

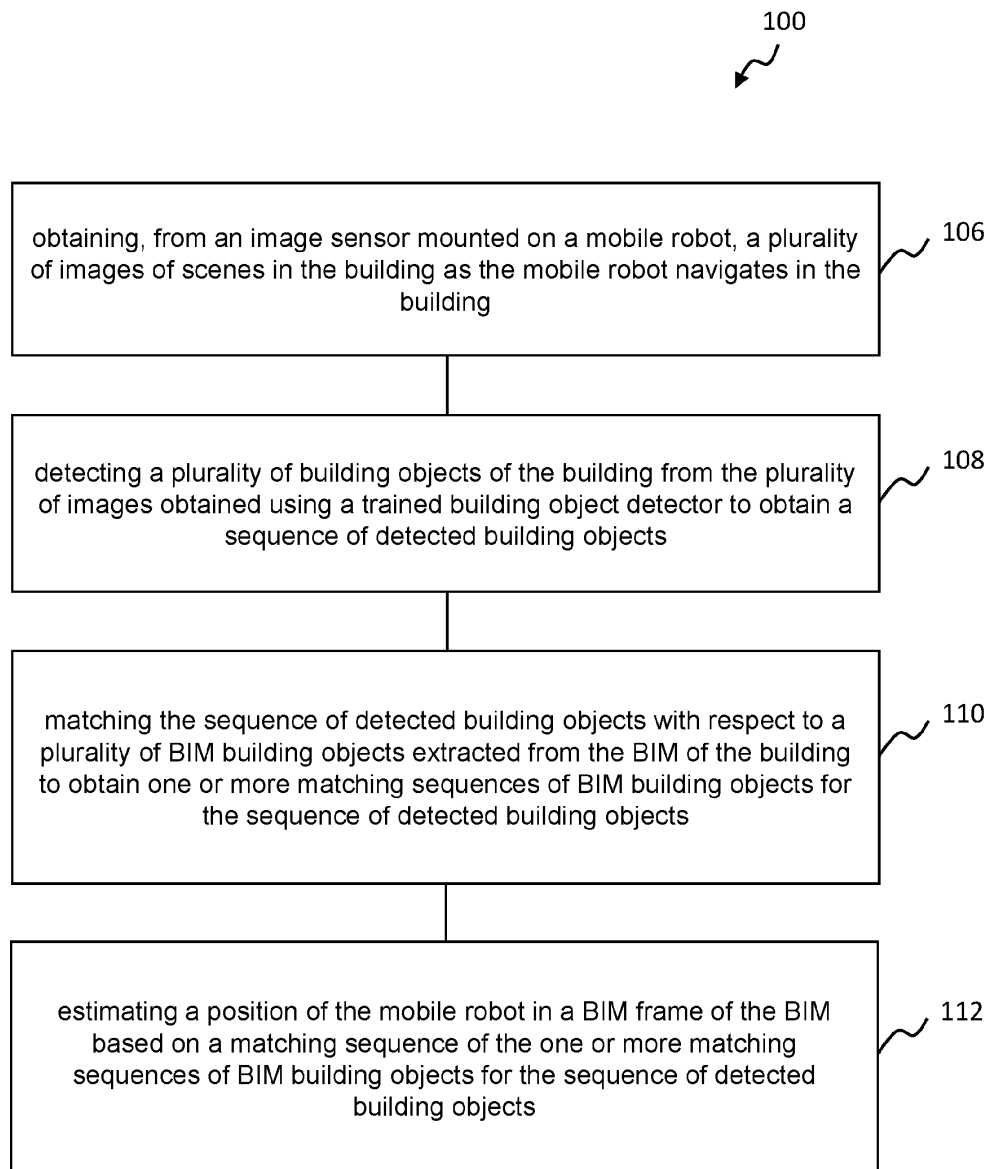


FIG. 1

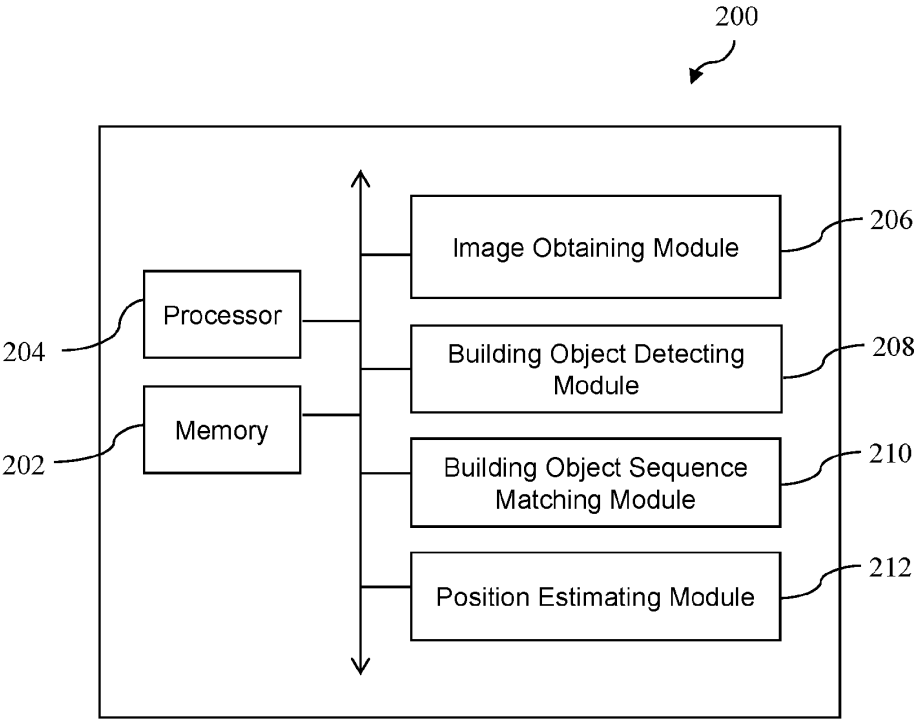


FIG. 2

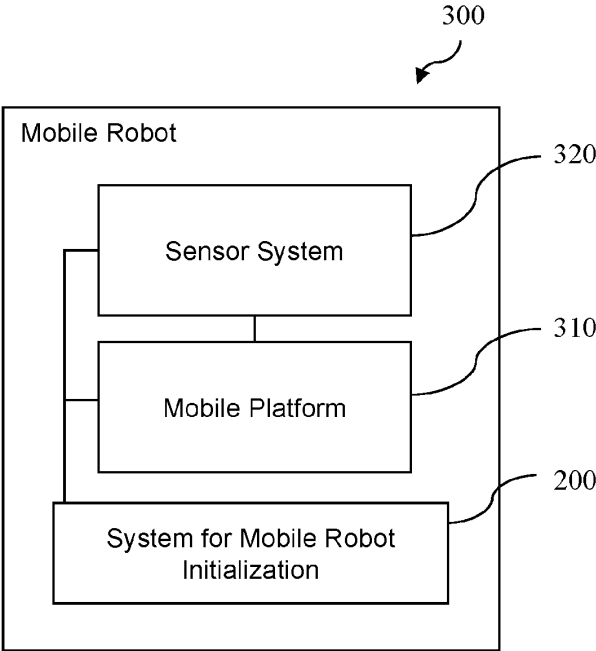


FIG. 3

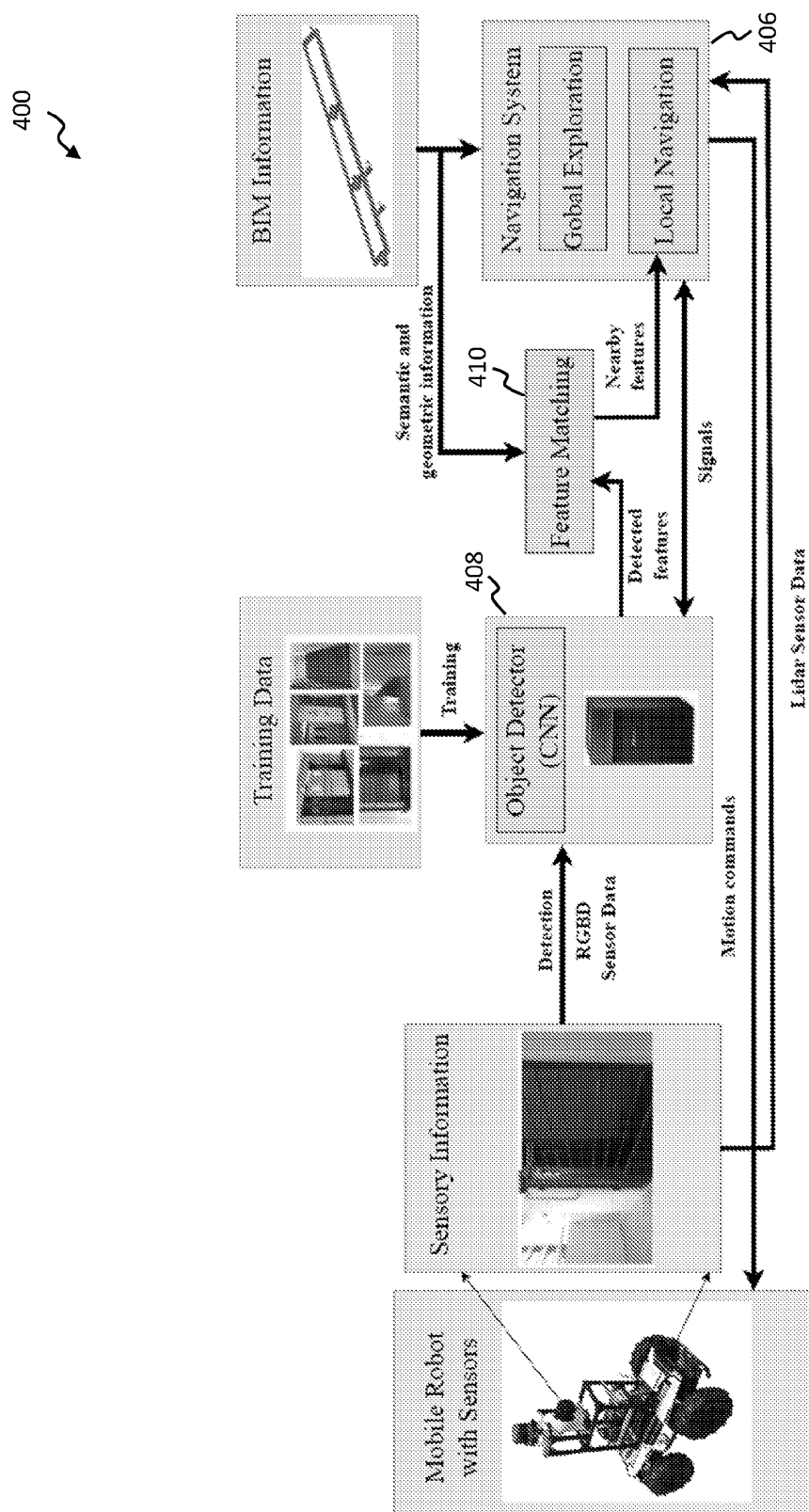


FIG. 4

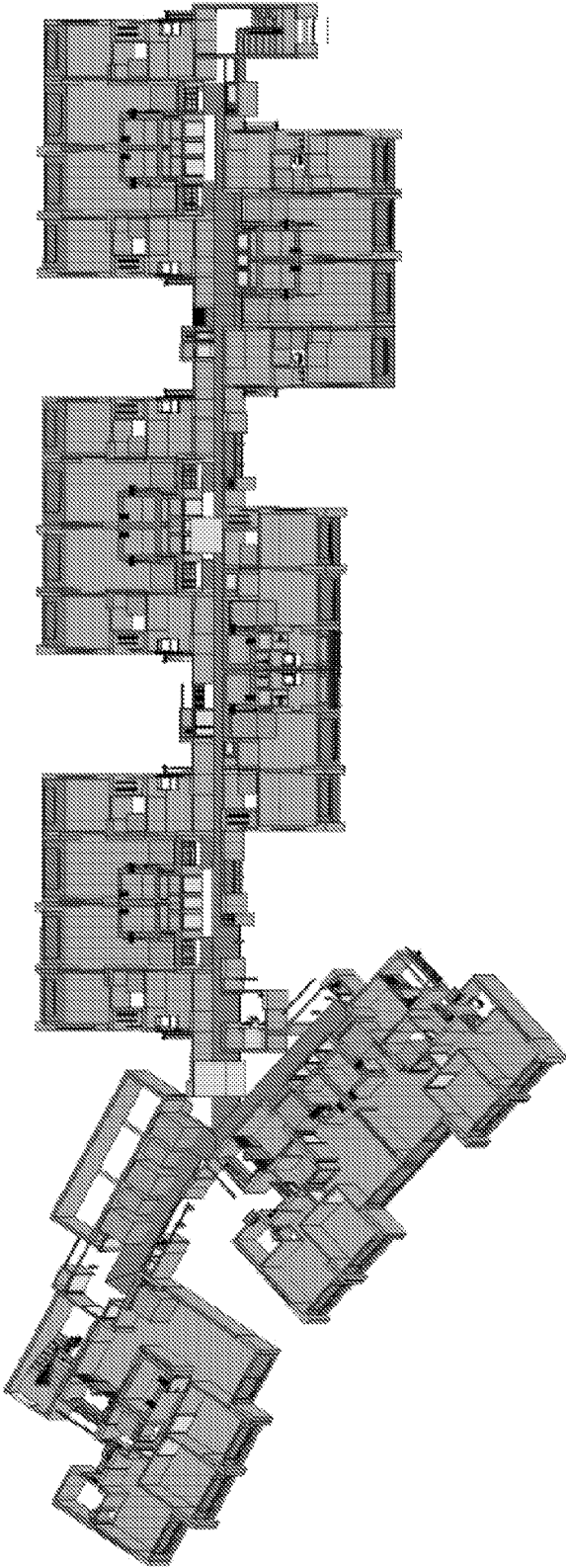


FIG. 5



FIG. 6A

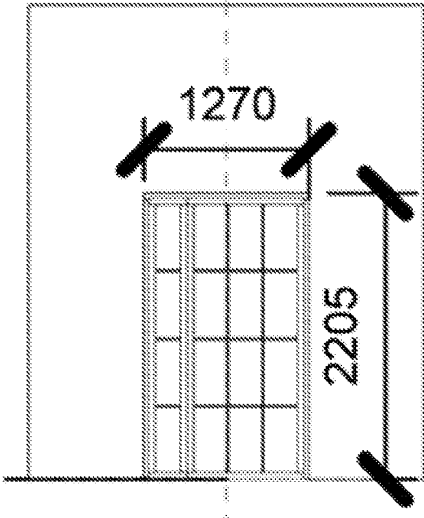


FIG. 6B

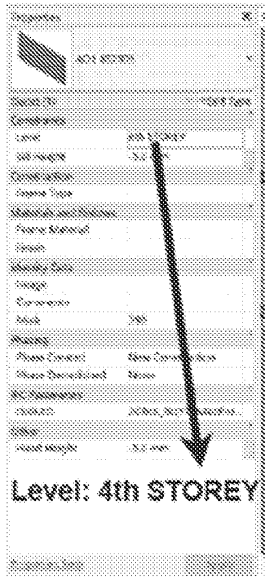


FIG. 6C

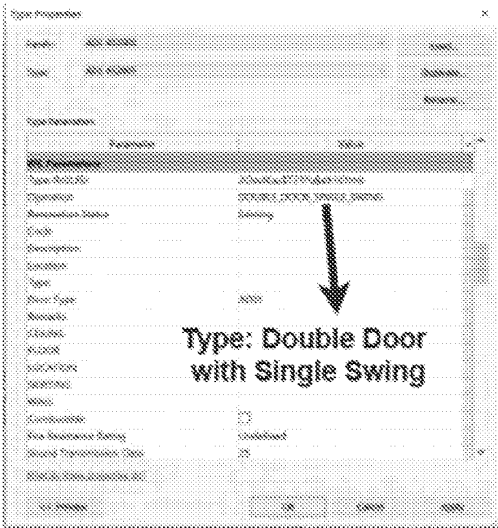


FIG. 6D

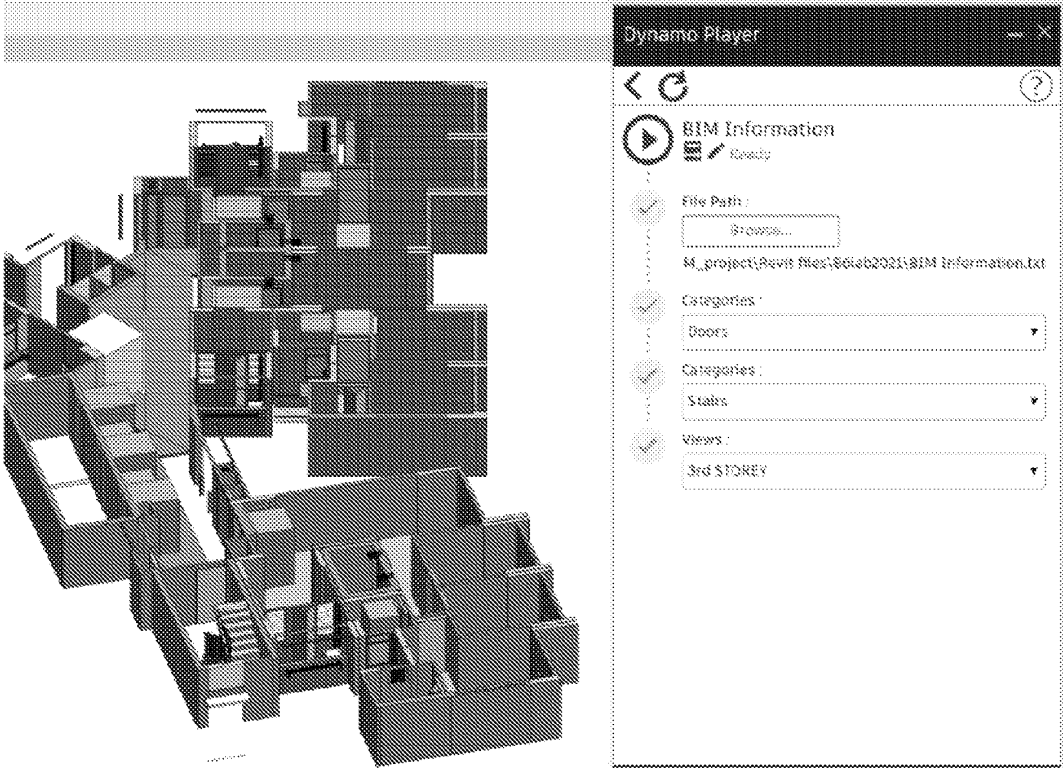


FIG. 7A

Table 1

| Element ID | Category              | X (m) | Y (m) | Norm x | Norm y | Width (m) | Height (m) |
|------------|-----------------------|-------|-------|--------|--------|-----------|------------|
| 344911     | Doors                 | 0     | 0     | 0      | -1     | 1.27      | 2.21       |
| 346996     | Windows               | 0.87  | 2.62  | 1      | 0      | 0.3       | 0.3        |
| 3483143    | Electrical Fixtures   | 2.24  | 7.04  | -1     | 0      | 0.14      | 0.09       |
| 3483144    | Communication Devices | 2.24  | 7.15  | -1     | 0      | 0.09      | 0.09       |
| 3483145    | Data Devices          | 2.24  | 7.23  | -1     | 0      | 0.09      | 0.09       |
| 3524792    | Lighting Fixtures     | 0.78  | 4.34  | 0      | 1      | 0.06      | 0.05       |

