.2
272
274.1
272.18
282.1.1
282.2
P_5
P_6
P_7
274.2.4.2b
282.1.2
272.1.2
272.2
254.2.1
274.1
252.2
252.2,252.1.2
254.2.2
254.4
254.4.1
P_1
236.4
x
z

FIG. 25B

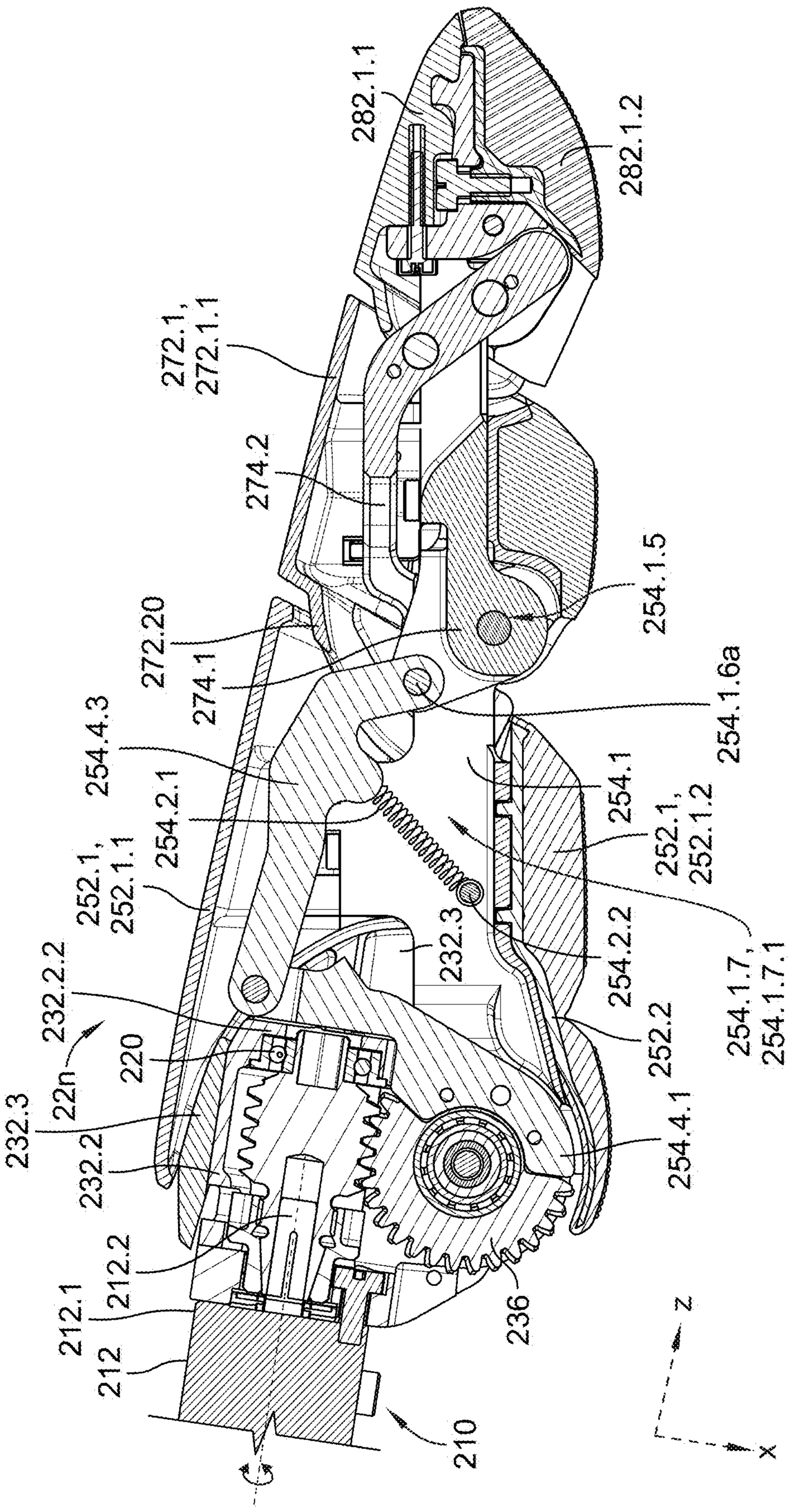

282.1.1
282.1.2
272.1,
272.1.1
274.2
272.20
274.1
254.1.5
254.4.3
254.1.6a
254.2.1
254.1
252.1,
252.1.1
252.1,
252.1.2
232.3
254.2.2
232.2.2
220
22n
252.2
232.3
254.4.1
232.2
212.2
212.1
236
212
z
x
210

FIG. 25C

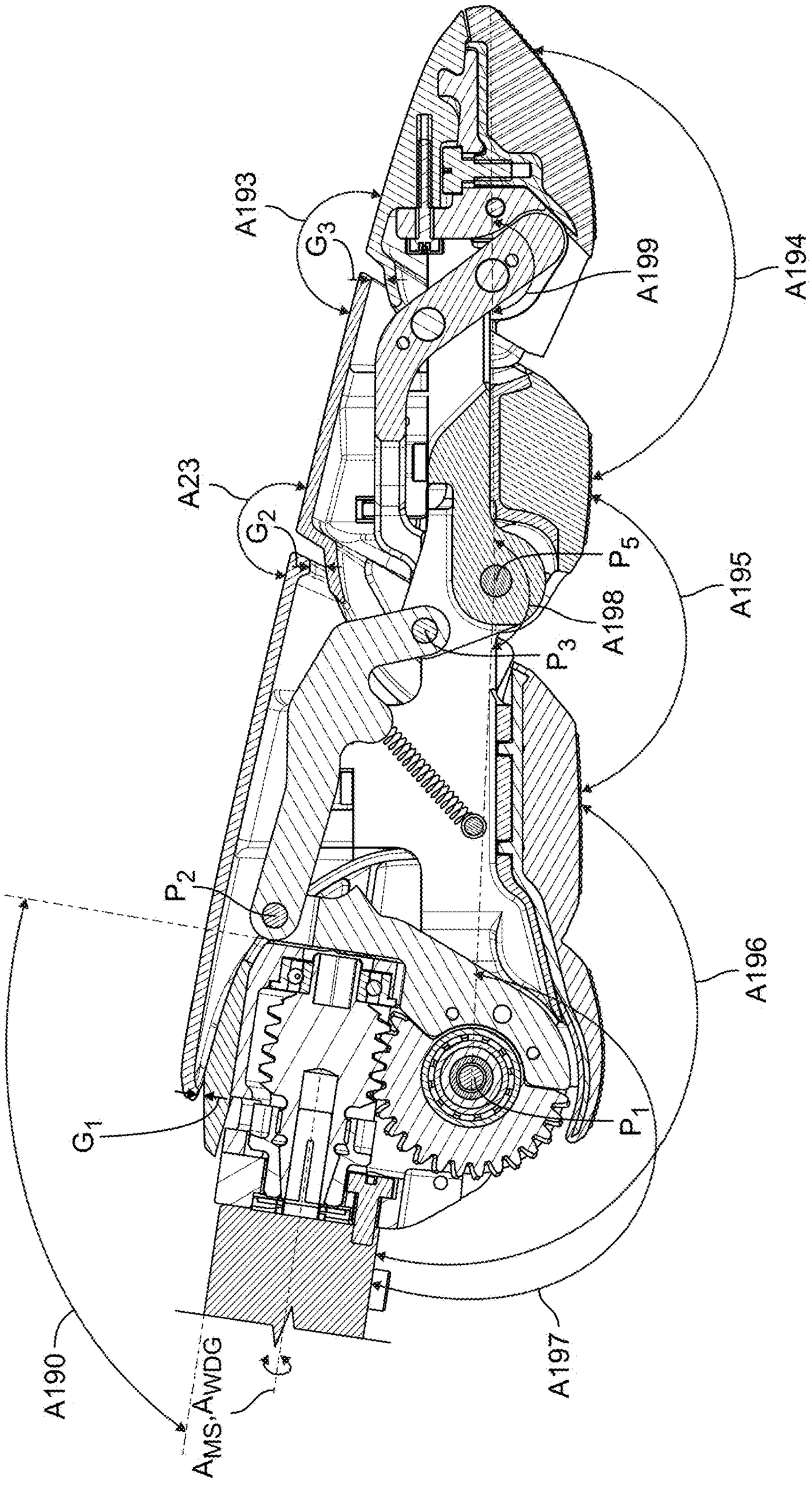

A193
G3
A199
A194
A23
G2
P5
A198
A195
P3
P2
P1
G1
A196
A190
AMS,AWDG
A197

FIG. 25D

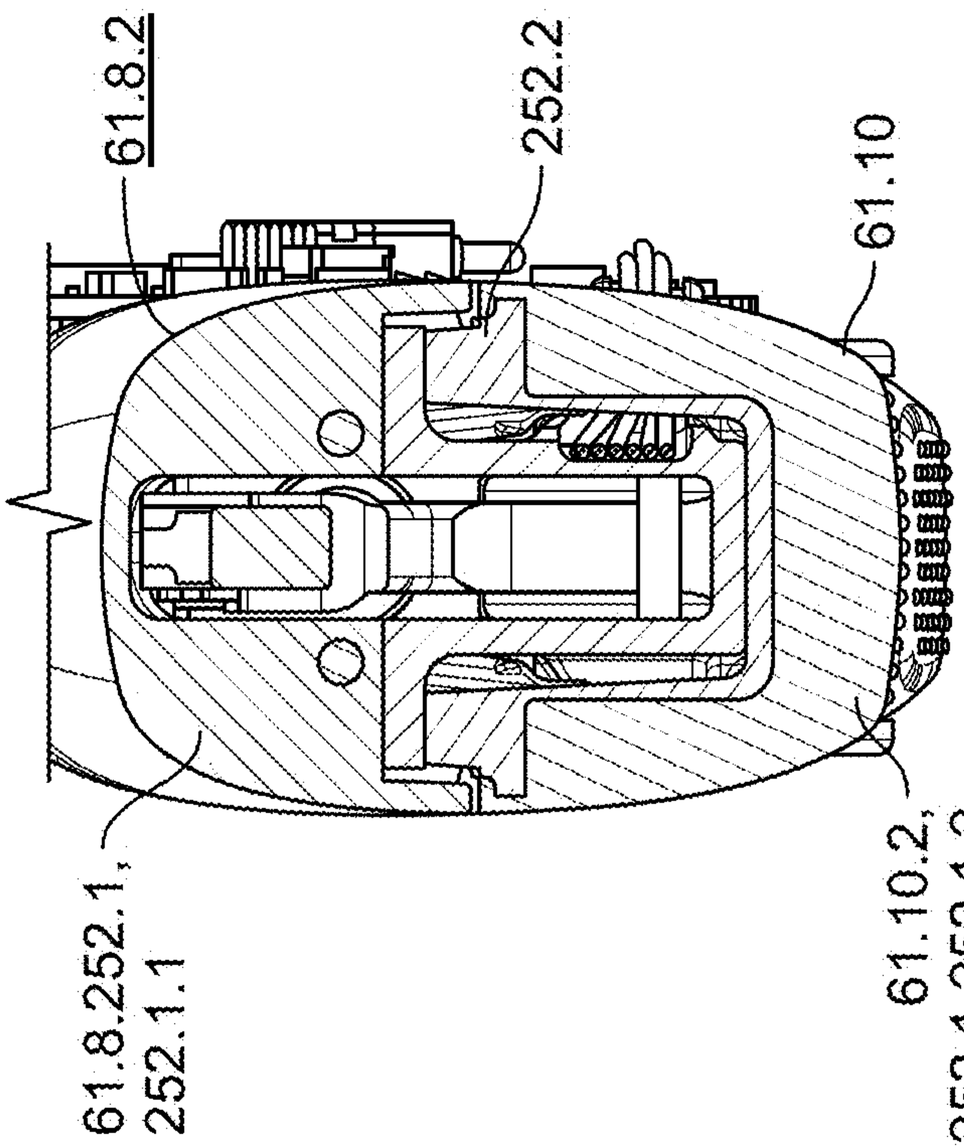


FIG. 26B

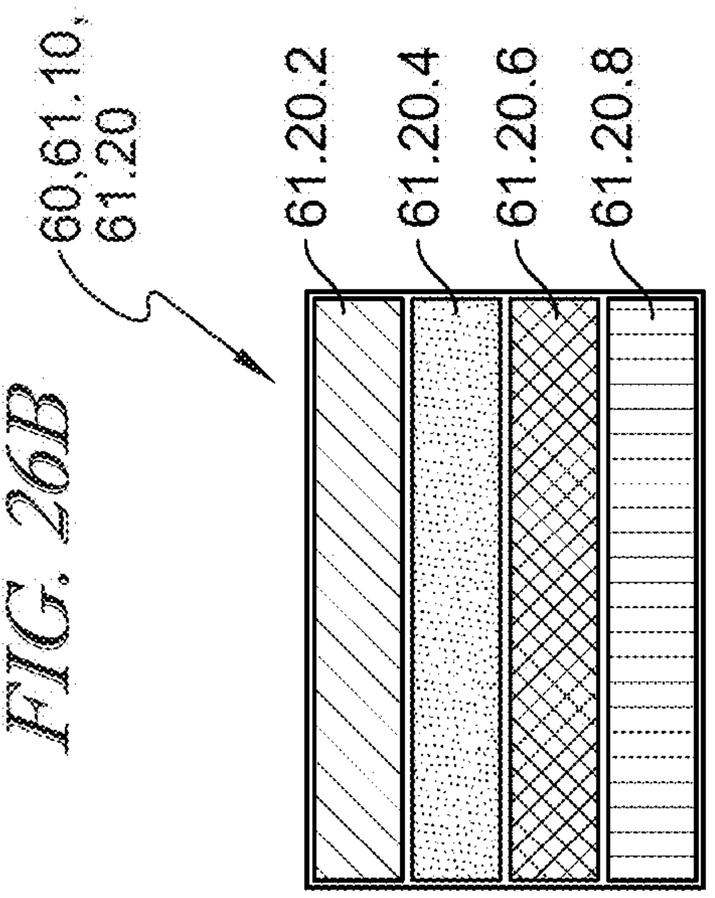


FIG. 27

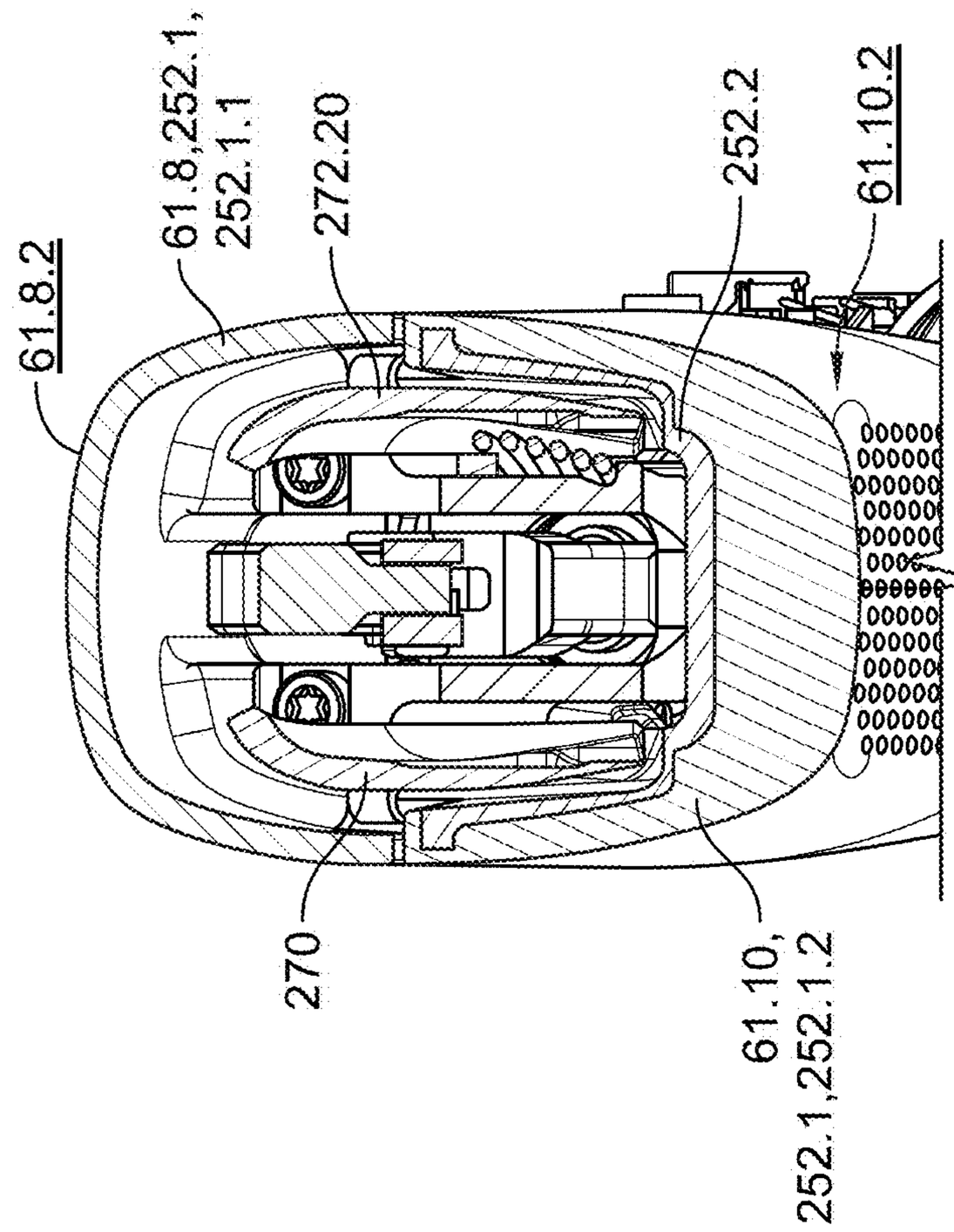


FIG. 26A

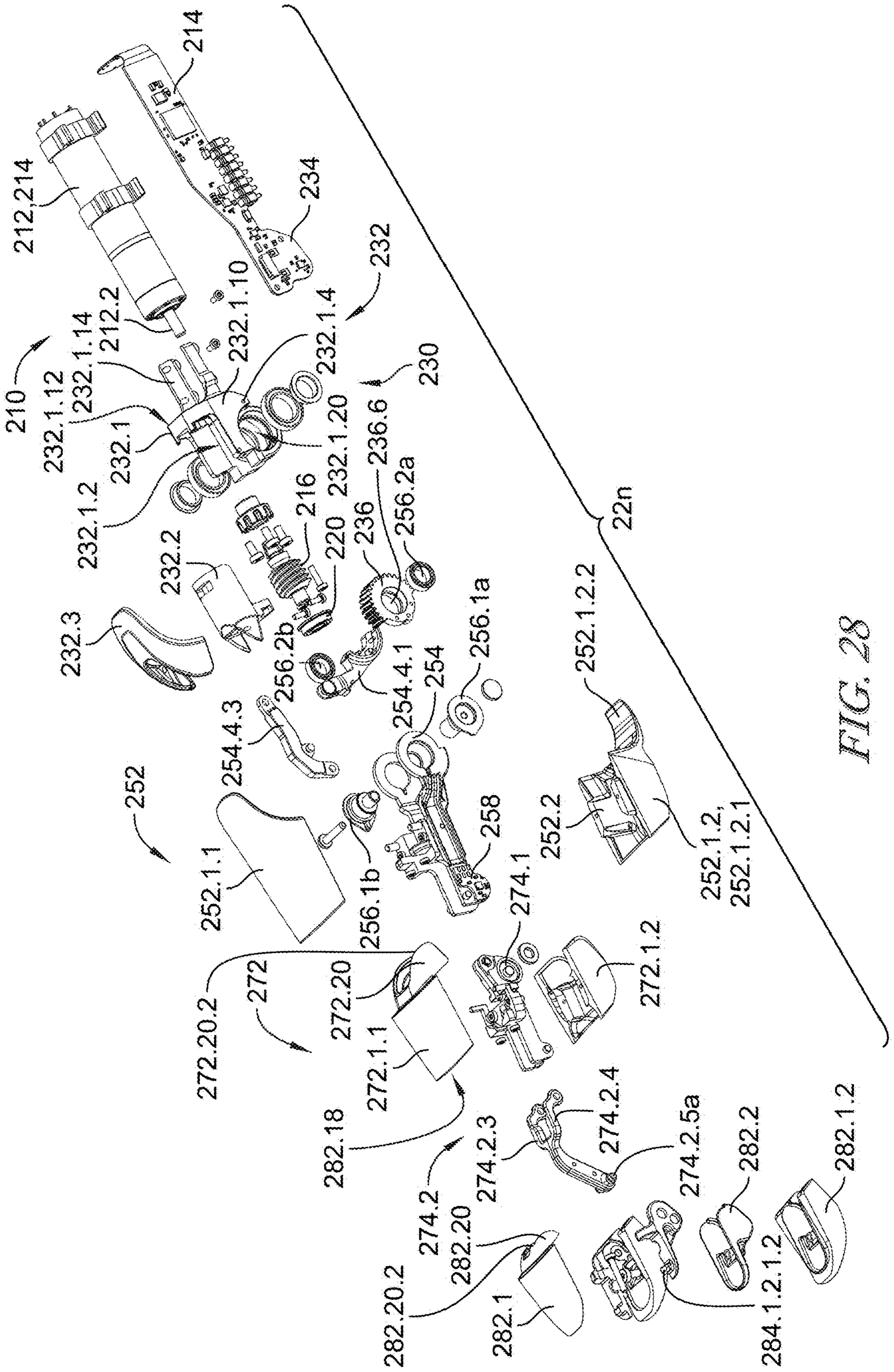

214
212,214
234
232.1.10
232
210
232.1.12
232.1.14
232.1
232.1.2
232.1.20
230
216
220
236
236.6
256.2a
232.2
232.3
256.2b
254.4.1
254
256.1a
254.4.3
252
252.1.1
256.1b
258
274.1
252.2
252.1.2.2
22n
252.1.2,
252.1.2.1
272.20.2
272
272.20
272.1.1
272.1.2
282.18
274.2
274.2.3
274.2.4
274.2.5a
282.2
282.20.2
282.20
282.1
284.1.2.1.2
282.1.2

FIG. 28

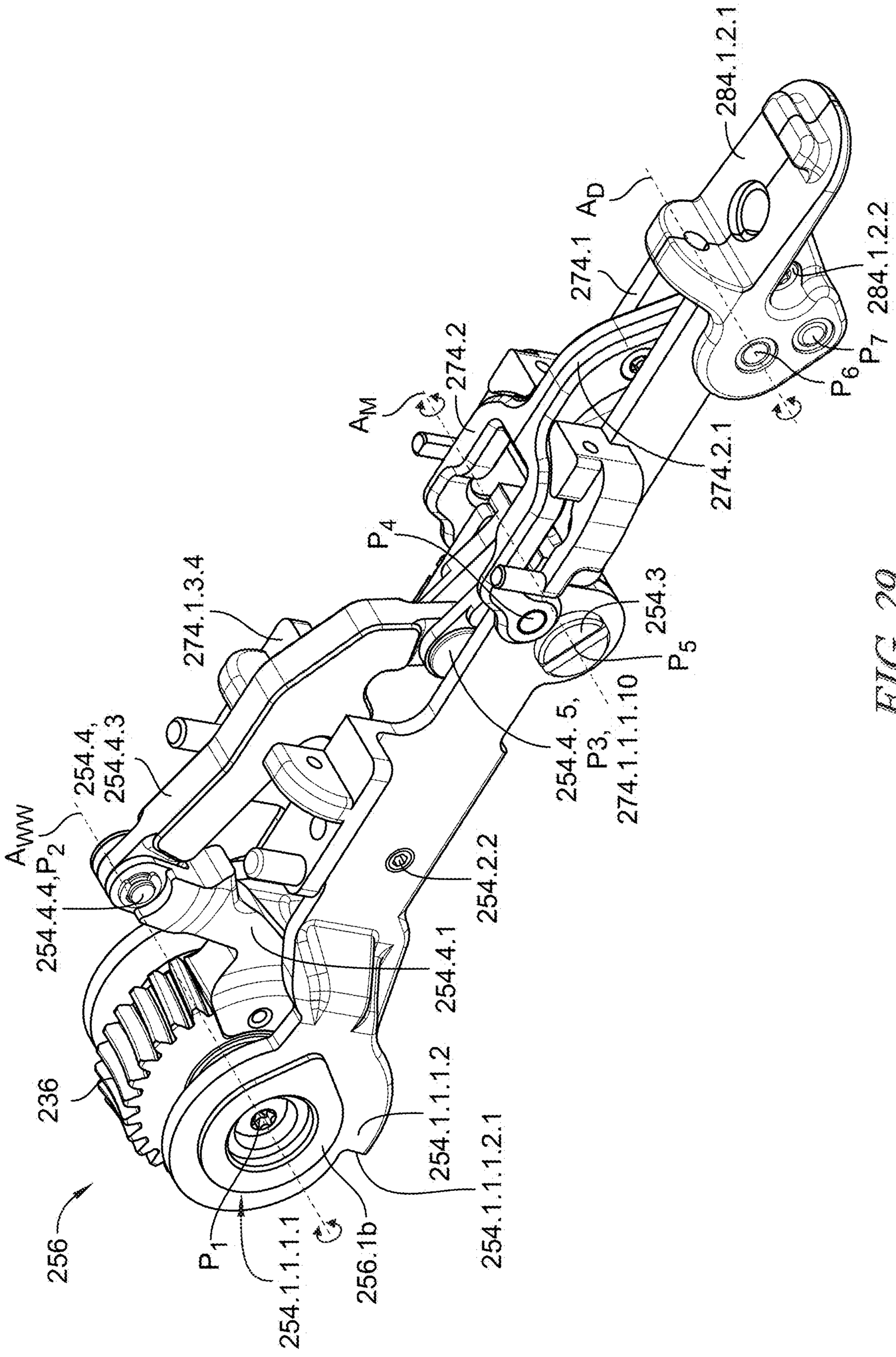

284.1.2.1
A_D
274.1
284.1.2.2
P_6
P_7
274.2
A_M
P_4
274.2.1
274.1.3.4
254.3
P_5
254.4. 5,
P3,
274.1.1.1.10
254.2.2
A_{WW}
254.4,
254.4.3
254.4.4,P_2
236
256
P_1
254.1.1.1.1
256.1b
254.4.1
254.1.1.1.2
254.1.1.1.2.1

FIG. 29

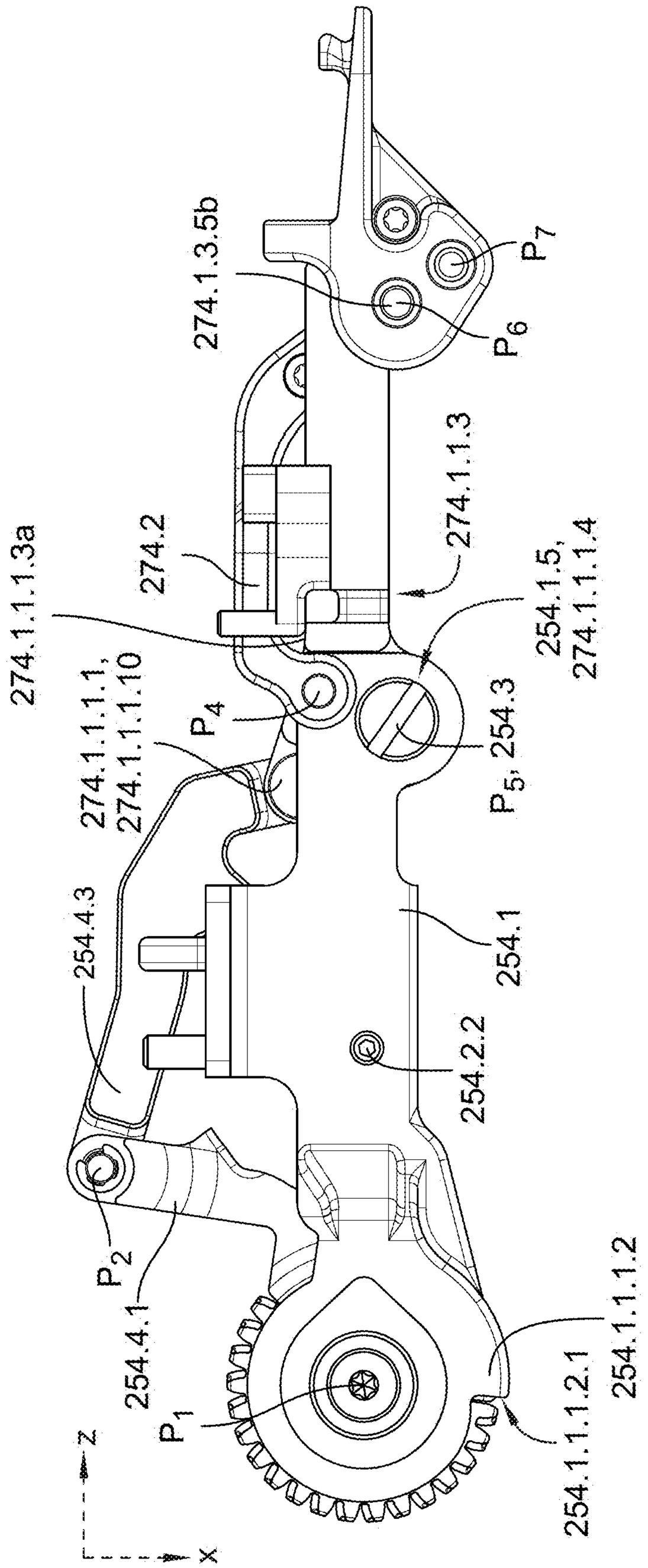

274.1.3.5b
P7
P6
274.1.1.3
274.1.1.3a
274.2
274.1.1.1.1,
274.1.1.1.10
254.1.5,
274.1.1.1.4
P4
P5, 254.3
254.4.3
254.1
254.2.2
P2
254.4.1
P1
254.1.1.1.2.1
254.1.1.1.2
Z
X

FIG. 30

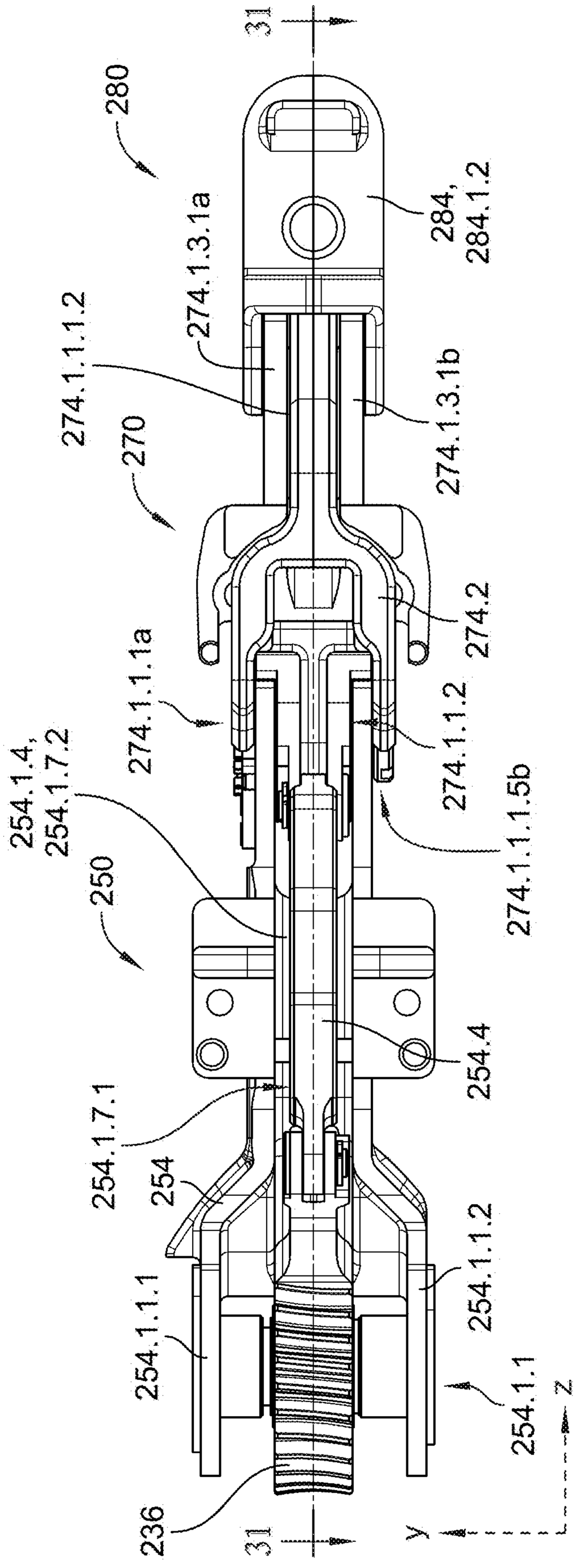

31
280
274.1.3.1a
284,
284.1.2
274.1.1.1.2
270
274.1.3.1b
274.2
274.1.1.1a
274.1.1.2
254.1.4,
254.1.7.2
274.1.1.5b
250
254.4
254.1.7.1
254
254.1.1.2
254.1.1.1
254.1.1
236
31
y
z