FIG. 8

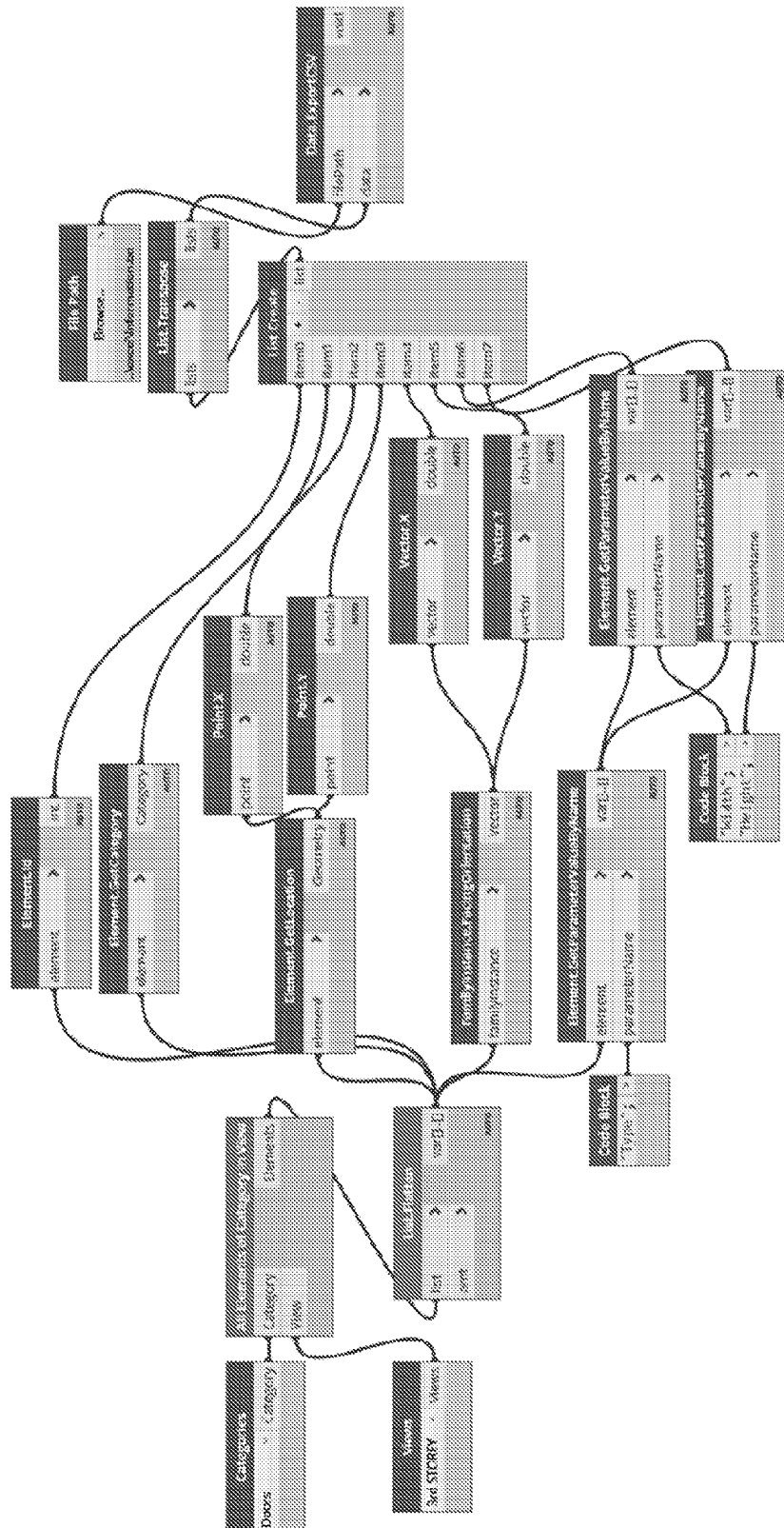


FIG. 7B

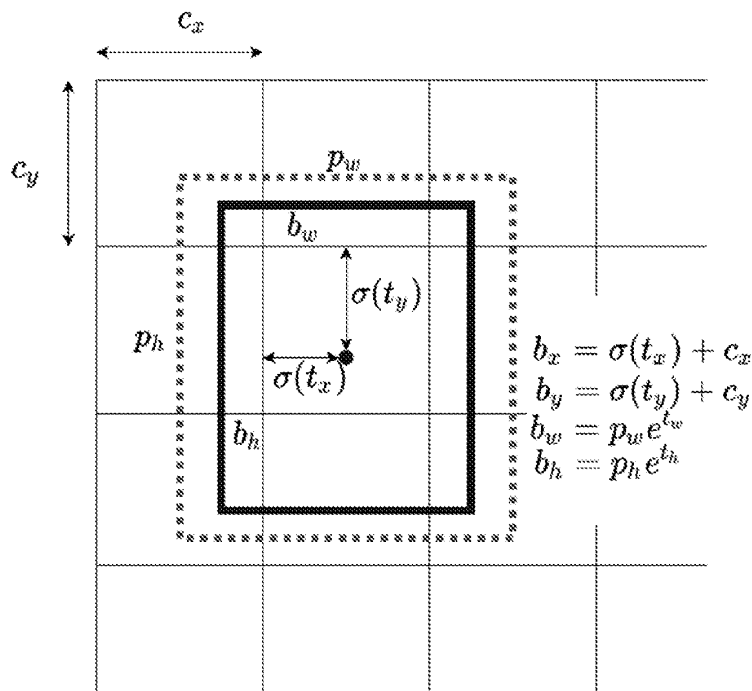


FIG. 9

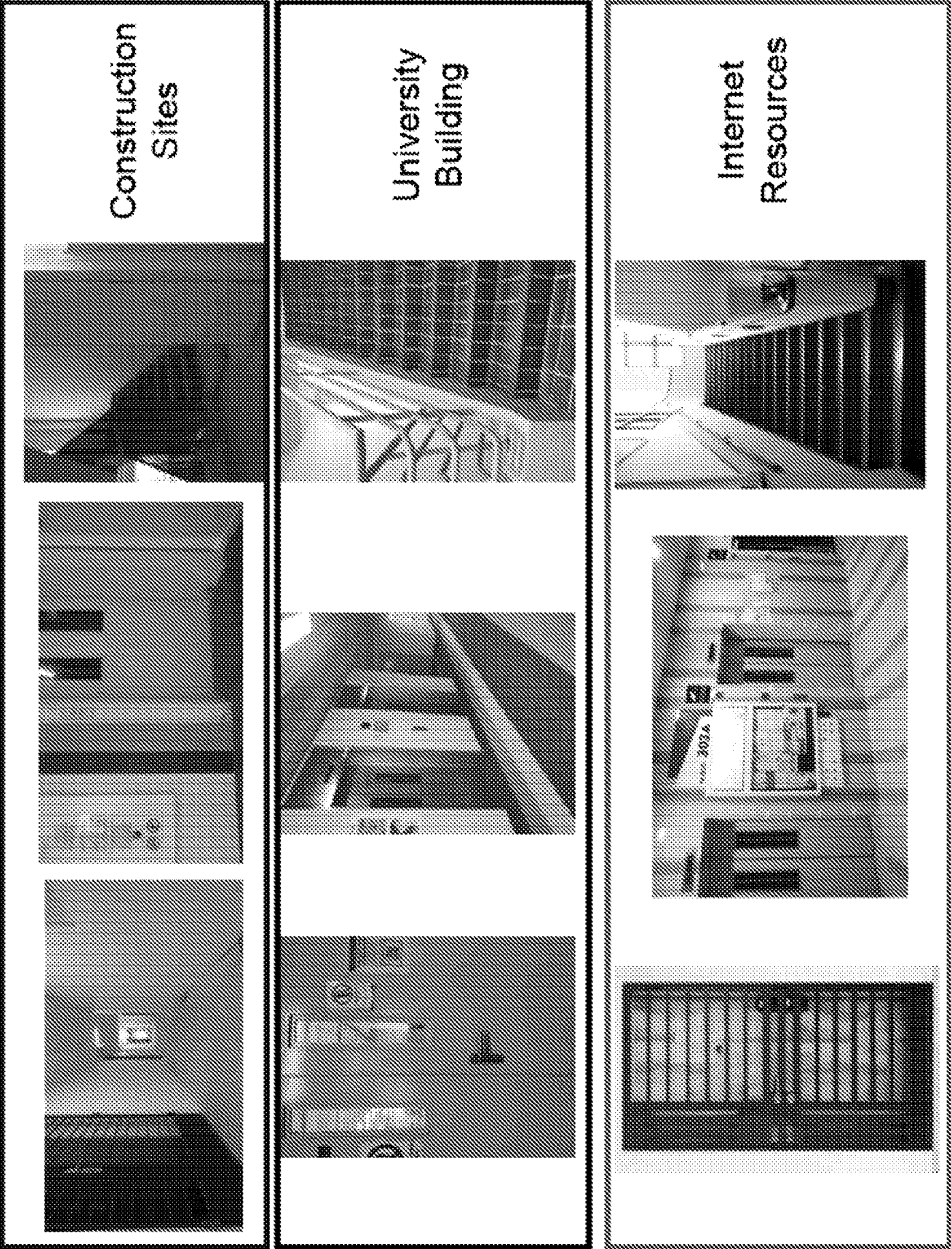


FIG. 10A

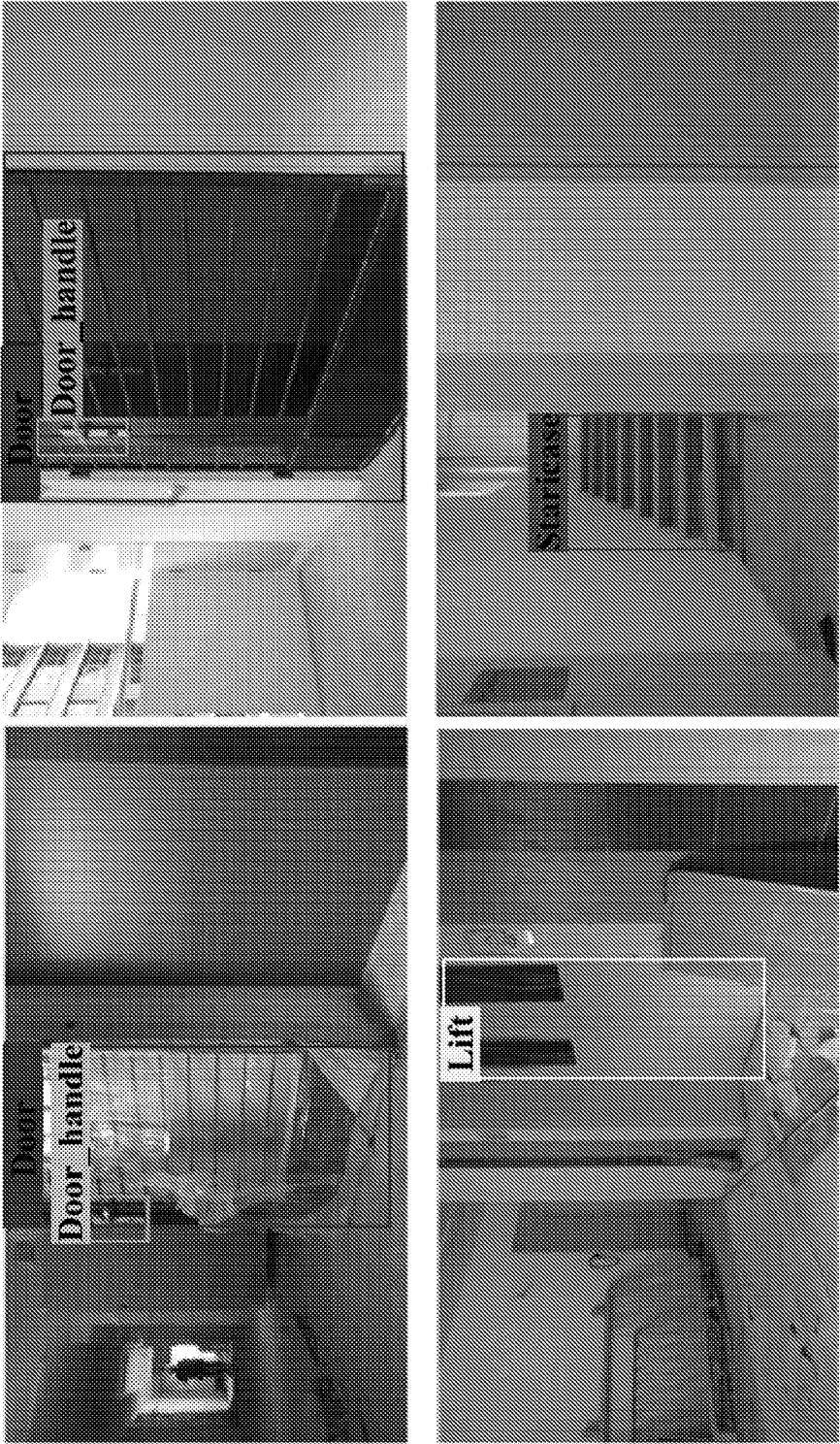


FIG. 10B

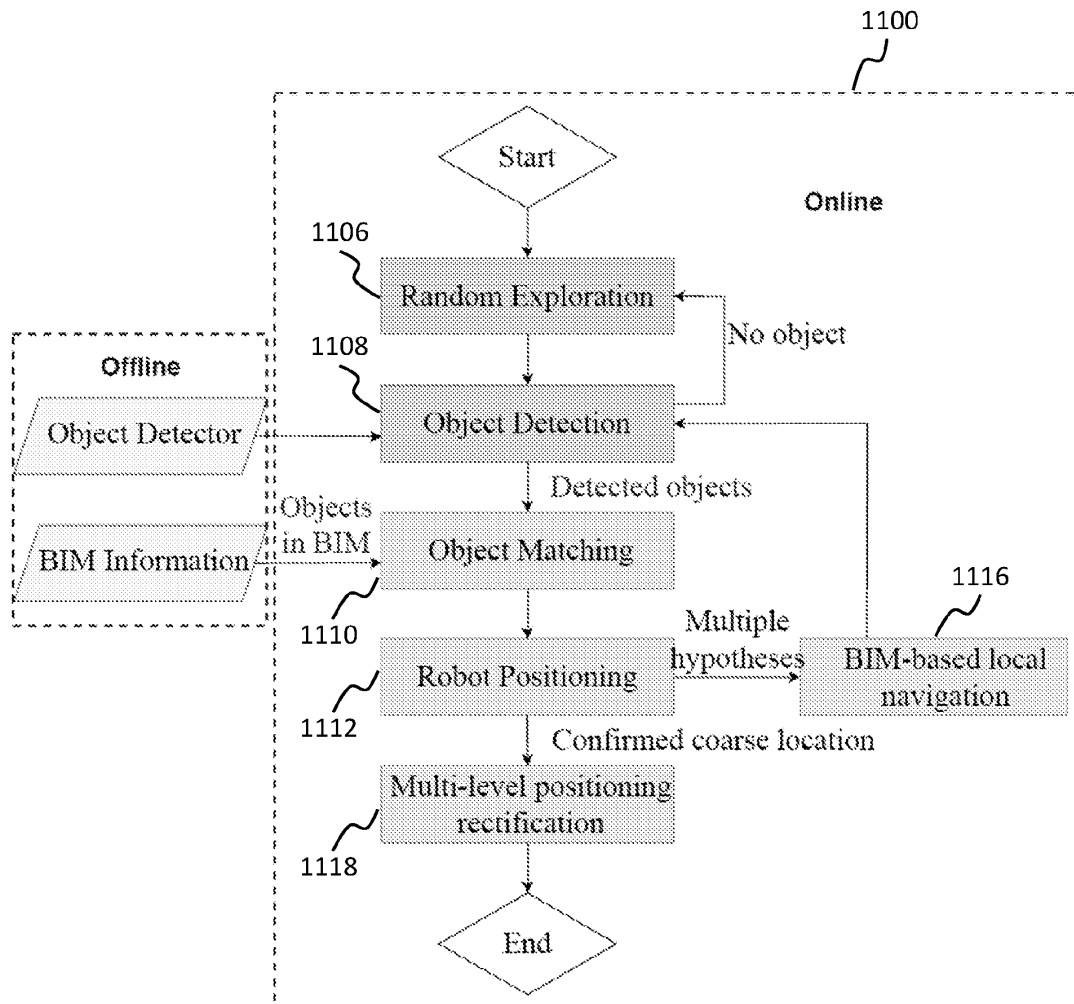


FIG. 11

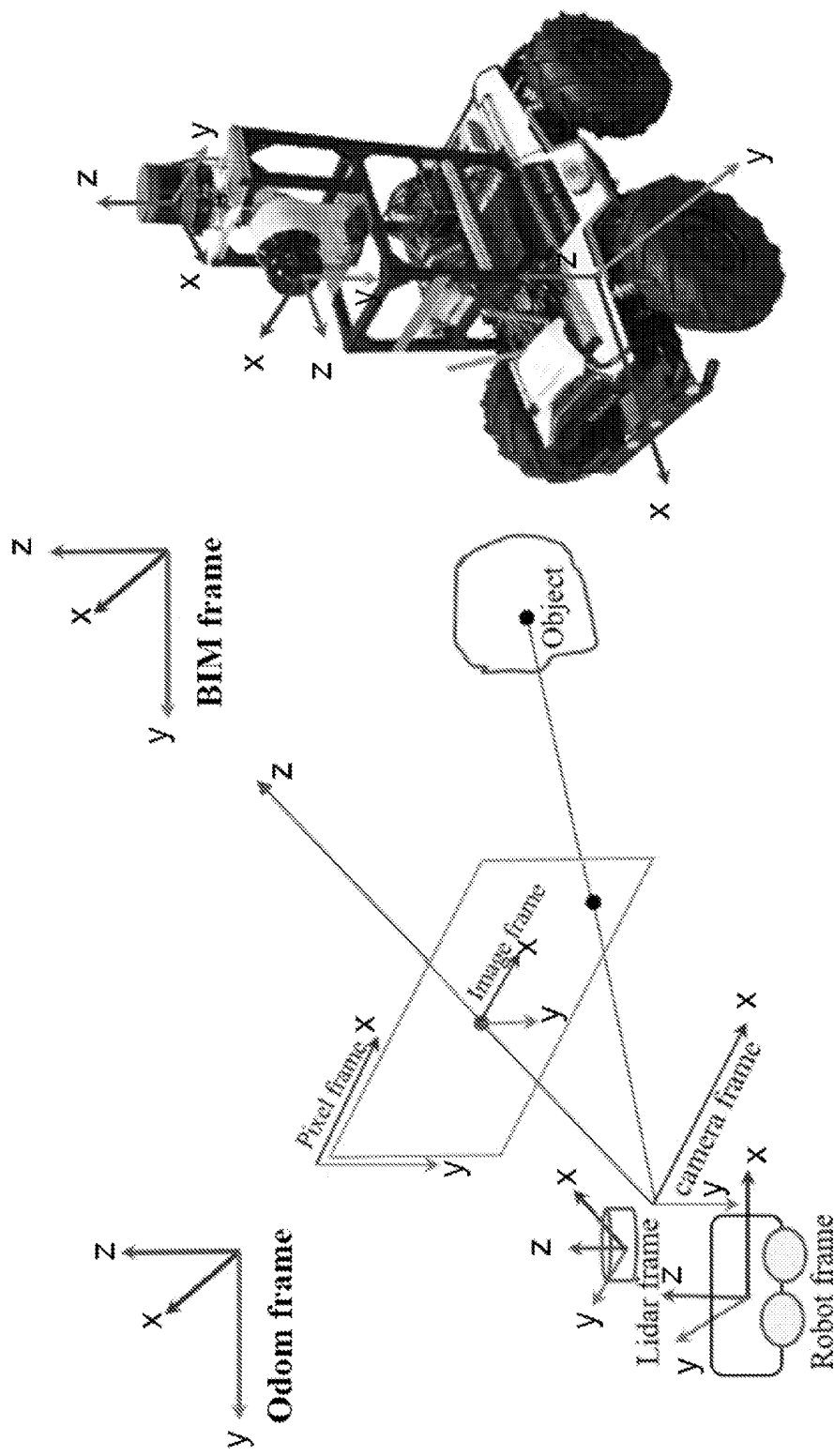


FIG. 12

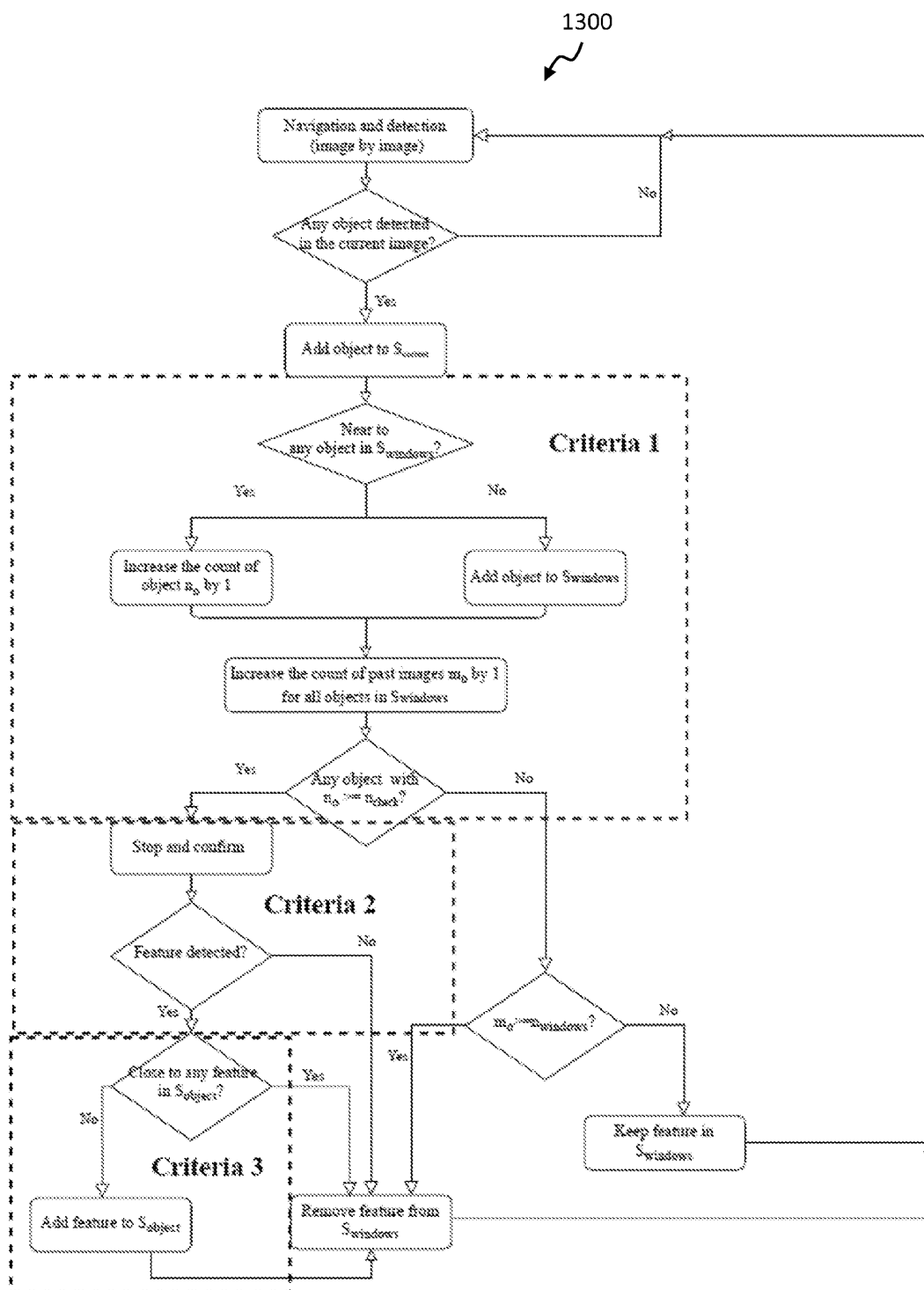


FIG. 13

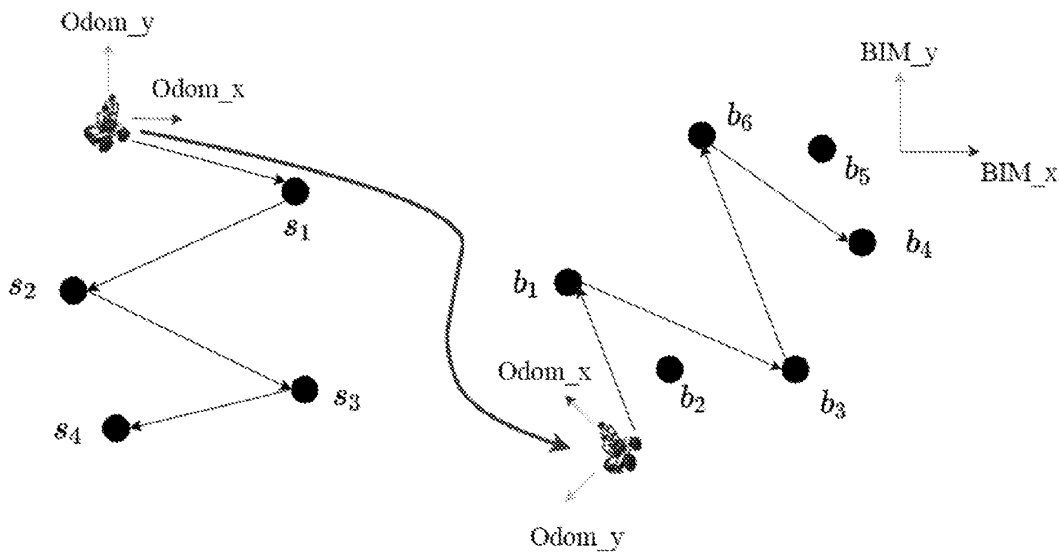


FIG. 14

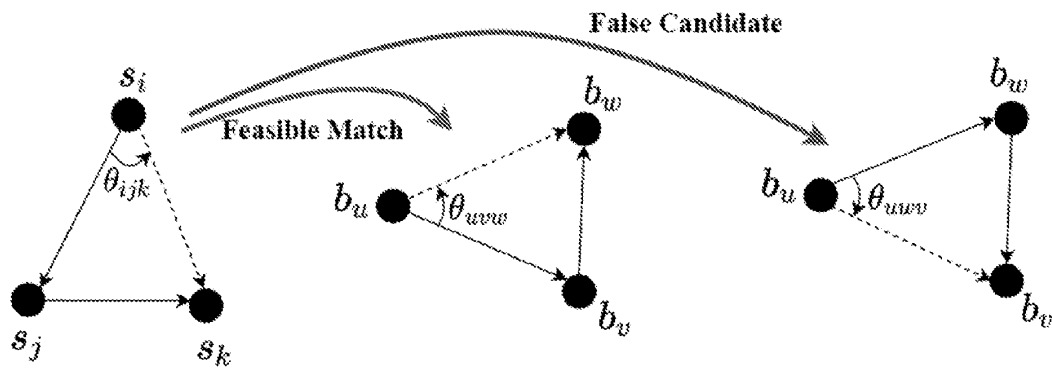


FIG. 15

**Algorithm 1:** Object matching algorithmInput: BIM object set ( $B_{object}$ ), Detected object set ( $S_{object}$ )Output: The set of feasible matches ( $M$ )Initializer:  $M = \emptyset$ 

```

1 for each  $b_u \in B$  and  $label(b_u) = label(s_1)$  do
2    $M_u \leftarrow (s_1, b_u)$ ;
3    $E \leftarrow \emptyset$ ;
4   for each  $b_v \in B_{object}$  and  $b_v \neq b_u$  do
5      $E \leftarrow E \cup [(s_1, b_u), (s_2, b_v)]$  if  $label(b_v) = label(s_2)$  and  $z(\{s_1, b_u\}, \{s_2, b_v\}) = 1$ ;
6      $M_u \leftarrow E$ ;
7   end
8   for each  $s_i \in S_{object}$  that  $i \geq 3$  do
9      $E \leftarrow \emptyset$ ;
10    for each  $m \in M_u$  and  $b_w \in B_{object}$  and  $w$  not matched with any object in  $S_{object}$  do
11       $m \leftarrow m \cup (s_i, b_w)$  if  $label(b_w) = label(s_i)$  and
12       $z(\{s_{i-2}, m(s_{i-2})\}, \{s_{i-1}, m(s_{i-1})\}, \{s_i, b_w\}) = 1$ ;
13       $E \leftarrow E \cup m$ ;
14    end
15     $M_u \leftarrow E$ ;
16  end
17 end

```

FIG. 16

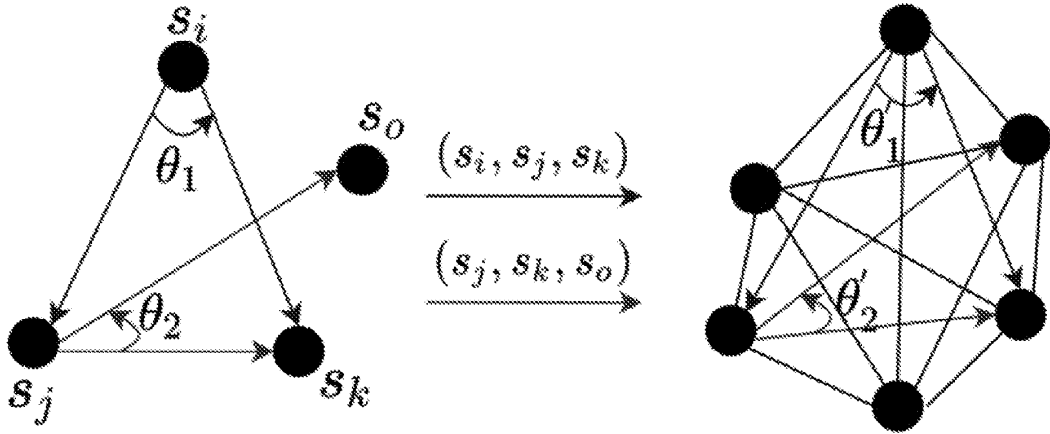


FIG. 17

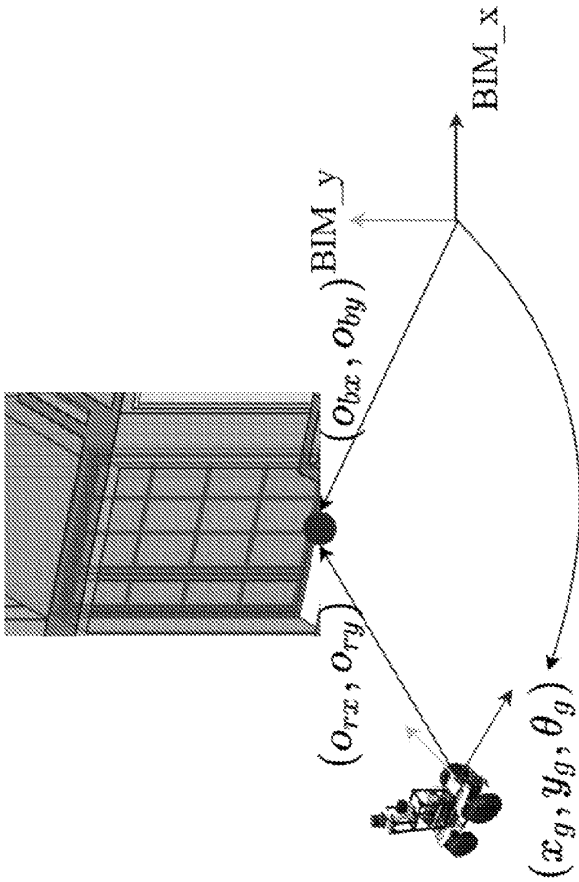


FIG. 18B

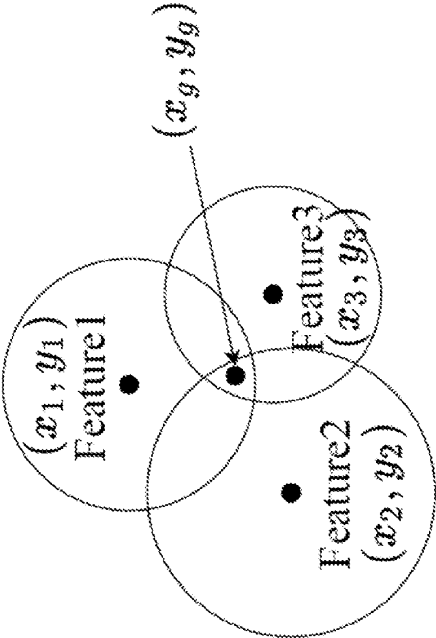


FIG. 18A

**Algorithm 2:** Robot local navigation

---

**Input:** target object location  $(x_t, y_t)$ , estimated robot position  $(x_g, y_g)$ , Lidar sensor data  $(d_f, d_l, d_r, d_{fl}, d_{fr})$

```

1 rotate and point to  $(x_t, y_t)$  ;
2 while (not reach target location) do
3   update yaw error  $\Delta_{yaw}$  ;
4   if (  $d_f, d_{fl}, d_{fr} \geq d_{min}$  and  $|\Delta_{yaw}| \leq \theta_1$  ) or (  $d_l, d_{fl} \geq d_{min}$  and  $\Delta_{yaw} > 0$  and  $\theta_1 < |\Delta_{yaw}| \leq \theta_2$  )
      or (  $d_r, d_{fr} \geq d_{min}$  and  $\Delta_{yaw} < 0$  and  $\theta_1 < |\Delta_{yaw}| \leq \theta_2$  ) then
5     rotate and point to  $(x_t, y_t)$  ;
6     go straight ;
7     if (deviate from target direction) then
8       adjust robot yaw angle;
9     end
10  else if (  $d_f < d_{min}$  ) then
11    if (  $d_{fl} \geq d_{fr}$  ) then
12      follow right wall ;
13    else
14      follow left wall ;
15    end
16 end