FIG. 31

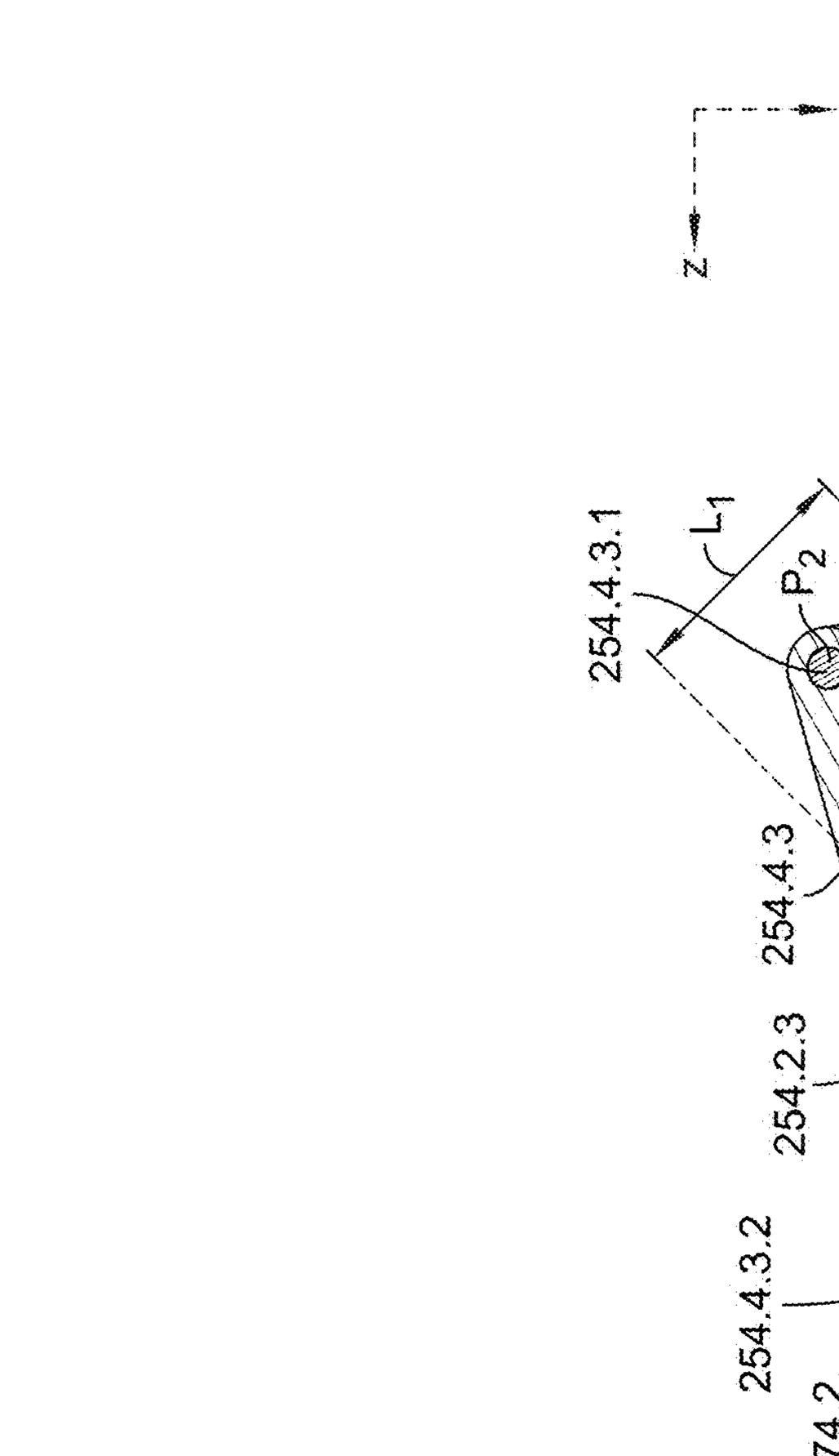

254.4.3
274.1.3.4
284.1.2.1
284.1.2.1.1
284.1.2.1.1b

FIG. 32

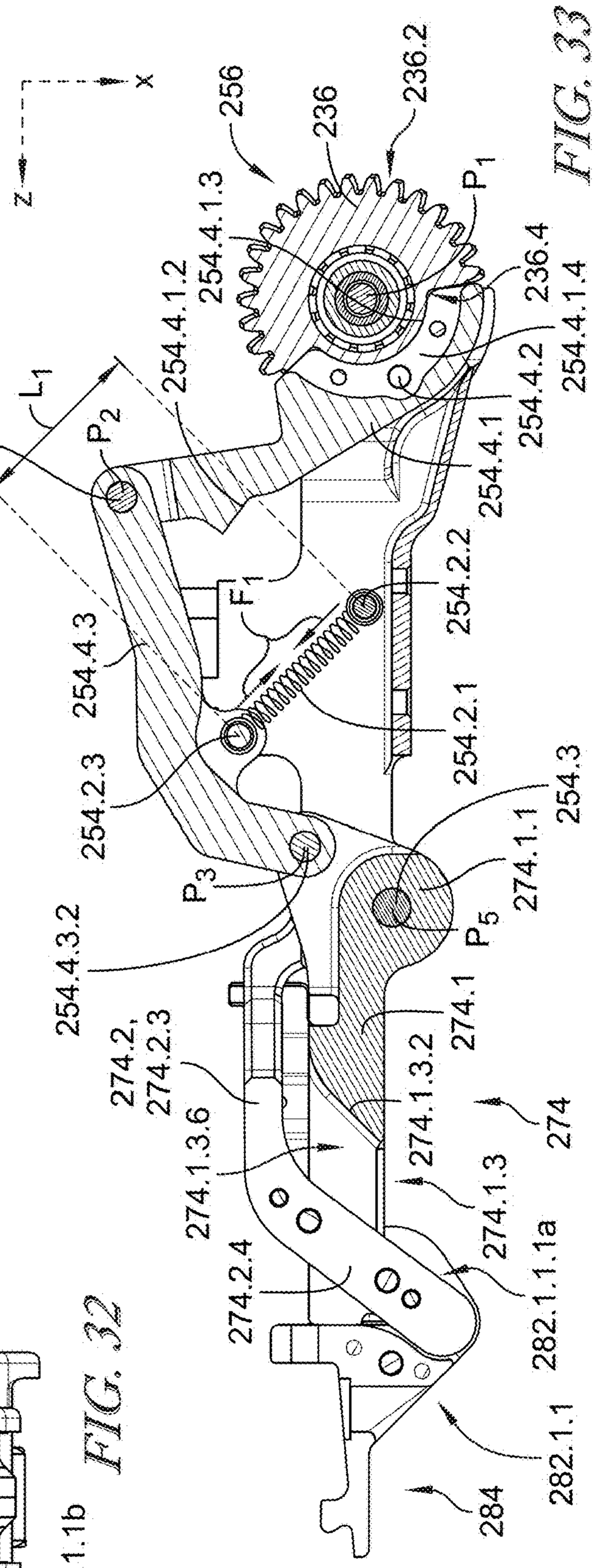

z
x
256
236
236.2
254.4.1.3
254.4.1.2
254.4.1.4
236.4
254.4.2
254.4.1
254.4.3.1
L_1
P_2
P_1
O_1
O_2
F_1
254.4.3
254.2.2
254.2.1
254.2.3
254.4.3.2
P_3
P_5
274.1.1
254.3
274.2,
274.2.3
274.1
274.1.3.6
274.1.3.2
274.2.4
274.1.3
274.1.1a
282.1.1.1a
282.1.1
284
274

FIG. 33

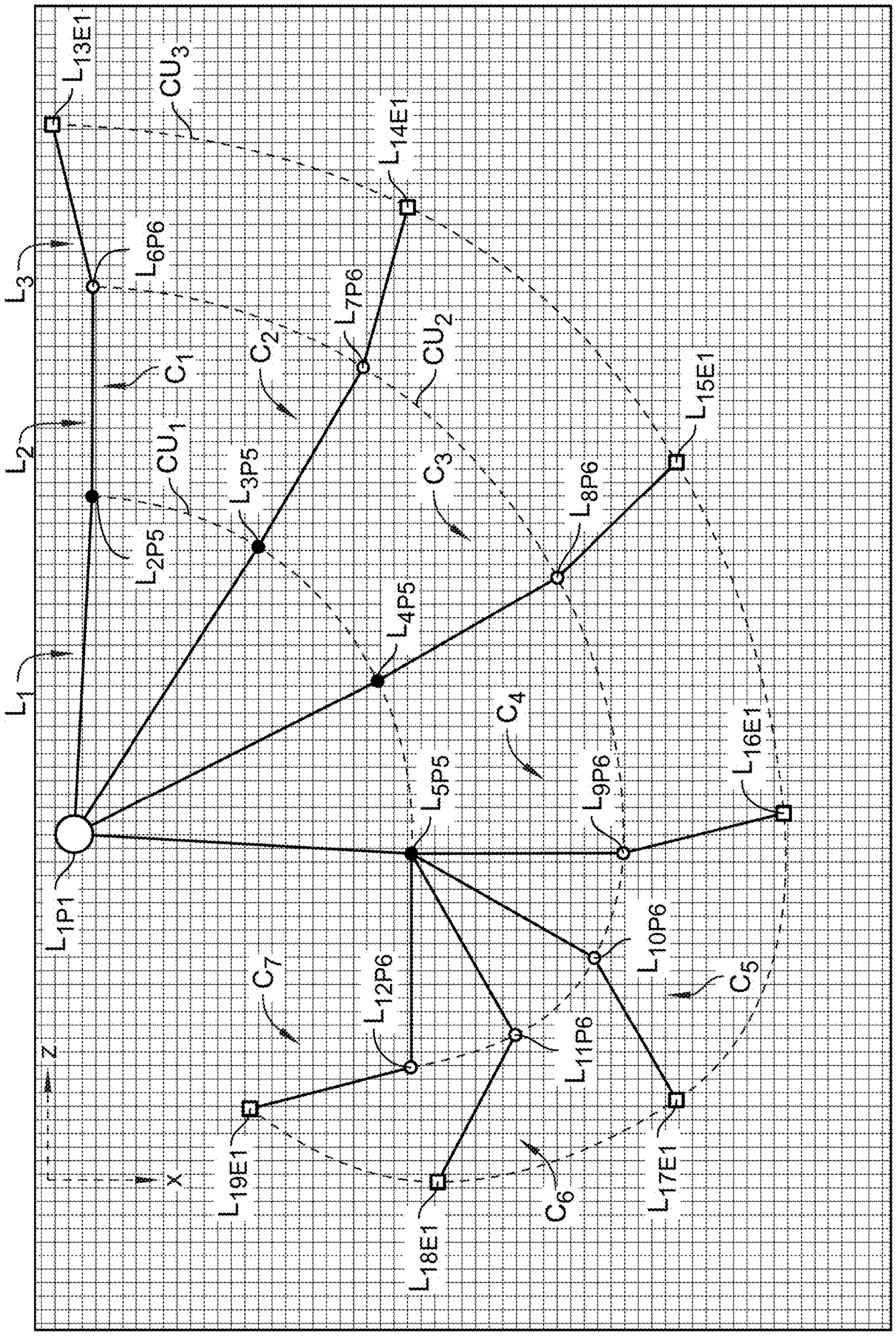

L13E1
CU3
L14E1
L6P6
L3
L7P6
C2
C1
CU2
L15E1
L2
CU1
L3P5
L2P5
C3
L8P6
L4P5
C4
L16E1
L5P5
L9P6
L1
L1P1
C7
L12P6
L10P6
C5
L11P6
Z
X
L19E1
C6
L17E1
L18E1