```

---

FIG. 19

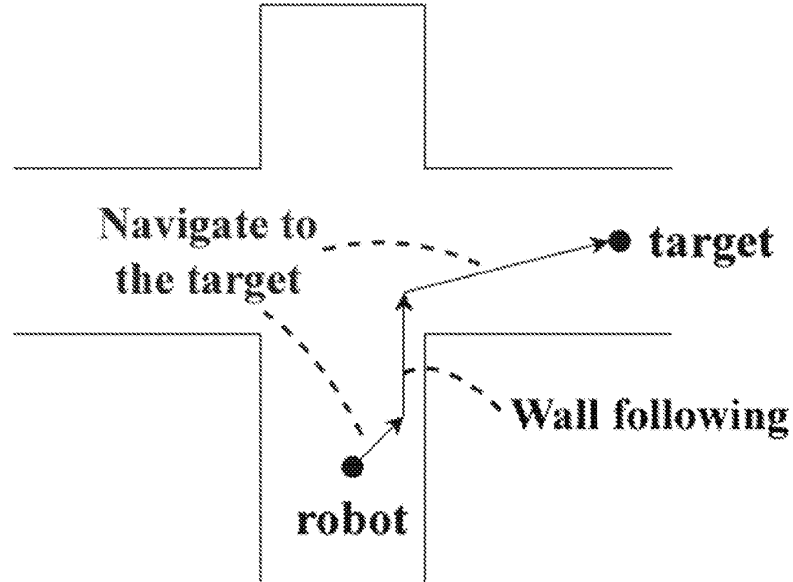


FIG. 20

---

**Algorithm 3:** Overall online decision making for coarse initialization

---

Input: BIM information ( $B_{object}$ ), RGBD sensor data, Lidar sensor data  
Output: *robot\_state*, signals to trigger sub-systems

```

1 while (robot position not found) do
2   robot_state  $\leftarrow$  global_exploration;
3   if ( $S_{current} \neq \emptyset$ ) then
4     object localization;
5     detected objects filtering ;
6      $S_{windows}, S_{object} \leftarrow Filter\_Detection(S_{current}, S_{windows}, S_{object})$ ;
7     if (new object detected) and ( $|S_{object}| \geq 3$ ) then
8       object matching (Algorithm1);
9        $M \leftarrow Match\_object(S_{object}, B_{object})$ ;
10      if ( $|M| = 1$ ) then
11        robot localization;
12        termination;
13      else
14        if ( $|M| \leq m_{thre}$ ) then
15           $P \leftarrow Calculate\_Location(M, S_{object}, S_{current})$ ;
16           $x_g, y_g \leftarrow P[0]$ ;
17           $x_t, y_t \leftarrow Find\_Nearest(B_{object}, x_g, y_g)$ ;
18          Local_Navigation( $x_t, y_t$ ) (Algorithm2);
19          while  $t \leq t_{thre}$  do
20            robot_state  $\leftarrow$  local_navigation;
21            if ( $S_{current} \neq \emptyset$ ) then
22              go to 4 ;
23            end
24          end
25          robot_state  $\leftarrow$  local_recovery;
26          if ( $S_{current} \neq \emptyset$ ) then
27            go to 4 ;
28          else
29            end
30          end
31        end
32      end
33 end

```

---

FIG. 21

1118

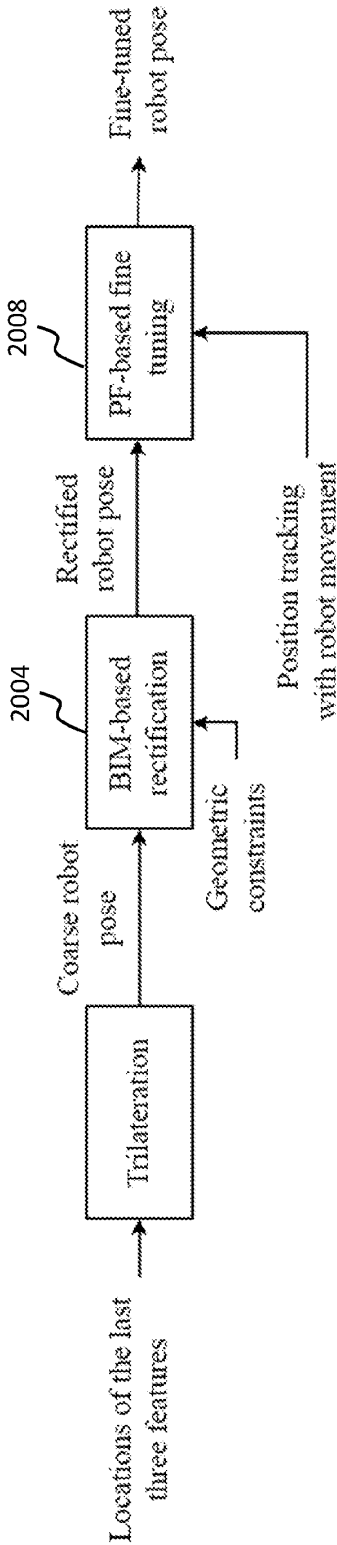


FIG. 22

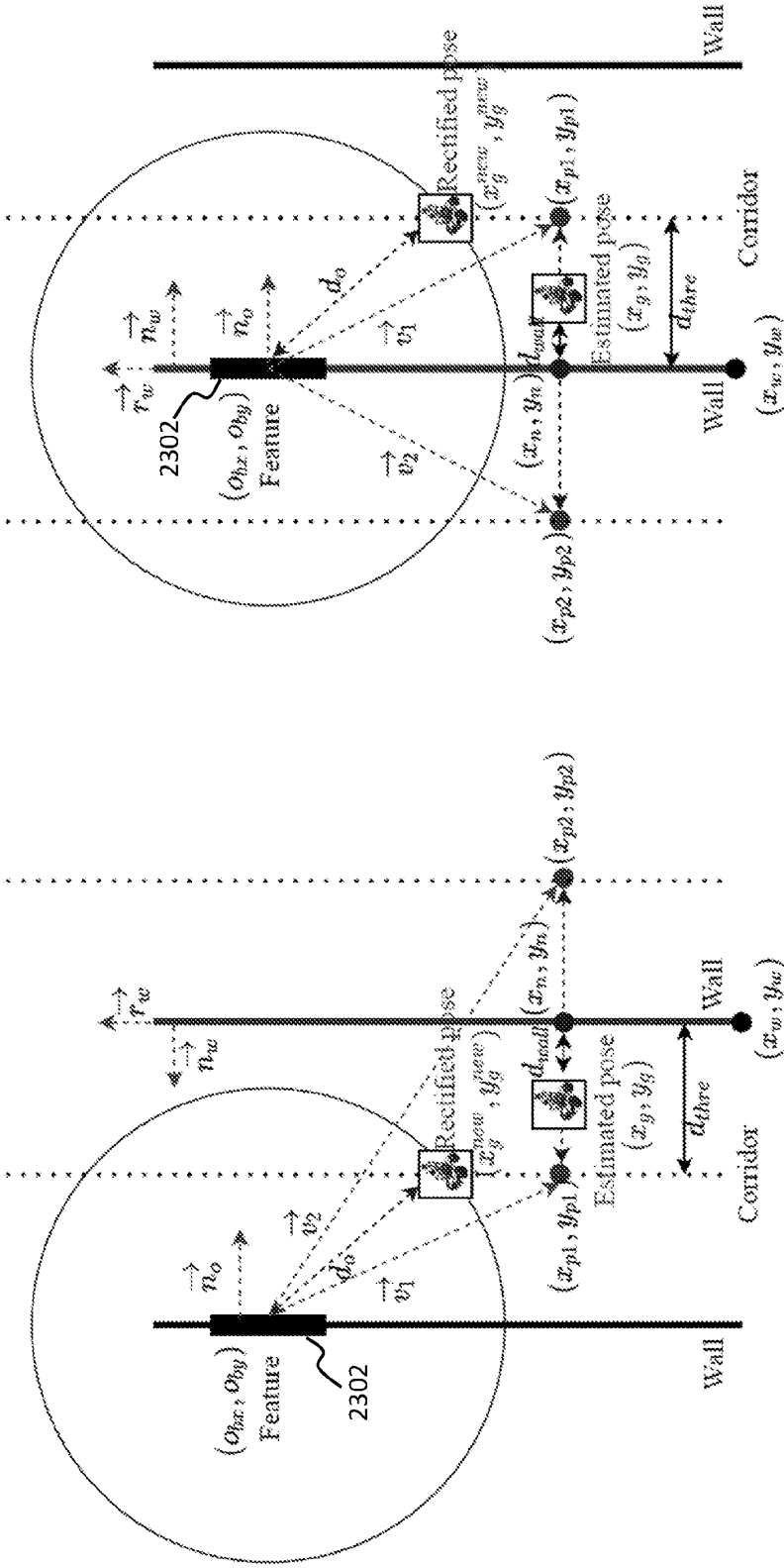


FIG. 23B

FIG. 23A

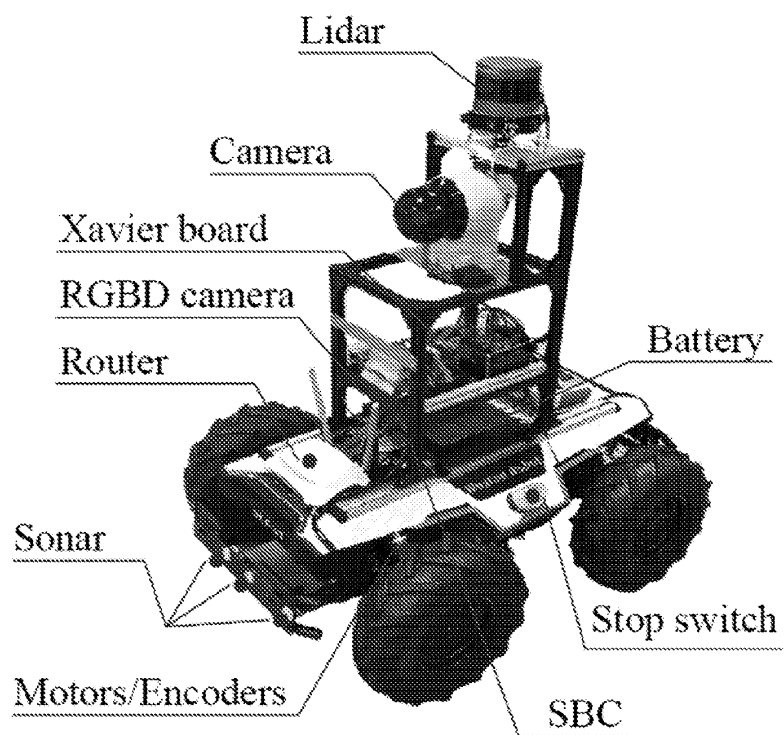


FIG. 24

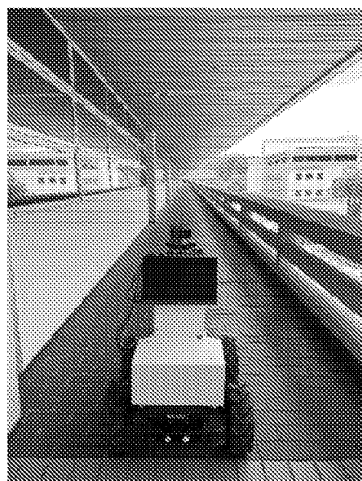


FIG. 25A

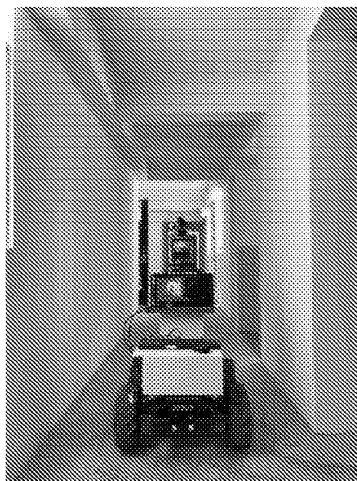


FIG. 25B

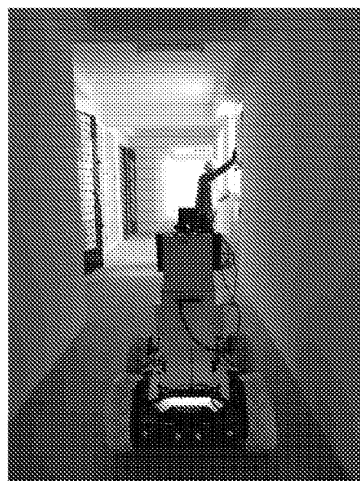


FIG. 25C

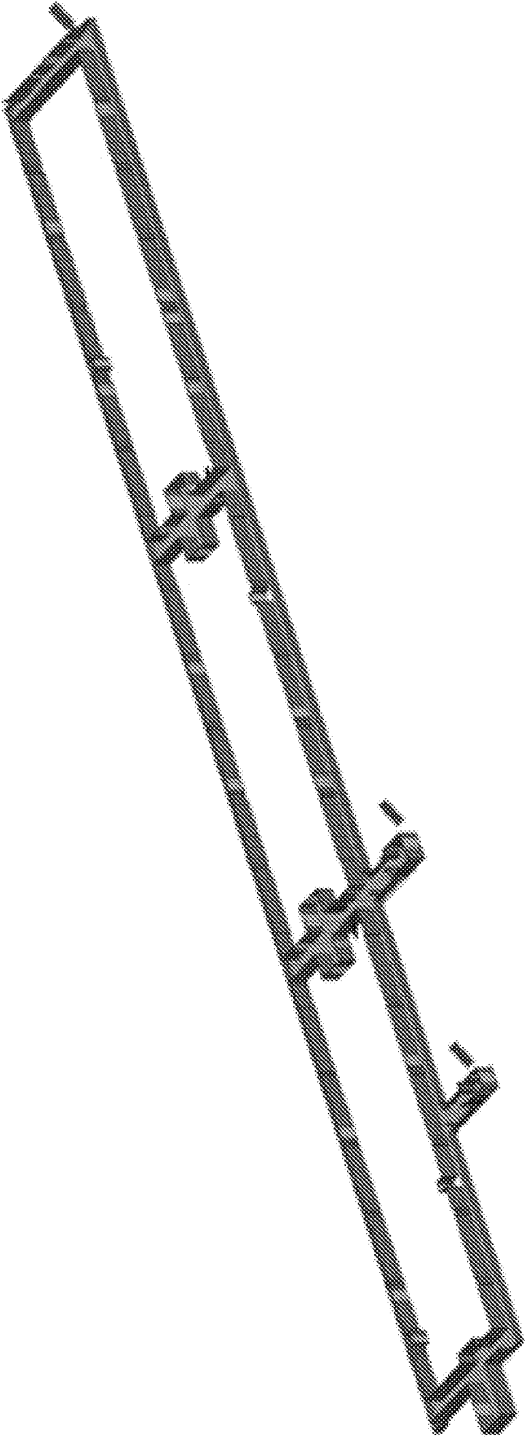


FIG. 26

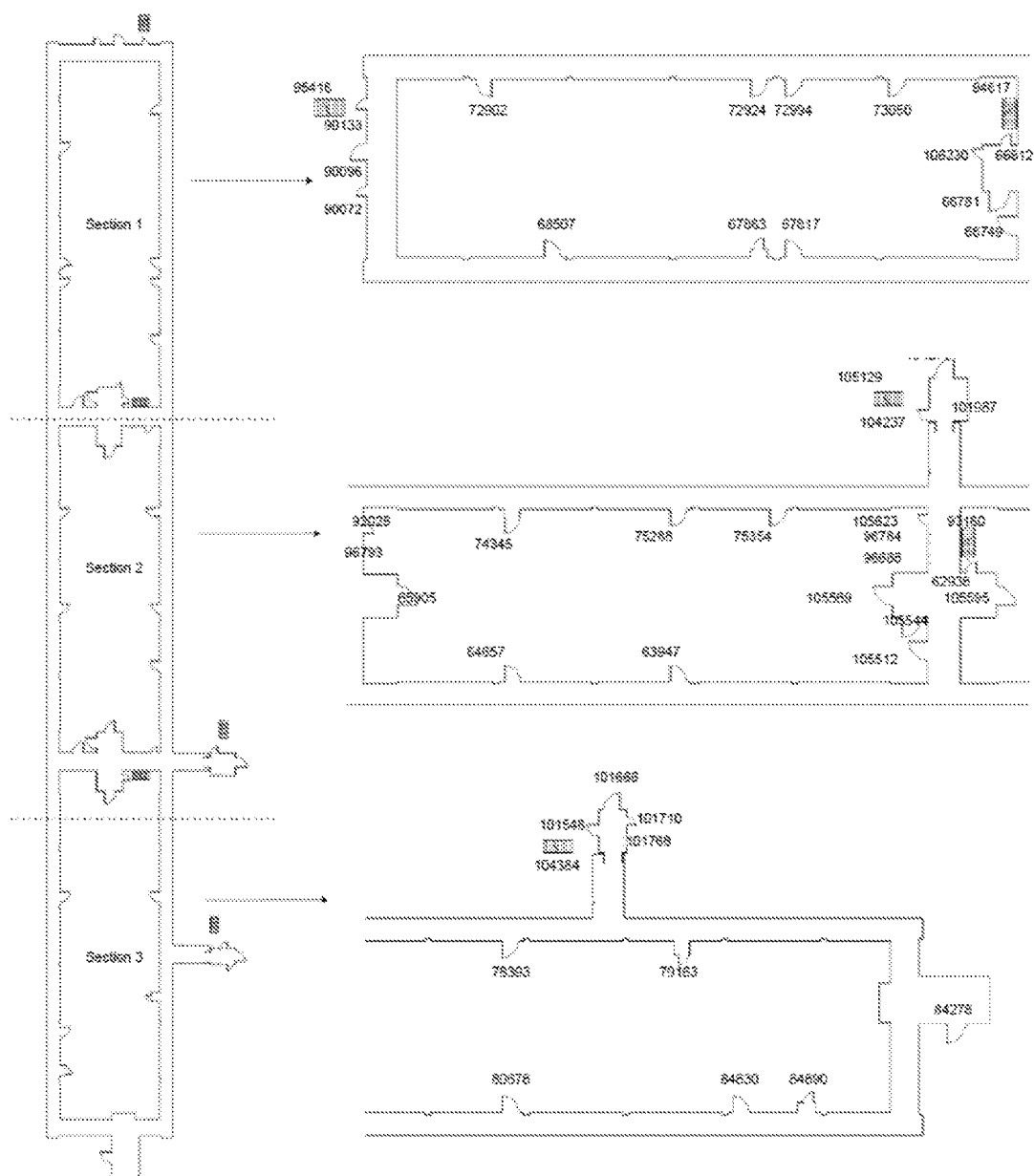


FIG. 27

Table 2

| Element ID | Category | X (m)  | Y (m) | Norm_x | Norm_y | Width (m) | Height (m) |
|------------|----------|--------|-------|--------|--------|-----------|------------|
| 62938      | Doors    | -6.38  | -4.14 | 1.00   | 0.00   | 1.05      | 2.30       |
| 63947      | Doors    | -16.88 | 24.10 | 1.00   | 0.00   | 1.60      | 2.30       |
| 64657      | Doors    | -16.88 | 40.13 | 1.00   | 0.00   | 1.60      | 2.30       |
| 65905      | Doors    | -8.57  | 51.16 | 0.00   | -1.00  | 1.88      | 2.30       |
| 66749      | Doors    | -13.90 | 57.71 | 0.00   | 1.00   | 1.88      | 2.30       |
| 66781      | Doors    | -10.69 | 59.36 | -1.00  | 0.00   | 1.88      | 2.30       |
| 96688      | Lift     | -5.07  | 0.00  | 0.00   | -1.00  | 1.10      | 2.12       |
| 96784      | Lift     | -2.96  | 0.00  | 0.00   | -1.00  | 1.10      | 2.12       |
| 96793      | Lift     | -4.46  | 54.56 | 0.00   | -1.00  | 2.10      | 2.12       |
| 93160      | Stairs   | -3.40  | -3.88 | -1.00  | 0.00   | 1.19      | 1.86       |
| 94617      | Stairs   | -3.39  | 58.41 | -1.00  | 0.00   | 1.19      | 1.86       |
| ...        | ...      | ...    | ...   | ...    | ...    | ...       | ...        |

FIG. 28

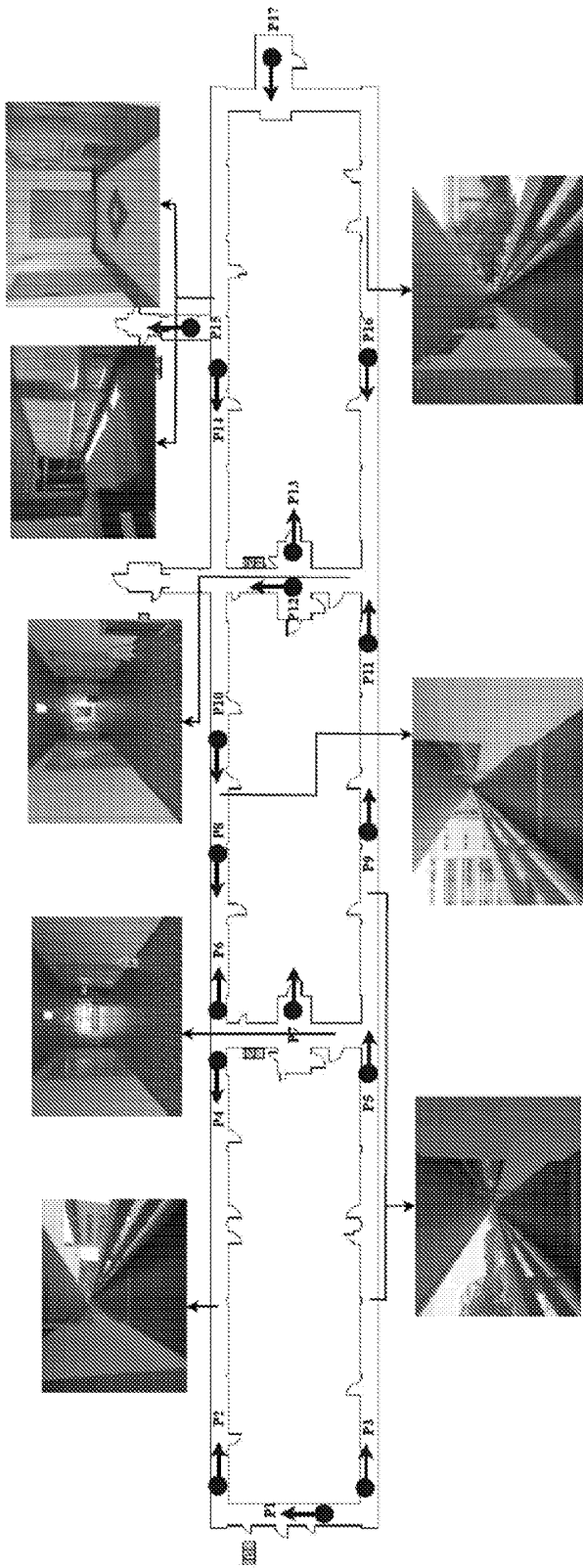


FIG. 29

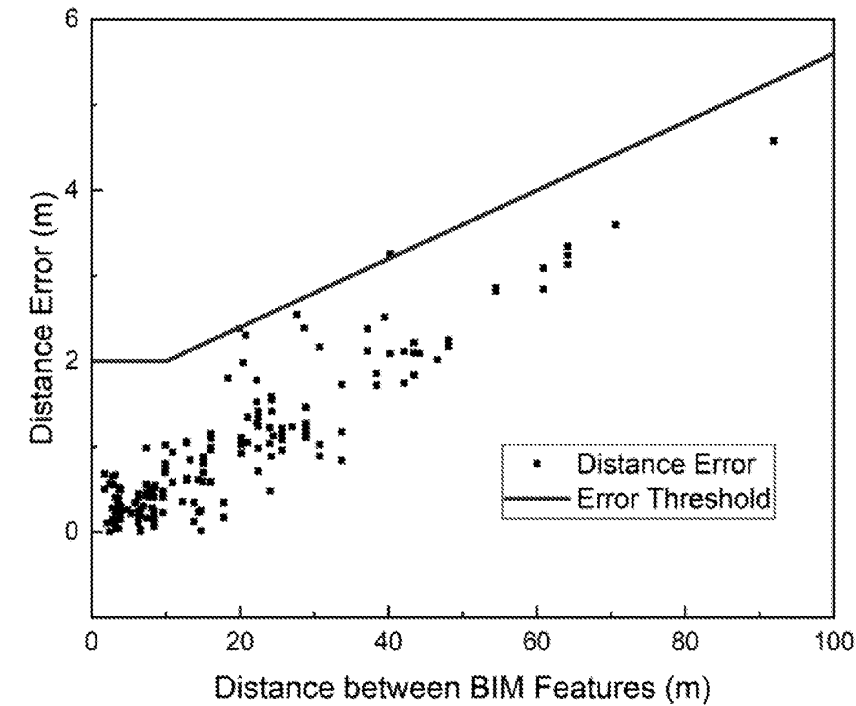


FIG. 30A

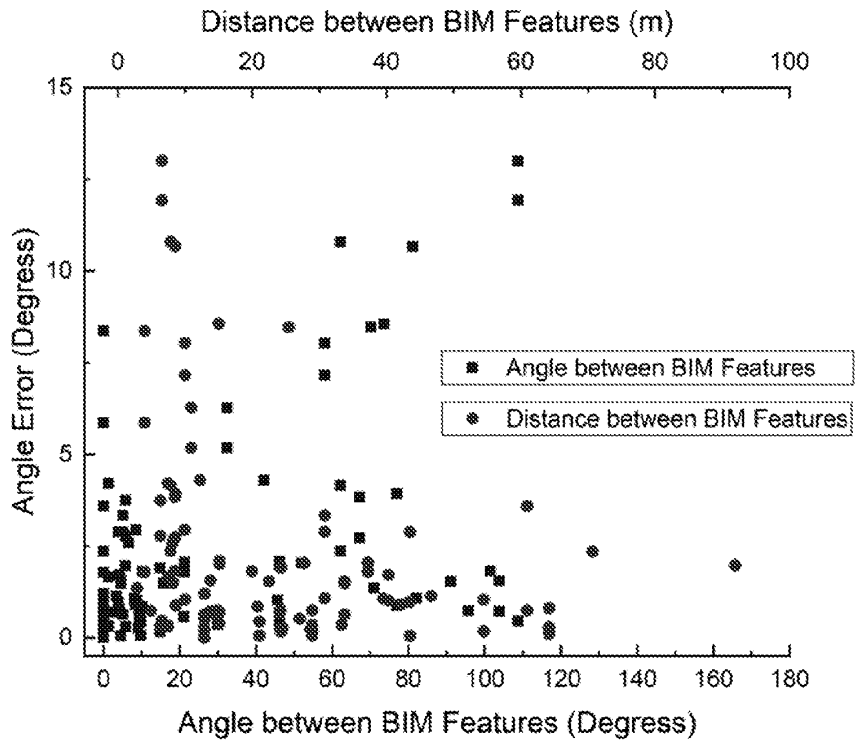


FIG. 30B

Table 3

| Starting Positions | Start X (m) | Start Y (m) | No. of Features | Distance (m) | Route                                       |
|--------------------|-------------|-------------|-----------------|--------------|---------------------------------------------|
| P1                 | -13.48      | 116.40      | 3               | 22.18        | [90072, 90096, 72902]                       |
| P2                 | 0.88        | 113.93      | 4               | 44.49        | [72902, 72924, 72994, 73050]                |
| P3                 | -18.06      | 114.00      | 6               | 73.89        | [68507, 67817, 66749, 66781, 106230, 96793] |
| P4                 | 0.93        | 58.01       | 4               | 48.53        | [73050, 72994, 72924, 72902]                |
| P5                 | -18.07      | 59.56       | 4               | 57.55        | [66781, 96793, 92028, 75288]                |
| P6                 | 1.20        | 51.21       | 4               | 65.65        | [75288, 75354, 104279, 101987]              |
| P7                 | -8.60       | 53.91       | 4               | 45.43        | [65905, 66749, 64657, 63947]                |
| P8                 | 0.50        | 34.71       | 4               | 37.32        | [74345, 96793, 65905, 66749]                |
| P9                 | -17.91      | 29.04       | 5               | 51.50        | [63947, 105512, 105569, 96784, 105623]      |
| P10                | 0.74        | 19.69       | 3               | 38.43        | [75288, 74345, 96793]                       |
| P11                | -18.13      | 3.23        | 4               | 22.22        | [105512, 105569, 105544, 96784]             |
| P12                | -6.97       | -1.10       | 3               | 5.44         | [96688, 96784, 105623]                      |
| P13                | -7.57       | -2.96       | 4               | 12.07        | [62938, 105595, 105512, 96688]              |
| P14                | 1.03        | -28.49      | 4               | 29.32        | [78393, 105623, 96784, 96688]               |
| P15                | 2.37        | -32.67      | 4               | 57.53        | [101710, 101548, 101768, 84278]             |
| P16                | -17.79      | -30.54      | 4               | 52.47        | [80678, 105595, 96688, 96784]               |
| P17                | -6.00       | -69.47      | 6               | 98.88        | [84278, 84830, 80678, 105595, 96688, 96784] |