FIG. 34

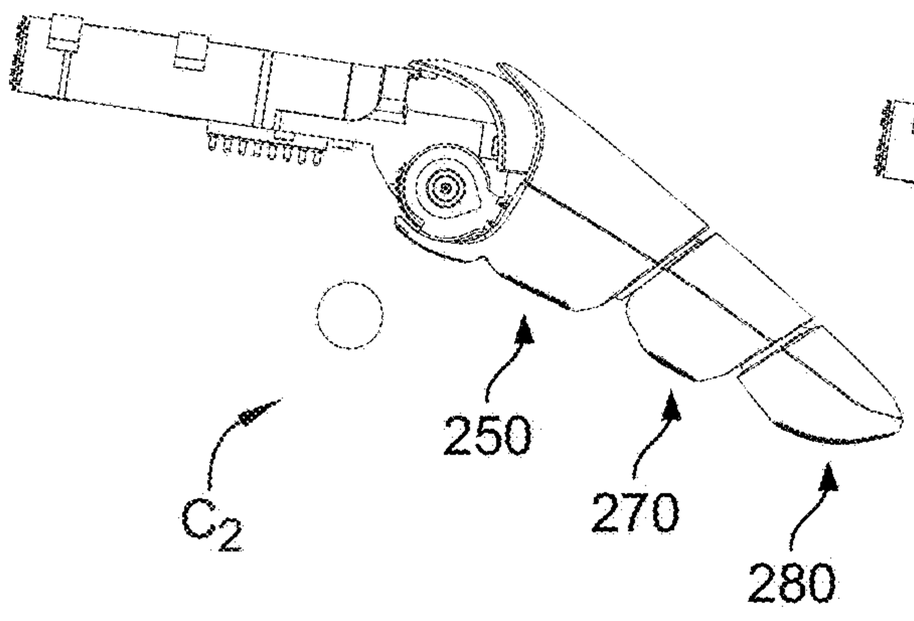


FIG. 35

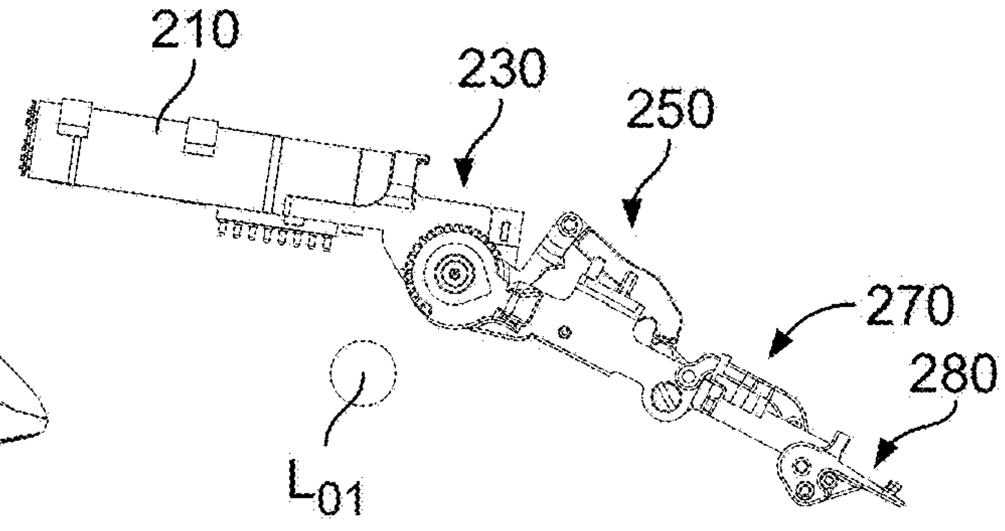


FIG. 36

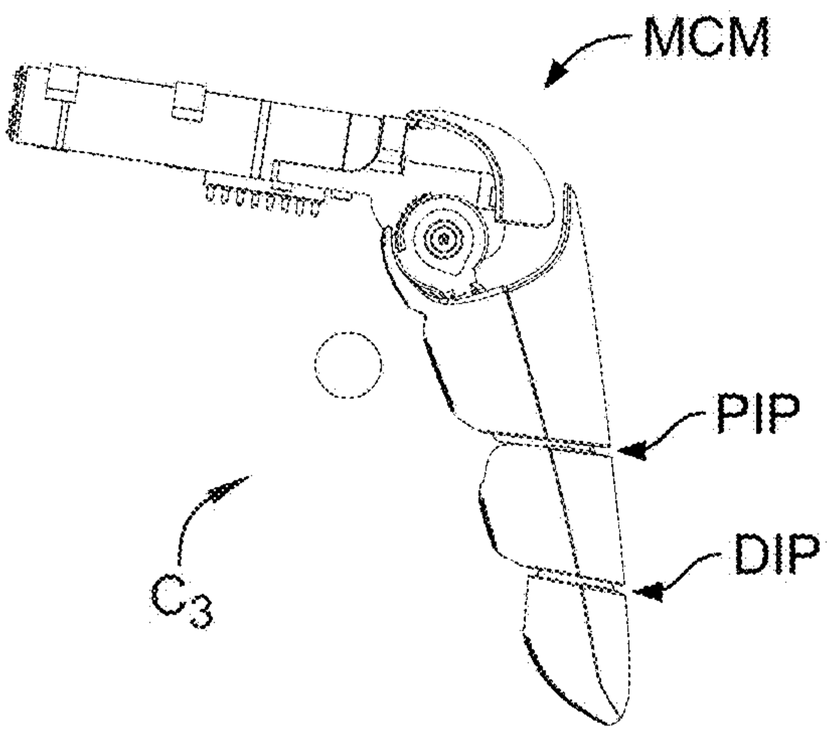


FIG. 37

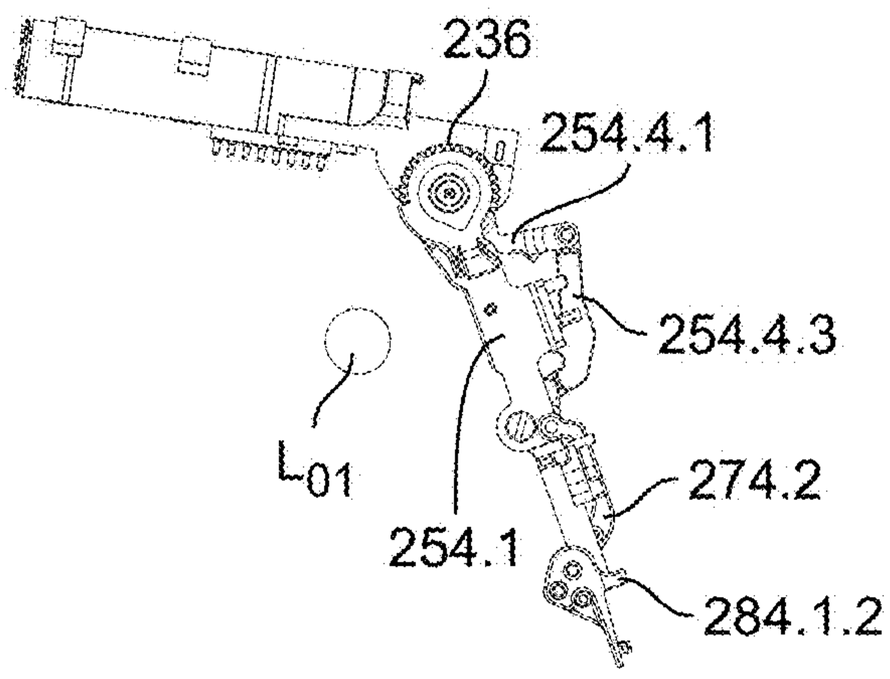


FIG. 38

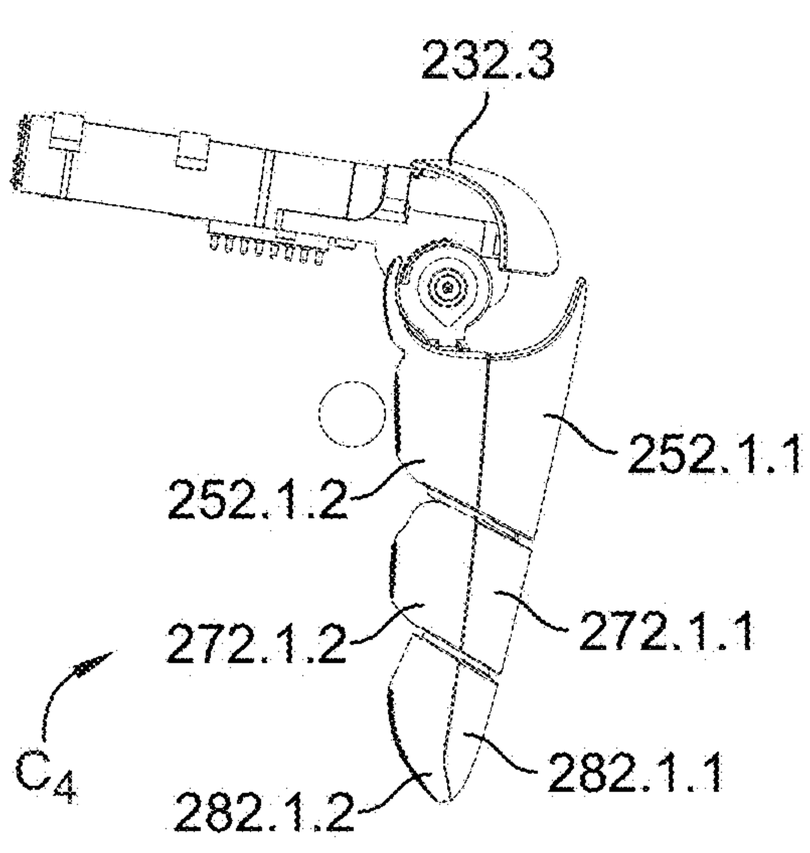


FIG. 39

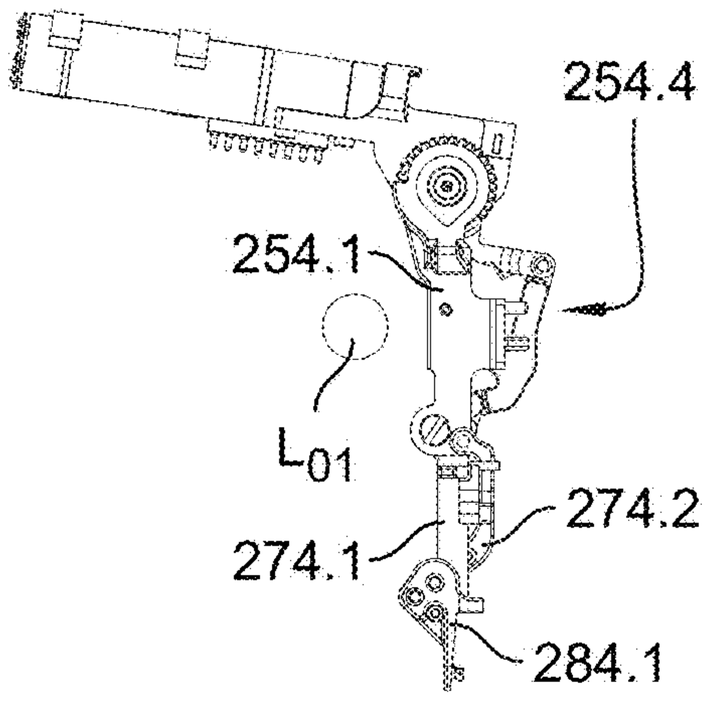


FIG. 40

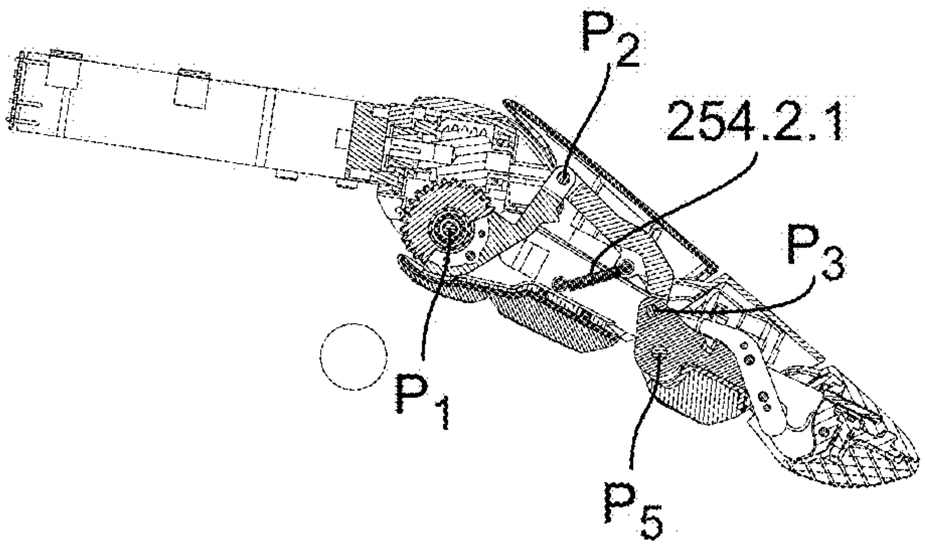


FIG. 41

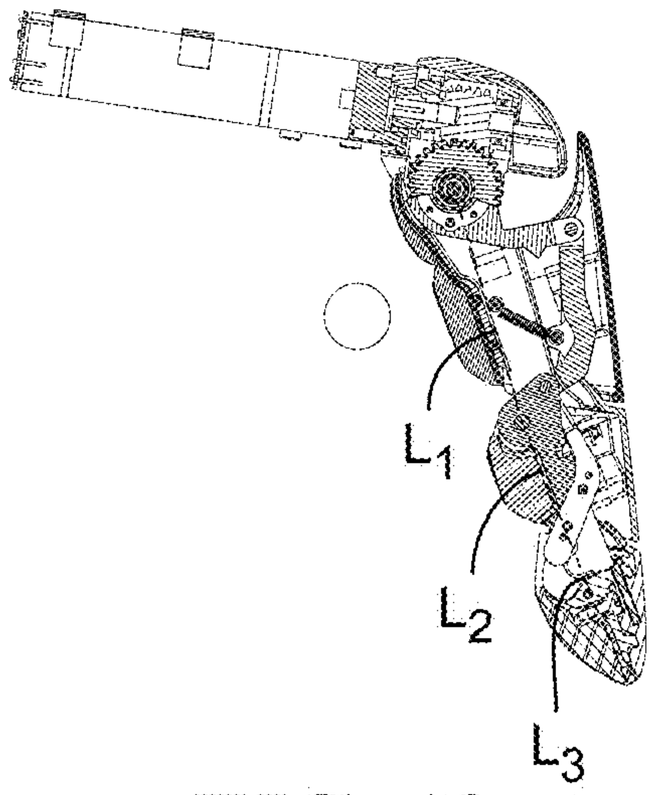


FIG. 42

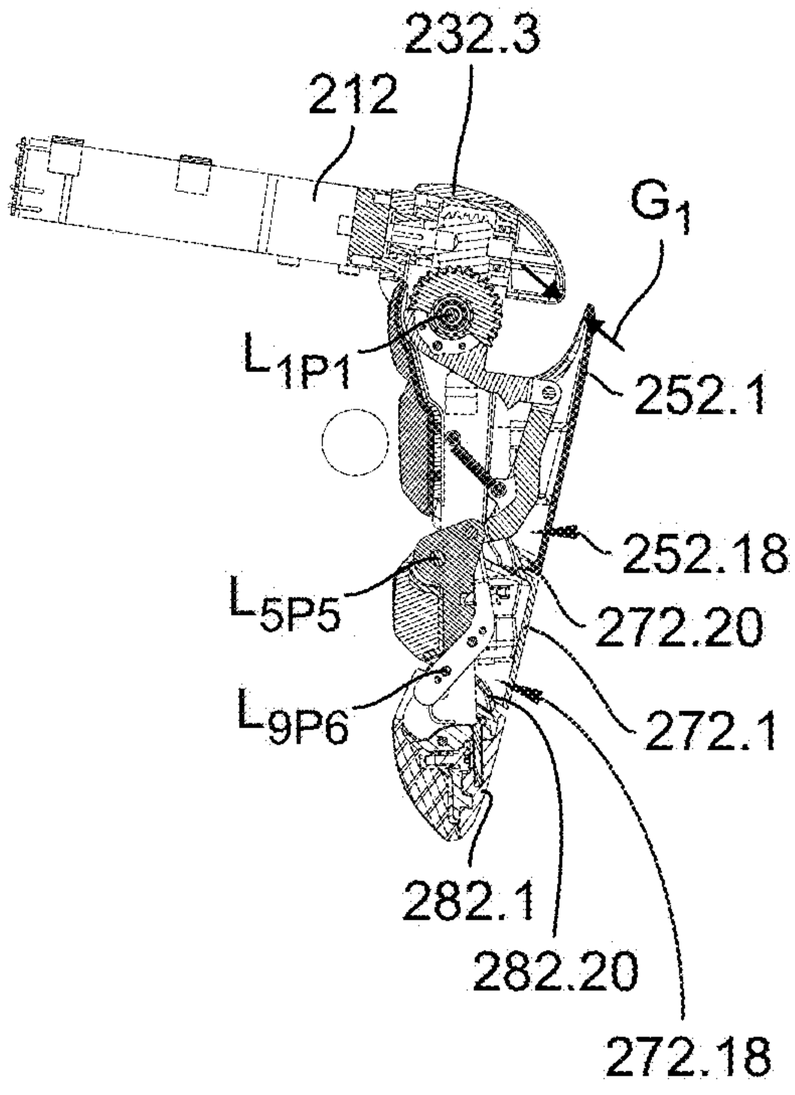


FIG. 43

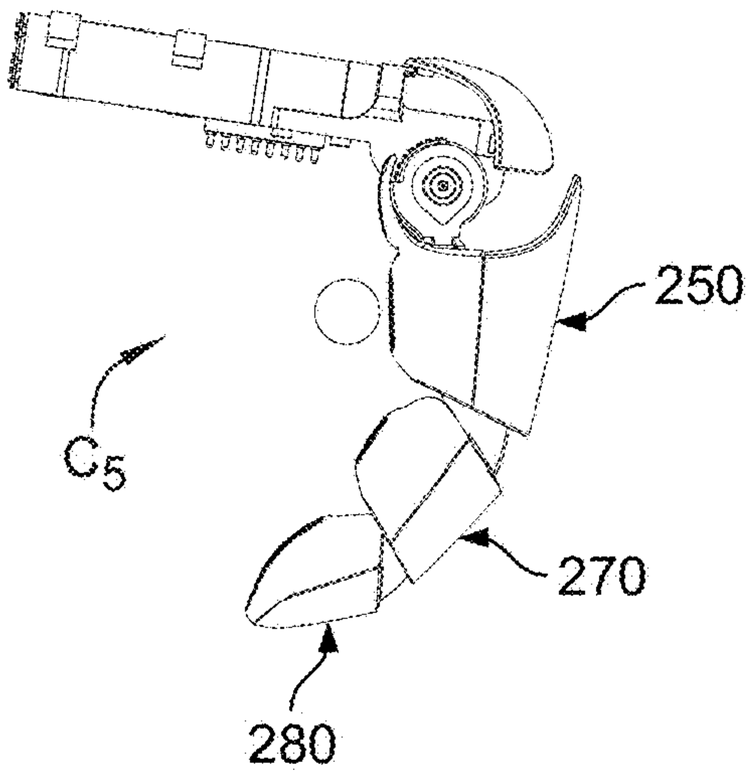


FIG. 44

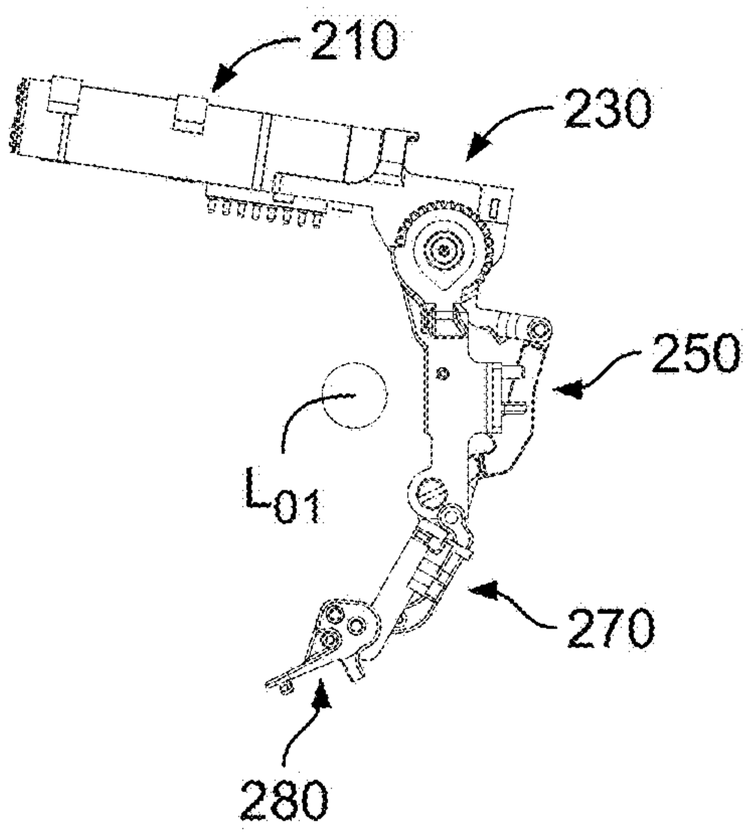


FIG. 45

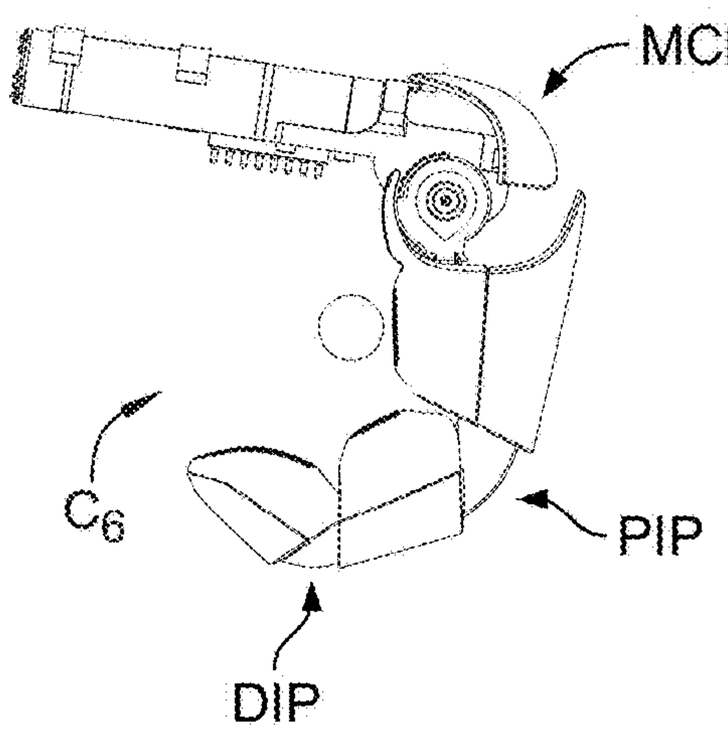


FIG. 46

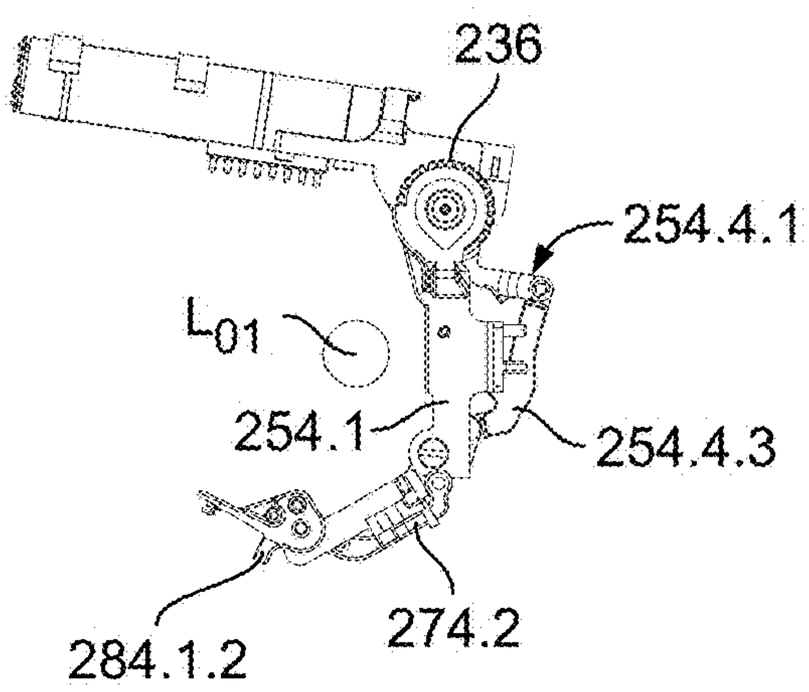


FIG. 47

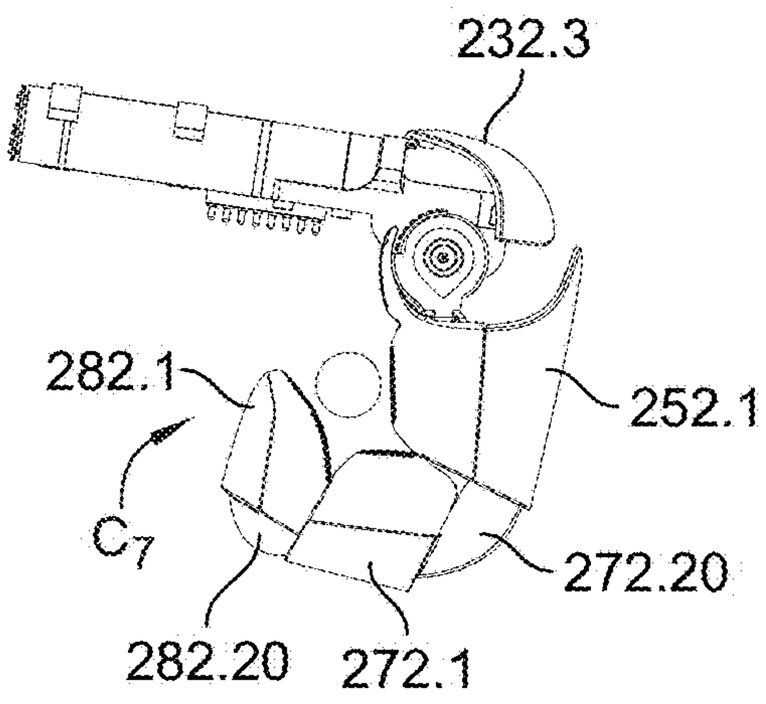


FIG. 48

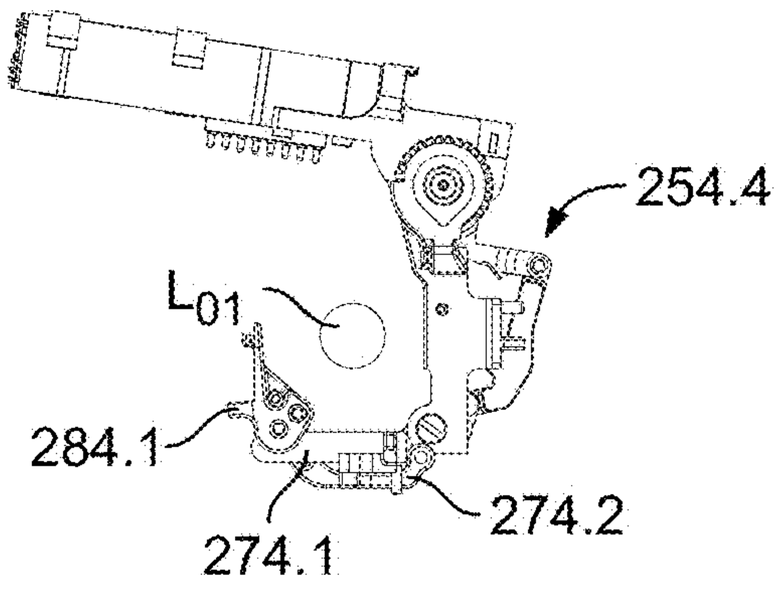


FIG. 49

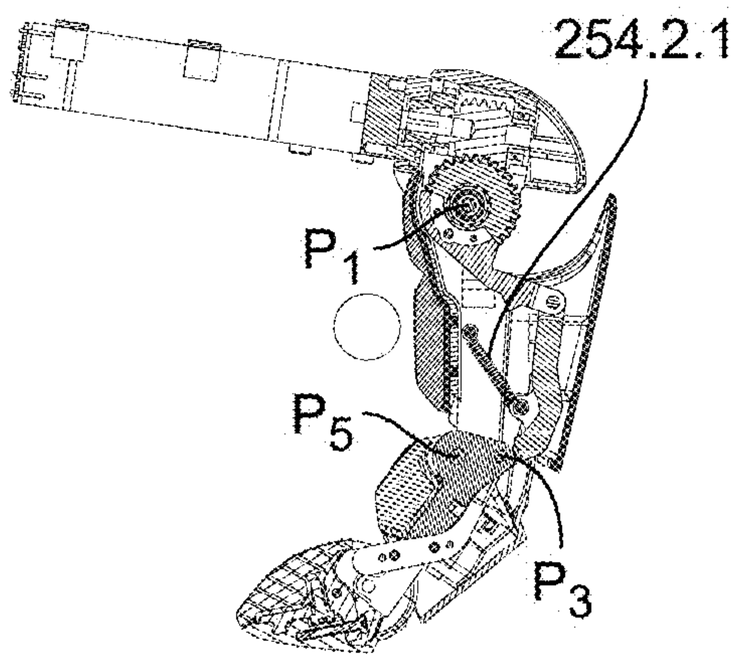


FIG. 50

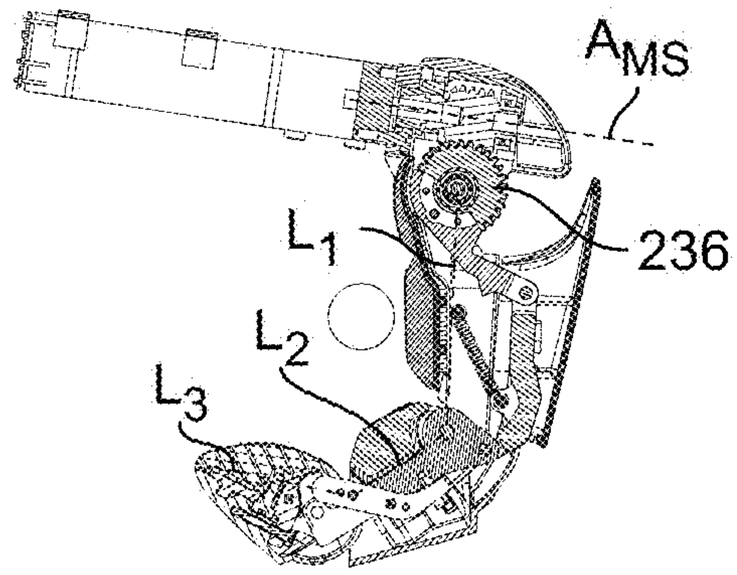


FIG. 51

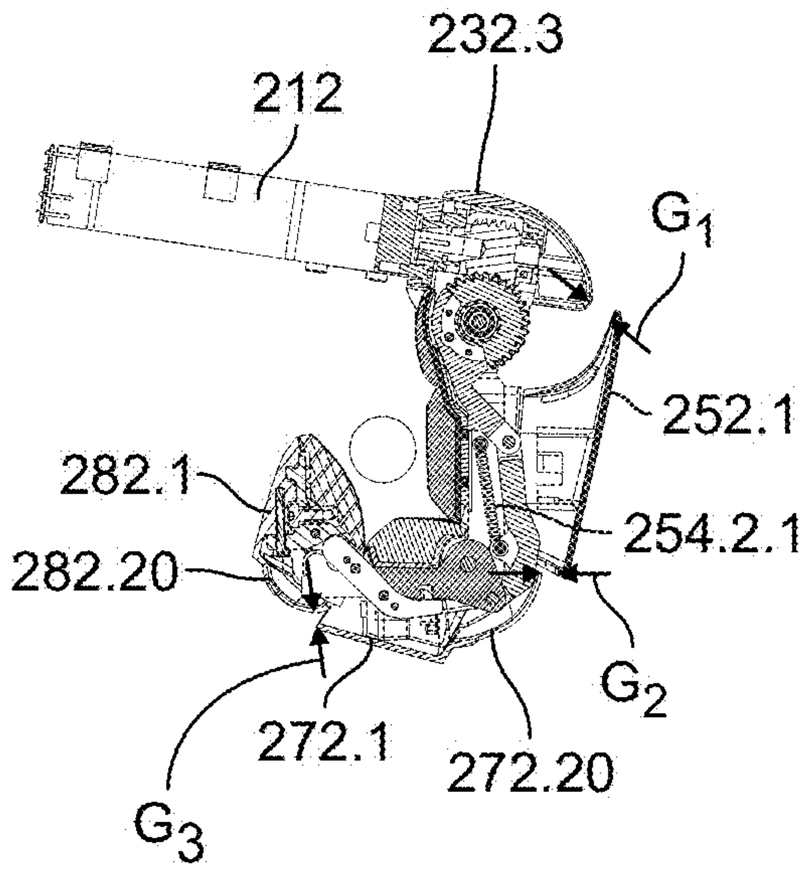


FIG. 52

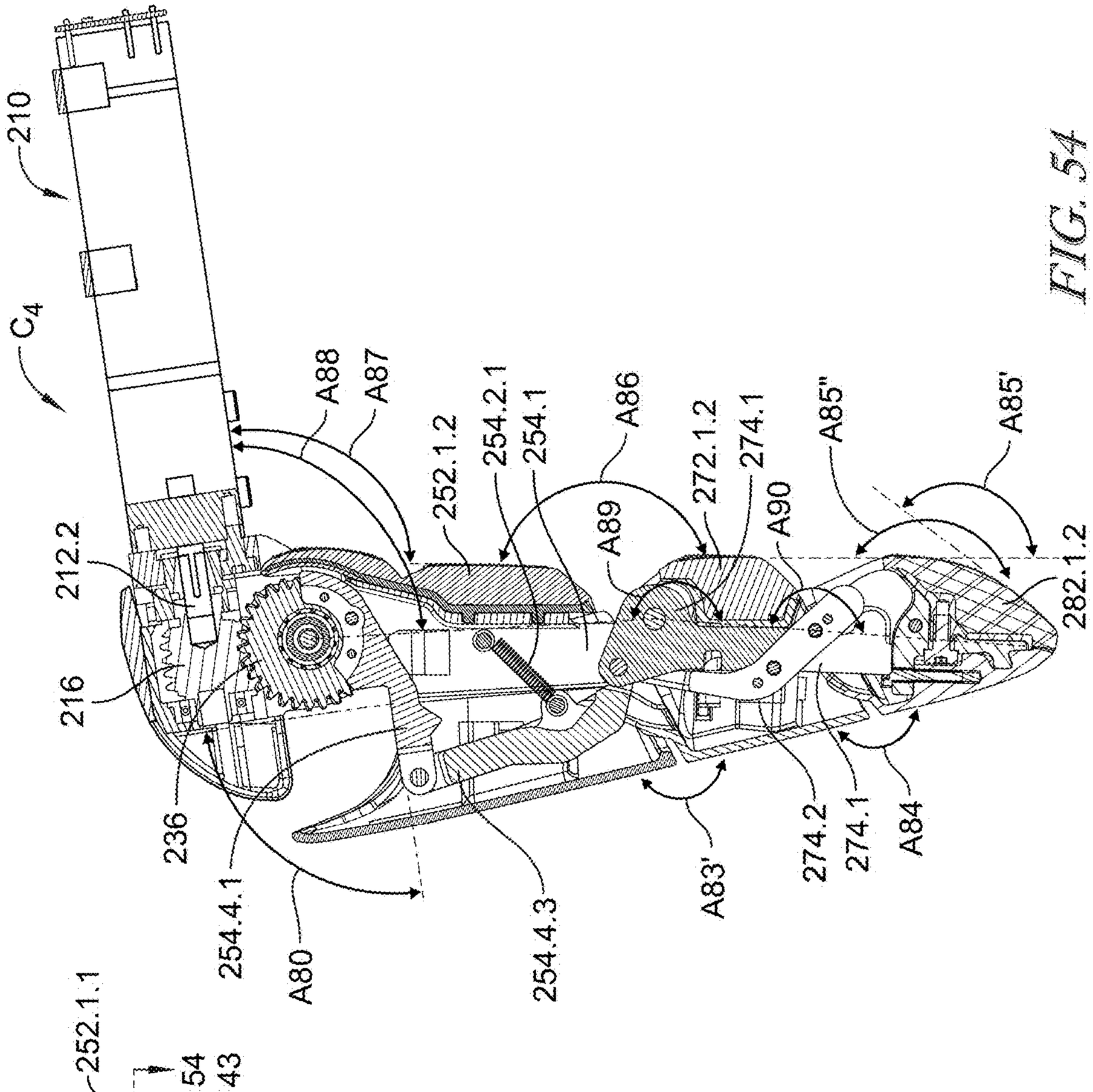

210
C4
A88
A87
252.1.2
254.2.1
254.1
A86
272.1.2
274.1
A85"
A85'
A89
A90
282.1.2
212.2
216
236
254.4.1
A80
254.4.3
A83'
274.2
274.1
A84

FIG. 54

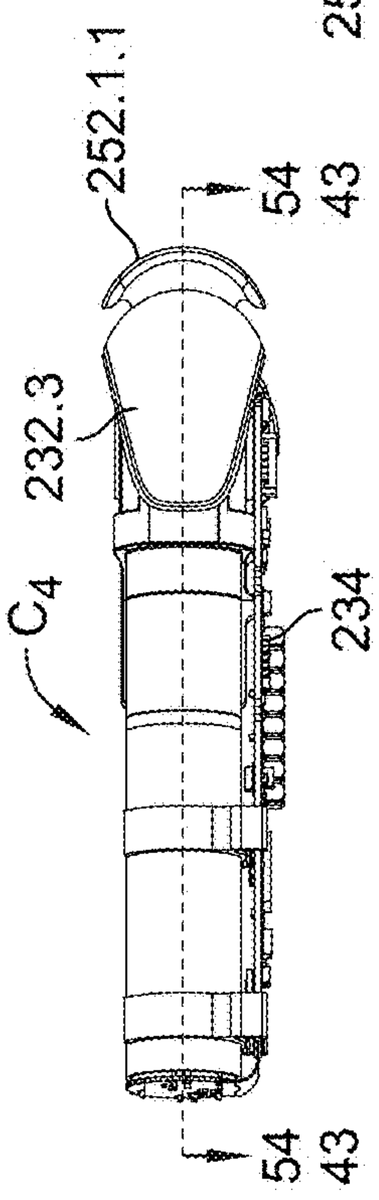

252.1.1
54
43
232.3
C4
234
54
43

FIG. 53

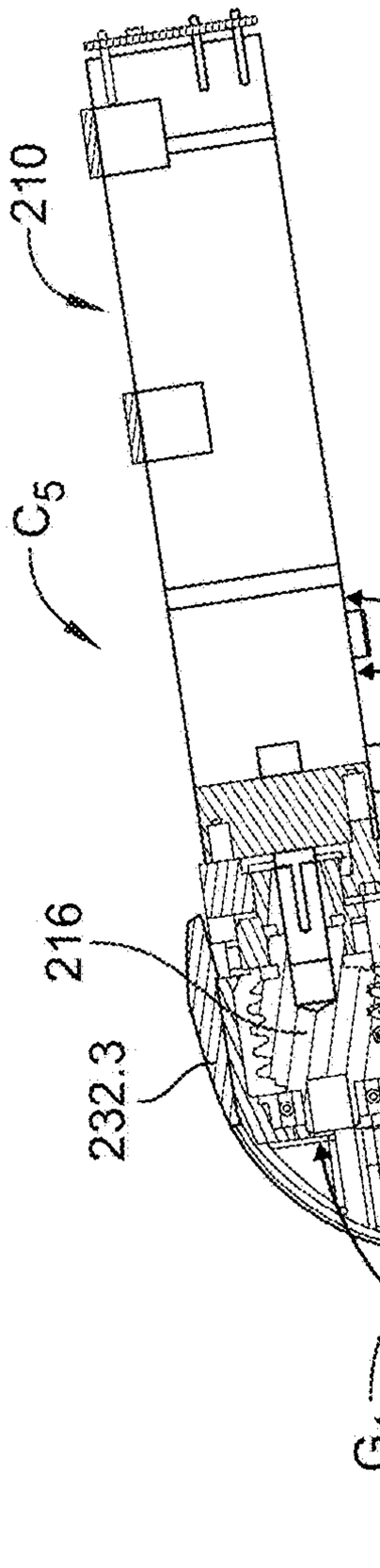

210
C5
20
56
46

FIG. 55

210
C5
A99
A98
252.1.2
254.2.2
236
216
232.3
G1
A91
254.4.1
P2
254.4.3
254.2.1
254.2.3
A94"
P3
A97
L5P5, L5
A96"
A96'
A101
A100
282.1.2
L16E1
282.1.1
274.2
P6, L9P6
A95"
A95'
56
46

FIG. 56

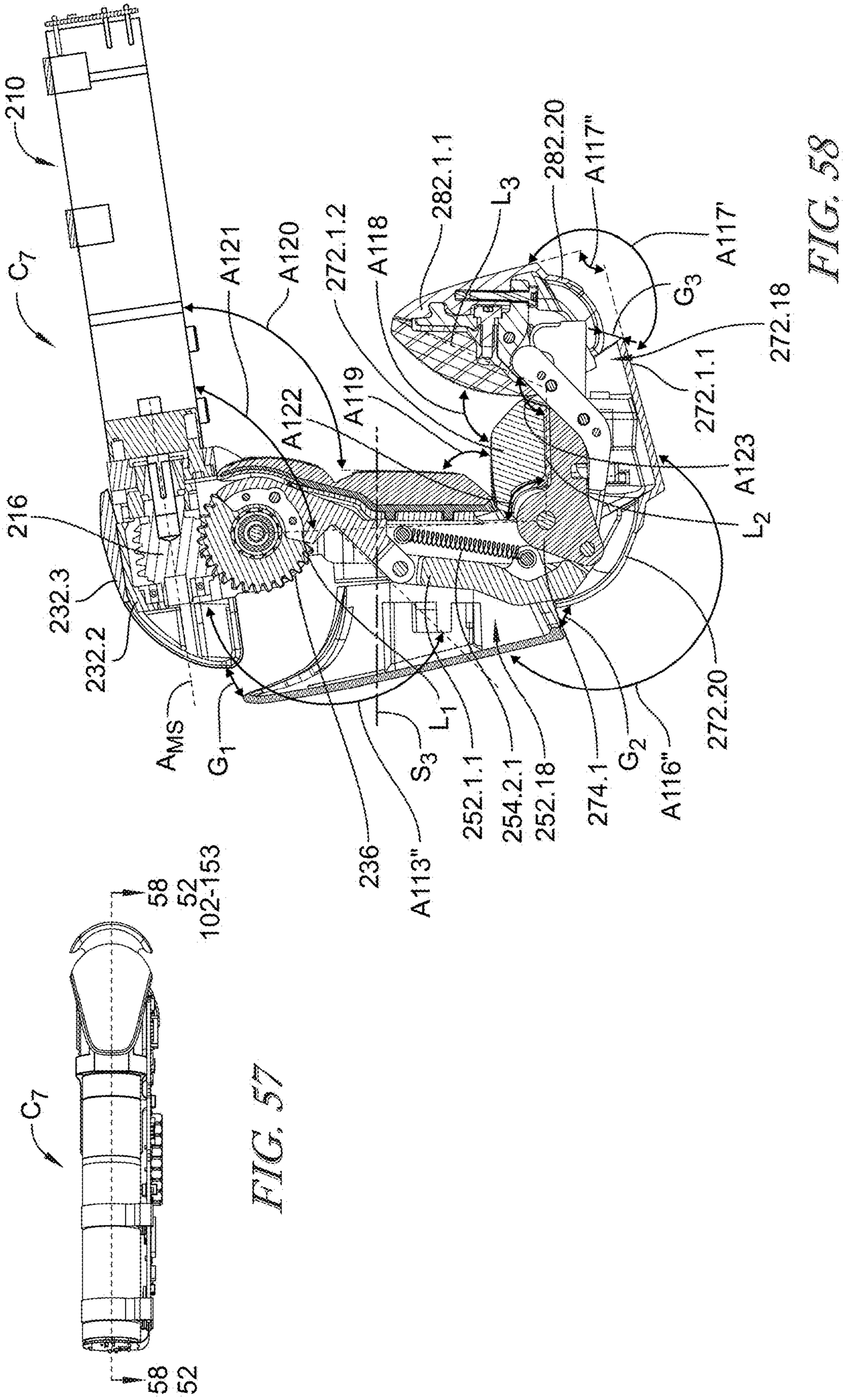

210
C7
A121
A120
272.1.2
A118
282.1.1
L3
282.20
A117"
A117'
G3
272.18
272.1.1
A119
A122
A123
L2
216
232.3
232.2
AMS
G1
S3
L1
252.1.1
254.2.1
252.18
274.1
G2
A116"
272.20
53
36
3"
58
52
102-1
C7
58
52

FIG. 58

FIG. 57

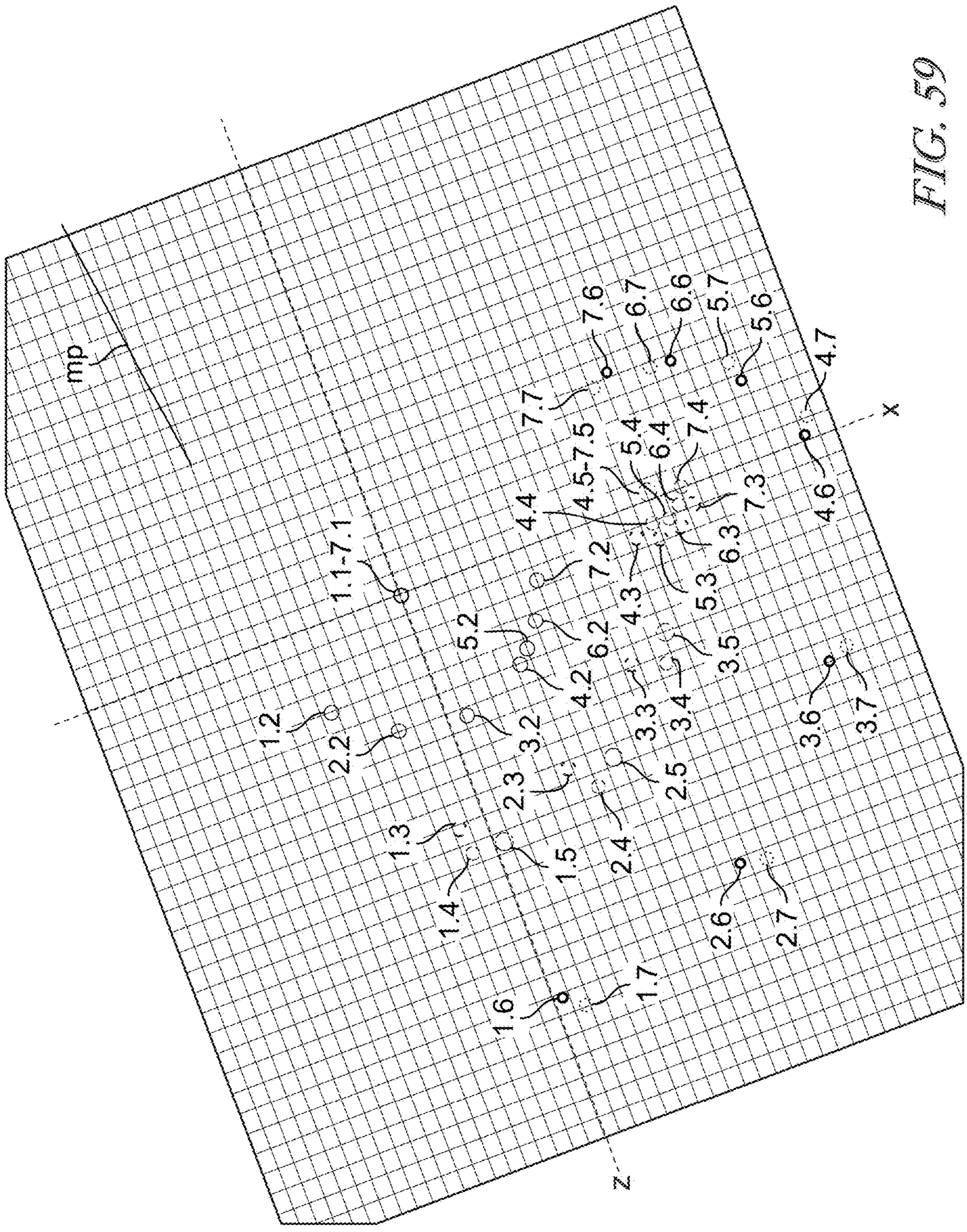

mp
x
z
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1.2
1.3
1.4
1.5
1.6
1.7
2.2
2.3
2.4
2.5
2.6
2.7
3.2
3.3
3.4
3.5
3.6
3.7
4.2
4.3
4.4
4.5-7.5
4.6
4.7
5.2
5.3
5.4
5.6
5.7
6.2
6.3
6.4
6.6
6.7
7.2
7.3
7.4
7.6
7.7