FIG. 31

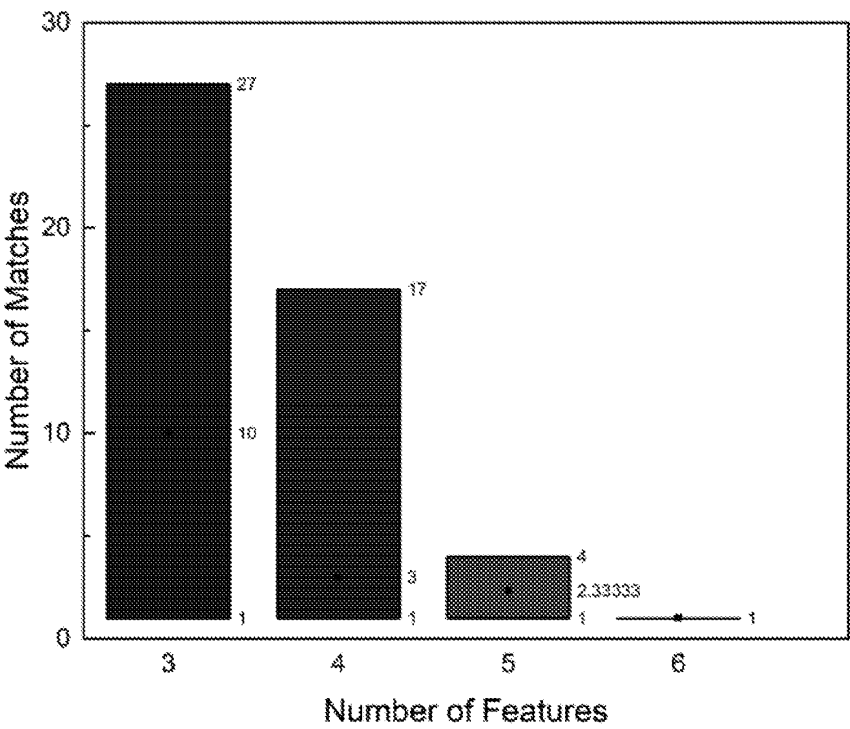


FIG. 32

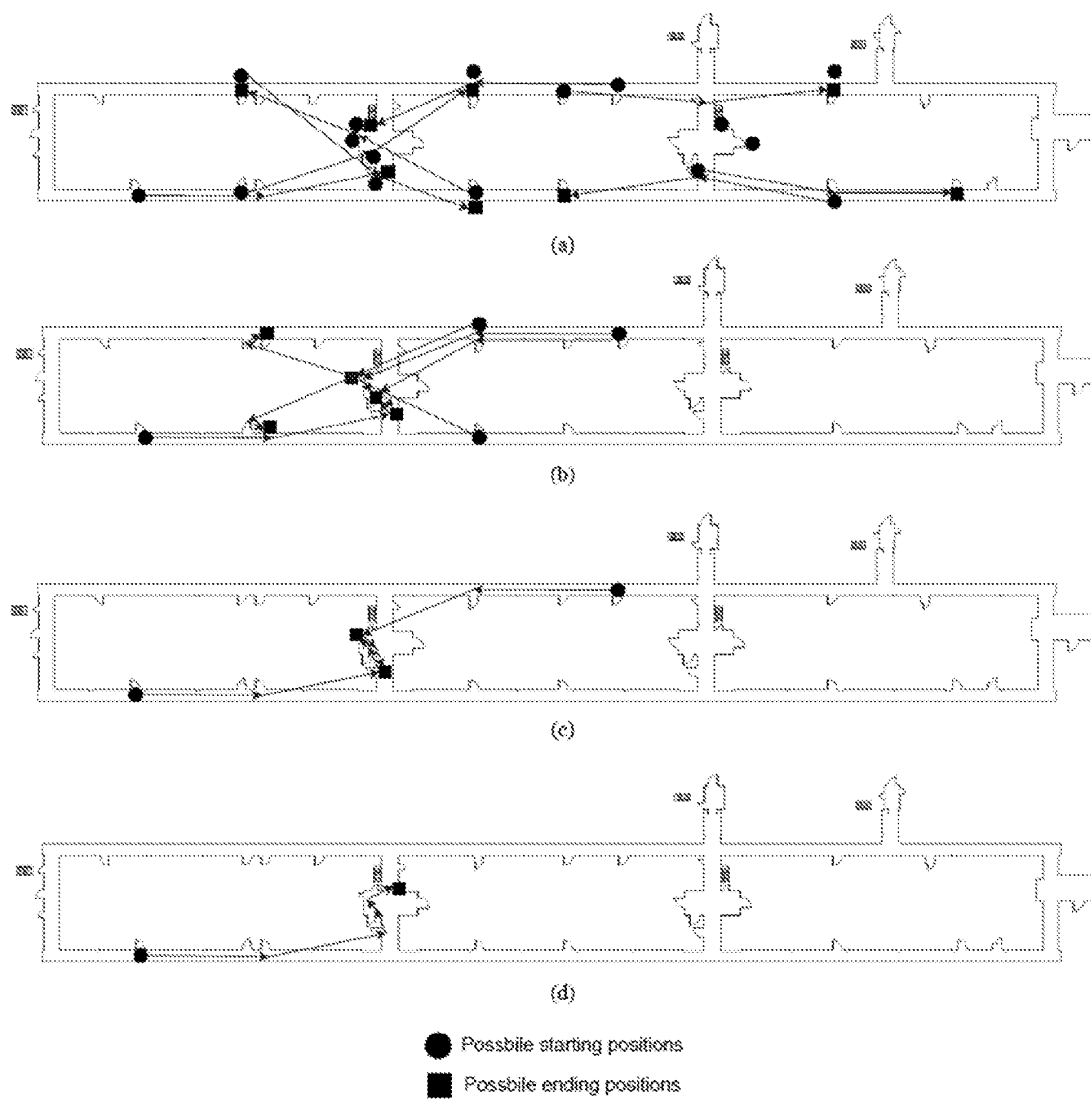


FIG. 33

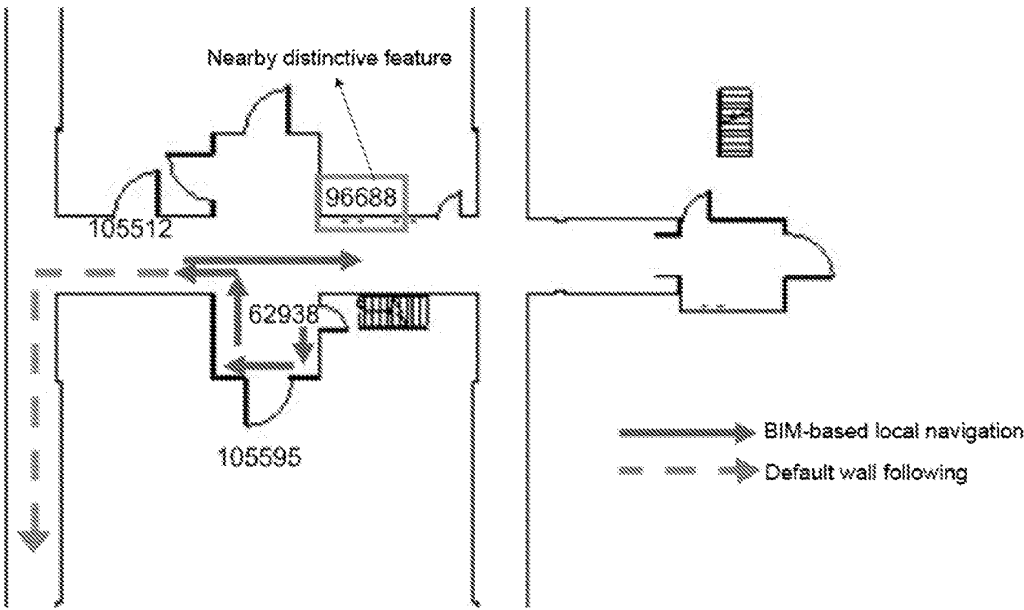


FIG. 34

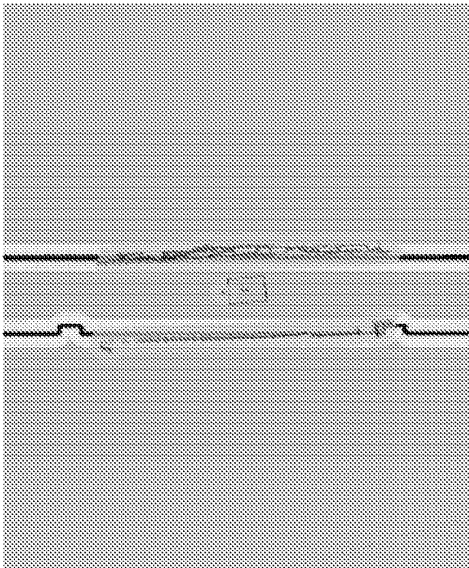


FIG. 35C

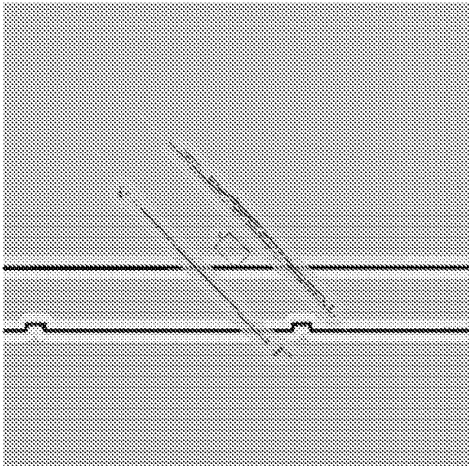


FIG. 35B

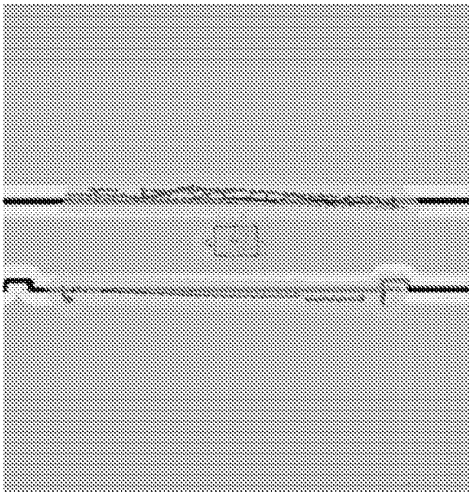


FIG. 35A

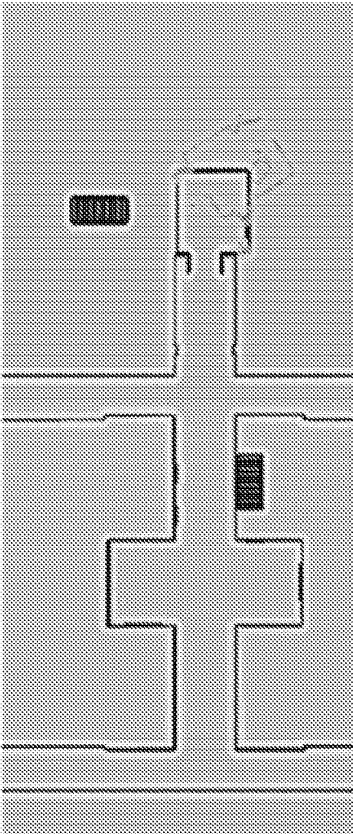


FIG. 36B

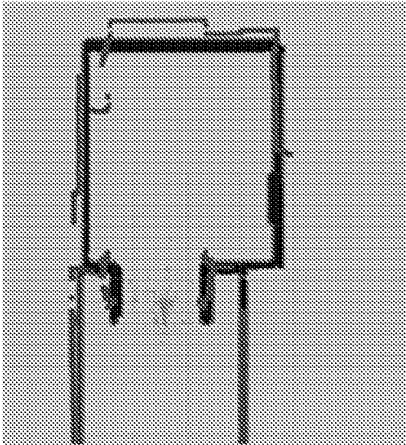


FIG. 36D

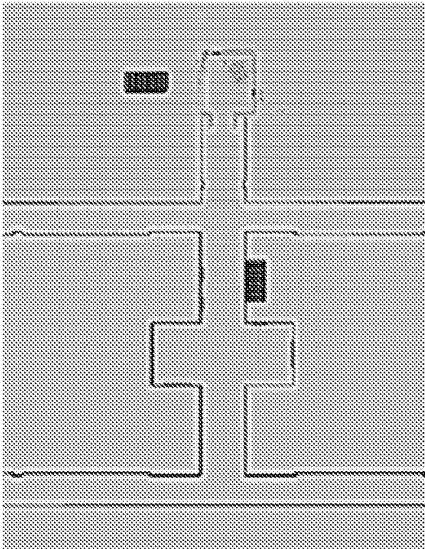


FIG. 36A

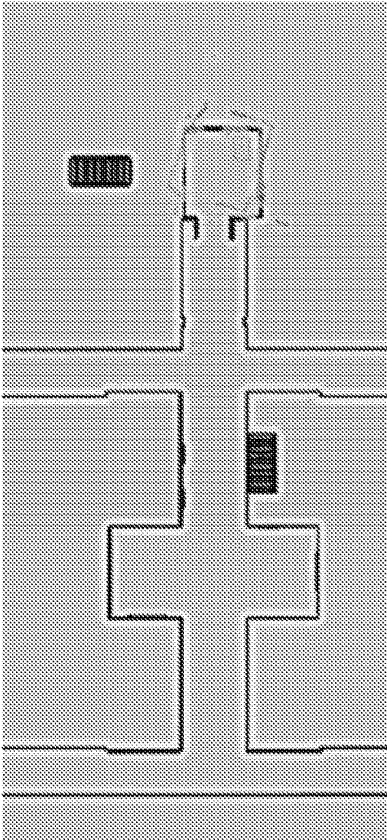


FIG. 36C

Table 4

| Starting Positions | No. of Features | Distance (m) | Error (Before Rectification) |                    | Error (IMM-based Rectification) |                    | Total Distance (m) |      | Error (PF-based Fine Tuning) |                    |
|--------------------|-----------------|--------------|------------------------------|--------------------|---------------------------------|--------------------|--------------------|------|------------------------------|--------------------|
|                    |                 |              | Positioning (m)              | Direction (Degree) | Positioning (m)                 | Direction (Degree) |                    |      | Positioning (m)              | Direction (Degree) |
| P1                 | 3               | 22.18        | 0.69                         | 14.07              | 0.78                            | 5.81               | 39.49              | 0.57 | 0.49                         |                    |
| P2                 | 4               | 44.49        | 1.03                         | 15.17              | 0.18                            | 4.28               | 57.41              | 0.11 | 0.37                         |                    |
| P3                 | 6               | 73.89        | 1.13                         | 1.76               | 1.13                            | 1.76               | 78.54              | 0.18 | 0.16                         |                    |
| P4                 | 4               | 48.53        | 1.95                         | 33.04              | 0.93                            | 7.47               | 58.26              | 0.26 | 0.96                         |                    |
| P5                 | 4               | 57.55        | 2.23                         | 43.70              | 0.36                            | 5.31               | 62.06              | 0.08 | 0.81                         |                    |
| P6                 | 4               | 65.65        | 2.10                         | 57.79              | 0.44                            | 17.90              | 69.12              | 0.07 | 6.07                         |                    |
| P7                 | 4               | 45.43        | 1.44                         | 47.08              | 0.48                            | 17.50              | 47.51              | 0.41 | 0.93                         |                    |
| P8                 | 4               | 37.32        | 0.93                         | 13.98              | 0.40                            | 3.69               | 40.63              | 0.36 | 0.26                         |                    |
| P9                 | 5               | 51.50        | 0.34                         | 9.06               | 0.34                            | 9.06               | 54.99              | 0.14 | 0.08                         |                    |
| P10                | 3               | 38.43        | 1.79                         | 18.47              | 1.50                            | 14.85              | 44.08              | 0.44 | 0.84                         |                    |
| P11                | 4               | 22.22        | 0.24                         | 10.16              | 0.24                            | 10.16              | 25.84              | 0.10 | 0.84                         |                    |
| P12                | 3               | 5.44         | 0.37                         | 17.70              | 0.37                            | 17.70              | 11.06              | 0.03 | 3.27                         |                    |
| P13                | 4               | 12.07        | 0.34                         | 13.12              | 0.34                            | 13.12              | 13.21              | 0.18 | 2.02                         |                    |
| P14                | 4               | 29.32        | 0.73                         | 4.75               | 0.73                            | 4.75               | 35.81              | 0.13 | 0.27                         |                    |
| P15                | 4               | 57.53        | 4.06                         | 40.58              | 1.06                            | 2.96               | 62.10              | 0.19 | 1.53                         |                    |
| P16                | 4               | 52.47        | 1.33                         | 19.48              | 0.69                            | 7.67               | 54.48              | 0.15 | 1.81                         |                    |
| P17                | 6               | 98.88        | 1.75                         | 24.87              | 0.37                            | 7.56               | 100.89             | 0.11 | 4.22                         |                    |

FIG. 37

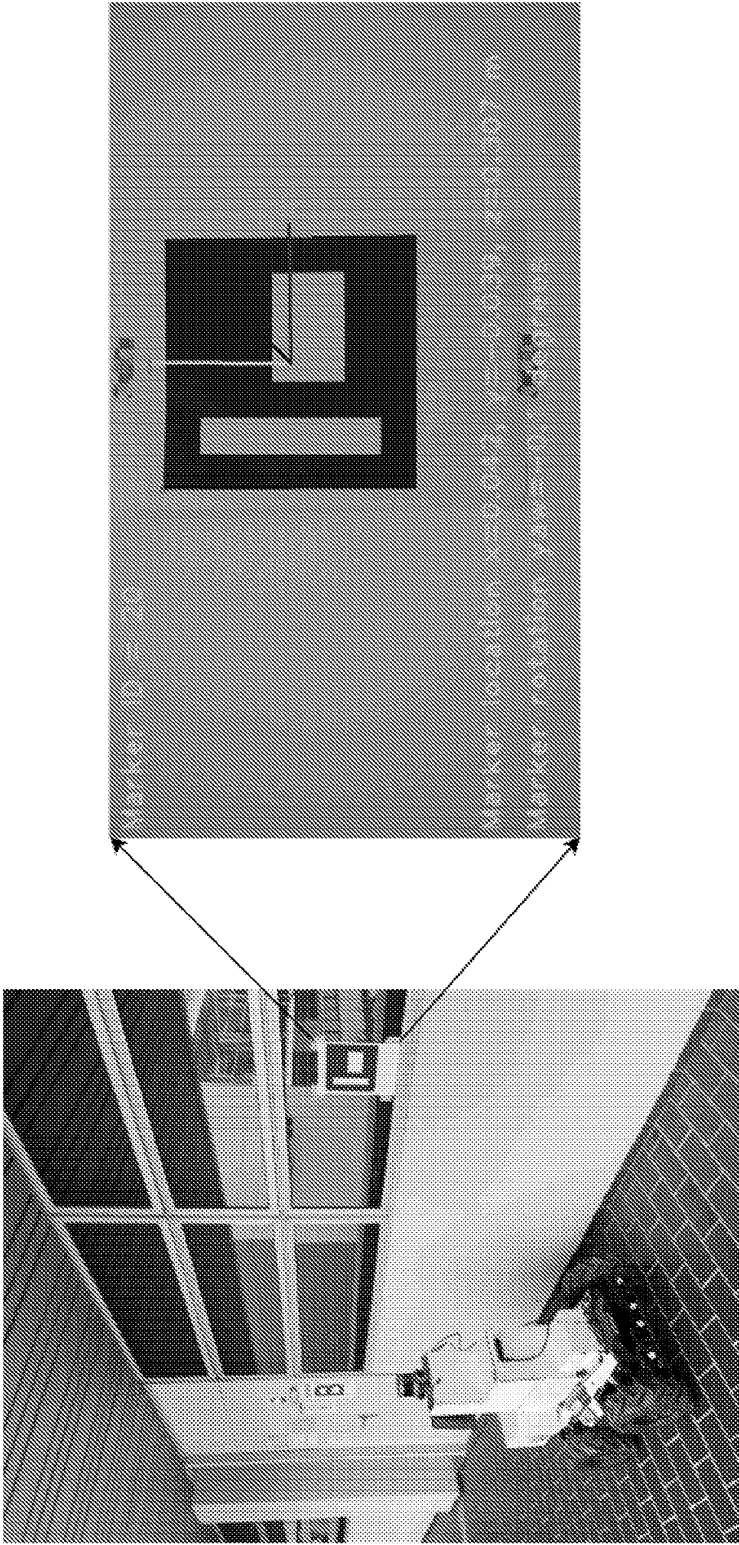


FIG. 38

Table 5

| Starting Positions | Succeed | No. of Markers | Distance (m) | Error           |                    |
|--------------------|---------|----------------|--------------|-----------------|--------------------|
|                    |         |                |              | Positioning (m) | Direction (Degree) |
| P1                 | Y       | 1              | 42.53        | 0.11            | 3.53               |
| P2                 | Y       | 1              | 24.27        | 0.15            | 3.66               |
| P3                 | Y       | 1              | 53.58        | 0.15            | 2.41               |
| P4                 | Y       | 1              | 27.33        | 0.37            | 1.72               |
| P5                 | Y       | 1              | 54.65        | 0.17            | 1.73               |
| P6                 | Y       | 1              | 21.24        | 0.09            | 0.92               |
| P7                 | Y       | 2              | 121.36       | 0.08            | 4.13               |
| P8                 | Y       | 1              | 72.79        | 0.08            | 3.23               |
| P9                 | Y       | 2              | 77.87        | 0.05            | 3.09               |
| P10                | Y       | 1              | 5.05         | 0.08            | 3.63               |
| P11                | Y       | 1              | 55.71        | 0.19            | 3.22               |
| P12                | Y       | 1              | 33.38        | 0.11            | 2.43               |
| P13                | Y       | 1              | 45.52        | 0.28            | 3.81               |
| P14                | Y       | 1              | 56.60        | 0.27            | 1.50               |
| P15                | N       | -              | -            | -               | -                  |
| P16                | Y       | 1              | 79.95        | 0.35            | 1.62               |
| P17                | Y       | 1              | 47.61        | 0.14            | 3.37               |

FIG. 39

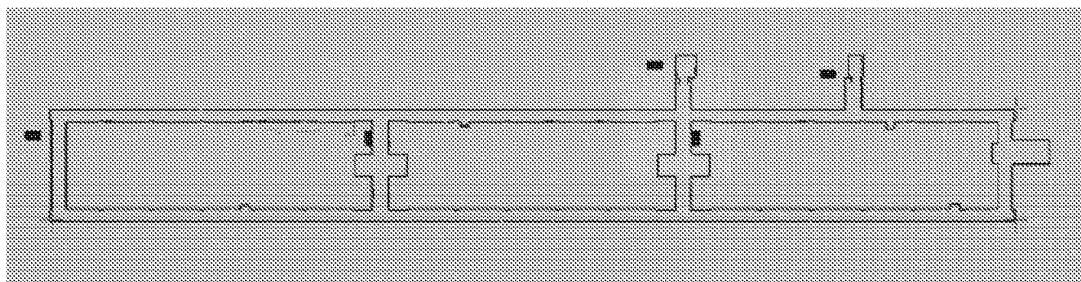


FIG. 40A

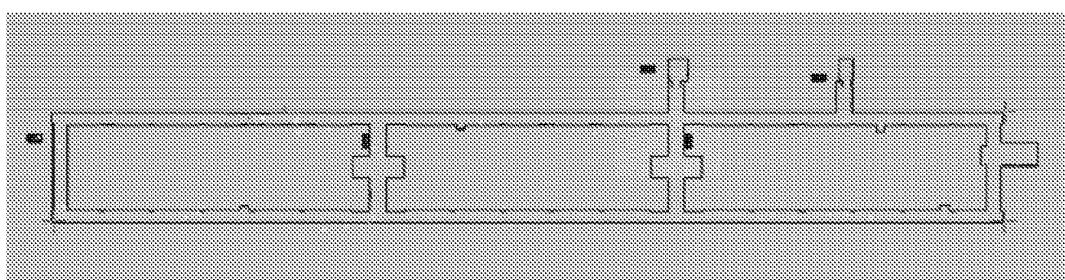


FIG. 40B

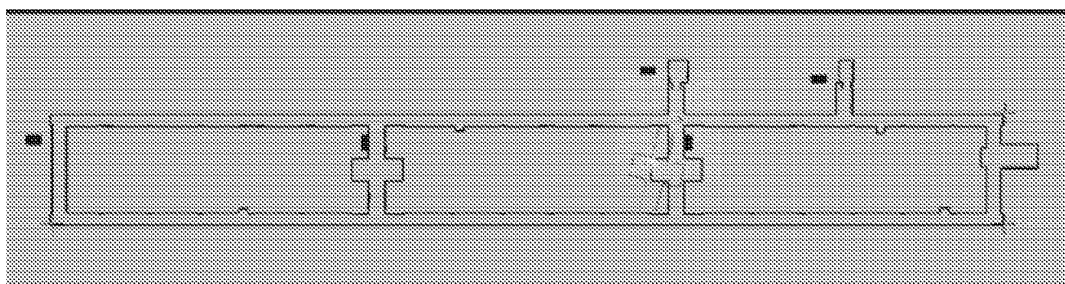


FIG. 40C

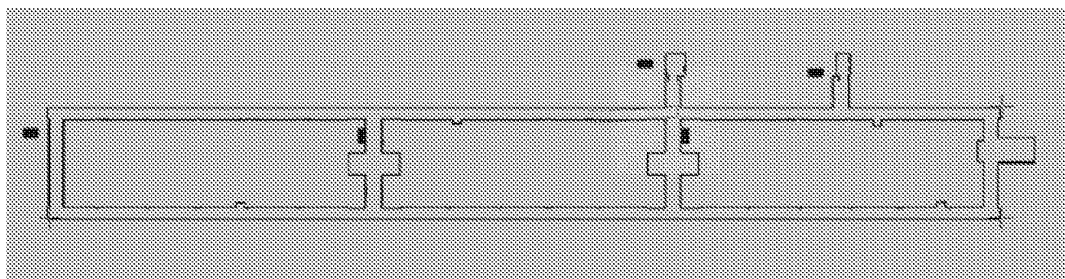


FIG. 40D

Table 6

| Starting Positions | Succeed | Distance (m) | Error           |                    |
|--------------------|---------|--------------|-----------------|--------------------|
|                    |         |              | Positioning (m) | Direction (Degree) |
| P1                 | Y       | 9.15         | 2.38            | 1.14               |
| P2                 | N       | -            | -               | -                  |
| P3                 | N       | -            | -               | -                  |
| P4                 | N       | -            | -               | -                  |
| P5                 | N       | -            | -               | -                  |
| P6                 | N       | -            | -               | -                  |
| P7                 | Y       | 11.12        | 0.16            | 0.67               |
| P8                 | N       | -            | -               | -                  |
| P9                 | N       | -            | -               | -                  |
| P10                | N       | -            | -               | -                  |
| P11                | Y       | 30.40        | 3.26            | 2.21               |
| P12                | Y       | 12.20        | 0.26            | 1.29               |
| P13                | Y       | 5.09         | 0.12            | 2.20               |
| P14                | N       | -            | -               | -                  |
| P15                | N       | -            | -               | -                  |
| P16                | N       | -            | -               | -                  |
| P17                | Y       | 4.05         | 0.05            | 1.06               |

FIG. 41

Table 7

| Methods                          | Success Rate (%) | Moving Distance (m) | Positioning Error (m) | Direction Error (Degree) |
|----------------------------------|------------------|---------------------|-----------------------|--------------------------|
| BIM-based rectification          | 100              | 44.88               | 0.61                  | 8.91                     |
| BIM-based + PF-based fine tuning | 100              | 50.32               | 0.21                  | 1.47                     |
| ArUco marker                     | 94               | 51.21               | 0.17                  | 2.75                     |
| AMCL                             | 35               | 12.00               | 1.04                  | 1.43                     |