FIG. 59

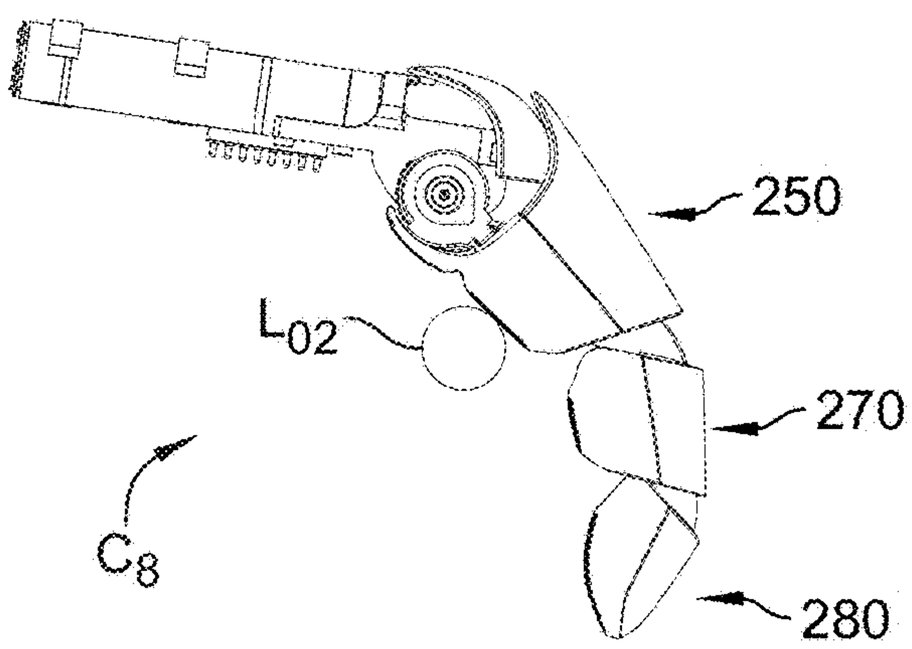


FIG. 60

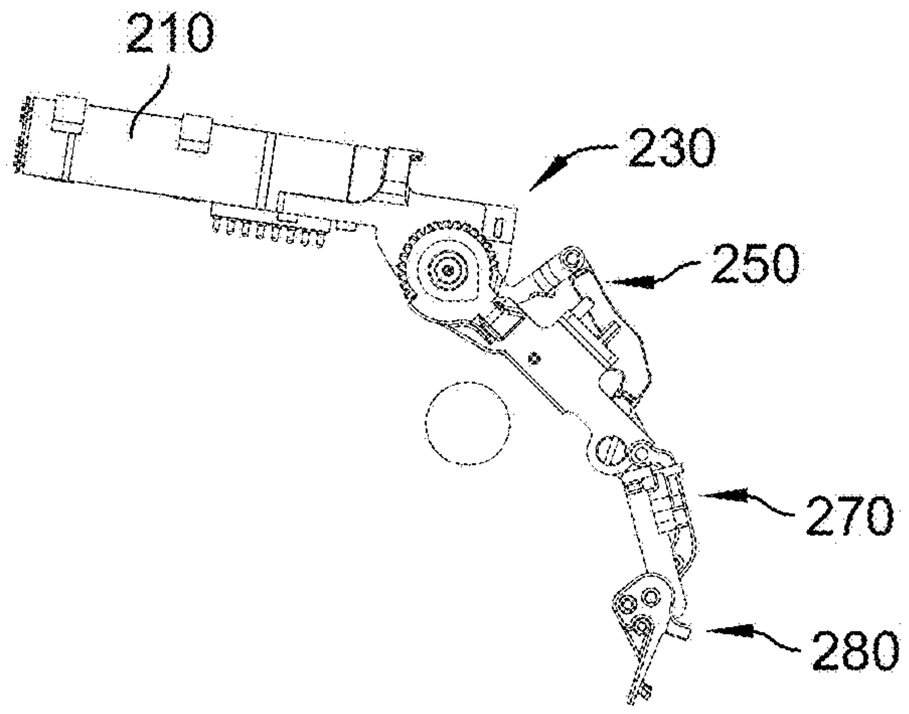


FIG. 61

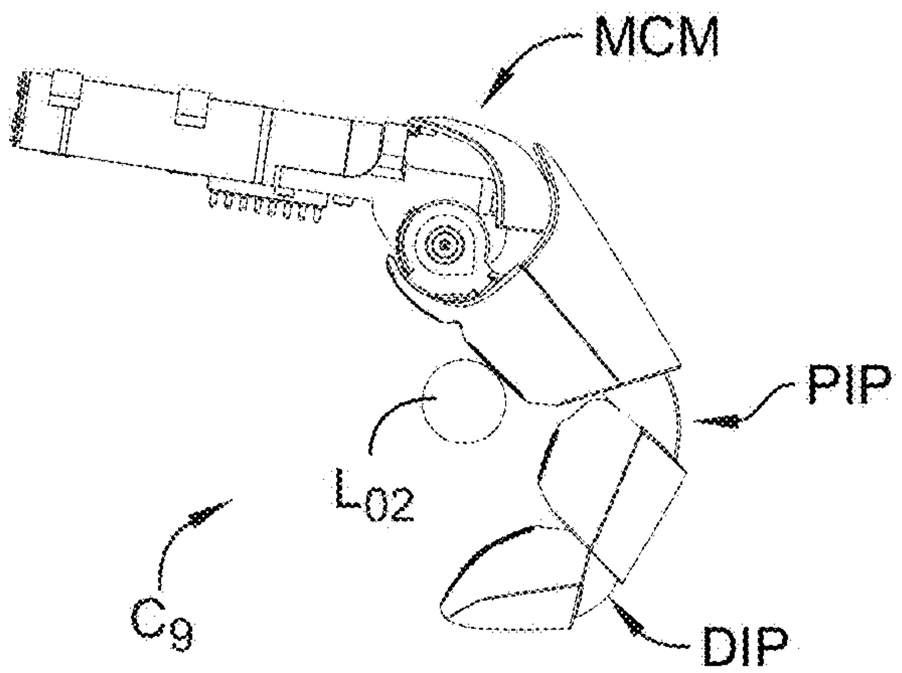


FIG. 62

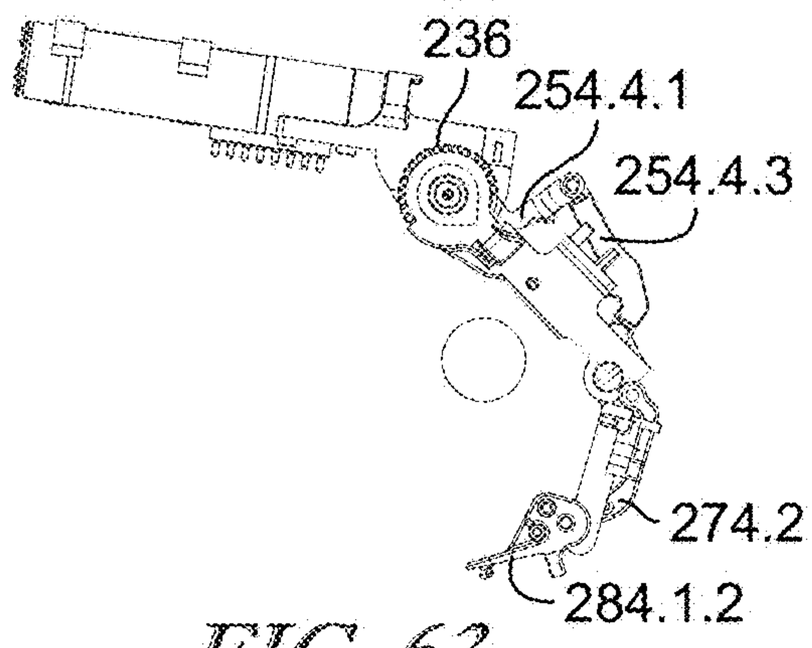


FIG. 63

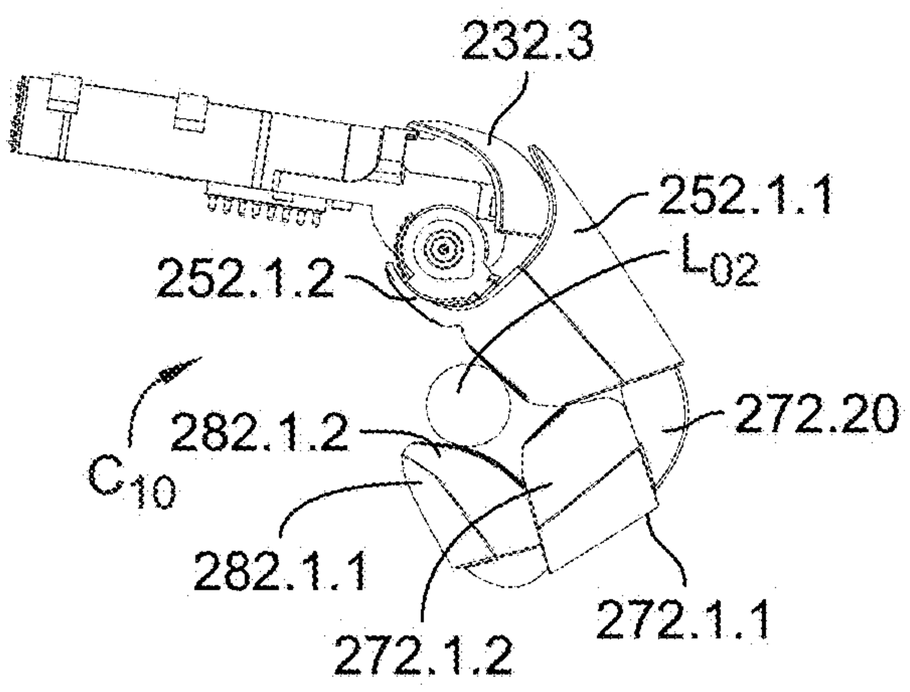


FIG. 64

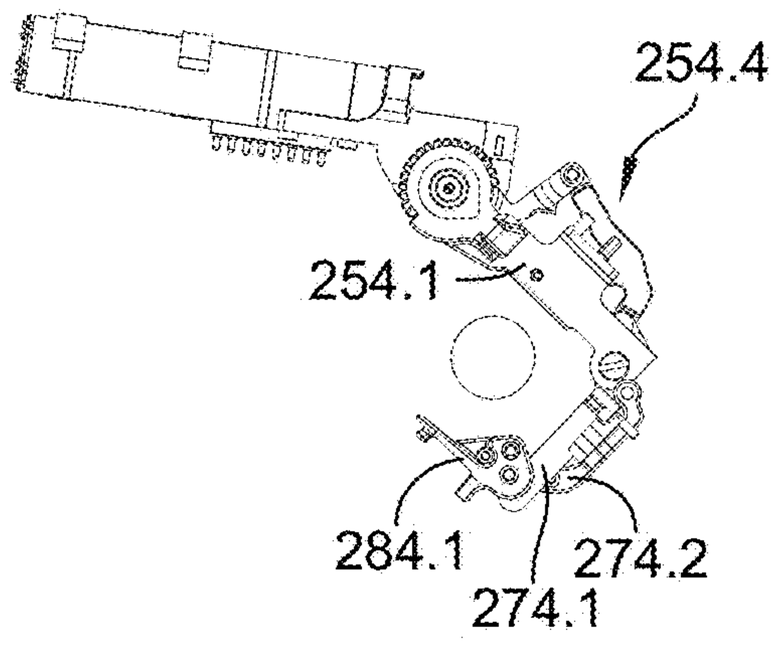


FIG. 65

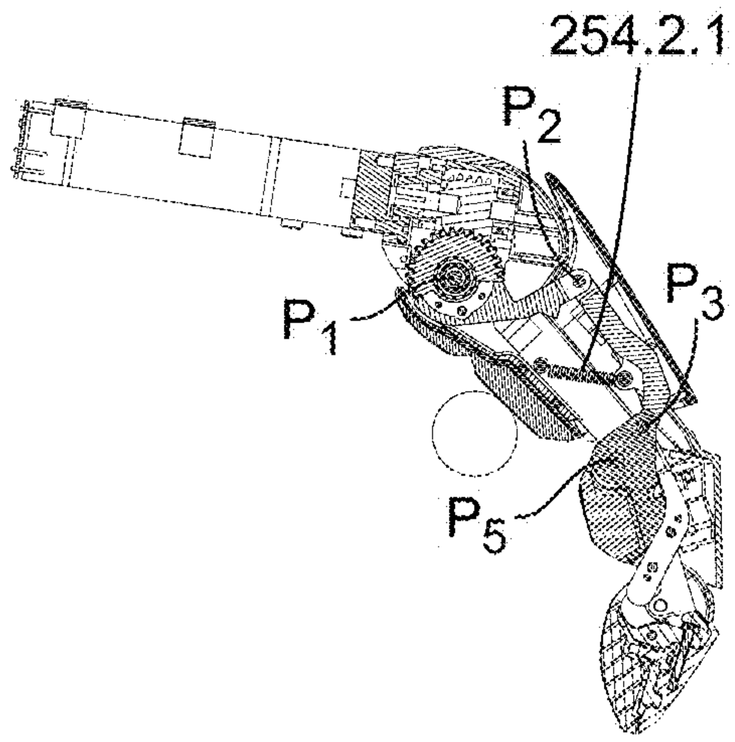


FIG. 66

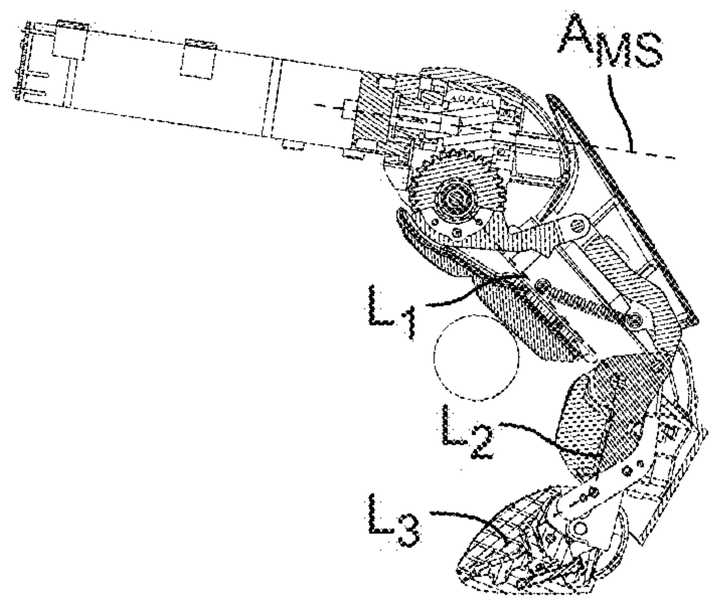


FIG. 67

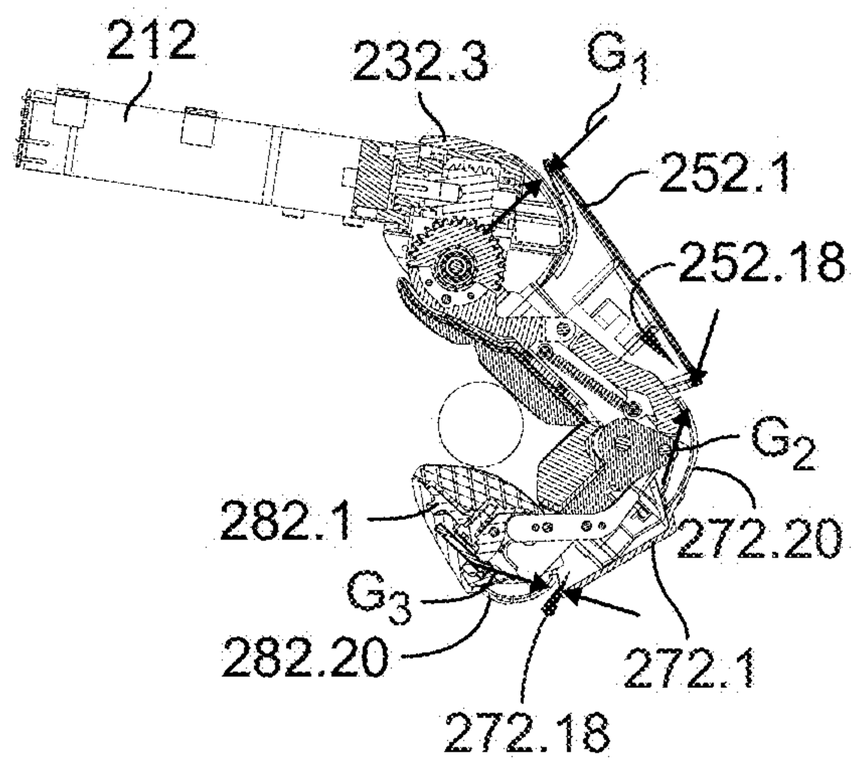


FIG. 68

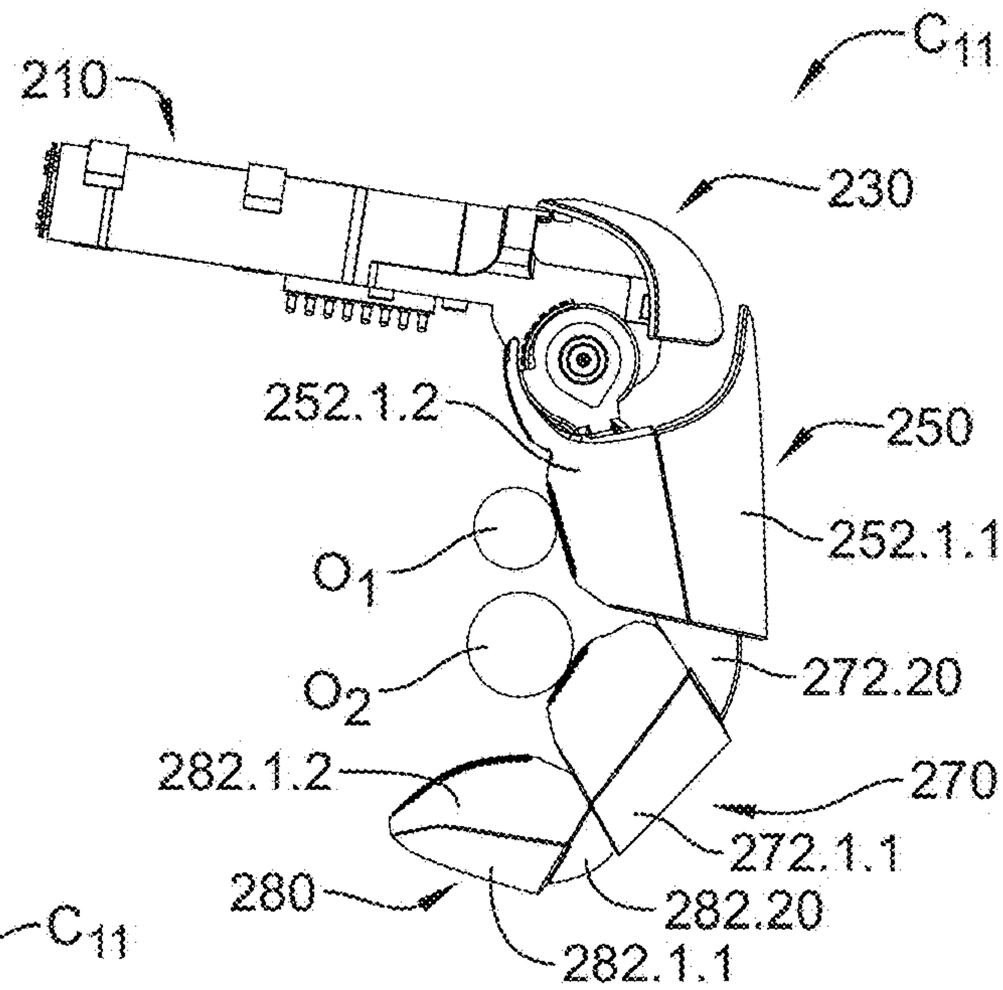


FIG. 69

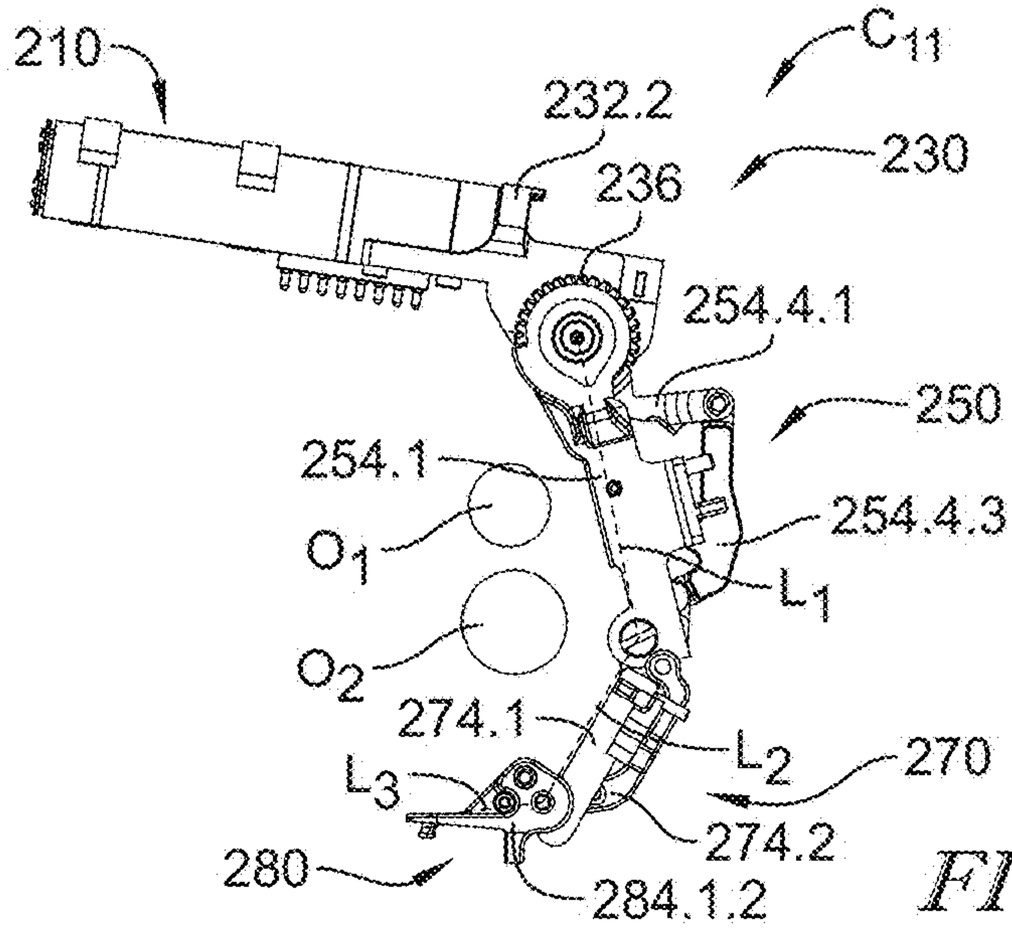


FIG. 70

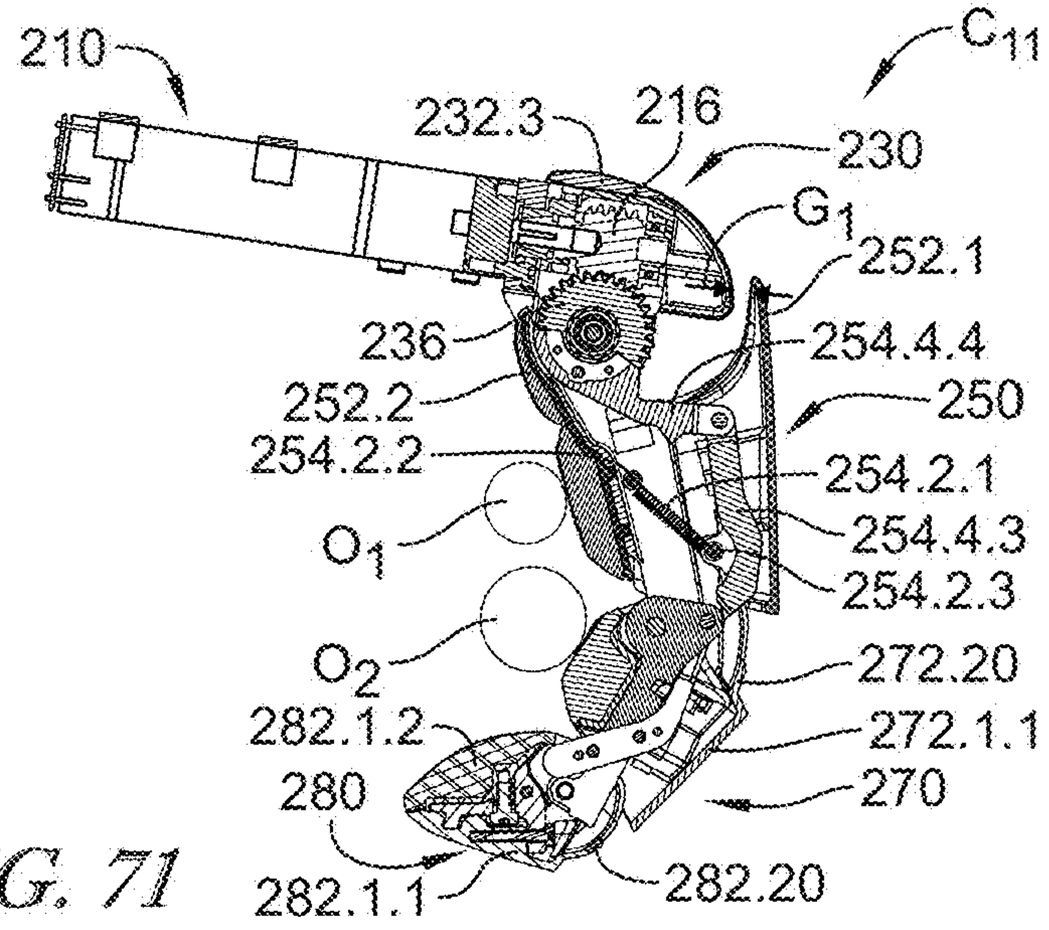


FIG. 71

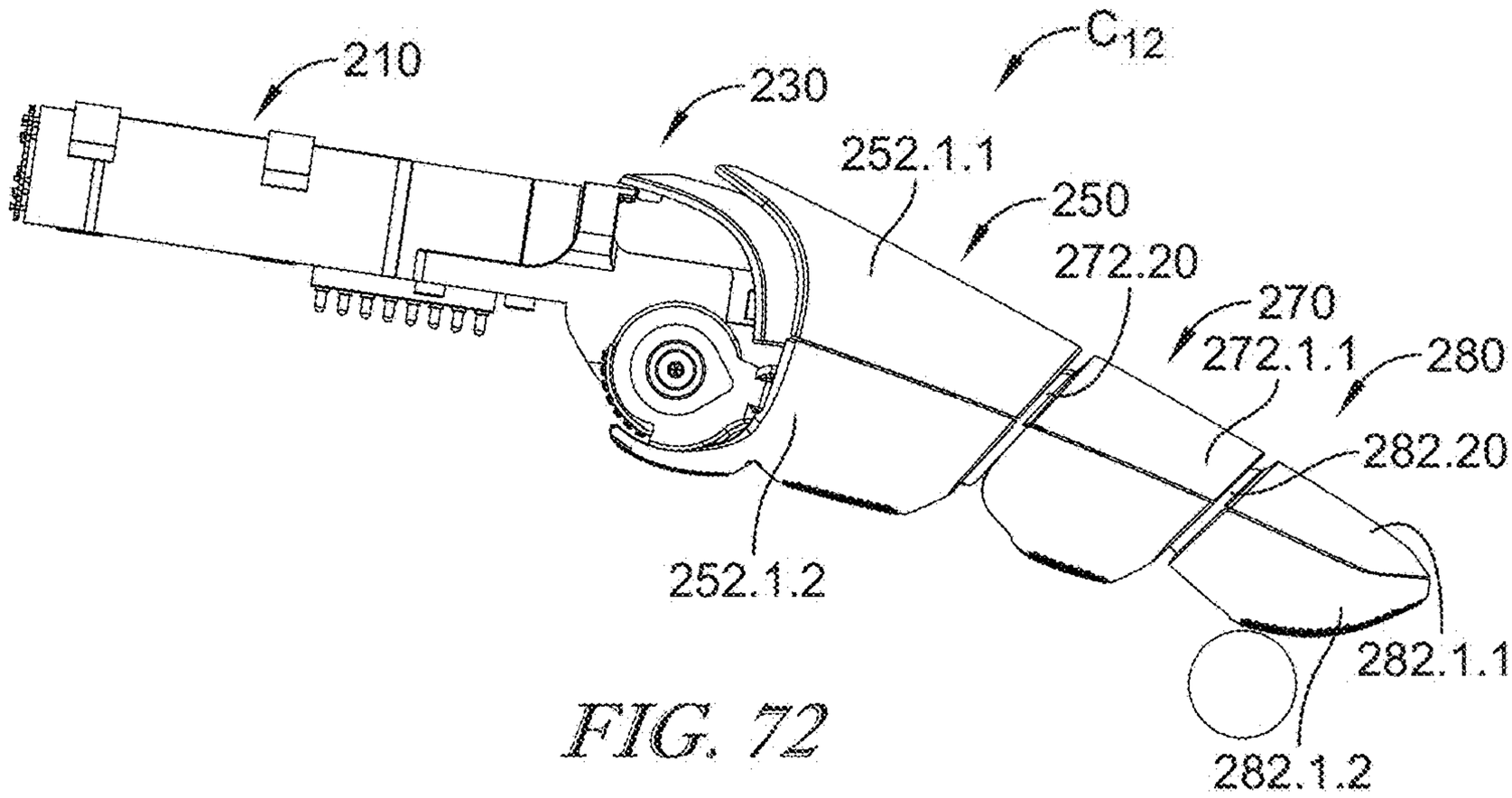


FIG. 72

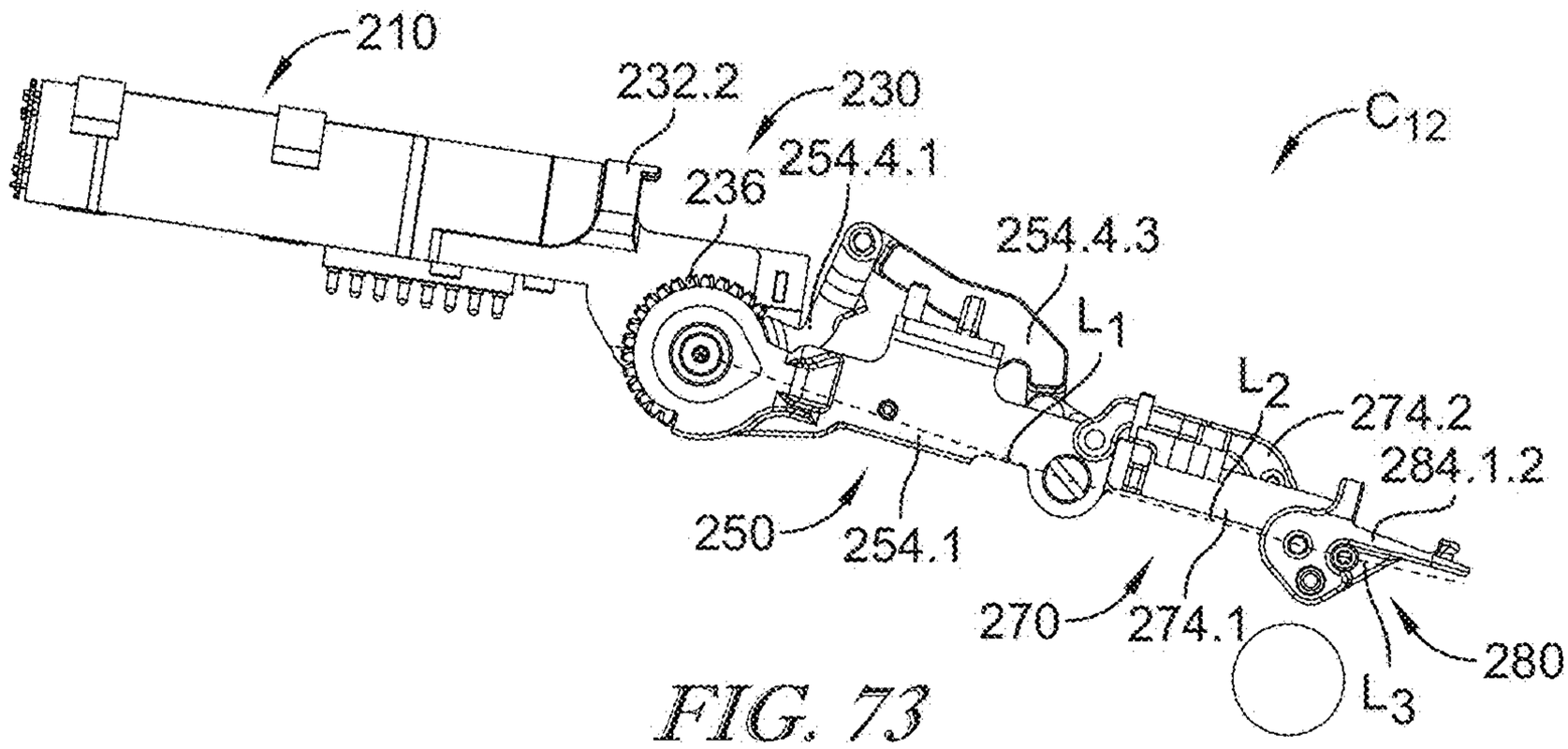


FIG. 73

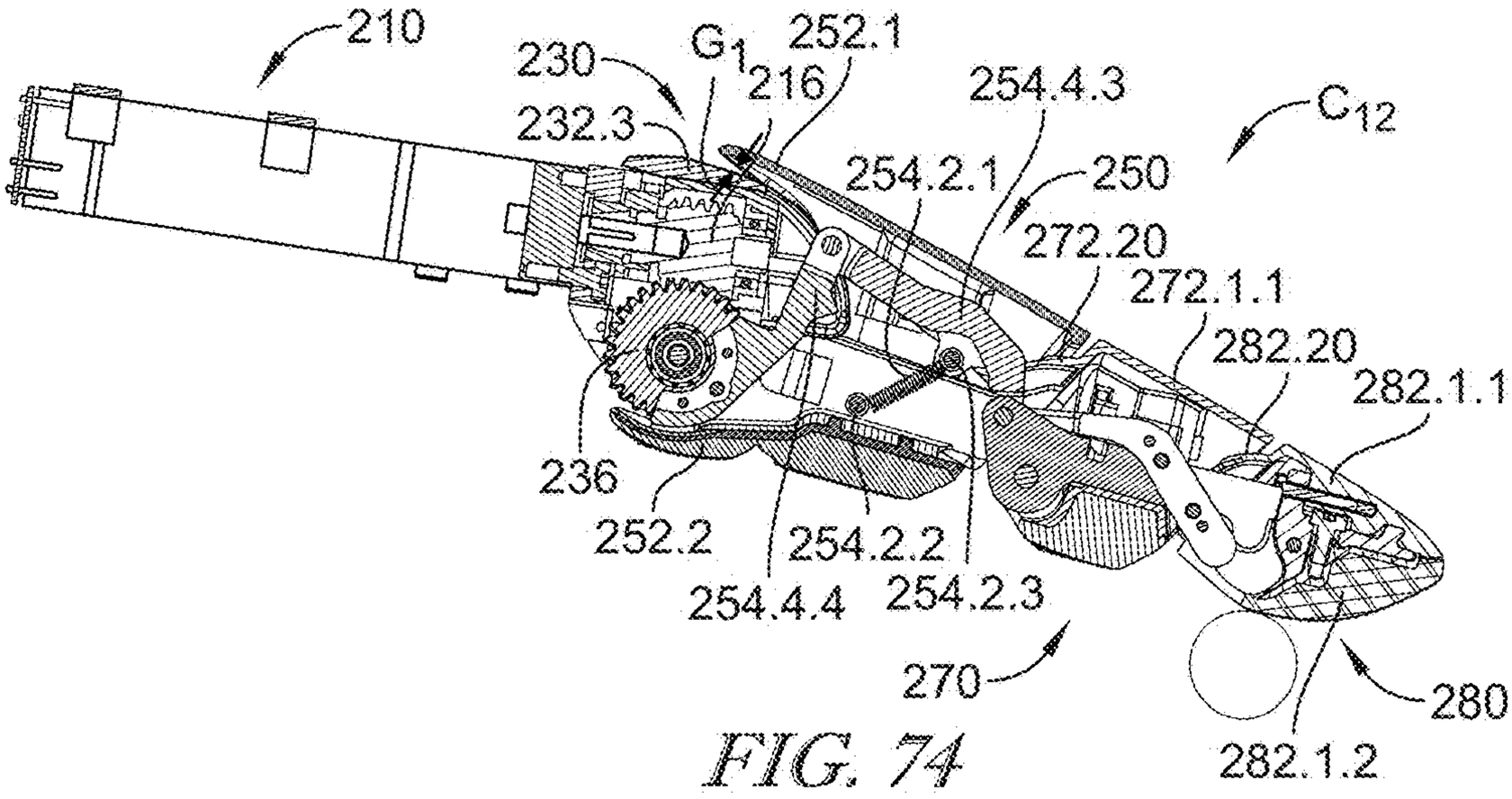


FIG. 74

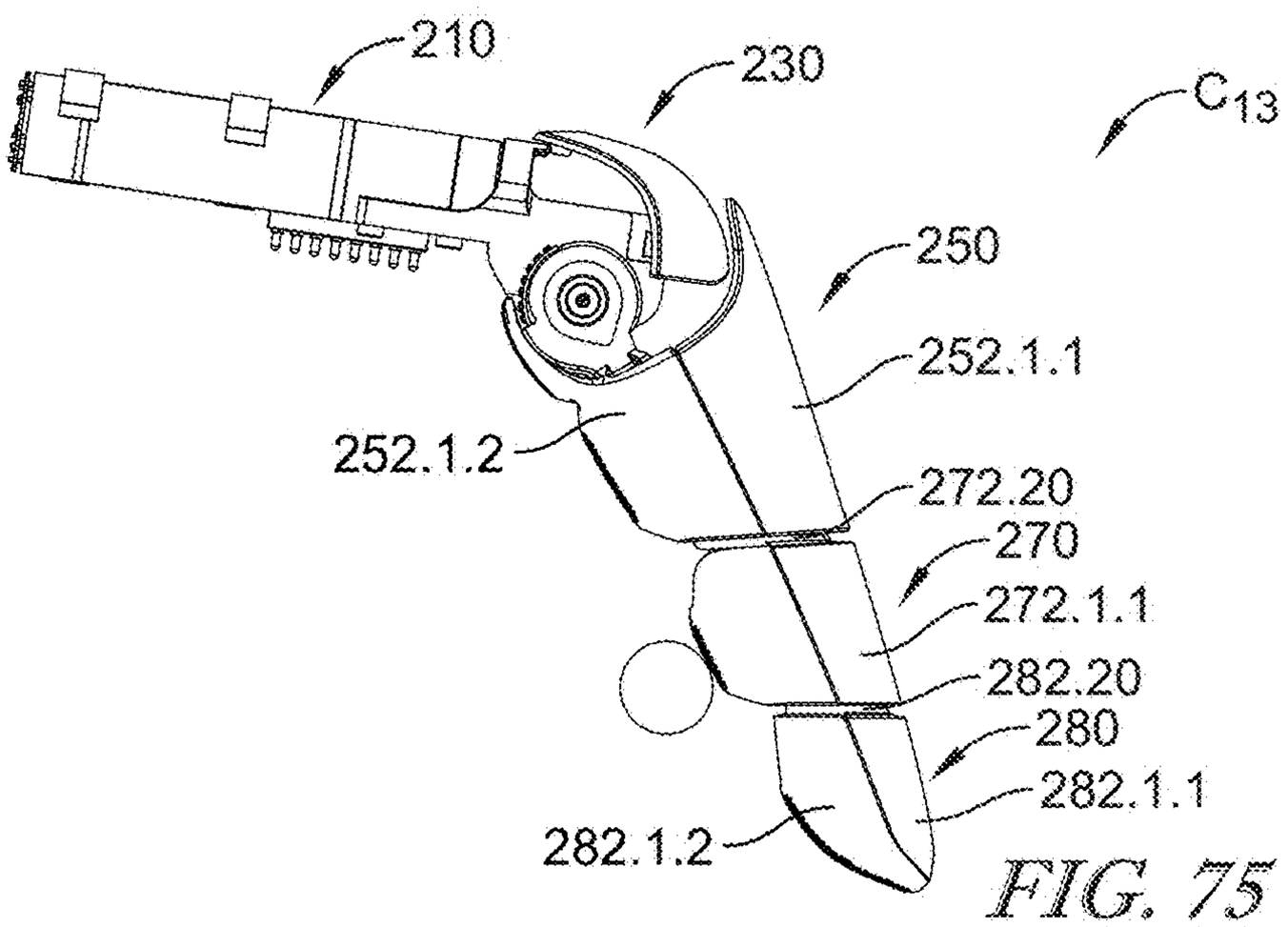


FIG. 75

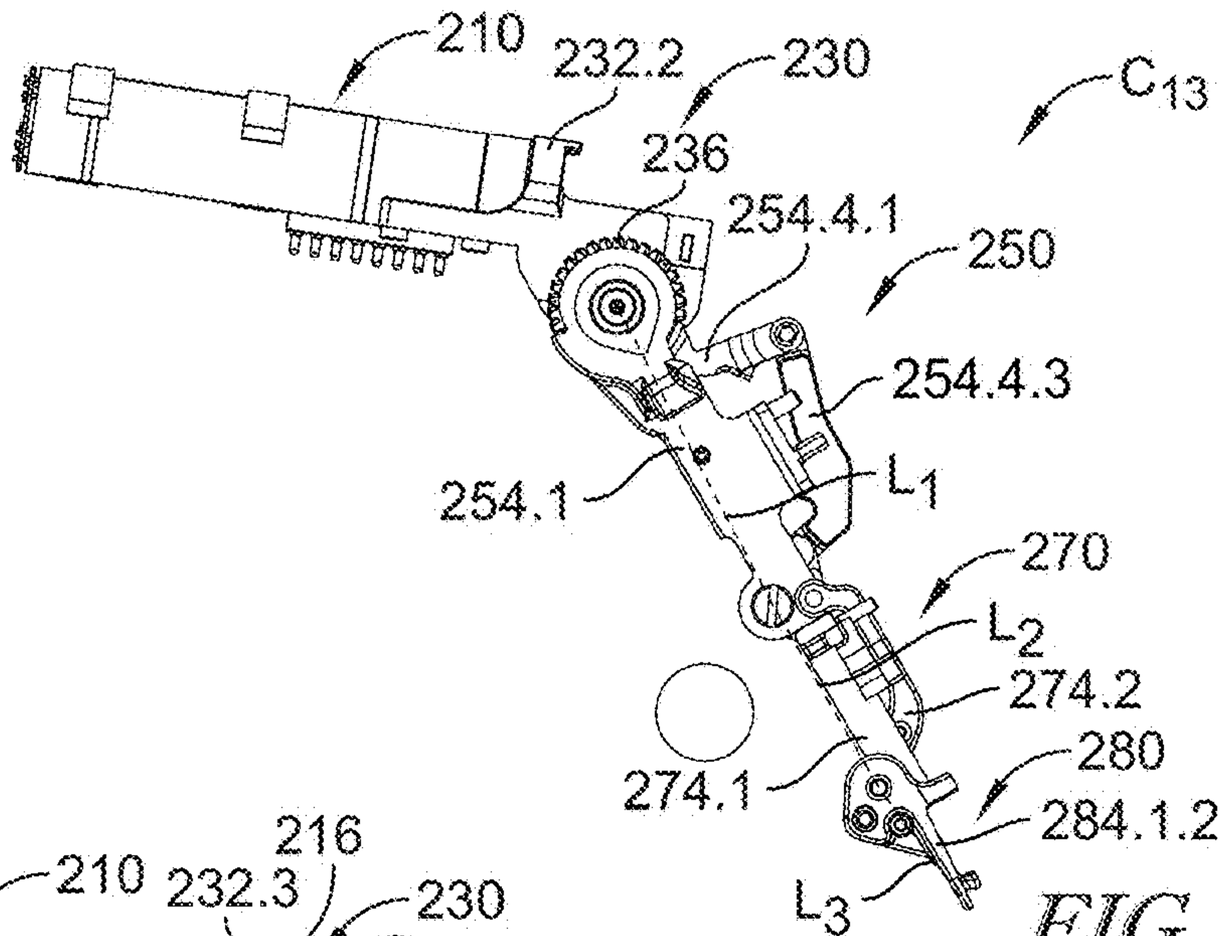


FIG. 76

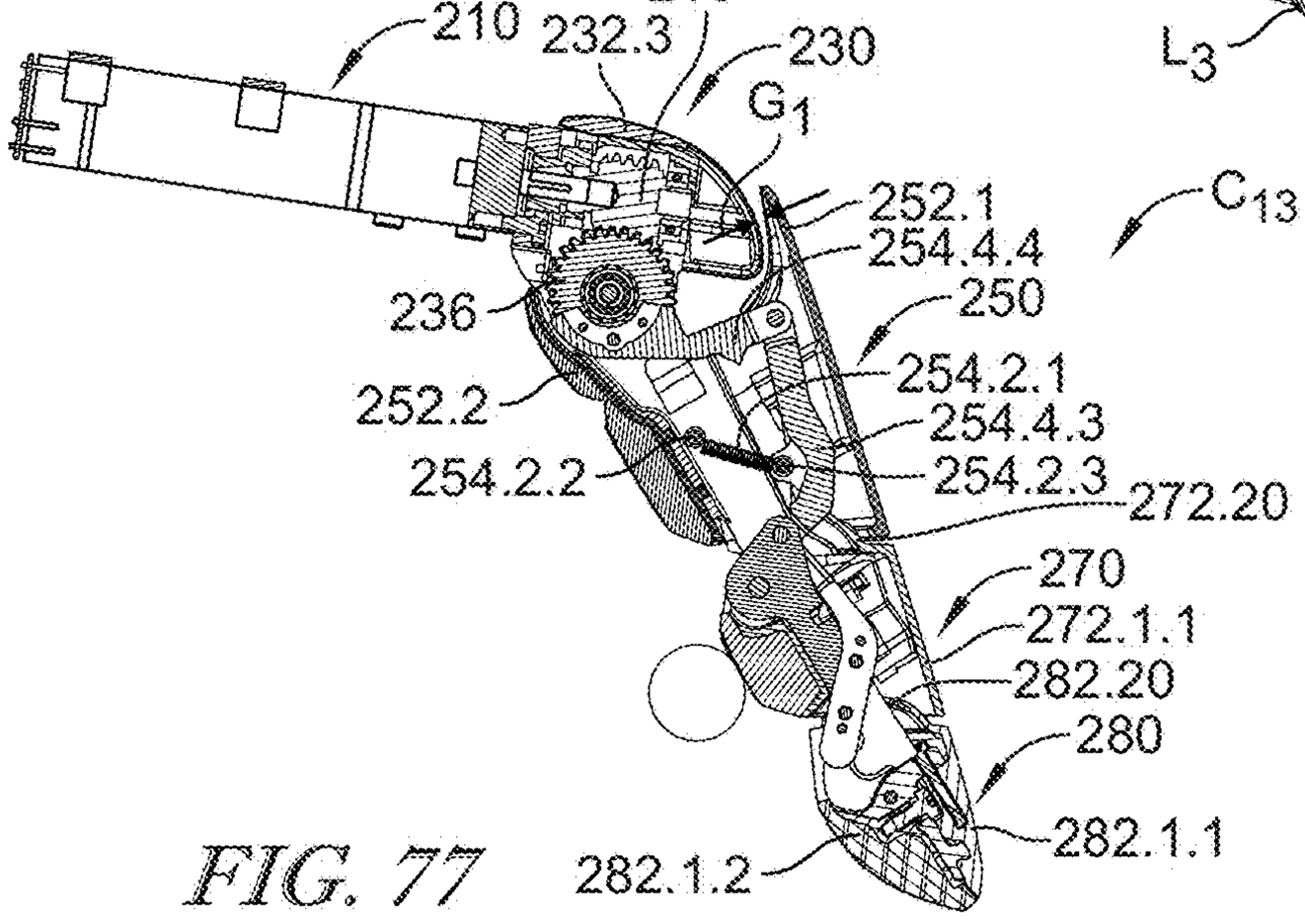


FIG. 77

KINEMATICS OF A MECHANICAL END EFFECTOR

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims benefit under 35 U.S.C. § 119 of U.S. Provisional Patent Applications Nos. 63/617,762, 63/561,315, 63/573,226, 63/620,633 all of which are incorporated herein by reference for any purpose. U.S. patent application Ser. Nos. 19/006,191, 19/000,626, 18/919,263 and 18/919,274, and U.S. Provisional Patent Application Nos. 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.

TECHNICAL FIELD

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

The current workplace landscape is marked by a significant 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 may face safety challenges or heightened physical strain. To address this widening labor gap, there is a 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 may be equipped with hardware and software architectures optimized for performing diverse tasks with efficiency, accuracy, and reliability in human-centric environments.

In order to fulfill the functional and ergonomic requirements of human-centric environments, general-purpose humanoid robots may be 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 may 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 may 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 may 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

The present disclosure provides a finger assembly for an underactuated end effector for a humanoid robot, comprising: a motor including a motor shaft having a motor shaft axis, wherein the motor shaft is configured to rotate about the motor shaft axis; a worm drive gear coupled to the motor shaft, wherein the worm drive gear has a worm drive gear axis that is coaxial with the motor shaft axis, and wherein the worm drive gear is configured for rotation with the motor shaft; a worm wheel in geared engagement with the worm drive gear, wherein the worm wheel has a worm wheel axis that is perpendicular to the worm drive gear axis, and wherein the worm wheel is configured for rotation about the worm wheel axis in response to rotation of the worm drive gear about the worm drive gear axis; a worm drive link fixedly connected to the worm wheel and configured to rotate about the worm wheel axis in response to rotation of the worm wheel about the worm wheel axis; a proximal drive link pivotably connected to the worm drive link configured to move in response to rotation of the worm drive link; and a proximal link having a proximal link pivot axis that is coaxial with the worm wheel axis, wherein the proximal link is configured to rotate about the worm wheel axis independently from rotation of the worm wheel.

The present disclosure provides an underactuated finger assembly for an end effector for a humanoid robot, comprising: a proximal link assembly; a medial link assembly pivotally coupled to the proximal link assembly and including a medial housing assembly, wherein the medial housing assembly defines an internal cavity; a distal link assembly pivotally coupled to the medial link assembly and including a distal housing assembly, wherein the distal housing assembly includes: (i) a rear external surface with a first end positioned adjacent the medial housing assembly when the finger assembly is in an uncurled state, and (ii) a tongue that extends towards the proximal link assembly and includes an upper surface that is offset inwardly from the rear external surface; wherein, when the finger assembly is in the uncurled state, a substantial majority of the tongue is positioned within the internal cavity of the medial housing assembly; and wherein, when the finger assembly is in a curled state, either a minority or none of the tongue is positioned within the internal cavity of the medial housing assembly.

The present disclosure provides a humanoid robot having an underactuated end effector, the underactuated end effector comprising: a frame; a plurality of finger assemblies coupled to the frame, each finger assembly of the plurality of finger assemblies comprising: a knuckle, a proximal assembly, a medial assembly, and a distal assembly; a metacarpophalangeal joint formed between the knuckle and the proximal assembly and having a metacarpophalangeal joint axis, wherein an extent of the proximal assembly is configured to be directly driven about the metacarpophalangeal joint axis in: (i) a first curling direction by a motor, and (ii) a second uncurling direction by the motor; a proximal finger interphalangeal joint formed between the proximal assembly and the medial assembly and having a proximal finger interphalangeal joint axis, wherein an extent of the medial assembly is configured to be indirectly driven about the proximal finger interphalangeal joint axis in: (i) the first curling

direction by the motor, and (ii) a second uncurling direction by a biasing assembly; a distal finger interphalangeal joint formed between the medial assembly and the distal assembly and having a distal finger interphalangeal joint axis, and wherein an extent of the distal assembly is indirectly driven about the distal finger interphalangeal joint axis in: (i) a first curling direction by the motor, and (ii) a second uncurling direction by the motor; and wherein the end effector lacks a mechanical cable configured to actuate the proximal assembly, the medial assembly, or the distal assembly.

The present disclosure provides an end effector for a humanoid robot, comprising: a frame; a finger assembly removably connected to the frame, the finger assembly comprising: a worm drive link; a proximal drive link pivotably coupled to the worm drive link; a proximal link having a proximal link recess configured to selectively receive at least a portion of the worm drive link and at least a portion of main main proximal drive link therein; a medial link pivotably connected to both the proximal link and the proximal drive link and including a medial link recess configured to receive an extent of a medial drive link; and the medial drive link pivotably connected to the medial link by at least one first pivotable coupling located on a first side of a sagittal plane extending through the finger assembly and at least one second pivotable coupling located on a second side of the sagittal plane.

The present disclosure provides a humanoid robot having an end effector, the end effector comprising: a frame; four finger assemblies, wherein each finger assembly of the four finger assemblies may be substantially identical to every other finger assembly of the four finger assemblies, and wherein each finger assembly of the four finger assemblies is removably connected to the frame at a respective point; wherein all of the finger assemblies of the four finger assemblies are located substantially in a single plane; wherein each finger assembly of the four finger assemblies is angularly offset within the single plane with respect to every other finger assembly of the four finger assemblies; wherein the respective points of connection of the four fingers assemblies to the frame are not co-linear; and wherein each finger assembly of the four finger assemblies lacks a mechanical cable configured to actuate any component of the finger assembly.

The present disclosure provides an underactuated end effector for a humanoid robot, comprising: a frame; a plurality of finger assemblies removably connected to the frame, each finger assembly of the plurality of finger assemblies comprising: a motor assembly including: (i) a motor having a motor housing, and (ii) a motor shaft having a motor shaft axis, and wherein the motor shaft is configured to rotate about said motor shaft axis; a worm drive gear coupled to the motor shaft and configured for rotation about: (i) the motor shaft axis, and (ii) a worm drive gear axis, and wherein the motor shaft axis and the worm drive gear axis are coaxial; a worm wheel in geared engagement with the worm drive gear and configured for rotation about a worm wheel axis in response to rotation of the worm drive gear, and wherein the worm wheel axis is perpendicular to the worm drive gear axis; a worm drive link having a first end and a second end, and wherein the first end of the worm drive link fixedly connected to the worm wheel so that the worm drive link is configured for rotation about the worm wheel axis in response to rotation of the worm wheel about the worm wheel axis; a proximal drive link having a first end and a second end, and wherein the first end of the proximal drive link pivotably connected to the second end of the worm drive link; and a biasing member configured to bias an extent of the proximal drive link toward a first location, and wherein the extent of the proximal drive link is in the first location when the finger assembly is in an uncurled state.

The underactuated finger assembly may also include a motor assembly with a motor shaft having a motor shaft axis, wherein the motor shaft is configured to rotate about the motor shaft axis. The assembly may have a worm drive gear coupled to the motor shaft, wherein the worm drive gear has a worm drive gear axis that is coaxial with the motor shaft axis. A worm wheel may be in geared engagement with the worm drive gear, wherein the worm wheel has a worm wheel axis that is perpendicular to the worm drive gear axis, and wherein the worm wheel is configured to rotate about the worm wheel axis in response to rotation of the worm drive gear about the worm drive gear axis. In some implementations, the proximal link assembly may include a proximal link recess configured to selectively receive at least a portion of a worm drive link and at least a portion of a proximal drive link.

The underactuated finger assembly may include a knuckle assembly positioned between a motor assembly and the proximal link assembly, wherein the knuckle assembly includes a worm wheel interface configured to allow the proximal link assembly to rotate about a worm wheel axis independently from rotation of a worm wheel. In other aspects, an extent of the proximal link assembly may be configured to be directly driven about a metacarpophalangeal joint axis in: (i) a first curling direction by a motor, and (ii) a second uncurling direction by the motor. An extent of a medial assembly may be configured to be indirectly driven about a proximal finger interphalangeal joint axis in: (i) the first curling direction by the motor, and (ii) the second uncurling direction by a biasing assembly. An extent of a distal assembly may be indirectly driven about a distal finger interphalangeal joint axis in: (i) the first curling direction by the motor, and (ii) the second uncurling direction by the motor. The proximal link assembly may include a primary proximal link with a proximal link body, proximal link frame, and proximal link extension. A biasing spring may be integrated into the proximal assembly, connecting to the proximal link assembly. The proximal drive link assembly may extend from this region and connect to the medial assembly. Multiple pivot points may facilitate articulation between the assemblies.

BRIEF DESCRIPTION OF THE DRAWINGS

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.

FIG. **1** is a perspective view of a wrist coupler and a mechanical end effector that is designed to emulate a human left hand, 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;

FIG. **2** is a perspective view of the wrist coupler and the mechanical end effector of FIG. **1**, wherein said wrist coupler is removably secured to a lower extent of a robot arm;

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

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

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

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

FIG. **7** is a rear view of the mechanical end effector of FIGS. **1-2**;

FIG. **8** is a front view of the mechanical end effector of FIGS. **1-2**;

FIG. **9** is a cross-sectional view of the mechanical end effector taken along line **9-9** of FIG. **10**;

FIG. **10** is a top view of the mechanical end effector of FIGS. **1-2**;

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

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

FIG. **13** is a bottom or palm view of the mechanical end effector of FIG. **11**;

FIG. **14** is a left side view of the mechanical end effector of FIG. **11**;

FIG. **15** is a palm schematic view that shows the 16 degrees of freedom contained in the mechanical end effector of FIG. **1-2**;

FIG. **16** is a bottom or palm view of the mechanical end effector of FIG. **11**, wherein the thumb has been removed to better isolate the finger assemblies and a frame of the mechanical end effector;

FIG. **17** is an upper right perspective view of a figure assembly of the plurality of figure assemblies contained in the mechanical end effector of FIGS. **1-2**, wherein said finger assembly is in an open, uncurled, or neutral state;

FIG. **18** is a bottom left perspective view of the figure assembly of FIG. **17**;

FIG. **19** is a left side view of the figure assembly of FIG. **17**;

FIG. **20** is a front view of the figure assembly of FIG. **17**;

FIG. **21** is a rear view of the figure assembly of FIG. **17**;

FIG. **22** is a left side view of a portion of the figure assembly of FIG. **17**;

FIG. **23** is a top view of the finger assembly of FIG. **17**;

FIG. **24** is a bottom view of the finger assembly of FIG. **17**;

FIG. **25**A is a cross-sectional view of the finger assembly taken along line **23**A-**23**A of FIG. **21**;

FIG. **25**B is a cross-sectional view of the finger assembly taken along line **23**B-**23**B of FIG. **21**;

FIG. **25**C-FIG. **25**D is a cross-sectional view of the finger assembly taken along line **23**C-**23**C of FIG. **21**;

FIG. **25**A is a cross-sectional view of the finger assembly taken along line **24**A-**24**A of FIG. **20**;

FIG. **25**B is a cross-sectional view of the finger assembly taken along line **24**B-**24**B of FIG. **20**;

FIG. **27** is a diagram showing layers of materials contained in the housing of the finger assembly of FIGS. **1-2**;

FIG. **28** is an exploded view of the finger assembly of FIG. **17**;

FIG. **29** is a perspective view of the finger assembly of FIG. **17**, wherein the housing and motor assembly have been removed to show an internal link assembly;

FIG. **30** is a side view of the internal link assembly of FIG. **29**;

FIG. **31** is a top view of the internal link assembly of FIG. **29**;

FIG. **32** is a front view of the internal link assembly of FIG. **29**;

FIG. **33** is a cross-sectional view of the internal link assembly taken along line **33-33** of FIG. **32**;

FIG. **34** is a schematic diagram showing the movement assembly moving from a first configuration to a configuration;

FIG. **35** shows an object in a first location and a right side view of the finger assembly in a second configuration C_2, wherein the proximal, medial, and distal assemblies are substantially aligned in a first state;

FIG. **36** shows the object in the first location and a right side view of the motor and movement assembly in the second configuration C_2;

FIG. **37** shows the object in the first location and a right side cross-sectional view of the finger assembly in the second configuration C_2;

FIG. **38** shows the object in the first location and a right side view of the finger assembly in a third configuration C_3, wherein the proximal, medial, and distal assemblies are substantially aligned in the first state;

FIG. **39** shows the object in the first location and a right side view of the motor and movement assembly in the third configuration C_3;

FIG. **40** shows the object in the first location and a right side cross-sectional view of the finger assembly in the third configuration C_3;

FIG. **41** shows the object in the first location and a right side view of the finger assembly in a fourth configuration C_4, wherein the proximal, medial, and distal assemblies are substantially aligned in the first state and the proximal assembly is at maximum flexion position;

FIG. **42** shows the object in the first location and a right side view of the motor and movement assembly in the fourth configuration C_4;

FIG. **43** shows the object in the first location and a cross-sectional view of the finger assembly in the fourth configuration C_4 taken through line **43-43** as shown in FIG. **53**;

FIG. **44** shows the object in the first location and a right side view of the finger assembly in a fifth configuration C_5, wherein the proximal assembly is at a maximum flexion position and the medial and distal assemblies are in a partially curled state;

FIG. **45** shows the object in the first location and a right side view of the motor and movement assembly in the fifth configuration C_5;

FIG. **46** shows the object in the first location and a right side cross-sectional view of the finger assembly in the fifth configuration C_5 taken through line **46-46** as shown in FIG. **55**;

FIG. **47** shows the object in the first location and a right side view of the finger assembly in a sixth configuration C_6, wherein the proximal assembly is at maximum flexion position and the medial and distal assemblies are in a partially curled state;

FIG. **48** shows the object in the first location and a right side view of the motor and movement assembly in the sixth configuration C_6;

FIG. **49** shows the object in the first location and a right side cross-sectional view of the finger assembly in the sixth configuration C_6;

FIG. **50** shows the object in the first location and a right side view of the finger assembly in a seventh configuration C_7, wherein the proximal, medial and distal assemblies are at maximum flexion position or the finger assembly is in a fully curled state;

FIG. **51** shows the object in the first location and a right side view of the motor and movement assembly in the seventh configuration C_7;

FIG. **52** shows the object in the first location and a right side cross-sectional view of the finger assembly in the seventh configuration C_7 taken through line **49-49** as shown in FIG. **57**;

FIG. **53** is a top view of the finger assembly in the fourth configuration C_4, wherein the proximal, medial, and distal assemblies are substantially aligned in the first state and the proximal assembly is at maximum flexion position;

FIG. **54** is a cross-sectional view of the finger assembly in the fourth configuration C_4 and taken along line **54-54** of FIG. **53**;

FIG. **55** is a top view of the finger assembly in the fifth configuration C_5, wherein the proximal assembly is at a maximum flexion position and the medial and distal assemblies are in a partially curled state;

FIG. **56** is a cross-sectional view of the finger assembly in the fifth configuration C_5 and taken along line **56-56** of FIG. **55**;

FIG. **57** is a top view of the finger assembly in a seventh configuration C_7, wherein the proximal, medial and distal assemblies are at maximum flexion position or the finger assembly is in a fully curled state;

FIG. **58** is a cross-sectional view of the finger assembly in the fifth configuration C_7 and taken along line **58-58** of FIG. **57**;

FIG. **59** is a schematic diagram showing the movement of the pivot points as the movement assembly moves from the first configuration to the seventh configuration;

FIG. **60** shows the object in a second location and a left side view of the finger assembly in an eighth configuration C_8, and wherein: (i) the proximal assembly is in contact with the object and (ii) the medial and distal assemblies are in a partially curled state;

FIG. **61** shows the object in the second location and a right side view of the motor and movement assembly in the eighth configuration C_8;

FIG. **62** shows the object in the second location and a right side cross-sectional view of the finger assembly in the eighth configuration C_8;

FIG. **63** shows the object in the second location and a right side view of the finger assembly in a ninth configuration C_9, and wherein: (i) the proximal assembly is in contact with the object, and (ii) the medial and distal assemblies are in a partially curled state;

FIG. **64** shows the object in the second location and a right side view of the motor and movement assembly in the ninth configuration C_9;

FIG. **65** shows the object in the second location and a right side cross-sectional view of the finger assembly in the ninth configuration C_9;

FIG. **66** shows the object in the second location and a right side view of the finger assembly in a tenth configuration C_{10}, and wherein: (i) the proximal assembly is in contact with the object, and (ii) the medial and distal assemblies are at maximum flexion position;

FIG. **67** shows the object in the second location and a right side view of the motor and movement assembly in the tenth configuration C_{10};

FIG. **68** shows the object in the second location and a right side cross-sectional view of the finger assembly in the tenth configuration C_{10};

FIG. **69** shows two objects in third and fourth locations and a right side view of the finger assembly in an eleventh configuration C_{11}, and wherein: (i) the proximal assembly is in contact with the first object, (ii) the medial assembly is in contact with the second object, and (iii) none of the proximal, medial, or distal assemblies are at minimum or maximum flexion position;

FIG. **70** shows the two objects in the third and fourth locations and a right side view of the motor and movement assembly in the eleventh configuration C_{11};

FIG. **71** shows the two objects in the third and fourth locations and a right side cross-sectional view of the finger assembly in the eleventh configuration C_{11};

FIG. **72** shows the object in a fifth location and a right side view of the finger assembly in a twelfth configuration C_{12}, and wherein: (i) the distal assembly is in contact with the object, and (ii) neither the proximal assembly nor medial assembly are at minimum or maximum flexion position;

FIG. **73** shows the object in the fifth location and a right side view of the motor and movement assembly in the twelfth configuration C_{12};

FIG. **74** shows the object in the fifth location and a right side cross-sectional view of the finger assembly in the twelfth configuration C_{12};

FIG. **75** shows the object in a sixth location and a right side view of the finger assembly in a thirteenth configuration C_{13}, and wherein: (i) the medial assembly is in contact with the object, and (ii) the proximal, medial, and distal assemblies are substantially aligned in the first state;

FIG. **76** shows the object in the sixth location and a right side view of the motor and movement assembly in the thirteenth configuration C_{13}; and

FIG. **77** shows the object in the sixth location and a cross-sectional view of the finger assembly in the thirteenth configuration C_{13}.

DETAILED DESCRIPTION

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.

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

The mechanical end effector **10** disclosed herein may be used as a component of a robot, for example, a versatile

humanoid robot. Enabling such a robot to execute general human tasks poses a challenge due to the vast array of potential positions, locations, and states the robot 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 can be either: (i) linked, or (ii) fixed to one another. When two or more components are linked or fixed to one another, movement of one of the components results in movement in another one of the components. In contrast to conventional end effectors that fix the medial and distal assemblies to one another, the disclosed finger assembly movably links the medial and distal assemblies to one another. Such linking may provide benefits over fixing because it allows for some independent movement of the medial assembly in relation to the distal assembly while still allowing for the movement of the medial assembly to result in movement of the distal assembly. Such linking allows the finger assembly 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 finger assembly. Indeed, the disclosed finger assembly includes only one motor that drives linkages that provide three degrees of freedom DoF per finger assembly. Thus, the end effector has at least 12 DoF, and preferably a total of 16 DoF.

Unlike conventional end effectors, the end effector **10** disclosed herein may utilize four identical finger assemblies that are aligned in a single plane (Y-Z), while being offset in two other orthogonal planes (X-Y, and X-Z). The use of identical finger assemblies may be beneficial because it reduces the number of distinct components, increases modularity, and reduces the cost of the end effector and the overall robot system. In an alternative embodiment, the end effector **10** may utilize two sets of identical finger assemblies (i.e., two finger assemblies in a first set of assemblies and two finger assemblies in a second set of finger assemblies, wherein each finger contained in the first and second sets of finger assemblies are identical).

While the structural configuration of each finger assembly will be discussed in greater detail below, it should be understood that each finger assembly is configured to be a separate component of the end effector that is modular and removably coupled to a frame of the end effector. As such, said finger assembly may be swappable (and in certain embodiments hot-swappable) with another finger assembly. The separate, modular, and swappable nature of the finger assemblies means that: (i) pulleys, articulation cables, pneumatic or hydraulic mechanisms may be omitted from the end effector, and (ii) components of the end effector are not located in the wrist, lower arm, or generally outside of each finger assembly. In other words, the motor, PCBs, encoders, and other electronic components needed to actuate each finger assembly may be fully contained within each finger assembly and are not distributed throughout the arm and/or robot. This full containment aspect may be desirable because it increases serviceability and thus decreases the cost of ownership and operation of the robot.

While the disclosed finger assemblies in the end effector **10** utilize a single biasing member (e.g., spring), said finger assemblies utilize a direct drive linkage system in order to eliminate the need to use more than one (e.g., multiple) biasing members (e.g., springs) to force the finger assembly to remain in a predefined state (e.g., open, uncurled, or neutral). Eliminating the use of multiple biasing members for this purpose may provide 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 multiple biasing members to move the finger assembly, and (ii) increases durability, robustness, and life of the end effector due to the fact that multiple biasing members can rapidly degrade over time.

Additionally, the disclosed direct drive linkages include components that nest within one another. The use of nesting components may be beneficial over conventional finger assemblies of end effectors because each link is supported by at least one coupling point on either side of a plane (e.g., sagittal plane) extending through the finger assembly. In other words, each link in the disclosed finger assembly is coupled on multiple sides, not simply coupled on a single side, which may increase the durability of the assembly.

The disclosed finger assemblies in the end effector **10** have a proximal assembly 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 is not directly tied to the movement of the motor. In fact, the proximal assembly utilizes a bearing to allow slippage between the motor and at least the proximal housing when an extent of the proximal assembly has come into contact with a resistance point/surface. This configuration may be beneficial over conventional end effectors because it allows a single motor to fully actuate the finger assembly, by allowing specific components within the proximal assembly to stop moving while the motor continues to drive other components.

Finally, the end effector **10** disclosed herein may lack several components typically found in conventional end effectors. For example, the disclosed end effector **10** lacks pulleys, articulation cables, components configured to allow the fingers to abduct or spread from one another, more than one motor per finger assembly, pressure sensors, force sensors, and other components typically found in conventional end effectors. Eliminating these components may reduce 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.

In some aspects, the end effector **10** may provide improved energy efficiency compared to conventional designs. By utilizing a single motor per finger assembly and eliminating components like pulleys and cables, the power consumption may be reduced. This could lead to longer operating times between charges for battery-powered robots. The simplified mechanical design with fewer components may result in improved reliability and reduced maintenance requirements. With fewer moving parts and potential failure points, the end effector may have longer intervals between servicing and a lower likelihood of breakdowns. This could translate to increased uptime and productivity in industrial applications. The underactuated nature of the finger assemblies may provide enhanced adaptability when grasping objects of various shapes and sizes. By allowing some

passive adaptation of the finger curvature, the end effector may conform more naturally to object contours without requiring complex control algorithms. This could improve grasping stability and versatility across a wide range of items. The compact design with integrated components may allow for a slimmer profile of the end effector. This could enable the robot to reach into tighter spaces or manipulate objects in more confined environments compared to bulkier conventional designs. The streamlined form factor may expand the potential applications and workspace of robots using this end effector.

B. End Effector

With reference, for example, to FIGS. **1-14**, 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 have: (i) a palm **62**, (ii) a back **64**, (iii) left and right sides **66**, **68**, and (iv) a front **70**. It should be understood 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, but instead may include a plurality of thumb assemblies.

As described above in an alternative embodiment, the interior bottom housing **61.10** may include a plurality of layers **61.20**, wherein a first interior layer **61.20.2** that is made from a first material having a first rigidity and a second exterior layer **61.20.4** that 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. It should be understood that the second material may be replaceable (i.e., removably coupled) or may not be permanently affixed to the end effector **10**. This design may allow for a softer material to be used on the palm surface **61.2.2** of the end effector **10** that is designed to be less durable, and thus needs 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). 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** that 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., textile assembly—namely, a glove). Said third layer **61.20.6** may be replaceable at pre-determined intervals and may be coupled to the end effector using snaps, buttons, removable fasteners, push-pins, or any other type of mechanical coupling mechanism. In a final example, 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.

In some aspects, the interior bottom housing **61.10** may include additional layers or configurations. For example, the plurality of layers **61.20** may include a fourth layer **61.20.8** made of a shock-absorbing material to provide additional protection against impacts. This fourth layer **61.20.8** may be positioned between the first layer **61.20.2** and the second layer **61.20.4**, or it may be the outermost layer. In some cases, one or more of the layers may incorporate sensors, such as pressure sensors or temperature sensors, to provide feedback about objects being manipulated. The layers may also vary in thickness across different regions of the end effector **10**, with thicker portions in high-wear areas and thinner portions in areas requiring more flexibility. Additionally, the layers may be designed with different textures or patterns on their surfaces to enhance gripping capabilities for various types of objects. In some implementations, the layers may be interchangeable, allowing for customization of the end effector **10** for specific tasks or environments. The coupling mechanisms between layers may also include magnetic connections or interlocking geometries in addition to mechanical fasteners. Furthermore, certain layers may incorporate self-healing materials that can repair minor damage over time, potentially extending the intervals between replacements.

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. Additionally, the housing assembly **60** and other components of the end effector **10** may be injection molded, 3D printed, subtractive manufactured, or created using any other known method of manufacturing. In some aspects, the materials may be selected to optimize specific properties such as strength-to-weight ratio, durability, flexibility, or electrical conductivity depending on the intended application. The manufacturing method may be chosen based on factors such as production volume, geometric complexity, or cost considerations. In some cases, hybrid manufacturing techniques combining multiple processes may be employed to achieve desired material properties or structural features.

FIG. **6** shows a finger side view of the end effector **10**, wherein a surface plane P_{SU} has been added to illustrate the 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 are formed between said surface and the end effector **10**, wherein a first contact point P_{C1} is formed near the tip of the middle finger **22***b* and a second contact point P_{C1} is formed near the base of the palm. The greatest distance D_{SU} between said surface plane P_{SU} and the housing **60** formed near the knuckle assembly is less than 10 mm, preferably less than 5 mm, and most preferably less than 1 mm. As shown in this Figure, it is beneficial to have the palm or inner surface of the end

effector **10** flat or nearly flat to help maximize the contact surface area between the end effector **10** and the surface plane P_{SU}, as this design simplifies approach angles, and reduces the need to perform complex grasping movers with the wrist.

As best shown in FIGS. **3-4**, the housing **60** includes a substantially smooth top or back surface SB and a rough or non-smooth or textured surface bottom or palm surface S_P. The rough or non-smooth palm surface S_P is created by adding a plurality of contact areas **61.4** to enhance gripping capability. In other words, the entire palm surface S_P is not textured, rough or non-smooth. Said plurality of contact areas **61.4** is designed to increase the end effector's **10** to grasp and hold an object. Specifically, the plurality of contact areas **61.4** are comprised of distinct regions **61.4.2-61.4.10** that include multiple bumps or projections **61.6**. Said regions **61.4.2-61.4.10** are formed on the palm, and each assembly (i.e., proximal, medial, and distal) contained within each finger assembly **22***a*-**22***d*. 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**, and the distal assemblies of the fingers **22***a*-**22***d* may also include one contact region **61.4.10**. 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. In some aspects, the plurality of contact areas **61.4** may be omitted, 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), the number of bumps or projections **64** within each region may be increased or decreased, and/or the height of the bumps or projections **61.6** may be increased or decreased.

As best shown in FIGS. **24**A-**24**B, the housing **60** of each finger assembly **22***a*-**22***d* and specifically the outer surfaces **61.8.2**, **61.10.2** of the exterior top housing **61.8** and the interior bottom housing **61.10** have a cross-sectional shape that is similar to an obround or a discorectangle. This cross-sectional shape may provide a narrow width, rounded edges that help the finger assemblies **22***a*-**22***d*: (i) avoid contact with one another and minimize the risk of snagging or catching on objects during operation, and (ii) provides substantially flat surfaces that help the finger assemblies **22***a*-**22***d* maximize contact with the object it is grasping. In some aspects, the width of the finger housing may be between 40% to 80%, and in some cases between 55% and 70% of the height of the finger housing. In other embodiments, the width-to-height ratio may be altered or changed in a manner that causes the height to be less than the width. However, this design or configuration may limit the space within the housing for components while potentially affecting the dexterously of the end effector **10**. In some implementations, the cross-sectional shape may be customized for specific grasping tasks or object types (e.g., home vs factory). The housing may also incorporate flexible or deformable sections to enhance gripping capabilities. Additionally, the surface texture or material of the housing may be varied along its length to optimize friction and contact properties for different parts of the finger.

With reference, for example, to FIGS. **1-13**, the end effector **10** comprises a thumb assembly **40**. The thumb assembly **40** is coupled to the palm surface **61.2.2** of the frame **61.2** and is replaceable (and in some embodiments, it may be hot-swapping with a replacement thumb assembly **40**). The replaceable aspect of the thumb assembly **40** may eliminate the need for 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 thumb assembly **40**. This configuration may ensure that components such as linkages, motors, PCBs, encoders, and other elements required to actuate each thumb assembly **40** are self-contained within the palm and/or the thumb assembly **40** and are not spread throughout the robot system. In some aspects, this setup may enhance serviceability, potentially reducing the overall cost of ownership and usage. The thumb assembly **40** may incorporate modular design principles, allowing for easy replacement or customization. In some cases, the thumb assembly **40** may include integrated sensors for improved tactile feedback.

As shown in FIG. **13**, the thumb motor plane P_{TM} may be offset by an angle gamma γ from line L_{M1}, wherein: (i) line L_{M1} is perpendicular to the sagittal plane PS or the middle finger plane P**22***b* and intersects with the center point of the knuckle assembly **230** of the middle finger **22***b*, and (ii) the angle gamma γ may be at least 1 degree, in some cases between 2 degrees and 12 degrees, and most preferably in some aspects between 4 degrees and 6 degrees, and likely less than 16 degrees may be less than 16 degrees. In some implementations, the angle gamma γ may be adjustable to optimize thumb positioning for different grasping tasks. The offset angle may allow the thumb to oppose the fingers more effectively in certain configurations. In some cases, the thumb motor plane P_{TM} may be dynamically adjustable during operation to adapt to different object shapes and sizes. The specific angle may be selected based on anthropometric data or empirical testing to achieve desired grasping capabilities for the end effector.

With reference, for example, to FIGS. **15-25**, the end effector **10** comprises four identical finger assemblies **22***a*-**22***d* that are coupled to the back surface **61.2.4** of the frame **61.2** and are configured to operate independent of one another. In embodiments, the end effector **10** may include more or fewer than four finger assemblies. Configuring the finger assemblies **22***a*-**22***d* identically may allow for reducing the number of distinct components required 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 in some cases may enable hot-swapping of the finger assemblies. The modular and replaceable aspect of the finger assemblies **22***a*-**22***d* may eliminate the need for 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 ensure that components such as linkages, motors, PCBs, encoders, and other elements required to actuate each finger assembly **22***a*-**22***d* are self-contained within the palm and/or within each finger assembly **22***a*-**22***d* and are not spread throughout the robot system. In some aspects, this setup may enhance serviceability, potentially reducing the overall cost of ownership and usage.

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.

With reference, for example, to FIGS. **11-14**, each finger assembly **22***a*-**22***d* may be connected to the back surface **61**.**2**.**4** of the frame **61**.**2**. Thus, the overall location of the figure assembly **22***a*-**22***d* cannot move in the Y-Z plane. Also, the finger assemblies **22***a*-**22***d* may be connected to the frame **61**.**2** in a manner that ensures that the 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 in the X-Z plane. This configuration of finger assembly **22***a*-**22***d* enables each finger assembly **22***a*-**22***d* 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***a*-**22***d* 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**.

As shown, the middle or third finger assembly **22***b* is positioned such that its sagittal plane is orientated substantially 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_{M1} and the center C_{22b} of the knuckle assembly of the middle finger **22***b* (see FIG. **12**), and (ii) are angled relative to the center of the knuckle assembly **230** of the middle finger **22***b* (see FIG. **14**). This configuration also causes the fasteners **61**.**30***a*-**61**.**30***b* that removably connected the finger assemblies **22***a*-**22***d* at a respective point **61**.**40***a*-**61**.**40***d* to the frame **61**.**2** to be not co-linear. At best, two of the respective point **61**.**40***a*-**61**.**40***d* may be co-linear, but all four points are not co-linear. However, all four respective point **61**.**40***a*-**61**.**40***d* are aligned in the same Y-Z plane.

FIGS. **11-14** also show that the pointer finger plane P_{22a} that bisects the pointer finger **22***a* along its length is offset from the sagittal plane P_S or the middle finger plane P_{22b} by an angle alpha α, wherein the angle alpha α is usually at least 0.25 degree, preferably between 0.5 degrees and 5 degrees, and most preferably between 2 degrees and 3 degrees, and likely less than 7 degrees. Likewise, the ring finger plane P_{22c} that bisects the ring finger **22***c* along its length is offset from the sagittal plane P_S or the middle finger plane P_{22b} by an angle beta β, wherein the angle beta β is usually at least 0.25 degree, preferably between 0.5 degrees and 5 degrees, and most preferably between 2 degrees and 3 degrees, and likely less than 7 degrees. Finally, the small finger plane P_{22d} that bisects the small finger **22***c* along its length is offset from the ring finger plane P_{22c} by an angle theta θ, wherein the angle theta θ is usually at least 0.25 degree, preferably between 0.5 degrees and 5 degrees, and most preferably between 2 degrees and 3 degrees, and likely less than 7 degrees.

Exemplary positional relationship between components of a finger assembly **22***a*-**22***d* is 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 without careful analysis and verification of the complex realities of designing, testing, manufacturing, training, and using the robot system with an end effector. 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.

TABLE 1

Angle	Lower Bound	Upper Bound	Preferred Lower Bound	Preferred Upper Bound
λ1	6.4°	10.6°	7.6°	9.3°
λ2	104.5°	174.2°	125.4°	153.3°
λ3	98.2°	163.6°	117.8°	144°
λ4	81.1°	135.2°	97.4°	119°
λ5	103.1°	171.8°	123.7°	151.1°
λ6	96.7°	161.2°	116°	141.8°
λ7	84.6°	140.9°	101.5°	124°
λ8	4.1°	6.9°	5°	6.1°
λ9	10.5°	17.5°	12.6°	15.4°

C. Finger Assembly

With reference, for example, to FIGS. **15-25**, each finger assembly **22***a*-**22***d* of the end effector **10** is comprised of a motor assembly **210**, a knuckle assembly **230**, a proximal assembly **250**, a medial assembly **270**, and a distal assembly **280**. Each of the knuckle assembly **230**, proximal assembly **250**, medial assembly **270**, and distal assembly **280** include internal linkages (in combination, internal linkage assembly) that can operate together to move the finger assembly **22***a*-**22***d*. 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

The motor assembly **210** may be configured to be releasably coupled to the top surface **61**.**2**.**4** of the housing frame **61**.**2**, and may include: (i) a motor **212**, (ii) controller **214**, (iii) a worm drive gear **216** that may be coupled to an extent of the motor **212**, and (v) a worm drive gear bearing **220**. Motor **212** may be a slotless BLDC motor, a brushed DC motor, a stepper motor, a switched reluctance motor, a permanent magnet synchronous motor, a servo motor, or any other suitable motor. As shown in the Figures, the motor assembly **210** for each finger assembly **22***a*-**22***d* may include only a single motor **212**; thus, said finger assembly **22***a*-**22***d* may not include more than one motor **212**. By limiting the number of motors **212** to the number of finger assemblies **22***a*-**22***d*, the end effector **10** may become underactuated. In other words, each finger assembly **22***a*-**22***d* may include three joints or 3 degrees of freedom (DoF), wherein each of the three joints or DoFs may be controlled by a single motor **212**. This configuration may simplify manufacturing, increase durability, enable the finger assemblies **22***a*-**22***d* to be modular, and may also reduce cost and complexity of control. In some aspects, the single motor configuration may allow for more compact designs and improved energy efficiency. Additionally, the underactuated nature of the system may provide adaptive grasping capabilities, potentially enhancing the end effector's ability to handle objects of various shapes and sizes.

As best shown in FIG. **23**C, the motor **212** includes: (i) internal components (not shown), (ii) a motor housing **212**.**1**, and (iii) a motor shaft **212**.**2**. The internal components of the motor **212** are designed to rotate the motor shaft **212**.**2** about a motor shaft axis A_{MS}. To help ensure that the motor shaft **212**.**2** rotates about the motor shaft axis A_{MS} at the desired speed, the internal components of the motor **212** may include a transmission, gear reduction, or other component. In addition to altering the speed of the motor shaft **212**.**2**, it should be understood that the transmission, gear reduction, or other component may prevent the motor shaft **212**.**2** from making full revolutions (i.e., 365 degrees) around the motor shaft axis A_{MS}. In fact, it may be beneficial to physically limit the rotational movement of the motor shaft **212**.**2** (as opposed to electronically limiting said rotation using programming or control methodologies) because it helps ensure that the finger assembly **22***a*-**22***d* cannot be over-rotated. However, in other embodiments, the transmission, gear reduction, or other component may not prevent the motor shaft **212**.**2** from making full revolutions (i.e., 365 degrees) around the motor shaft axis A_{MS}. In this embodiment, electronically limiting said rotation using programming or control methodologies may be used to help ensure that the finger assembly **22***a*-**22***d* is not over-rotated. Alternatively, it may be desirable to allow the motor shaft **212**.**2** to full revolutions (i.e., 365 degrees) based on the gearing ratio.

As shown in the Figure, the worm drive gear **216** extends past a frontal portion of the motor housing **212**.**1** and: (i) includes an extent that is designed to receive the motor shaft **212**.**2** to enable said worm drive gear **216** to be coupled to the motor shaft **212**.**2**, and (ii) has helical or screw-like threads. Coupling said worm drive gear **216** to the motor shaft **212**.**2** enables the internal components of the motor **212** to rotate the motor shaft **212**.**2** around the motor shaft axis A_{MS}, wherein said rotation of the motor shaft **212**.**2** around the motor shaft axis A_{MS} causes the worm drive gear **216** to rotate about a worm drive gear axis A_{WDG}. Due to the configuration of the motor assembly **210** and the worm drive gear **216**, the motor shaft axis A_{MS} and the worm drive gear axis A_{WDG} are parallel, aligned, and coaxial. Additionally, this configuration also causes the motor shaft axis A_{MS} and the worm drive gear axis A_{WDG} to be parallel with (and potentially, coaxial with) the finger motor plane P_{FM}. It should be understood that in other embodiments, the motor shaft axis A_{MS}, the worm drive gear axis A_{WDG}, and finger motor plane P_{FM} may not be parallel, aligned, and coaxial. Instead, the motor shaft axis Ans and the worm drive gear axis A_{WDG} may be perpendicular to one another, while the finger motor plane P_{FM} may be parallel with the motor shaft axis A_{MS}.

As described above, the motor assembly **210** may also include a worm drive gear bearing **220** that is positioned within an extent of the knuckle assembly **230** and may be designed to support the distal, rotating end of the worm drive gear **216**. In some aspects, the worm drive gear bearing **220** may be omitted or integrally formed with the worm drive gear **216**. In some implementations, the motor shaft **212**.**2** and the worm drive gear **216** may be integrally formed and/or sealed. Additionally, the worm drive gear bearing **220** may incorporate different bearing types such as ball bearings, roller bearings, or bushings depending on load requirements and desired performance characteristics. The positioning of the worm drive gear bearing **220** within the knuckle assembly **230** may allow for a more compact design while providing support for the rotating components. In some cases, multiple bearings may be used to support the worm drive gear **216** at different points along its length. The integration of the worm drive gear bearing **220** with other components may reduce the overall part count and simplify assembly procedures. The material selection for the worm drive gear bearing **220** may be optimized for factors such as wear resistance, load capacity, and operating temperature range to enhance the longevity and reliability of the mechanism.

As best shown in FIGS. **23**A-**23**C and discussed below, the worm drive gear **216** may be designed to be in geared engagement with an extent of the knuckle assembly **230**, wherein said geared engagement may enable the rotation of the worm drive gear **216**, via the motor shaft **212**.**2**, to cause the finger assembly **22***a*-**22***d* to move. As shown in the Figures, the motor assembly **210** may be a part of the finger assembly **22***a*-**22***d* and may not be located in a remote portion of the robot system. While this may limit the dimensions of the end effector (i.e., how small), it may reduce linkages, increase modularity, reduce parts, increase accessibility into the working environment and increase the reliability of the finger assembly **22***a*-**22***d*. In some aspects, the motor assembly **210** may be positioned in different locations within the finger assembly **22***a*-**22***d* to optimize space utilization or weight distribution. The geared engagement between the worm drive gear **216** and the knuckle assembly **230** may be designed with various gear ratios to achieve different torque and speed characteristics. In some implementations, additional gearing mechanisms may be incorporated to further refine the movement control of the finger assembly. The integration of the motor assembly **210** within the finger assembly **22***a*-**22***d* may allow for more compact designs and potentially improved responsiveness in certain applications.

b. Knuckle Assembly

The knuckle assembly **230** is positioned forward of a majority of the motor assembly **210** and is configured to allow the finger assembly **22***a*-**22***d* to move from the open, uncurled, or neutral state to the closed, curled, or inwardly rotated state. In said closed, curled, or inwardly rotated state, an acute interior angle is formed between the palm **62** and an interior surface of the finger assembly **22***a*-**22***d*. With

reference, for example, to FIGS. **15** and **23**A-**23**C, the knuckle assembly **230** includes: (i) a housing assembly **232**, (ii) a knuckle PCB **234**, and (iii) a worm wheel **236** that is in contact with and configured to interact with the worm drive gear **216**.

The housing assembly **232** includes a frame **232.1**, a knuckle cover **232.2**, and an external skin **232.3**. The frame **232.1** includes: (i) sidewalls **232.1.10**, (ii) a headwall **232.1.12**, and (iii) a rearward extending mounting projection **232.1.14**. The mounting projection **232.1.14** is designed to be coupled with the motor housing **212.1**, while the headwall **232.1.12** is designed to be positioned adjacent to a frontal extent of the motor housing **212.1**. Thus, the frame **232.1** is positioned adjacent to both the lateral surface and the frontal surface of the motor housing **212.1**. This helps provide sufficient support for the knuckle and the portion of the finger assembly **22***a*-**22***d* that extends therefrom. In other words, the frame **232.1** is made from a material that is sufficiently rigid to withstand the torque/other forces that are associated with the movement of the various assemblies.

The sidewalls **232.1.10** of the frame **232.1** extend forward from the headwall **232.1.12**. Said sidewalls **232.1.10** also form a proximal link aperture **232.1.2** that is configured to receive an extent of a worm wheel interface **256** (discussed further below) and is configured to: (i) be secured to an extent of the housing frame **61.2**, and (ii) at least partially surround the worm wheel **236**, worm drive gear **216**, and an extent of the motor **212**. This design helps protect the motor shaft **212.2** and the worm drive gear **216** from damage that may be caused by an external force. The sidewalls **232.1.10** also include: (i) coupling points **232.1.4** for the knuckle PCB **234**, which is configured to control an extent of the finger assembly **22***a*-**22***d* and provide positional information back to the robot system, and (ii) bearing apertures **232.1.20** that are designed to receive the bearings that allow the motor assembly **210** to continue driving the worm drive gear **216** after an extent of the proximal assembly **250** has reached a resistance point (e.g., contact with an object).

The knuckle cover **232.2** is positioned adjacent to the sidewalls **232.1.10**, includes a frontal wall **232.2.2** that has a recess that is designed to receive the worm drive gear bearing **220**, and is designed to overlay an upper extent of the worm drive gear **216**. As such, the knuckle cover **232.2** supports and protects the worm drive gear **216** and an extent of the motor **212**. The support and protection provided by the knuckle cover **232.2** allows the external skin **232.3** to be: (i) less rigid than the knuckle cover **232.2**, (ii) easily replaceable in case of damage, and (iii) focused on minimizing the gap G that is formed between knuckle assembly **230** and the proximal assembly **250**. To minimize the gap G, the external skin **232.3** has: (i) a left to right, arched configuration, (ii) a front to back, curvilinear design, and (iii) varying thicknesses (see FIGS. **23**A-**23**C, **26**). The complex design of the external skin **232.3** enables: (i) a substantial extent of the external skin **232.3** to be positioned within an extent of the proximal assembly **250**, when the finger assembly **22***a*-**22***d* is in the open, uncurled, or neutral state, and (ii) a minor extent of, or none of, the external skin **232.3** to be positioned within an extent of the proximal assembly **250**, when the finger assembly **22***a*-**22***d* is in the closed, curled, or inwardly rotated state. By enabling at least a minimal extent of the external skin **232.3** to be positioned within, or adjacent to, the proximal assembly **250**, the gap G_1 formed between the assemblies **230** and **250** is minimized, and wherein said minimization of said gap G_1 is beneficial because it minimizes the chance or probability that a textile assembly—namely, a glove—or external covering can be caught or pinched between these assemblies. In light of the above disclosure, the knuckle cover **232.2** may be made from metal or a sufficiently rigid material, while the external skin **232.3** may be made from deformable silicon, thermoset plastic, or any other suitable materials disclosed herein or known in the art.

The worm wheel **236** is a semi-circular toothed gear that is designed to be in geared engagement with the worm drive gear **216**. In particular, the worm wheel **236** includes: (i) a toothed section **236.2** that includes 18 teeth that encircle 220 degrees of the worm wheel **236**, (ii) a recessed portion **236.4** that is designed to receive an extent of the worm drive link **254.4.1**, and (iii) a central bearing opening **236.6** that are designed to receive a first and second worm bearings **256.2***a*, **256.2***b* (as discussed below). Said worm wheel **236** is designed to rotate about a worm wheel axis A_{WW}, wherein said worm wheel axis A_{WW} is located at the center of the central bearing opening **236.6** and the first pivot point P_1. It should be understood that in other embodiments, the worm wheel **236** may include additional teeth (e.g., between 19 and 50) or fewer teeth (e.g., between 5 and 17). Additionally, the toothed section **236.2** 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).

As discussed above, the rotation of the motor shaft **212.2** around the motor shaft axis A_{MS} causes the worm drive gear **216** to rotate about a worm drive gear axis A_{WDG}. The rotation of the worm drive gear **216** about a worm drive gear axis A_{WDG} causes the worm wheel **236** to rotate above the worm wheel axis A_{WW} or the first pivot point P_1. Because the toothed section **236.2** of the worm wheel **236** only encircles 220 degrees of the worm wheel **236**, said worm wheel **236** can only rotate approximately 220 degrees above the worm wheel axis A_{WW} or the first pivot point P_1. In other words, the worm wheel **236** cannot fully rotate (i.e., at least 365 degrees or more) around the worm wheel axis A_{WW} or the first pivot point P_1. Due to the configuration of the motor assembly **210**, the worm drive gear **216**, and worm wheel **236**, the worm wheel axis A_{WW} is perpendicular to the motor shaft axis A_{MS}, the worm drive gear axis A_{WDG}, and the finger motor plane P_{FM}. However, as shown in the Figures, both the motor shaft axis Ans and the worm drive gear axis A_{WDG} are positioned above or away from the palm in comparison to the worm wheel axis A_{WW} or the first pivot point P_1. In other words, the worm wheel axis A_{WW} or the first pivot point P_1 underlies an extent of the motor shaft axis A_{MS} and the worm drive gear axis A_{WDG}.

The knuckle PCB **234** includes a first finger encoder (e.g., magnetic, optical, capacitive, resistive, etc.) that is positioned proximate to the metacarpophalangeal joint MJ and configured to collect proximal data, wherein said proximal data includes information related to the rotation of the metacarpophalangeal joint MJ. Said proximal data may use the robot system to generate a vector representation (e.g., a space embedding) indicating the state of the proximal assembly **250** or the environment around the proximal assembly **250**. The encoder of the knuckle PCB **234** may collect data upon a specific command from the robot system or periodically (e.g., between 500 times per second to every minute). Also, as shown in the Figures, the controller **214** and said knuckle PCB can be co-located on a single PCB. In other embodiments, the controller **214** and the knuckle PCB **234** may be split on different PCBs.

c. Proximal Assembly

The proximal assembly **250** is positioned between the knuckle assembly **230** and the medial assembly **270** and is the first portion of the finger assembly **22***a*-**22***d* configured

to move relative to the housing frame **61**.**2** and the palm **62** in response to actuation of the motor **210** and worm drive gear **216**. The proximal assembly **250** includes: (i) a proximal housing assembly **252**, (ii) a proximal link assembly **254**, (iii) the worm wheel interface **256**, and (iv) a proximal PCB **258**.

i. Proximal Housing Assembly

As shown in FIGS. **23**A-**24**B and **32**-**34**, the proximal housing assembly **252** is designed to substantially surround a majority of the other components of the proximal assembly **250**. To achieve this, the proximal housing assembly **252** forms an internal proximal recess **252**.**18**. The internal proximal recess **252**.**18** is designed to not only surround components of the proximal assembly **250**, but is also designed to receive: (i) an extent of the medial assembly **270** (namely, the medial tongue **272**.**20**), when the finger assembly **22***a*-**22***d* is in the open, uncurled, or neutral state, and (ii) a lesser extent of, or none of, the medial assembly **270** (namely, the medial tongue **272**.**20**), when the finger assembly **22***a*-**22***d* is in the closed, curled, or inwardly rotated state. In other words, the proximal housing assembly **252** overlies: (i) a substantial extent of the medial tongue **272**.**20** when the finger assembly **22***a*-**22***d* is in the open, uncurled, or neutral state, and (ii) a minor extent of, or none of, the medial tongue **272**.**20** when the finger assembly **22***a*-**22***d* is in the closed, curled, or inwardly rotated state. Stated another way, the percentage of the medial assembly **270** (namely, the medial tongue **272**.**20**) that is positioned within the proximal housing assembly **252** is reduced when the finger assembly **22***a*-**22***d* moves from the open, uncurled, or neutral state to the closed, curled, or inwardly rotated state. By enabling at least a minimal extent of the medial assembly **270** (namely, the medial tongue **272**.**20**) to be positioned within or adjacent to the proximal assembly **250**, the gap G_2 formed between the assemblies **250** and **270** is minimized, and wherein said minimization of said gap G_2 is beneficial because it minimizes the chance or probability that a textile assembly—namely, a glove—or external covering can be caught or pinched between these assemblies.

As shown in FIGS. **17**-**26** and **32**-**33**, the proximal housing assembly **252** specifically includes: (i) a proximal jacket assembly **252**.**1** with a top member **252**.**1**.**1** and a bottom member **252**.**1**.**2**, and (ii) a proximal bottom casing assembly **252**.**2**. While the bottom member **252**.**1**.**2** is in direct contact with and underlies the proximal bottom casing assembly **252**.**2**, the finger assembly **22***a*-**22***d* lacks a proximal top casing assembly that is in direct contact with the top member **252**.**1**.**1**. This design is advantageous because the proximal bottom casing assembly **252**.**2** provides the bottom member **252**.**1**.**2** with additional rigidity, which enables said bottom member **252**.**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 **252**.**1**.**1** does not need to include a softer, easier-to-form, and potentially less durable material because said top member **252**.**1**.**1** is not designed to come into regular contact with objects. Additionally, even if the materials of the proximal bottom casing assembly **252**.**2** and the bottom member **252**.**1**.**2** are the same, it may be desirable to form these components as two separate components to facilitate replicability without exposing an inner extent of the finger assembly **22***a*-**22***d*. Another way of describing this beneficial configuration includes the fact that the proximal jacket assembly **252**.**1** is configured to provide the primary external shape of the finger assembly **22***a*-**22***d*, while the proximal casing assembly **252**.**2** is configured to protect the proximal PCB **258** and provide a spacer between the proximal link assembly **254** and the proximal jacket assembly **252**.**1**. Nevertheless, it should be understood that in an alternative embodiment, the bottom member **252**.**1**.**2** and the proximal bottom casing assembly **252**.**2** may be integrally formed as a single structure.

As best shown in FIGS. **23**A-**24**B, the top member **252**.**1**.**1** of the proximal jacket assembly **252**.**1** includes an exterior surface back with a curvilinear extent in a first direction (namely, across the width of the finger assembly **22***a*-**22***d*), and the bottom member **252**.**1**.**2** of the proximal jacket assembly **252**.**1** includes an exterior palm surface with a curvilinear extent in the first direction (namely, across the width of the finger assembly **22***a*-**22***d*) and a second direction (namely, across the length of the finger assembly **22***a*-**22***d*). The curvilinear extent in the first direction helps ensure that the finger assembly **22***a*-**22***d* 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, the bottom member **252**.**1**.**2** of the proximal jacket assembly **252**.**1** may include a main body portion **252**.**1**.**2**.**1** and a rearward projection **252**.**1**.**2**.**2**, wherein said main body portion is designed to be positioned forward of the first joint or metacarpophalangeal joint MJ, while the rearward projection **252**.**1**.**2**.**2** is designed to underlie and protect the metacarpophalangeal joint MJ. Due to the fact that the bottom member **252**.**1**.**2** includes two distinct portions **252**.**1**.**2**.**1**, **252**.**1**.**2**.**2**, said bottom member **252**.**1**.**2** also includes two contact regions **61**.**4**.**4**, **61**.**4**.**6**. It should be understood that in an alternative embodiment, the portions **252**.**1**.**2**.**1**, **252**.**1**.**2**.**2** of the bottom member **252**.**1**.**2** may be omitted.

As discussed above, the proximal housing assembly **252** 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. In some aspects, the proximal housing assembly **252** may include additional components or layers (e.g., between three and an nth). The proximal housing assembly **252** may incorporate specialized materials or coatings to enhance grip, durability, or sensor capabilities. For example, a layer of electroactive polymer may be included to enable shape-changing properties, or a layer of piezoelectric material may be added for tactile sensing. In some implementations, the layers may be interchangeable to allow customization for different tasks or environments. The assembly may also feature self-healing materials in certain layers to extend the lifespan of high-wear areas.

ii. Proximal Link Assembly

As shown in FIGS. **27**-**42**, the proximal link assembly **254** includes: (i) a primary or main proximal link or first bar **254**.**1**, (ii) a biasing assembly **254**.**2**, (iii) a medial assembly coupler **254**.**3**, and (iv) a proximal drive link assembly **254**.**4**. The proximal link assembly **254** is involved with all movements of the finger assembly **22***a*-**22***d*. In other words, at least one aspect of the proximal link assembly **254** must move in order to cause any portion of the finger assembly **22***a*-**22***d* to move. This feature is beneficial because it reduces complexities, reduces components, cost, weight, increases reliability, and may have other benefits.

The primary or main proximal link or first bar **254**.**1** is best shown in FIGS. **27** and **38**-**40**. The main proximal link **254**.**1** includes: (i) partially-circular frame members or first proximal link segment **254**.**1**.**1**, (ii) second proximal link segment **254**.**1**.**2**, (iii) third proximal link segment **254**.**1**.**3**,

(iv) proximal link bridge **254.1.4**, (v) medial assembly opening **254.1.5**, and (vi) first and second medial link projections **254.1.6***a*, **254.1.6***b*. The partially-circular frame members segment **254.1.1** include left and right extents **254.1.1.1**, **254.1.1.2** that extend from the rearmost extent of the main proximal link **254.1** to line S_1 shown in FIG. **39**. Like partially-circular frame members segment **254.1.1**, the second proximal link segment **254.1.2** also includes left and right extents **254.1.2.1**, **254.1.2.2** that extend between lines S_1 and S_2 shown in FIG. **39**. As shown in FIG. **39**, the left and right extents **254.1.2.1**, **254.1.2.2** taper inward as they extend from line S_1 to line S_2, which reduces the overall width of the link **254.1**. The reduction in width is beneficial because it allows for a reduction in the width of the finger assembly **22***a*-**22***d* to allow for conformal materials to aid in gripping objects. It should be understood that in other embodiments, the taper may be greater or lesser, or it may be eliminated.

Also, as shown in FIG. **39**, like the second proximal link segment **254.1.2**, the third proximal link segment **254.1.3** also includes left and right extents **254.1.3.1**, **254.1.3.2** that extend forward from line S_2 toward the forward most extent of main proximal link or first bar **254.1**. These left and right extents **254.1.3.1**, **254.1.3.2** may be substantially parallel to the left and right extents **254.1.1.1**, **254.1.1.2**, but may not be aligned therewith due to the taper of the left and right extents **254.1.2.1**, **254.1.2.2**. In some aspects, said left and right extents **254.1.3.1**, **254.1.3.2** may not be substantially parallel and/or may be substantially aligned with other components of the main proximal link **254.1**. The configuration of these extents may allow for customization of the finger assembly's shape and movement characteristics. In some implementations, the taper and alignment of the various extents may be adjustable to optimize grasping capabilities for different object types or sizes. The parallel arrangement in some cases may provide structural stability, while non-parallel configurations may offer increased flexibility in certain grasping scenarios. The specific geometry of these components may be tailored to meet particular functional requirements or to enhance overall dexterity of the robotic finger.

As shown in FIG. **38**, the partially-circular frame members segment **254.1.1** includes a metacarpophalangeal joint coupler **254.1.1.1** that helps form a first joint or metacarpophalangeal joint MJ and includes an axle aperture **254.1.1.1.1** and stopping projection **254.1.1.1.2**. As such, the first joint or metacarpophalangeal joint MJ is formed between the knuckle assembly **230** and the proximal assembly **250**. The axle aperture **254.1.1.1.1** of the metacarpophalangeal joint coupler **254.1.1.1** is non-circular and is configured to receive an extent of the worm wheel interface **256** (which will be discussed later). The non-circular configuration allows helps ensure that the worm wheel interface **256** does not slip within the aperture **254.1.1.1.1**, when the motor assembly **210** drives the worm drive gear **216**, which turns the worm wheel **236**, and whereby causing the worm drive link **254.4.1** and the proximal drive link **254.4.3** to move the primary or main proximal link or first bar **254.1**. Slipping within said aperture **254.1.1.1.1** would not only cause the finger assembly **22***a*-**22***d* to fail to properly move, but it would also cause the encoders and other sensors to error in knowing the finger assemblies **22***a*-**22***d* location and position in space. It should be understood that other non-circular configurations of the axle aperture **254.1.1.1.1** are contemplated by this disclosure (e.g., tear-drop).

Referring to FIGS. **27**, **28**, **34**, and **40**, the stopping projection **254.1.1.1.2** may be positioned in a lower extent of the partially-circular frame members segment **254.1.1**. When the proximal assembly **250** is closed, curled, or in the inwardly rotated state, the stopping projection **254.1.1.1.2** may include a first limiting interface region **254.1.1.1.2.1** that may be configured to interact with or contact an extent of the knuckle frame member **232.1**. It should be understood that the above described interface region **254.1.1.1.2.1** need not make contact with the described adjacent structures, and instead, a gap may be present between these structures regardless of the state of the finger assembly **22***a*-**22***d*. In some aspects, the stopping projection **254.1.1.1.2** may be adjustable to allow for fine-tuning of the finger assembly's range of motion. The first limiting interface region **254.1.1.1.2.1** may be coated with a low-friction material to reduce wear during repeated interactions. In some implementations, multiple stopping projections may be incorporated at different positions to provide staged limiting of movement. The interaction between the stopping projection and the knuckle frame member may be monitored by sensors to provide feedback on the finger assembly's position. In some cases, the stopping projection may be designed with a cushioning mechanism to soften the impact when reaching the limit of movement.

As shown in FIGS. **38-40**, the third segment **254.1.3** of the main proximal link **254.1** includes the second limiting interface region **254.1.3.1** and housing mounting projections **254.1.3.2**. The second limiting interface region **254.1.3.1** is best shown in FIGS. **23**A and **38-40** and is configured to prevent the proximal assembly **250** from over-rotating or curling backward. While the second limiting interface region **254.1.3.1** is positioned on the forwardmost extent of the third segment **254.1.3**, the housing mounting projections **254.1.3.2** are positioned on the uppermost point of the third segment **254.1.3** and are configured to couple to both the proximal jacket and proximal casing assemblies **252.1**, **252.2** within the finger assembly **22***a*-**22***d*. Other methods of preventing over-rotation and coupling the housing assembly **252** within the finger assembly **22***a*-**22***d* are contemplated by this disclosure. For example, the housing assembly **252** may be configured to prevent over-rotation, while said housing assembly **252** may be formed from a single piece of material.

As shown in FIG. **39**, the proximal bridge **254.1.4** extends between the left and right extents **254.1.3.1** and **254.1.3.2** of the third proximal link segment **254.1.3**. Thus, the combination of the proximal bridge **254.1.4** and the left and right extents **254.1.3.1**, **254.1.3.2** forms a U-shaped member with a proximal link recess **254.1.7**. Said proximal link recess **254.1.7** includes a first portion **254.1.7.1** and a second portion **254.1.7.2**. When the finger assembly **22***a*-**22***d* is closed, curled, or inwardly rotated position: (i) the first portion **254.1.7.1** that extends rearward from line S_3 is configured to receive the worm drive link **254.4.1**, and (ii) the second portion **254.1.7.2** that extends forward from line S_3 is configured to receive the proximal drive link **254.4.3**. Finally, the medial assembly opening **254.1.5** and first and second medial link projections **254.1.6** are positioned in a forward extent of the proximal link **254.1** (i.e., forward of line S_3) and are configured to interact with the medial assembly **270**.

As shown in FIG. **52**, the biasing assembly **254.2** includes a biasing member **254.2.1**, a first biasing coupler **254.2.2**, and a second biasing coupler **254.2.3**. The first biasing coupler **254.2.2** is positioned within the first portion **254.1.7.1** of the proximal link recess **254.1.7** of the main proximal link **254.1** and extends between the left and right extents **254.1.3.1**, **254.1.3.2** of the third proximal link segment **254.1.3**. Meanwhile, the second biasing coupler

254.2.3 is coupled to a projection that depends from the proximal drive link **254.4.3** (discussed further below). As such, one end of the biasing member **254.2.1** is coupled to the first biasing coupler **254.2.2**, while a second opposed end of the biasing member **254.2.1** is coupled to the second biasing coupler **254.2.3**. The biasing member **254.2.1** may be a spring (e.g., coil spring) or any other member (e.g., magnet) that can provide a biasing force on an extent of the finger assembly **22***a*-**22***d* in order to control the order of closure/collapse of the components contained in said finger assembly **22***a*-**22***d*.

As shown in FIGS. **31** and **57**, when the finger assembly **22***a*-**22***d* moves from the open, uncurled, or neutral state to the closed, curled, or inwardly rotated state, the biasing member **254.2.1** moves from a first or collapsed position with a length of LT_1 to a second or extended position with a length LT_2. In the first or collapsed position, the biasing member **254.2.1** 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 **254.2.1** is designed to prevent the medial or distal assemblies **270**, **280** before the proximal housing **252** has come into contact with a resistance point (e.g., an object). Once said proximal housing **252** has come into contact with a resistance point (e.g., an object), the main proximal link **254.1** and the proximal housing **252** stops moving. However, the motor assembly **210** can continue driving the worm drive gear **216** in a first direction, which turns the worm wheel **236**, whereby causing the worm drive link **254.4.1** and the proximal drive link **254.4.3** to move into the proximal link recess **254.1.7** and rotation about the worm wheel axis A_{WW}, thus forcing the biasing member **254.2.1** to expand for its original state, and therefore forces the medial and distal assemblies **270**, **280** to curl inwards. The finger assembly **22***a*-**22***d* can uncurl or return to its original state, if the motor assembly **210** drove driving the worm drive gear **216** in a second direction, which turns the worm wheel **236**, whereby causing the worm drive link **254.4.1** and the proximal drive link **254.4.3** to move out of the proximal link recess **254.1.7**, thus forcing the medial and distal assemblies **270**, **280** to uncurl, therefore allowing the biasing member **254.2.1** to return to its original state, and consequently allowing the main proximal link **254.1** and the proximal housing assembly **252** to return to their original state. In should be understood that other biasing members, structures, assemblies, or components may be used instead of the coil spring shown in the figures and in certain embodiments, that biasing assembly **254.2** may be eliminated.

As shown in in FIGS. **37** and **41-42**, the drive link assembly **254.4** includes: (i) worm drive link or second bar **254.4.1**, (ii) worm wheel coupler **254.4.2**, (iii) proximal drive link, angled link, third bar **254.4.3**, (iv) drive link coupler **254.4.4**. The worm drive link **254.4.1** includes: (i) a worm wheel interface region **254.4.1.3** at a first end of the worm drive link **254.4.1**, and wherein said worm wheel interface region **254.4.1.3** is configured to be positioned adjacent to and fixedly connected with the worm wheel **236**, and (ii) a worm wheel coupler recess **254.4.1.4** that is positioned adjacent to the worm wheel interface region **254.4.1.3** and configured to: (a) increase the interactive surface area between the worm drive link **254.4.1** and worm wheel **236**, (b) align the worm drive link **254.4.1** with the worm wheel **236**, and (c) is designed to ensure that the worm wheel coupler **254.4.2** does not interfere with the movement of the worm wheel **236**. It should be understood that the worm wheel coupler recess **254.4.1.4** may be omitted in other embodiments and an alternative version of the worm wheel coupler **254.4.2** may be used that lacks the clearance requirements necessitating the worm wheel coupler recess **254.4.1.4**.

The worm drive link **254.4.1** includes two interface regions, namely a third limiting interface region **254.4.1.1**, and a fourth limiting interface region **254.4.1.2**. The third limiting interface region **254.4.1.1** extends along a rear extent of the worm drive link **254.4.1** and is configured to be positioned adjacent to an extent of the knuckle cover **232.2** of the knuckle housing assembly **232** when the finger assembly **22***a*-**22***d* is in the open, uncurled, or neutral position. Meanwhile, the fourth limiting interface region **254.4.1.2** is positioned along a forward extent of the worm drive link **254.4.1** and is configured to be positioned adjacent to an extent of the main proximal link **254.1** when the finger assembly **22***a*-**22***d* is in the closed, curled, or inwardly rotated state. It should be understood that the above described interface regions **254.4.1.1**, **254.4.1.2** need not make contact with the described adjacent structure. Instead, a gap may be present between these structures regardless of the state of the finger assembly **22***a*-**22***d*.

The proximal drive link, angled link, third bar **254.4.3** includes a worm drive link opening **254.4.3.1** at a first end and a medial link opening **254.4.3.2** at a second end. Said proximal drive link **254.4.3** is configured to be coupled between: (i) the worm drive link **254.4.1** using a drive link coupler **254.4.4** that is inserted through the worm drive link opening **254.4.3.1** and an extent of the worm drive link **254.4.1**, and (ii) a main medial link **274.1** (discussed further below) using a main medial link coupler **254.4.5** that is inserted through the medial link opening **254.4.3.2** and an extent of the main medial link **274.1**. The drive link coupler **254.4.4** enables the worm drive link **254.4.1** to be pivotably connected to the proximal drive link **254.4.3** in order to form a second pivot point P_2, and wherein the second pivot point P_2 is designed to move from a first location when the finger assembly **22***a*-**22***d* is in open, uncurled, or neutral state (FIG. **23**C) to a second location the finger assembly **22***a*-**22***d* is in the closed, curled, or inwardly rotated state (FIG. **57**). In comparing FIG. **23**C with FIG. **57**, it can be seen that the first location in further away from the palm **62** and is positioned closer to the motor assembly **210** in comparison to the second location. Said movement of the second pivot point P_2 enables the finger assembly **22***a*-**22***d* to transfer the movement of the worm drive link **254.4.1** to the main medial link **274.1**. As shown in FIGS. **23**C and **57**, this transfer of movement or energy, the angle between the worm drive link **254.4.1** and the proximal drive link **254.4.3** changes depending on the position of the finger assembly **22***a*-**22***d*.

iii. Worm Wheel Interface and Proximal PCB

The worm wheel interface **256** includes first and second worm locking members **256.1***a*, **256.1***b*, along with first and second worm bearings **256.2***a*, **256.2***b*. The worm wheel assembly **256** utilizes the configuration of the locking members and bearings **256.1***a*, **256.1***b*, **256.2***a*, **256.2***b* to allow the main proximal link **254.1** to remain in a fixed position once it has come into contact with a resistance point, while the motor assembly **210** continues to drive the proximal drive link assembly **254.4** (causing movement of the medial and distal assemblies **270**, **280**). In other words, the bearings **256.1***a*, **256.1***b* allow the main proximal link **254.1** to stop rotating even when the worm wheel **236** continues to rotate. It should be understood that without this slippage between the main proximal link **254.1** and the worm wheel **236**, the finger assembly **22***a*-**22***d* could not rotate the medial and distal assemblies **270**, **280** once the proximal assembly **250** came into contact with a resistance point.

The proximal PCB **258** includes a second finger encoder (e.g., magnetic, optical, capacitive, resistive, etc.) that is positioned proximate to the proximal interphalangeal joint PIJ and configured to collect medial data, wherein said medial data includes information related to the rotation of the proximal interphalangeal joint PIJ. Said medial data may use the robot system to generate a vector representation (e.g., a space embedding) indicating the state of the medial assembly **270** or the environment around the medial assembly **270**. The encoder of the proximal PCB **258** may collect data upon a specific command from the robot system or periodically (e.g., between 500 times per second to every minute).

d. Medial Assembly

The medial assembly **270** is positioned between the proximal assembly **250** and the distal assembly **280** and is the second portion of the finger assembly **22***a*-**22***d* configured to move relative to the palm **610**. The medial assembly **270** includes: (i) a medial housing assembly **272**, and (ii) a medial link assembly **274**.

i. Medial Housing Assembly

As shown in FIGS. **23**A-**24**B, **43**-**45**, and **57**, the medial housing assembly **272** is designed to substantially surround a majority of the other components of the medial assembly **270**. To achieve this, the medial housing assembly **272** forms an internal medial recess **272**.**18**. The internal medial recess **272**.**18** is designed to not only surround components of the medial assembly **270**, but is also designed to receive: (i) an extent of the distal assembly **280** (namely, the distal tongue **282**.**20**), when the finger assembly **22***a*-**22***d* is in the open, uncurled, or neutral state, and (ii) a lesser extent of, or none of, the distal assembly **280** (namely, the distal tongue **282**.**20**), when the finger assembly **22***a*-**22***d* is in the closed, curled, or inwardly rotated state. In other words, the medial housing assembly **272** overlies: (i) a substantial extent of the distal tongue **282**.**20** when the finger assembly **22***a*-**22***d* is in the open, uncurled, or neutral state, and (ii) a minor extent of, or none of, the distal tongue **282**.**20** when the finger assembly **22***a*-**22***d* is in the closed, curled, or inwardly rotated state. Stated another way, the percentage of the distal assembly **280** (namely, the distal tongue **282**.**20**) that is positioned within the medial housing assembly **272** is reduced when the finger assembly **22***a*-**22***d* moves from the open, uncurled, or neutral state to the closed, curled, or inwardly rotated state. By enabling at least a minimal extent of the distal assembly **280** (namely, the distal tongue **282**.**20**) to be positioned within or adjacent to the medial assembly **270**, the gap G_3 formed between the assemblies **270** and **280** is minimized, and wherein said minimization of said gap G_3 is beneficial because it minimizes the chance or probability that a textile assembly—namely, a glove—or external covering can be caught or pinched between these assemblies.

As shown in FIGS. **17**-**26** and **43**-**45**, the medial housing assembly **272** specifically includes: (i) a medial jacket assembly **272**.**1** with a top member **272**.**1**.**1** and a bottom member **272**.**1**.**2**, and (ii) a medial bottom casing assembly **272**.**2**. While the bottom member **272**.**1**.**2** is in direct contact with and underlies the medial bottom casing assembly **272**.**2**, the finger assembly **22***a*-**22***d* lacks a medial top casing assembly that is in direct contact with the top member **272**.**1**.**1**. This design is advantageous because the medial bottom casing assembly **272**.**2** provides the bottom member **272**.**1**.**2** with additional rigidity, which enables said bottom member **272**.**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 **272**.**1**.**1** does not need to include a softer, easier-to-form, and potentially less durable material because said top member **272**.**1**.**1** is not designed to come into regular contact with objects. Additionally, even if the materials of the medial bottom casing assembly **272**.**2** and the bottom member **272**.**1**.**2** are the same, it may be desirable to form these components as two separate components to facilitate replicability without exposing an inner extent of the finger assembly **22***a*-**22***d*. Another way of describing this beneficial configuration includes the fact that the medial jacket assembly **272**.**1** is configured to provide the primary external shape of the finger assembly **22***a*-**22***d*, while the medial casing assembly **272**.**2** is configured to protect the proximal PCB **258** and provide a spacer between the medial link assembly **274** and the medial jacket assembly **272**.**1**. Nevertheless, it should be understood that in an alternative embodiment, the bottom member **272**.**1**.**2** and the medial bottom casing assembly **272**.**2** may be integrally formed as a single structure.

As best shown in FIGS. **23**A-**24**B, the top member **272**.**1**.**1** of the medial jacket assembly **272**.**1** includes an exterior surface back with a curvilinear extent in a first direction (namely, across the width of the finger assembly **22***a*-**22***d*), and the bottom member **272**.**1**.**2** of the medial jacket assembly **272**.**1** includes an exterior palm surface that is curvilinear extent in the first direction (namely, across the width of the finger assembly **22***a*-**22***d*) and a second direction (namely, across the length of the finger assembly **22***a*-**22***d*). The curvilinear extent in the first direction helps ensure that the finger assembly **22***a*-**22***d* 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 **272**.**1**.**1** of the medial jacket assembly **272**.**1** includes a rearwardly extending medial tongue **272**.**20**. The medial tongue **272**.**20** has an arched shape with a curvilinear rear surface **272**.**20**.**2**, wherein the width of said medial tongue **272**.**20** is reduced from a first or front width W_1 to a second or rear width W_2. As such, the medial tongue **272**.**20** includes curvilinear extents in at least two directions. As discussed above, the medial tongue **272**.**20** is designed to be positioned within or adjacent to proximal housing assembly **252** and configured to minimize the gap G_2 that is formed between assemblies **250** and **270**. It should be understood that in an alternative embodiment, the medial tongue **272**.**20** may be omitted.

As discussed above, the medial housing assembly **272** 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 know material used in robot systems. In some aspects, the medial housing assembly **272** may include additional components or layers (e.g., between three and an nth). The medial housing assembly **272** may incorporate specialized materials or coatings to enhance grip, durability, or sensor capabilities. For example, a layer of electroactive polymer may be included to enable shape-changing properties, or a layer of piezoelectric material may be added for tactile sensing. In some implementations, the layers may be interchangeable to allow customization for different tasks or environments. The assembly may also feature self-healing materials in certain layers to extend the lifespan of high-wear areas. It should be also be understood in alternative embodiments that the medial jacket assembly **272**.**1** and the medial casing assembly **272**.**2**

may be combined into a single component and/or additional exterior members may be added to the end effector **10**/finger assembly **22***a*-**22***d*.

ii. Medial Link Assembly **274**

As shown in FIG. **40**, the medial link assembly **274** includes: (i) a primary or main medial link or fourth bar **274.1**, (ii) a medial drive link or fifth bar **274.2**, and (iii) a main/drive link couplers or sixth bar **274.3***a*, **274.3***b*. The medial link assembly **274** is involved with a majority of the movements of the finger assembly **22***a*-**22***d*. While the proximal assembly **250** could move without causing a positional change between said proximal assembly **250** and the medial assembly **270**, the distal assembly **280** cannot move without causing a positional change between said distal assembly **280** and the medial assembly **270**. Because most movements of the end effector **10** involve movement of the medial assembly **270** relative to the proximal assembly **250** and/or distal assembly **280**, said medial assembly **270** is involved with a majority of the movements of the finger assembly **22***a*-**22***d*. As discussed above, this is contrast to conventional end effectors and/or conventional fingers and is beneficial because it reduces complexities, reduces components, increases reliability, and may afford other benefits.

The primary or main medial link or fourth bar **274.1** is best shown in FIGS. **46-53**. The main medial link **274.1** helps form a second or proximal interphalangeal joint PIJ that is positioned between the proximal assembly **250** and the medial assembly **270**. The main medial link **274.1** is designed to be pivotably connected to both the proximal link **254.1** and the proximal drive link **254.4.3** and includes three integrally formed components, wherein said components include: (i) proximal interphalangeal joint coupler **274.1.1** that extends rearward from line M_1, (ii) medial link neck or biasing neck **274.1.2** that extends between lines M_1 and M_2, and (iii) medial link extension **274.1.3** that extends forward from M_2. The first component of the main medial link **274.1** is the proximal interphalangeal joint coupler **274.1.1** and is comprised of: (i) a first and second partially-triangular frame members **274.1.1.1***a*, **274.1.1.1***b*, (ii) a first medial link or interphalangeal joint recesses **274.1.1.2**, and (iii) medial link bridge **274.1.1.3** that couples the first and second partially-triangular frame members **274.1.1.1***a*, **274.1.1.1***b* to one another. The first and second partially-triangular frame members **274.1.1.1***a*, **274.1.1.1***b* are the rearmost extent of the main medial link **274.1** and have: (i) a proximal drive link aperture **274.1.1.1.1**, (ii) a drive link assembly recesses **274.1.1.2**, (iii) first and second limiting projections **274.1.1.1.3***a*, **274.1.1.1.3***b*, and (vi) a proximal main link aperture **274.1.1.1.4**.

As discussed above, the first and second partially-triangular frame members **274.1.1.1***a*, **274.1.1.1***b* of the proximal interphalangeal joint coupler **274.1.1** of the main medial link **274.1** include the proximal drive link aperture **274.1.1.1.1**. In particular, the proximal drive link aperture **274.1.1.1.1** is formed in the drive link assembly recesses **274.1.1.1.5***a*, **274.1.1.1.5***b* and is configured to receive an extent of a securement member **274.1.1.1.10** that pivotally connects the proximal drive link assembly **254.4** to the main medial link **274.1**. Pivotally connecting the proximal drive link assembly **254.4** to the main medial link **274.1** forms a third pivot point P_3, which further enables the transfer of energy from the motor assembly **210** to the distal assembly **280**. Like a majority of the pivot points, the third pivot point P_3 is configured to move from a first location to a second location when the finger assembly **22***a*-**22***d* moves from the open, uncurled, or neutral state to the closed, curled, or inwardly rotated state. When comparing FIG. **31** to FIG. **57**, the first location is positioned rearward and above or towards the back of the end effector **10** in comparison to the second location.

The proximal link opening **274.1.1.1.4** that is formed in the first and second partially-triangular frame members **274.1.1.1***a*, **274.1.1.1***b* and is positioned forward and below the proximal drive link aperture **274.1.1.1.1**. In particular, the proximal link opening **274.1.1.1.4** pivotally couples the main proximal link **254.1** to the main medial link **274.1** using the medial assembly coupler **254.3**, and whereby creating a fifth pivot point P_5. Unlike a majority of the other pivot points, the fifth pivot point P_5 is semi-fixed because: (i) unlike the first pivot point P_1, it moves when the proximal assembly **250** moves, and (ii) unlike the second pivot point P_2 or the third pivot point P_3, it cannot move relative to the proximal assembly **250**. Thus, the movement of the fifth pivot point P_5 is between the movement capabilities of the fixed and non-fixed pivot points and therefore is semi-fixed. Said fifth pivot point P_5 needs to be fixed relative to the proximal assembly **250** to enable the proximal drive link assembly **254.4** to force the medial assembly **270** around a pivot point P_5 or medial axis A_M. Said medial axis A_M is parallel with the worm wheel axis A_{WW}, but is perpendicular (in one direction) to both the motor shaft axis A_{MS} and the worm drive gear axis A_{WDG}.

The first and second limiting projections **274.1.1.1.3***a*, **274.1.1.3***b* of the proximal interphalangeal joint coupler **274.1.1** have a wedge configuration that forms the sixth limiting interface regions **274.1.1.1.1.1***a*, **274.1.1.1.1.1***b*. Said sixth limiting interface regions **274.1.1.1.1.1***a* and **274.1.1.1.1.1***b* are positioned adjacent to the medial drive link **274.2** and help ensure that the medial assembly **274** does not over-rotate or curl backward. Finally, the combination of the first and second partially-triangular frame members **274.1.1.1***a*, **274.1.1.1***b* and the medial link bridge **274.1.1.3** form a U-shaped extent, which said first medial link or interphalangeal joint recess **274.1.1.2** is formed therebetween. Said interphalangeal joint recess **274.1.1.2** is designed to receive an extent of the proximal link assembly **254**, and specifically an second end of the proximal drive link **254.4.3**. The interlocking, stacking, and/or overlying nature of these connections will be discussed in greater detail below.

The medial link neck or biasing neck **274.1.2** extends forward from the first and second partially-triangular frame members **274.1.1.1***a*, **274.1.1.1***b* and couples the first and second partially-triangular frame members **274.1.1.1***a*, **274.1.1.1***b* to a medial link extension **274.1.3**. The medial link extension **274.1.3** is configured to be coupled to the medial housing assembly **272** and provides a majority of the structural body of said main medial link **274.1**. The medial link extension **274.1.3** includes: (i) a medial link frame member **274.1.3.1**, (ii) a medial link sloped member **274.1.3.2**, (iii) a housing mounting projections **274.1.3.4**, and (iv) medial drive link projections **274.1.3.5***a*, **274.1.3.5***b*. The combination of the frame members **274.1.3.1**, sloped member **274.1.3.2**, and frontal member **274.1.3.3** form a medial link recess or truncated rectangular-shaped recess **274.1.3.6** in the middle of the medial link extension **274.1.3**. This medial link recess or truncated rectangular-shaped recess **274.1.3.6** is configured to receive an extent of the medial drive link **274.2** and allow sufficient clearance for the movement of the medial drive link **274.2** relative to the medial link extension **274.1.3**. Meanwhile, the housing mounting projections **274.1.3.4** are positioned on the uppermost point of the medial link frame member

274.1.3.1 and are configured to couple both the medial jacket and medial casing assemblies 272.1, 272.2 to the main medial link 274.1.

The medial drive link projections 274.1.3.5*a*, 274.1.3.5*b* extend from the sides of the medial link extension 274.1.3 and are configured to be positioned within the distal housing assembly 282. Like the fifth pivot point P_5, the sixth pivot point P_6 is semi-fixed because: (i) unlike the first pivot point P_1, it moves when the medial assembly 270 moves, and (ii) unlike the second pivot point P_2 or the third pivot point P_3, it cannot move relative to the medial assembly 270. Thus, the movement of the sixth pivot point P_6 is between the movement capabilities of the fixed and non-fixed pivot points and therefore is semi-fixed. Said sixth pivot point P_6 needs to be fixed relative to the medial assembly 270 to enable the movement of the medial drive link 274.2 to force the distal assembly 280 around a pivot point P_6 or distal axis A_D. Said distal axis A_D is parallel with the medical axis A_M and the worm wheel axis A_{WW}, but is perpendicular (in one direction) to both the motor shaft axis Aus and the worm drive gear axis A_{WDG}.

The medial drive link, or fifth bar 274.2 is best shown in FIGS. 26-31 and 46-53. The medial drive link 274.2 includes: (i) an angled segment 274.2.2 forward from a rearmost point of the medial drive link 274.2 to line M_3, (iii) lateral segment 274.2.3 extending from line M_3 to M_4, and (iv) the elongated segment 274.2.4 extending forward from line M_4. This complex geometry can be best seen in FIG. 53. The angled segment 274.2.2 of the medial drive link 274.2 includes main proximal link opening 274.2.2.1 that are configured to receive first and second medial link projections 254.1.6*a*, 254.1.6*b* to form the fourth pivot point P_4. In other words, the medial drive link 274.2 is pivotably connected to the medial link 274.1: (i) on a first side of a sagittal plane extending through the finger assembly via opening 274.2.2.1 and a projection 254.1.6*a*, and (ii) on a second side of a sagittal plane extending through the finger assembly via opening 274.2.2.1 and a projection 254.1.6*b*. Like the fifth pivot point P_5 and the sixth pivot point P_6, the fourth pivot point P_4 is semi-fixed because: (i) unlike the first pivot point P_1, it moves when the proximal assembly 250 moves, and (ii) unlike the second pivot point P_2 or the third pivot point P_3, it cannot move relative to the proximal assembly 250. Thus, the movement of the fourth pivot point P_4 is between the movement capabilities of the fixed and non-fixed pivot points and therefore is semi-fixed. Said fourth pivot point P_4 needs to be fixed relative to the proximal assembly 250 to enable the medial drive link 274.2 to rotate around the fourth pivot point P_4.

The main/drive link couplers or sixth bar 274.3*a*, 274.3*b* is secured within an extent of the distal housing assembly 282 and is configured to couple the main medial link 274.1 and the medial drive link 274.2 to one another, while being positioned within an extent of the distal assembly 280. The main/drive link couplers 274.3*a*, 274.3*b*.3 includes: (i) a main body 274.3.1 with a first aperture or upper coupler aperture 274.3.1.1, and a second aperture or lower coupler aperture 274.3.1.2, and (ii) first and second flanges 274.3.2*a*, 274.3.2*b*. While the flanges 274.3.2*a*, 274.3.2*b* surround the apertures 274.3.1.1, 274.3.1.2: (i) the apertures 274.3.1.1 are configured to receive the medial drive link projections 274.1.3.5*a*, 274.1.3.5*b*, and (ii) the apertures 274.3.1.2 are configured to receive the left and right portion couplers 274.2.5*a*, 274.2.5*b*. It should be understood that the main/drive link couplers 274.3*a*, 274.3*b* may be eliminated in certain embodiments, and instead, the main medial link 274.1 and the medial drive link 274.2 may be coupled to one another differently.

As shown in the Figures, the link assemblies 254, 274, and 284 have interlocking, overlapping, underlying, and/or stacking configuration. This complex configuration helps increase the durability of the finger assembly 22*a*-22*d*. In particular, the worm drive link 254.4.1 includes a forked second end that is designed to receive an extent of the first end of the proximal drive link 254.4.3. Likewise, the main medial link 274.1 also includes a forked rear end that is formed by the first and second partially-triangular frame members 274.1.1.1*a*, 274.1.1.1*b* that is designed to receive a second end of the proximal drive link 254.4.3. As such, both ends of the proximal drive link 254.4.3 is centered within a fork-like recess formed in the adjacent links. The links also are designed to position the primary proximal link 254.1 outside of the worm wheel 236 and an extent of the medial primary 274.1. This not only provides the finger assembly 22*a*-22*d* with rigidity, but it also allows the finger assembly 22*a*-22*d* to narrow as it extends from the base of the finger assembly 22*a*-22*d* to the tip of the said finger assembly 22*a*-22*d*. This configuration also allows for the second end of the proximal drive link 254.4.3 to be positioned within the main medial link 274.1, which is also positioned within the primary proximal link 254.1. The medial drive link 274.2 not only includes an extent that is positioned outside of the main medial link 274.1, but it also includes an extent that is positioned within the main medial link 274.1. And finally, an extent of the distal assembly 280 is positioned outside of the main medial link 274.1. In sum, each of the links is supported on two sides, and therefore, said links are not solely supported on a single side. Nevertheless, in an alternative embodiment, the links could be supported on a single side.

Based on the above disclosure, as best shown in FIG. 57, and when the finger assembly 22*a*-22*d* is in the closed, curled, or in the inwardly rotated state, the proximal link recess 254.1.7 may be designed to receive a substantial extent of the proximal link assembly 254. Additionally, the medial link recess or truncated rectangular-shaped recess 274.1.3.6 may be designed to receive differing extents of the medial drive link 274.2 based on the position of the finger assembly 22*a*-22*d*. Further, the interphalangeal joint recesses 274.1.1.2 may be designed to receive the second end of the proximal link assembly 254. In some aspects, the configuration of these recesses may allow for more compact folding of the finger assembly when in a closed state. The design may enable smoother transitions between open and closed states, potentially enhancing the overall dexterity and range of motion of the finger assembly. In some cases, the specific dimensions and shapes of these recesses may be optimized for particular grasping tasks or object sizes.

e. Distal Assembly 280

The distal assembly 280 is positioned forward of the medial assembly 270 and is the third portion of the finger assembly 22*a*-22*d* configured to move relative to the palm 610. The distal assembly 280 includes: (i) a distal housing assembly 282, and (ii) a distal link assembly 284.

i. Distal Housing Assembly 282

As shown in FIGS. 23A-24B, 43-45, and 57, the distal housing assembly 282 is designed to substantially surround a majority of the other components of the distal assembly 280. To achieve this, the distal housing assembly 282 forms an internal distal recess 282.18 and specifically includes: (i) a distal jacket assembly 282.1 with a top member 282.1.1 and a bottom member 282.1.2, and (ii) a distal bottom casing

assembly **282.2**. While the bottom member **282.1.2** is in direct contact with and underlies the distal bottom casing assembly **282.2**, the finger assembly **22***a*-**22***d* lacks a distal top casing assembly that is in direct contact with the top member **282.1.1**. This design is advantageous because the distal bottom casing assembly **282.2** provides the bottom member **282.1.2** with additional rigidity, which enables said bottom member **282.1.2** 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 **282.1.1** does not need to include a softer, easier-to-form, and potentially less durable material because said top member **282.1.1** is not designed to come into regular contact with objects. Additionally, even if the materials of the distal bottom casing assembly **282.2** and the bottom member **282.1.2** are the same, it may be desirable to form these components as two separate components to facilitate replicability without exposing an inner extent of the finger assembly **22***a*-**22***d*. Another way of describing this beneficial configuration includes the fact that the distal jacket assembly **282.1** is configured to provide the primary external shape of the finger assembly **22***a*-**22***d*, while the distal casing assembly **282.2** is configured to protect the distal link assembly **284**. Nevertheless, it should be understood that in an alternative embodiment, the bottom member **282.1.2** and the distal bottom casing assembly **282.2** may be integrally formed as a single structure.

As best shown in FIGS. **23**A-**24**B, the top member **282.1.1** of the distal jacket assembly **282.1** includes an exterior surface back with a curvilinear extent in a first direction (namely, across the width of the finger assembly **22***a*-**22***d*), and the bottom member **282.1.2** of the distal jacket assembly **282.1** includes an exterior palm surface that is curvilinear extent in the first direction (namely, across the width of the finger assembly **22***a*-**22***d*) and a second direction (namely, across the length of the finger assembly **22***a*-**22***d*). The curvilinear extent in the first direction helps ensure that the finger assembly **22***a*-**22***d* 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 **282.1.1** of the distal jacket assembly **282.1** includes a rearwardly extending distal tongue **282.20**. The distal tongue **282.20** has an arched shape with a curvilinear rear surface **282.20.2**, wherein the width of said distal tongue **282.20** is reduced from a first or front width to a second or rear width. As such, the distal tongue **282.20** includes curvilinear extents in at least two directions. As discussed above, the distal tongue **282.20** is designed to be positioned within or adjacent to medial housing assembly **272** and configured to minimize the gap G_3 that is formed between assemblies **270** and **280**. It should be understood that in an alternative embodiment, the distal tongue **282.20** may be omitted.

As discussed above, the distal housing assembly **282** 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 know material used in robot systems. In some aspects, the distal housing assembly **282** may include additional components or layers (e.g., between three and an nth). The distal housing assembly **282** may incorporate specialized materials or coatings to enhance grip, durability, or sensor capabilities. For example, a layer of electroactive polymer may be included to enable shape-changing properties, or a layer of piezoelectric material may be added for tactile sensing. In some implementations, the layers may be interchangeable to allow customization for different tasks or environments. The assembly may also feature self-healing materials in certain layers to extend the lifespan of high-wear areas. It should be also be understood in alternative embodiments that the distal jacket assembly **282.1** and the distal casing assembly **282.2** may be combined into a single component and/or additional exterior members may be added to the end effector **10**/finger assembly **22***a*-**22***d*.

ii. Distal Link Assembly **284**

As shown in FIGS. **54**-**55**, the distal link assembly **284** may include a primary or main distal link or seventh bar **284.1** that helps form a third joint or distal interphalangeal joint **284.1.1**, and may include a tip assembly **284.1.2**. The third joint or distal interphalangeal joint **284.1.1** may be formed between the medial assembly **270** and the distal assembly **280**. The distal link assembly **284** may be involved in fewer movements of the finger assembly **22***a*-**22***d* compared to the number of movements involving the proximal and medial assemblies **250**, **270**. As best shown in FIGS. **54**-**55**, the third joint **284.1.1** may include first and second coupler recesses **284.1.1.1***a*, **284.1.1.1***b*, while the tip assembly **284.1.2** may have: (i) a tip body **284.1.2.1** with first and second portions **284.1.2.1.1***a*, **284.1.2.1.1***b*, and internal projections **284.1.2.1.2**, and (ii) tip coupler **284.1.2.2** for coupling the first and second portions **284.1.2.1.1***a*, **284.1.2.1.1***b* of the tip body **284.1.2.1** to one another. In some aspects, the tip assembly **284.1.2** may incorporate sensors to provide tactile feedback. The internal projections **284.1.2.1.2** may be designed to enhance grip strength or manipulate small objects. The tip coupler **284.1.2.2** may allow for interchangeable tip designs to adapt to different tasks.

D. Kinematics of the End Effector

As best shown in FIGS. **12** and **15**, 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 interphalangeals (DIP) joint **25***a*-**25***e*, and (iv) at least one carpometacarpal (CMC) joint **26***a*, **26***b*. As shown in these Figures, each finger assembly **22***a*-**22***d* includes a MCP joint **23***a*-**23***d* or a first joint (IFJ**1**, MFJ**1**, RFJ**1**, LFJ**1**), (ii) a PIP joint **24***a*-**24***d* or a second joint (IFJ**2**, MFJ**2**, RFJ**2**, LFJ**2**), and (iii) a DIP joint **25***a*-**25***d* or a third joint (IFJ**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**.

The MCP joints **23***a*-**23***d* of each finger assembly **22***a*-**22***d* is defined between a lower extent of the motor assembly **210** and the First Link Plane L_1 (i.e., the plane that extends from the first pivot point P_1 to the fifth pivot point P_5) and has a range of motion that is between 70° and 135°, preferably between 80° and 120°, and most preferably between 75° and 110°. To provide the range of motion associated with the MCP joint **23***a*-**23***d*, the internal angles (e.g., A**88**, A**99**, A**121**) ranges from 223° in the first configuration C_1 to 76° in configurations 4-7 C_4-C_7. It should be understood that the internal angle that extends from the lower extent of the motor assembly **210** to the contact pad/internal surface of the proximal assembly **250** ranges from 226° to 79°. As such, the internal angle has a range of motion that is between 70° and 110° and most preferably between 85° and 95°.

PIP joint **24***a*-**24***d* is defined between the First Link Plane L_1 and the Second Link Plane L_2 (i.e., the plane that extends from the first pivot point P_5 to the sixth pivot point P_6) and has a range of motion that is between 65° and 140°, preferably between 75° and 120°, and most preferably between 85° and 105°. To provide the range of motion associated with the PIP joint, the internal angle (e.g., A**89**, A**111**, A**122**) ranges from 210° in configurations 1-4 C_1-C_4 to 74° in the seventh configuration C_7. It should be understood that the contact pad/internal surface of the proximal assembly **250** to the contact pad/internal surface of the medial assembly **270** ranges from 226° to 72°. As such, the internal angle has a range of motion that is between 70° and 110° and most preferably between 85° and 95°.

The DIP joint **25***a*-**25***d* is defined between the Second Link Plane L_2 and the Third Link Plane L_3 (i.e., the plane that extends from the sixth pivot point P_6 to the forward most point of the finger FP) and has a range of motion that is between 30° and 90°, preferably between 50° and 70°, and most preferably between 55° and 75°. To provide the range of motion associated with the DIP joint **25***a*-**25***d*, the internal angles (e.g., A**90**, A**101**, A**123**) ranges from 206° in configurations 1-4 C_1-C_4 to 104° in the seventh configuration C_7. It should be understood that the contact pad/internal surface of the medial assembly **270** to the contact pad/internal surface of the distal assembly **280** ranges from 248° to 95°. As such, the internal angle has a range of motion that is between 70° and 110° and most preferably between 85° and 95°. In summary: (i) the DIP joint **25***a*-**25***d* is configured to have the largest range of motion, while the PIP joint **24***a*-**24***d* has the smallest range of motion, (ii) the smallest internal angle is associated with the PIP joint **24***a*-**24***d*, while the largest internal angle is associated with the DIP joint **25***a*-**25***d*. Based on the above summary, the MCP joint **23***a*-**23***d*: (i) has a range of motion that is between the PIP joint **24***a*-**24***d* and the DIP joint **25***a*-**25***d*, and (ii) does not have the smallest or largest internal angle.

As described above, the PIP joint **24***a*-**24***d* and DIP joint **25***a*-**25***d* are linked together in order to allow the finger assembly **20** to be underactuated. In operation, once the independent proximal assembly **250** comes into contact with a resistance point/surface (i.e., an object or the first limiting interface region **254**.**1**.**1**.**1**.**2**.**1** contacts an extent of the frame **232**.**1**), the dependent medial and distal assemblies **270**, **280** start moving or curling inward towards the palm **602**. However, the differences between the internal angles that are formed between: (i) the First Link Plane L_1 and the Second Link Plane L_2, and (ii) the Second Link Plane L_2 and the Third Link Plane L_3 are substantially equal. In particular, said differences between the above described internal angles are less than 30°, preferably less than 20°, and most preferably less than 15°. Limiting the difference between the internal angles that are formed at the PIP joint **24***a*-**24***d* and DIP joint **25***a*-**25***d* helps ensure that the distal assembly **280** curls inward at a rate (i.e., Dcurl rate) that is approximately equal to a curl rate (i.e., Mcurl rate) of the medial assembly **270**. Without having the Mcurl rate approximately (e.g., +/−20%) match the Deurl rate, the finger assembly **20** would either: (i) fully curl the medial assembly **270** well before the distal assembly **280** was fully curled, or (ii) fully curl the distal assembly **280** well before the medial assembly is fully curled. Either one of these scenarios is not beneficial because it will limit the grasping ability of the end effector **10**. Nevertheless, it should be understood that: (i) when the internal angle formed at the PIP joint **24***a*-**24***d* joint is between approximately 180° to 120°, the internal angle formed at the DIP joint **25***a*-**25***d* is less than the angle formed at the PIP joint **24***a*-**24***d*, and (ii) when the internal angle formed at the PIP joint **24***a*-**24***d* joint is between approximately 120° to 90°, the internal angle formed at the DIP joint **25***a*-**25***d* is greater than the angle formed at the PIP joint **24***a*-**24***d*. Additionally, other alterations or modifications to the movement of the PIP joint **24***a*-**24***d*, DIP joint **25***a*-**25***d*, curl rates, and/or ratios between the angles formed between said joints **24***a*-**24***d*, **25***a*-**25***d* is contemplated by this disclosure.

In addition to the above disclosed ratios and angles, the disclosed end effector **10** has the following upper and lower angular limits: (i) extending between the front edge of the knuckle assembly **230** and the rear surface of the proximal drive link **254**.**4**.**3** is between 0° and 153°, as such the range of motion is 153°, (ii) extending between the front edge of the knuckle assembly **230** and the top surface of the proximal assembly **250** is between 65° and 205°, as such the range of motion is 140°, (iii) extending between the top surface of the knuckle assembly **230** and the top surface of the proximal assembly **250** is between 5° and 98°, as such the range of motion is 93°, (iv) extending between the top surface of the proximal assembly **250** and the top surface of the medial assembly **270** is between 150° and 334°, as such the range of motion is 184°, (v) extending between the top surface of the medial assembly **270** and top surface of the distal assembly **280** and is between 143° and 320°, as such the range of motion is 177°, (vi) extending between the contact pad of the distal assembly **280** and the contact pad of the medial assembly **270** is between 95° and 248°, as such the range of motion is 154°, (vii) extending between the contact pad of the medial assembly **270** and the contact pad of the proximal assembly **250** is between 72° and 216°, as such the range of motion is 144°, (vii) extending between the contact pad of the proximal assembly **250** and a bottom extent of the motor **212** is between 79° and 208°, as such the range of motion is 129°. It should be understood that the above values are approximations and other similar values are contemplated by this disclosure. Also, other ratios, angles, and data can be derived from the figures and the below table of values.

a. Scenario 1: FIGS. **34**-**58**

The finger assembly **22***a*-**22***d* moves from the first configuration C_1 until it reaches the seventh configuration C_7. During the movement between these configurations, the finger assembly **22***a*-**22***d* curls around an object located at a first location L_{O1}, but does not come into contact with said object. In other words, the finger assembly **22***a*-**22***d* is free to move, without being stopped or interrupted by making contact with said object from: (i) the open, uncurled, or neutral state, to (ii) a point where the proximal, medial and distal assemblies are at a maximum flexion position or the finger assembly is in a fully curled state. FIG. **34** is a schematic that shows the movement of the fifth pivot point (i.e., from the second location L_{2P5} to the fifth location L_{5P5}), the sixth pivot point (i.e., from the sixth location L_{6P6} to the twelfth location L_{12P6}), the end point of the finger assembly **20** (i.e., from the thirteenth location L_{13PE1} to the nineteenth location L_{19P5}), 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 finger assembly **20** from the first configuration C_1 to the seventh configuration C_7. As shown in this schematic, movement of said finger assembly **20** from the first configuration to the seventh configuration causes the fifth pivot point to move along a first curvilinear path CU_1, the sixth pivot point to move along a second curvilinear path CU_2, and the end point of the finger assembly **20** to move along a third curvilinear path CU_3, wherein 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 finger assembly moves to the fifth configuration C_5. Further, it can be seen that the First Link Plane L_1 does not move after the finger assembly has reached the fourth configuration C_4.

As will be discussed in greater detail below, FIG. **61** is a schematic that shows the movement of each of the seven pivot points that are caused by the movement of the finger assembly **20** from the first configuration to the seventh configuration. Each pivot point is labeled X·Y, wherein X is the configuration of the finger assembly and Y is the number of the pivot point. For example, 4.2 indicates the location of the second pivot point when the finger assembly is in the fourth configuration. As shown in this schematic, movement of said finger assembly **20** from the first configuration C_1 to the seventh configuration C_7 causes the third and fourth pivot points to rotate around the fifth pivot point, the seventh pivot point to rotate around the sixth pivot point, all pivot points to rotate around the first pivot point, and other information that is discernable by one of skill in the art based on their review of the figures in this application, including FIG. **61**.

FIGS. **1-33** show the finger assemblies **22***a*-**22***d* in the first configuration C_1, wherein: (i) the proximal assembly **250** is offset from being parallel with the motor **112** by less than 15° (preferably less than 10°), and (ii) the proximal, medial, and distal assemblies **250**, **270**, **280** are substantially aligned in a first state. In this first configuration C_1, the finger assemblies **22***a*-**22***d* are in the best position to start or begin to start the procedure for grasping an item due to the fact they are in hyperextension or near hyperextension.

FIGS. **32-37** show the finger assemblies **22***a*-**22***d* in a second configuration C_2, wherein: (i) the proximal assembly **250** is offset from being parallel with the motor **112** by between 17° and 26°, and (ii) the proximal, medial, and distal assemblies **250**, **270**, **280** are still in the first state. In comparing FIGS. **1-33** and **35-37**, the movement from the first configuration C_1 to the second configuration C_2 has caused the proximal assembly **250** to revolve around the first pivot point by approximately 10° to 15°.

FIGS. **38-40** show the finger assemblies **22***a*-**22***d* in a third configuration C_3, wherein: (i) the proximal assembly **250** is offset from being parallel with the motor **112** by between 41° and 62°, and (ii) the proximal, medial, and distal assemblies **250**, **270**, **280** are still in the first state. In comparing FIGS. **35-37** and **38-40**, the movement from the second configuration C_2 to the third configuration C_3 has caused the proximal assembly **250** to revolve around the first pivot point by approximately 25° to 35°.

FIGS. **41-43** and **53-54** show the finger assemblies **22***a*-**22***d* in a fourth configuration C_4, wherein: (i) the proximal assembly **250** is offset from being parallel with the motor **112** by between 65° and 98°, and (ii) the proximal, medial, and distal assemblies **250**, **270**, **280** are still in the first state. As discussed below, the proximal assembly **250** is at maximum flexion position in configurations four through seven C_4-C_7. In comparing FIGS. **38-40** and **41-43**, **53-54**, the movement from the third configuration to the fourth configuration has caused the proximal assembly **250** to revolve around the first pivot point by approximately 25° to 35°. At this fourth configuration C_4, the first limiting interface region **254.1.1.1.2.1** of the primary proximal link **254.1** has come into contact with the frame assembly **232.1** of the knuckle assembly **230**, which in turn has limited the revolution of the proximal assembly **250** around said first pivot point. Because of the interaction between an extent (i.e., first limiting interface region **254.1.1.1.2.1**) of the proximal assembly **250** and the resistance surface/point (i.e., frame assembly **232.1**), movement beyond the fourth configuration C_4 will: (i) not allow the proximal assembly **250** to curl or revolve inward, and (ii) cause engagement between the primary proximal link **254.1** and the worm bearings **256.2** in order to allow the finger assembly **22***a*-**22***d* to continue bending or curling towards the palm **602**. Without utilization of the worm bearings **256.2**, the finger assembly **22***a*-**22***d* could not continue bending or curling towards the palm **602** (i.e., the finger assembly **22***a*-**22***d* would be locked out). It should be understood that in other embodiments, the frame assembly **232.1** may be modified in order to allow the proximal assembly **250** to: (i) further revolve around said first pivot point by another 10° to 40°, or (ii) revolve a smaller amount around said first pivot point by another 10° to 40°.

As discussed above, the movement from the fourth configuration C_4 to the fifth configuration C_5 causes: (i) the proximal housing assembly **252** to remain frozen in its position, and (ii) the medial and distal assemblies **270**, **280** to start moving around additional pivot points (i.e., points **5** and **6**). It should be understood from reviewing the Figures of this Application, that while the proximal housing assembly **252** may be frozen in its position due to the fact that said housing assembly **252** came into contact with the resistant point/surface, other components (e.g., biasing assembly **254.2** and the proximal drive link assembly **254.4**) of the proximal assembly **250** can continue to move or are not frozen. Without permitting the movement of these other components, the motor **212** could not continue driving the closure of the finger assembly **22***a*-**22***d* once the proximal assembly **250** comes into contact with a resistant surface/point. It should be understood that additional or fewer components of the finger assemblies **22***a*-**22***d* may not be permitted to move once said assemblies **22***a*-**22***d* to the fourth configuration.

FIGS. **44-46** and **55-56** show the finger assemblies **22***a*-**22***d* in a fifth configuration C_5, wherein: (i) the proximal assembly **250** is in contact with a resistance point/surface, and (ii) the proximal, medial, and distal assemblies **250**, **270**, **280** are in a second state, wherein none of the assemblies **250**, **270**, **280** are substantially aligned. In said fifth configuration C_5, the proximal assembly is at a maximum flexion position and the medial and distal assemblies are in a partially curled state. In comparing FIGS. **41-43**, **53-54** and **44-46**, **55-56**, the movement from the fourth configuration to the fifth configuration has caused: (i) the medial assembly **270** to revolve around the fifth pivot point by approximately 15° to 30°, and (ii) the distal assembly **280** to revolve around the sixth pivot point by approximately 10° to 25°. Movement from the fourth configuration C_4 to the fifth configuration illustrates that the medial assembly **270** may revolve around the fifth pivot point faster than the distal assembly revolves around the sixth pivot point.

FIGS. **47-49** show the finger assemblies **22***a*-**22***d* in a sixth configuration C_6, wherein: (i) the proximal assembly **250** is in contact with a resistance point/surface, and (ii) the proximal, medial, and distal assemblies **250**, **270**, **280** are in a second state, wherein none of the assemblies **250**, **270**, **280** are substantially aligned. In said sixth configuration C_6, the proximal assembly is at maximum flexion position and the medial and distal assemblies are in a partially curled state. In comparing FIGS. **44-46**, **55-56** and **47-49**, the movement from the fifth configuration to the sixth configuration has caused: (i) the medial assembly **270** to revolve around the

fifth pivot point by approximately 30° to 50°, and (ii) the distal assembly **280** to revolve around the sixth pivot point by approximately 20° to 35°. Movement from the fifth configuration C_5 to the sixth configuration C_6 illustrates that medial assembly **270** may revolve around the fifth pivot point faster than the distal assembly revolves around the sixth pivot point.

FIGS. **50-52** and **57-58** show the finger assemblies **22***a*-**22***d* in a seventh configuration C_7, wherein: (i) the proximal assembly **250** is in contact with a resistance point/surface, (ii) the proximal, medial, and distal assemblies **250**, **270**, **280** are in a second state, wherein none of the assemblies **250**, **270**, **280** are substantially aligned, and (iii) the proximal, medial and distal assemblies are at maximum flexion position or the finger assembly is in a fully curled state. In comparing FIGS. **77-80** and FIGS. **81-83**B, the movement from the sixth configuration to the seventh configuration has caused: (i) the medial assembly **270** to revolve around the fifth pivot point by approximately 16° to 24°, and (ii) the distal assembly **280** to revolve around the sixth pivot point by approximately 14° to 22°. Movement from the sixth configuration C_6 to the seventh configuration C_7 illustrates that the medial assembly **270** revolves around the fifth pivot point faster than the distal assembly revolves around the sixth pivot point. Overall, the quicker revolution of the medial assembly **270** around the fifth pivot point in comparison to the revolution of the distal assembly **280** around the sixth pivot point is desirable because the range of motion of the PIP joint **24***a*-**24***d* is larger than the range of motion of the DIP joint **25***a*-**25***d*.

In summary and to enable the finger assemblies **22***a*-**22***d* to move in the above described fashion from the first configuration C_1 or open, uncurled, or neutral state until it reaches the seventh configuration C_7 or fully curled state, the internal components of the motor **212** are configured to rotate the motor shaft **212.2** around the motor shaft axis A_{MS}. The rotation of the motor shaft **212.2** around the motor shaft axis A_{MS} causes the worm drive gear **216** to rotate about a worm drive gear axis A_{WDG}. The rotation of the worm drive gear **216** about a worm drive gear axis A_{WDG} causes the worm wheel **236** to rotate above the worm wheel axis A_{WW} or the first pivot point P_1. The rotation of the worm wheel **236** causes the worm drive link **254.4.1** to also rotate about the worm wheel axis A_{WW} or the first pivot point P_1. Said rotation of the worm drive link **254.4.1** causes rotation of: (i) the main proximal link **254.1**, and (ii) proximal drive link **254.4.3**, and (iii) a majority of the components of said finger assembly **22***a*-**22***d*. The movement of the proximal drive link **254.4.3** causes: (i) the main medial link **274.1** to rotate about the pivot point P_5 or medial axis A_M, (ii) the distal housing **282** to rotate about the pivot point P_6 or distal axis A_D. The rotation of the main proximal link **254.1** and the main medial link **274.1** causes the proximal housing assembly **252** and medial housing assembly **272** to rotate, respectively. It should be understood that the main proximal link **254.1** will continue rotating in response to the rotation of the worm wheel **236** until it reaches a contact or resistance point. Once it makes contact with said resistance point, the main proximal link **254.1** will stop rotating and the bias member **254.2.1** will start moving or deforming from a first or collapsed position with a length of LT_1 to a second or extended position with a length LT_2.

b. Scenario 2: FIGS. **62-70**

The finger assembly **22***a*-**22***d* moves from the first configuration C_1 to configurations eight through ten C_8-C_{10}. During the movement, the finger assembly **22***a*-**22***d* starts to curl, but the proximal assembly **250** come into contact with an object before the proximal assembly **250** can be fully curled inward (i.e., allow contact between the first limiting interface region **254.1.1.1.2** and the frame **232.1**). In other words, by positioning the object in a second location the finger assembly **22***a*-**22***d* cannot maximize the range of movement of each joint contained in said finger assembly **22***a*-**22***d*. FIGS. **62-64** show the finger assemblies **22***a*-**22***d* in an eighth configuration, wherein: (i) the proximal assembly **250** is in contact with a resistance point/surface (i.e., the object), and (ii) the proximal, medial, and distal assemblies **250**, **270**, **280** are in a second state, wherein none of the assemblies **250**, **270**, **280** are substantially aligned. In these Figures: (i) proximal assembly **250** revolved about the first pivot point by approximately 25° to 45°, (ii) the medial assembly **270** to revolve around the fifth pivot point by approximately 15° to 30°, and (ii) the distal assembly **280** to revolve around the sixth pivot point by approximately 10° to 25°. In the eighth and ninth configurations C_8-C_{10} the medial and distal assemblies are in partially curled states, while the medial and distal assemblies are at maximum flexion position or the finger assembly is in a fully curled state.

For sake of brevity, movement from configuration eight to nine and from configuration nine to ten will not be discussed due to the fact that these movements are similar, if not the same as, the movements that the finger assembly **22***a*-**22***d* undergoes when moving from the fourth configuration to the seventh configuration C_4-C_7. However, it should be noted that the ninth configuration is not the same as any of the first through the seventh configurations C_1-C_7 because the rotation of the components is slightly different. In particular, the positional relationships between: (i) the medial and distal assemblies **270**, **280**: (a) shown in FIGS. **62-64** (e.g., configuration eight) are positioned between the relationships discussed in connection with fifth and sixth configurations, and (b) shown in FIGS. **65-67** (i.e., configuration nine) are positioned between the relationships discussed in connection with sixth and seventh configurations, and (ii) the motor **112** and the proximal assembly **250** of the eight-tenth configurations are positioned between the relationships discussed in connection with second and third configurations.

c. Scenario 3: FIGS. **71-73**

The finger assembly **22***a*-**22***d* moves from the first configuration C_1 to the eleventh configuration C_{11}. During the movement, the finger assembly **22***a*-**22***d* starts to curl, but the proximal assembly **250** comes into contact with a first object and then the medial assembly **270** come into contact with a second object. Contact between the first and second objects and the assemblies **250**, **270** prevents the finger assembly **22***a*-**22***d* being fully curled inward. In other words, by positioning the first and second objects in the disclosed locations, the finger assembly **22***a*-**22***d* cannot maximize the range of movement of each joint contained in said finger assembly **22***a*-**22***d*. In fact, said contact between the second object and the medial assembly **270** locks the finger **22***a*-**22***d* in position. Stated another way, said contact prevents the finger assembly **22***a*-**22***d* from curling around the object. If this scenario happens while the end effector **10** is in use, said system will typically move the objects due to compliance in the overall environment or the robot will try to reposition the finger assembly **22***a*-**22***d* within the environment.

FIGS. **71-73** show the finger assemblies **22***a*-**22***d* in the eleventh configuration C_{11}, wherein: (i) the medial assembly **270** is in contact with a resistance point/surface (i.e., the object), and (ii) the proximal, medial, and distal assemblies **250**, **270**, **280** are in a second state, wherein none of the assemblies **250**, **270**, **280** are substantially aligned. In said eleventh configuration neither the proximal assembly nor

distal assembly are at minimum or maximum flexion position. In these Figures: (i) proximal assembly **250** revolved about the first pivot point by approximately 50° to 75°, (ii) the medial assembly **270** to revolve around the fifth pivot point by approximately 30° to 45°, and (ii) the distal assembly **280** to revolve around the sixth pivot point by approximately 25° to 40°. It should be noted that the eleventh configuration is not the same as any of the first through the tenth configurations C_1-C_{10} because the rotation of the components is slightly different. In particular, the positional relationships between: (i) the medial and distal assemblies **270**, **280** are positioned between the relationships discussed in connection with eighth and ninth configurations, and (ii) the motor **112** and the proximal assembly **250** is positioned between the relationships discussed in connection with second and third configurations.

d. Scenario 4: FIGS. **71-76**

The finger assembly **22***a*-**22***d* moves from the first configuration C_1 to the twelfth configuration C_{12}. During the movement, the finger assembly **22***a*-**22***d* starts to curl, but the distal assembly **280** come into contact with an object before the proximal assembly **250** can be fully curled inward (i.e., allow contact between the first limiting interface region **254**.1.1.1.2 and the frame **232**.1). In other words, by positioning the object in a fourth location the finger assembly **22***a*-**22***d* cannot maximize the range of movement of each joint contained in said finger assembly **22***a*-**22***d*. In fact, said contact between the object and the distal assembly **280** locks the finger **22***a*-**22***d* in position. Stated another way, said contact prevents the finger assembly **22***a*-**22***d* from curling around the object. If this scenario happens while the end effector **10** is in use, said system will typically try to reposition the finger assembly **22***a*-**22***d* and try and grasp the object with a different approach angle.

FIGS. **74-76** show the finger assemblies **22***a*-**22***d* in the twelfth configuration C_{12}, wherein: (i) the distal assembly **280** is in contact with a resistance point/surface (i.e., the object), and (ii) the proximal, medial, and distal assemblies **250**, **270**, **280** are in the first state, wherein all assemblies **250**, **270**, **280** are substantially aligned. In said twelfth configuration C_{12} neither the proximal assembly nor medial assembly are at minimum or maximum flexion position. In these Figures: (i) proximal assembly **250** revolved about the first pivot point by approximately 2° to 10°, (ii) the medial assembly **270** has not revolved around the fifth pivot point, and (ii) the distal assembly **280** has not revolved around the sixth pivot point. It should be noted that the twelfth configuration 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 the motor **112** and the proximal assembly **250** is positioned between the relationships discussed in connection with first and second configurations.

e. Scenario 5: FIGS. **77-79**

The finger assembly **22***a*-**22***d* moves from the first configuration C_1 to the thirteenth configuration C_{13}. During the movement, the finger assembly **22***a*-**22***d* starts to curl, but the medial assembly **270** come into contact with an object before the proximal assembly **250** can be fully curled inward (i.e., allow contact between the first limiting interface region **254**.1.1.1.2 and the frame **232**.1). In other words, by positioning the object in a fifth location the finger assembly **22***a*-**22***d* cannot maximize the range of movement of each joint contained in said finger assembly **22***a*-**22***d*. In fact, said contact between the object and the medial assembly **270** locks the finger **22***a*-**22***d* in position. Stated another way, said contact prevents the finger assembly **22***a*-**22***d* from curling around the object. If this scenario happens while the end effector **10** is in use, said system will typically move the objects due to compliance in the overall environment or the robot will try to reposition the finger assembly **22***a*-**22***d* within the environment.

FIGS. **77-79** show the finger assemblies **22***a*-**22***d* in the thirteenth configuration C_{13}, wherein: (i) the medial assembly **270** is in contact with a resistance point/surface (i.e., the object), and (ii) the proximal, medial, and distal assemblies **250**, **270**, **280** are in the first state, wherein all assemblies **250**, **270**, **280** are substantially aligned. In these Figures: (i) proximal assembly **250** revolved about the first pivot point by approximately 45° to 70°, (ii) the medial assembly **270** has not revolved around the fifth pivot point, and (ii) the distal assembly **280** has not revolved around the sixth pivot point. It should be noted that the thirteenth configuration is not the same as any of the first through the eleventh configurations because the rotation of the components is slightly different. In particular, the positional relationships between the motor **112** and the proximal assembly **250** is positioned between the relationships discussed in connection with third and eleventh configurations.

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

TABLES 3 and 4

C_1	First Configuration	P_1	First Pivot Point-Fixed
C_2	Second Configuration	P_2	Second Pivot Point-Not Fixed
C_3	Third Configuration	P_3	Third Pivot Point-Not Fixed
C_4	Fourth Configuration	P_4	Fourth Pivot Point-Semi-Fixed
C_5	Fifth Configuration	P_5	Fifth Pivot Point-Semi-Fixed
C_6	Sixth Configuration	P_6	Sixth Pivot Point-Semi-Fixed
C_7	Seventh Configuration	P_7	Seventh Pivot Point-Not Fixed

TABLE 5

P_{22a}	Pointer Finger Plane
P_S, P_{22b}	Sagittal Plane or Middle Finger Plane
P_{22c}	Ring Finger Plane
P_{22d}	Small Finger Plane
P_{FM}	Finger Motor Plane
P_{TM}	Thumb Motor Plane
P_{FC}	Finger Coronal Plane
P_{SU}	Surface Plane
S_1	First Section Plane
S_2	Second Section Plane
S_3	Third Section Plane
M_1	First Medial Section Plane
M_2	Second Medial Section Plane

TABLE 6

F_{CP}	Finger Coronal Plane	Extends Between P_1 and LFP
L_1	First Link Plane	Extends Between P_1 and P_5
L_2	Second Link Plane	Extends Between P_5 and P_6
L_3	Third Link Plane	Extends Between P_6 and FP
L_4	Fourth Link Plane	Extends Between P_1 and P_6
L_5	Fifth Link Plane	Extends Between P_1 and P_2
L_6	Sixth Link Plane	Extends Between P_2 and P_6
L_7	Seventh Link Plane	Extends Between P_2 and P_3
L_8	Eighth Link Plane	Extends Between P_3 and P_6
L_9	Ninth Link Plane	Extends Between P_4 and P_6
L_{10}	Tenth Link Plane	Extends Between P_1 and P_3
L_{11}	Eleventh Link Plane	Extends Between P_4 and P_7
L_{12}	Twelfth Link Plane	Extends Between P_3 and P_7
L_{13}	Thirteenth Link Plane	Extends Between P_5 and P_7
L_{14}	Fourteen Link Plane	Extends Between P_6 and P_7

TABLE 7

1.1	First Configuration, First Pivot Point
2.1	Second Configuration, First Pivot Point
3.1	Third Configuration, First Pivot Point
4.1	Fourth Configuration, First Pivot Point
5.1	Fifth Configuration, First Pivot Point
6.1	Sixth Configuration, First Pivot Point
7.1	Seventh Configuration, First Pivot Point
1.2	First Configuration, Second Pivot Point
2.2	Second Configuration, Second Pivot Point
3.2	Third Configuration, Second Pivot Point
4.2	Fourth Configuration, Second Pivot Point
5.2	Fifth Configuration, Second Pivot Point
3.4	Third Configuration, Fourth Pivot Point
4.4	Fourth Configuration, Fourth Pivot Point
5.4	Fifth Configuration, Fourth Pivot Point
6.4	Sixth Configuration, Fourth Pivot Point
7.4	Seventh Configuration, Fourth Pivot Point
1.5	First Configuration, Fifth Pivot Point
2.5	Second Configuration, Fifth Pivot Point
3.5	Third Configuration, Fifth Pivot Point
4.5	Fourth Configuration, Fifth Pivot Point
5.5	Fifth Configuration, Fifth Pivot Point
6.5	Sixth Configuration, Fifth Pivot Point
7.5	Seventh Configuration, Fifth Pivot Point
1.6	First Configuration, Sixth Pivot Point
2.6	Second Configuration, Sixth Pivot Point
3.6	Third Configuration, Sixth Pivot Point
6.2	Sixth Configuration, Second Pivot Point
7.2	Seventh Configuration, Second Pivot Point
1.3	First Configuration, Third Pivot Point
2.3	Second Configuration, Third Pivot Point
3.3	Third Configuration, Third Pivot Point
4.3	Fourth Configuration, Third Pivot Point
5.3	Fifth Configuration, Third Pivot Point
6.3	Sixth Configuration, Third Pivot Point
7.3	Seventh Configuration, Third Pivot Point
1.4	First Configuration, Fourth Pivot Point
2.4	Second Configuration, Fourth Pivot Point
4.6	Fourth Configuration, Sixth Pivot Point
5.6	Fifth Configuration, Sixth Pivot Point
6.6	Sixth Configuration, Sixth Pivot Point
7.6	Seventh Configuration, Sixth Pivot Point
1.7	First Configuration, Seventh Pivot Point
2.7	Second Configuration, Seventh Pivot Point
3.7	Third Configuration, Seventh Pivot Point
4.7	Fourth Configuration, Seventh Pivot Point
5.7	Fifth Configuration, Seventh Pivot Point
6.7	Sixth Configuration, Seventh Pivot Point
7.7	Seventh Configuration, Seventh Pivot Point

TABLE 8

Configuration 1			Configuration 4		
Angle	Lower Bound	Upper Bound	Angle	Lower Bound	Upper Bound
A190	72°	108°	A80	72°	108°
A23	150°	224°	A83'	150°	224°
A193	150°	224°	A84	143°	214°
A194	166°	248°	A85"	166°	248°
A195	144°	216°	A86	144°	216°
A196	137°	205°	A87	79°	118°
A197	149°	223°	A88	77°	115°
A198	140°	210°	A89	140°	210°
A199	165°	247°	A90	165°	247°

Configuration 5			Configuration 7		
Angle	Lower Bound	Upper Bound	Angle	Lower Bound	Upper Bound
A91	78°	117°	A113"	102°	153°
A94"	174°	260°	A116"	222°	332°
A95"	178°	266°	A117"	214°	320°
A96"	130°	196°	A118	95°	142°
A97	120°	180°	A119	72°	108°
A98	79°	118°	A120	79°	118°
A99	77°	115°	A121	76°	115°
A100	122°	183°	A122	74°	111°
A101	120°	180°	A123	84°	125°

F. Industrial Application

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. Additionally, 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.

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 compo-

nent 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.

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.

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 Tec) shaped, rectangular shaped, delta shaped, stacked), (v) diaphragm strain gauges, (vi) biaxial strain gauges, (vii) bidirectional 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.

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) isoelastic (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.

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 Bruel & 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 sen-

sors, 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.

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.

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.

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.

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.

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.

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.

The invention claimed is:

1. A finger assembly for an underactuated end effector for a humanoid robot, the finger assembly comprising:

a motor including a motor shaft with a motor shaft axis, wherein the motor shaft is configured to rotate about the motor shaft axis;

a worm drive gear coupled to the motor shaft, wherein the worm drive gear has a worm drive gear axis that is coaxial with the motor shaft axis, and wherein the worm drive gear is configured for rotation with the motor shaft;

a worm wheel in geared engagement with the worm drive gear, wherein the worm wheel has a worm wheel axis that is arranged perpendicular to the worm drive gear axis, and wherein the worm wheel is configured for rotation about the worm wheel axis in response to rotation of the worm drive gear about the worm drive gear axis;

a worm drive link fixedly connected to the worm wheel and rotatable about the worm wheel axis in response to rotation of the worm wheel about the worm wheel axis;

a proximal drive link pivotably connected to the worm drive link and moveable in response to rotation of the worm drive link; and

a main proximal link having a proximal link pivot axis that is coaxial with the worm wheel axis, wherein the main proximal link is rotatable about the worm wheel axis independently from rotation of the worm wheel.

2. The finger assembly of claim **1**, the finger assembly further comprising:

a medial housing assembly having an internal cavity;

a distal housing assembly including: (i) a rear external surface with a first end positioned adjacent to the medial housing assembly when the finger assembly is in an uncurled state, and (ii) a rearwardly extending distal tongue that has an upper surface that is offset inwardly from the rear external surface; and

wherein, when the finger assembly is in the uncurled state, a majority of the tongue is positioned within the internal cavity of the medial housing assembly.

3. The finger assembly of claim **1**, wherein the finger assembly is designed to be encased within a textile covering.

4. The finger assembly of claim **1**, wherein the finger assembly further comprises a biasing member having both a first extent connected to the main proximal link and a second extent connected to the proximal drive link, and wherein the biasing member is configured to bias the proximal drive link toward an uncurled state.

5. The finger assembly of claim **1**, wherein the finger assembly further includes:

a knuckle assembly;

a proximal assembly pivotably coupled to the knuckle assembly and having a medial end, and wherein said proximal assembly includes the main proximal link and the proximal drive link;

a medial assembly pivotably coupled to the medial end of the proximal assembly and having a distal end;

a distal assembly pivotably coupled to the distal end of the medial assembly;

a metacarpophalangeal joint formed between the knuckle assembly and the proximal assembly;

a proximal finger interphalangeal joint formed between the proximal assembly and the medial assembly; and

a distal finger interphalangeal joint formed between the medial assembly and the distal assembly.

6. The finger assembly of claim **5**, further comprising:

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

a second finger encoder positioned proximate to the proximal finger interphalangeal joint and configured to collect data related to rotation of the proximal finger interphalangeal joint.

7. The finger assembly of claim **5**, wherein:

an extent of the proximal assembly is configured to be directly driven about a metacarpophalangeal joint axis between: (i) a first curling direction by the motor, and (ii) a second uncurling direction by the motor;

an extent of the medial assembly is configured to be indirectly driven about a proximal finger interphalangeal joint axis between: (i) the first curling direction by the motor, and (ii) the second uncurling direction by a biasing member; and

an extent of the distal assembly is configured to be indirectly driven about a distal finger interphalangeal joint axis between: (i) the first curling direction by the motor, and (ii) the second uncurling direction by the motor.

8. The finger assembly of claim **1**, wherein the main proximal link includes a proximal link recess configured to selectively receive both at least a portion of the worm drive link and at least a portion of the proximal drive link.

9. The finger assembly of claim **1**, further comprising a knuckle assembly positioned between the motor and the main proximal link, wherein the knuckle assembly includes a worm wheel interface that allows the main proximal link to rotate about the worm wheel axis independently from rotation of the worm wheel.

10. The finger assembly of claim **9**, wherein the main proximal link includes a limiting interface region configured to contact a portion of the knuckle assembly to limit rotation of the main proximal link.

11. The finger assembly of claim **1**, wherein the main proximal link is configured to stop rotating when contacting a resistance point while the worm wheel continues to rotate.

12. The finger assembly of claim **1**, wherein the finger assembly lacks articulation cables for actuating movement of the finger assembly.

13. The finger assembly of claim **1**, wherein the finger assembly includes a distal link assembly having a tip assembly configured to accept interchangeable tip members.

14. The finger assembly of claim **1**, wherein the finger assembly includes a distal housing assembly having a distal jacket assembly with: a top member made from a first material, and a bottom member made from a second material that is softer than the first material.

15. The finger assembly of claim **1**, further comprising a medial link pivotably connected to a proximal drive link and including a medial link recess configured to receive an extent of a medial drive link; and

the medial drive link pivotably connected to the medial link within the medial link recess by at least one first pivotable coupling located on a first side of a sagittal

plane extending through the finger assembly and at least one second pivotable coupling located on a second side of the sagittal plane.

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

a frame;

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

a motor assembly including: a motor having a motor housing, and a motor shaft rotatable about a motor shaft axis;

a worm drive gear coupled to the motor shaft and configured for rotation about: the motor shaft axis, and a worm drive gear axis, and wherein the motor shaft axis and the worm drive gear axis are arranged coaxially to each other;

a worm wheel in geared engagement with the worm drive gear and configured for rotation about a worm wheel axis in response to rotation of the worm drive gear, and wherein the worm wheel axis is arranged perpendicular to the worm drive gear axis;

a worm drive link having a first end and a second end, and wherein the first end of the worm drive link is fixedly connected to the worm wheel whereby the worm drive link is rotatable about the worm wheel axis in response to rotation of the worm wheel about the worm wheel axis;

a proximal drive link having a first end and a second end, and wherein the first end of the proximal drive link is pivotably connected to the second end of the worm drive link; and

a biasing member configured to bias an extent of the proximal drive link toward a first location, and wherein said extent of the proximal drive link is in the first location when the finger assembly is in an uncurled state.

17. The underactuated end effector of claim **16**, wherein a finger assembly of the plurality of finger assemblies includes: (i) a proximal housing assembly with an internal proximal recess, and (ii) a medial housing assembly with a tongue;

wherein said tongue is positioned within the internal proximal recess of the proximal housing assembly when the finger assembly is in the uncurled state; and

wherein said tongue is not positioned within the internal proximal recess of the proximal housing assembly when the finger assembly is in a curled state.

18. The underactuated end effector of claim **16**, wherein a finger assembly of the plurality of finger assemblies includes further includes:

a proximal assembly that includes the worm drive link, the proximal drive link and a main proximal link;

a knuckle positioned adjacent to the proximal assembly;

a metacarpophalangeal joint located between the knuckle and the proximal assembly; and

a first finger encoder configured to collect data related to rotation of the metacarpophalangeal joint.

19. The underactuated end effector of claim **16**, further comprising a medial link pivotably connected to the proximal drive link and including a medial link recess configured to receive an extent of a medial drive link; and

the medial drive link pivotably connected to the medial link within the medial link recess by at least one first pivotable coupling located on a first side of a sagittal plane extending through the finger assembly and at least one second pivotable coupling located on a second side of the sagittal plane.

20. The underactuated end effector of claim **16**, wherein the end effector includes more than twelve degrees of freedom and less than eight motors.

21. The underactuated end effector of claim **16**, wherein each finger assembly of the plurality of finger assemblies lacks a mechanical cable configured to actuate any component of the finger assembly.

22. The underactuated end effector of claim **16**, wherein each finger assembly of the plurality of finger assemblies are configured to be swappable with every other finger assembly of the plurality of finger assemblies that is removably connected to the frame.

23. The underactuated end effector of claim **16**, wherein in the uncurled state, each finger assembly is angularly offset within a single plane with respect to every other finger assembly of the plurality of finger assemblies.

24. The underactuated end effector of claim **16**, wherein the finger assembly includes a distal housing assembly having a distal jacket assembly with: a top member made from a first material, and a bottom member made from a second material that is softer than the first material.

25. The underactuated end effector of claim **16**, wherein the finger assembly includes a distal link assembly having a tip assembly with interchangeable tip members.

26. The underactuated end effector of claim **16**, further comprising a main proximal link pivotably connected to the worm drive link, and wherein the main proximal link is configured to stop rotating when contacting a resistance point while the worm wheel continues to rotate.

27. The underactuated end effector of claim **16**, wherein the end effector is designed to be encased within a textile covering.

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