FIG. 42A

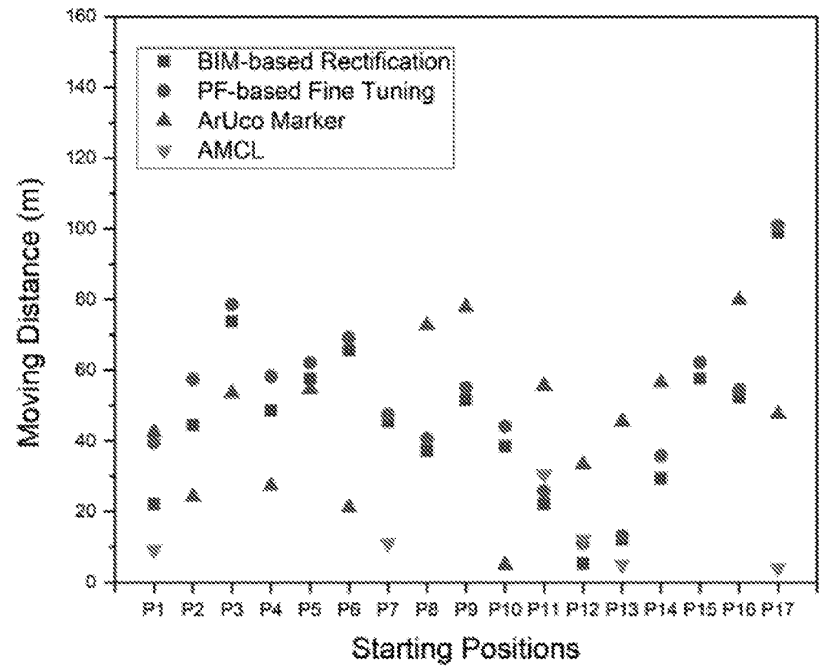


FIG. 42B

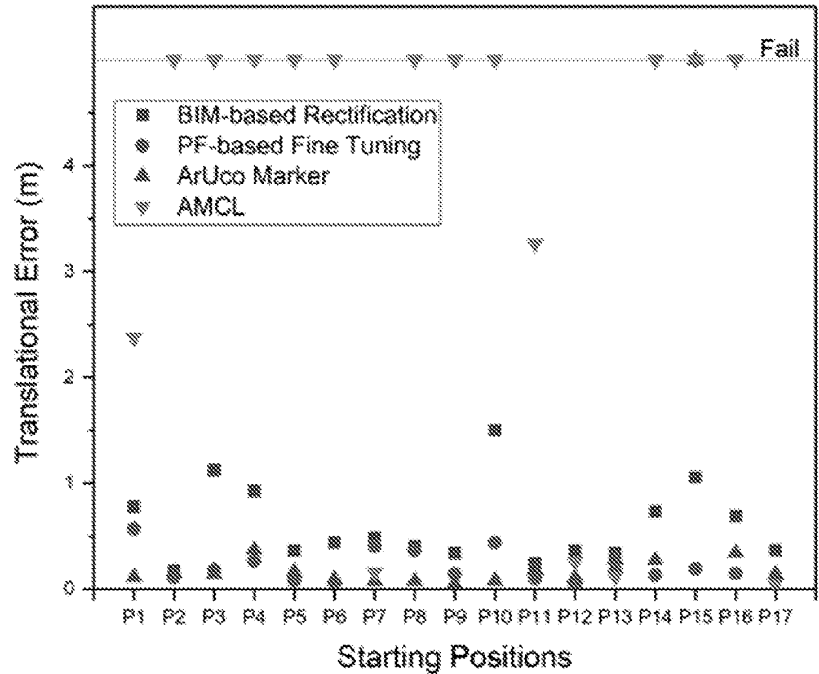


FIG. 42C

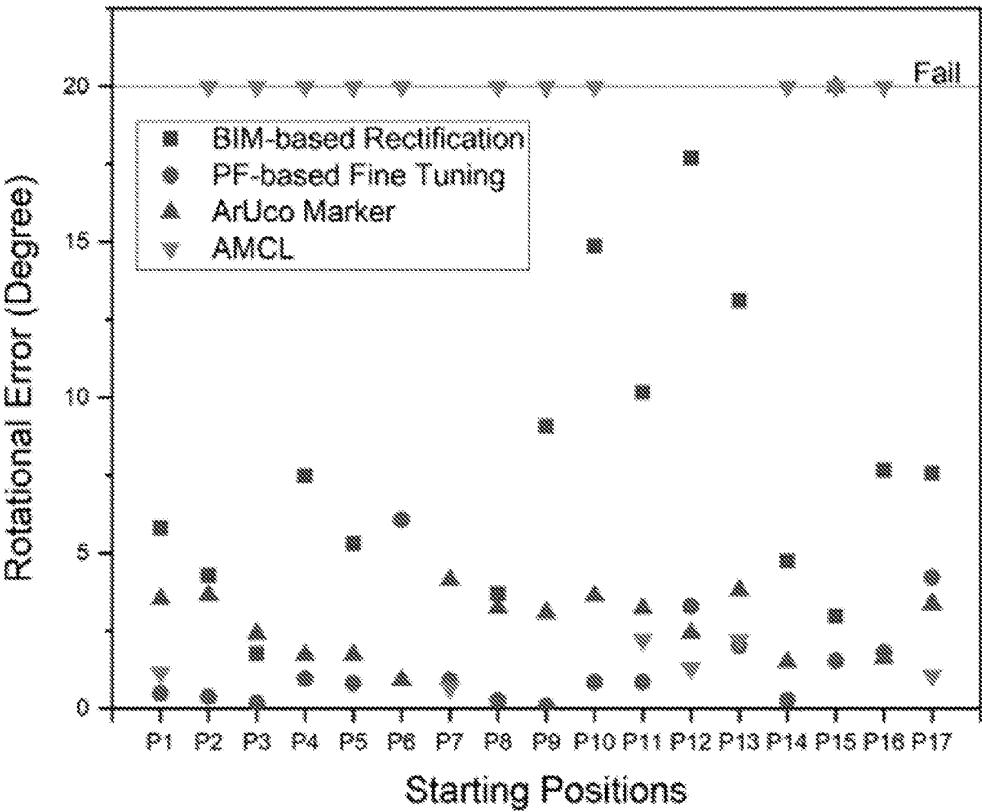


FIG. 42D

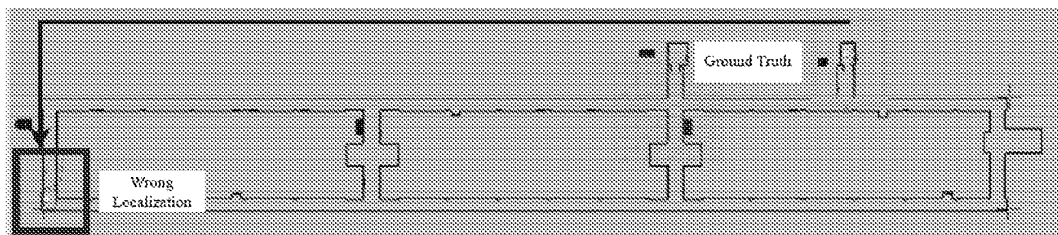


FIG. 43A

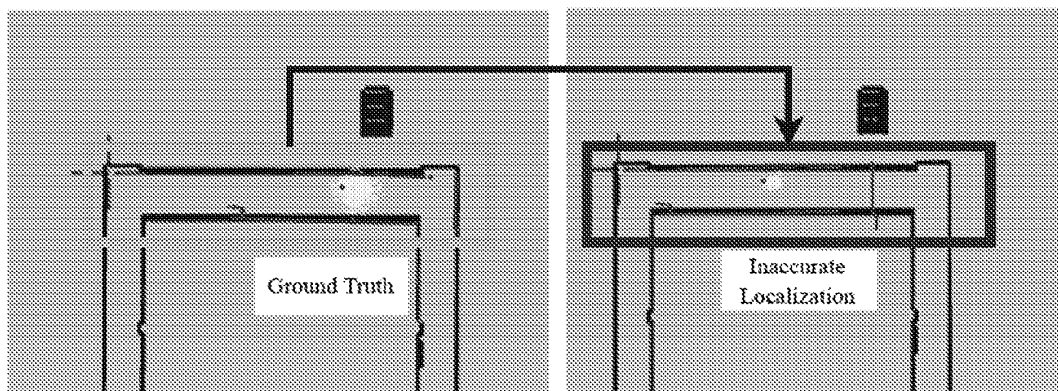


FIG. 43B

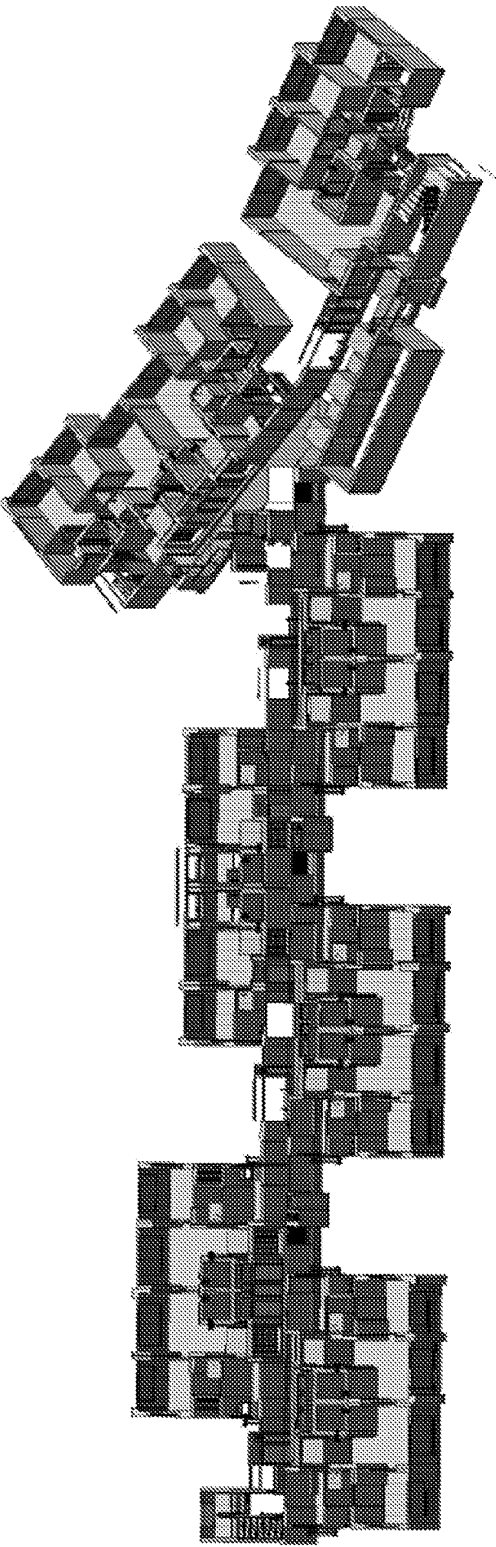


FIG. 44A

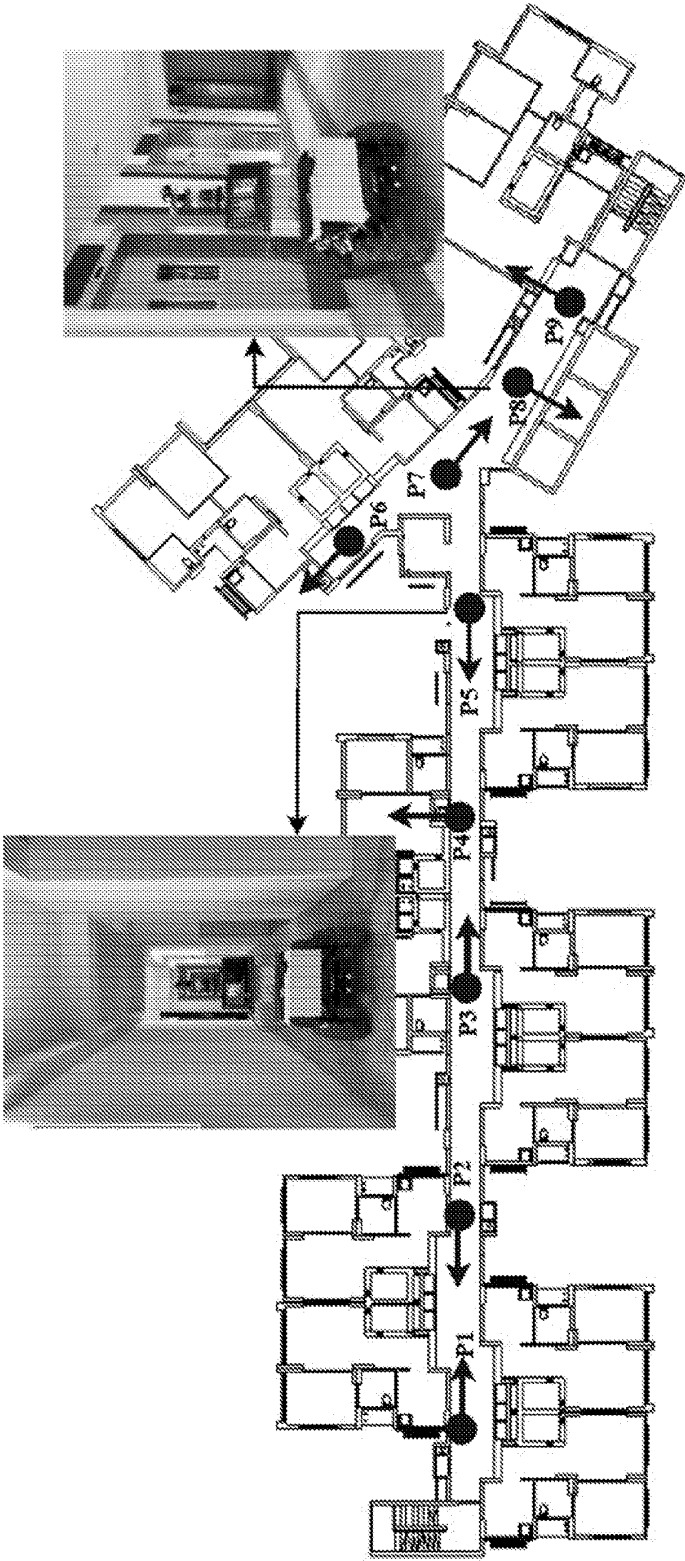


FIG. 44B

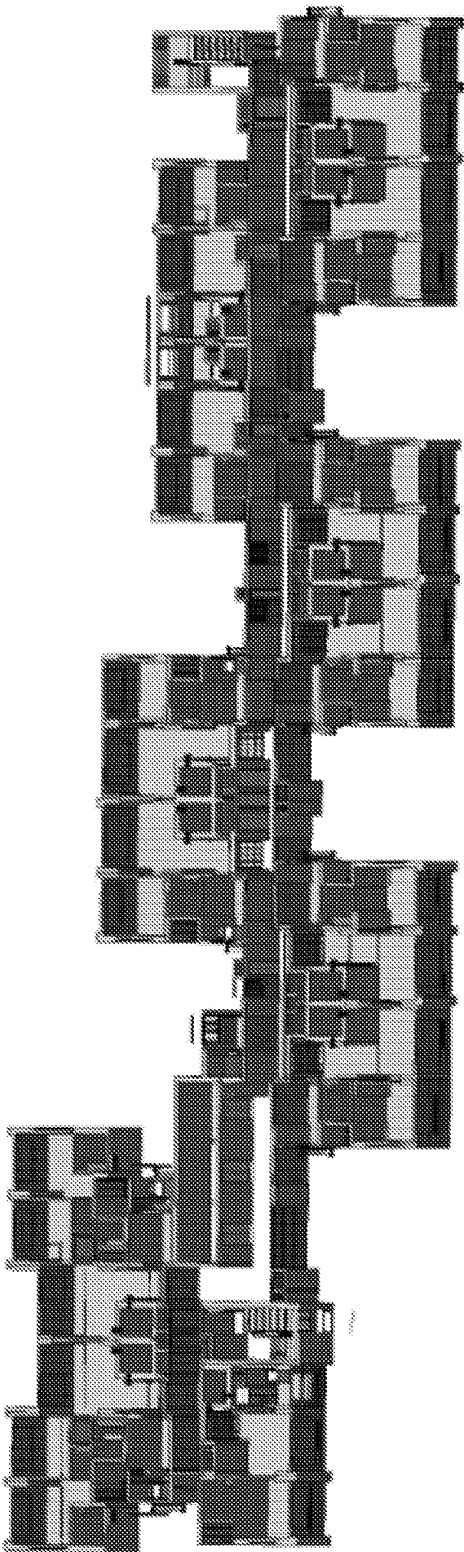


FIG. 45A

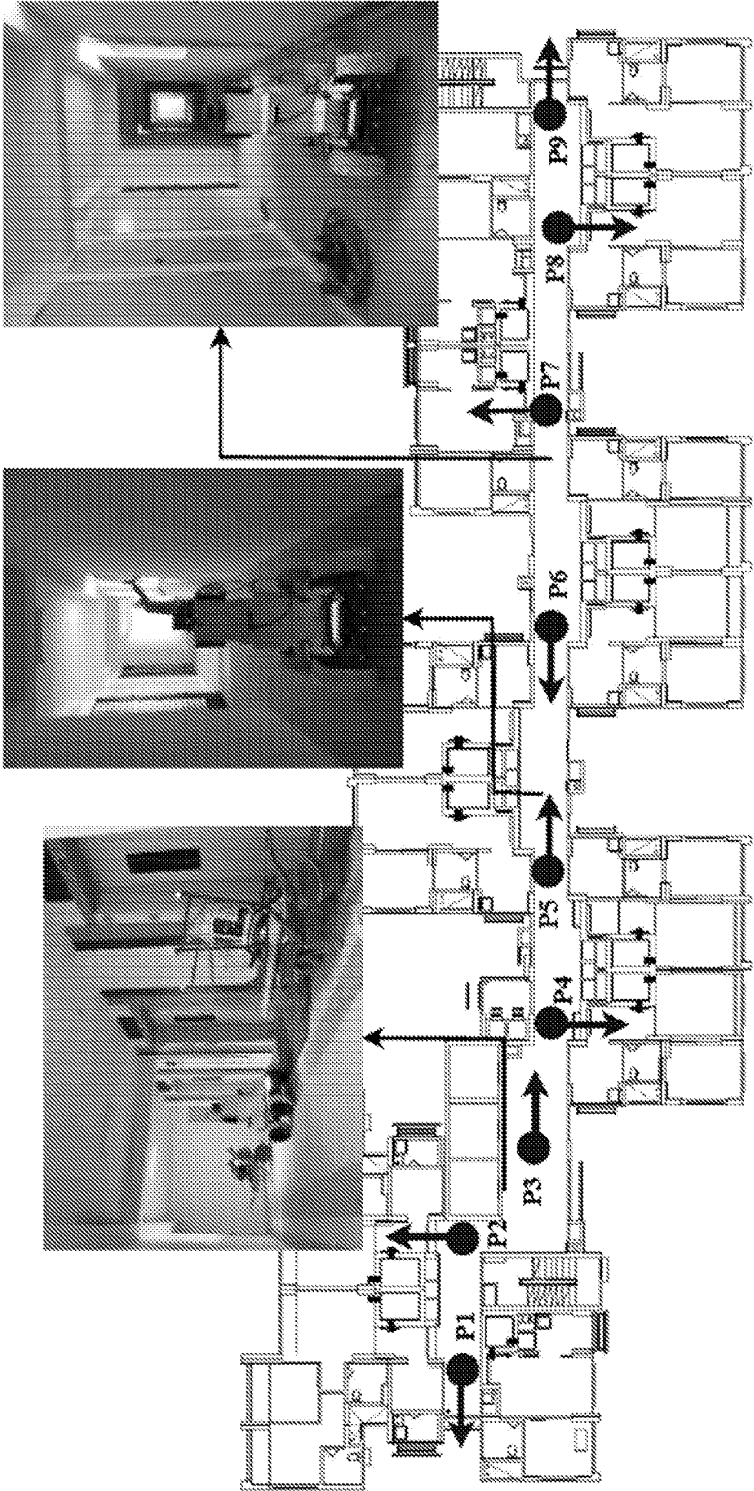


FIG. 45B

Table 8

| Starting Positions | No. of Features | Distance (m) | Error (Before Rectification)<br>Positioning (m) | Error (Before Rectification)<br>Direction (Degree) | Error (BIM-based Rectification)<br>Positioning (m) | Error (BIM-based Rectification)<br>Direction (Degree) | Total Distance (m) | Error (PT-based Fine Tuning)<br>Positioning (m) | Error (PT-based Fine Tuning)<br>Direction (Degree) |
|--------------------|-----------------|--------------|-------------------------------------------------|----------------------------------------------------|----------------------------------------------------|-------------------------------------------------------|--------------------|-------------------------------------------------|----------------------------------------------------|
| P1                 | 4               | 18.19        | 0.64                                            | 15.36                                              | 0.78                                               | 7.59                                                  | 26.27              | 0.18                                            | 3.98                                               |
| P2                 | 5               | 19.21        | 0.69                                            | 16.46                                              | 0.68                                               | 7.41                                                  | 27.29              | 0.09                                            | 2.81                                               |
| P3                 | 6               | 28.31        | 0.39                                            | 2.33                                               | 0.39                                               | 2.33                                                  | 29.32              | 0.05                                            | 3.10                                               |
| P4                 | 4               | 18.17        | 0.15                                            | 1.83                                               | 0.15                                               | 1.83                                                  | 22.20              | 0.21                                            | 1.32                                               |
| P5                 | 5               | 19.18        | 0.52                                            | 13.49                                              | 0.17                                               | 0.92                                                  | 41.41              | 0.13                                            | 0.65                                               |
| P6                 | 5               | 13.12        | 0.18                                            | 0.31                                               | 0.18                                               | 0.31                                                  | 18.18              | 0.14                                            | 1.27                                               |
| P7                 | 3               | 5.05         | 0.41                                            | 3.67                                               | 0.41                                               | 3.67                                                  | 13.10              | 0.09                                            | 5.86                                               |
| P8                 | 4               | 10.08        | 0.19                                            | 2.79                                               | 0.19                                               | 2.79                                                  | 13.10              | 0.12                                            | 1.57                                               |
| P9                 | 3               | 2.01         | 0.78                                            | 17.61                                              | 0.41                                               | 18.14                                                 | 7.05               | 0.10                                            | 1.58                                               |

FIG. 46

Table 9

| Starting Positions | No. of Features | Distance (m) | Error (Before Rectification)<br>Positioning (m) | Error (Before Rectification)<br>Direction (Degree) | Error (BIM-based Rectification)<br>Positioning (m) | Error (BIM-based Rectification)<br>Direction (Degree) | Total Distance (m) | Error (PT-based Fine Tuning)<br>Positioning (m) | Error (PT-based Fine Tuning)<br>Direction (Degree) |
|--------------------|-----------------|--------------|-------------------------------------------------|----------------------------------------------------|----------------------------------------------------|-------------------------------------------------------|--------------------|-------------------------------------------------|----------------------------------------------------|
| P1                 | 4               | 10.06        | 0.29                                            | 4.04                                               | 0.29                                               | 4.04                                                  | 18.11              | 0.17                                            | 0.73                                               |
| P2                 | 6               | 20.19        | 1.13                                            | 35.75                                              | 0.26                                               | 9.46                                                  | 24.22              | 0.14                                            | 1.06                                               |
| P3                 | 5               | 15.20        | 0.55                                            | 21.07                                              | 0.25                                               | 9.81                                                  | 22.26              | 0.16                                            | 2.13                                               |
| P4                 | 6               | 16.13        | 0.94                                            | 18.31                                              | 0.17                                               | 0.66                                                  | 22.16              | 0.12                                            | 0.28                                               |
| P5                 | 6               | 26.30        | 0.33                                            | 7.27                                               | 0.18                                               | 1.88                                                  | 30.32              | 0.16                                            | 1.35                                               |
| P6                 | 7               | 25.22        | 0.67                                            | 7.00                                               | 0.45                                               | 4.15                                                  | 28.24              | 0.17                                            | 0.99                                               |
| P7                 | 3               | 14.13        | 0.42                                            | 7.83                                               | 0.33                                               | 5.54                                                  | 26.21              | 0.23                                            | 1.72                                               |
| P8                 | 5               | 16.18        | 1.65                                            | 40.37                                              | 0.21                                               | 3.96                                                  | 21.20              | 0.04                                            | 0.85                                               |
| P9                 | 4               | 6.08         | 0.99                                            | 24.88                                              | 0.23                                               | 2.73                                                  | 12.13              | 0.17                                            | 1.39                                               |

FIG. 47

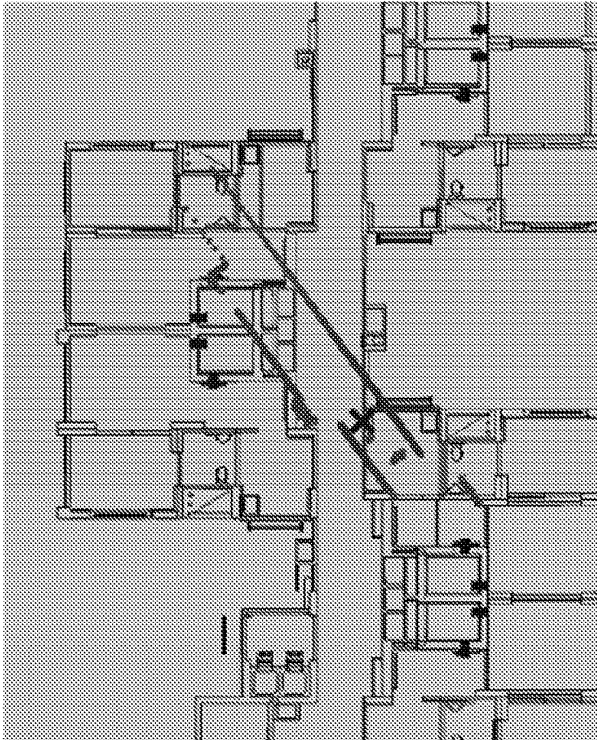


FIG. 48B

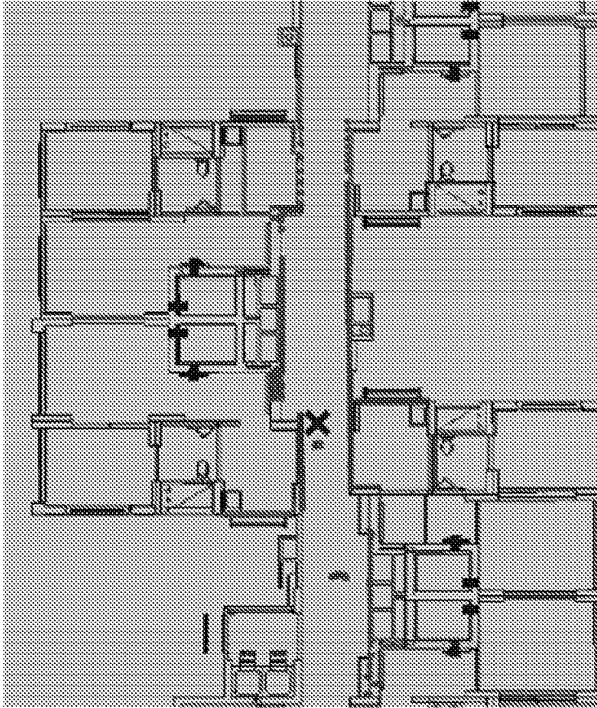


FIG. 48A

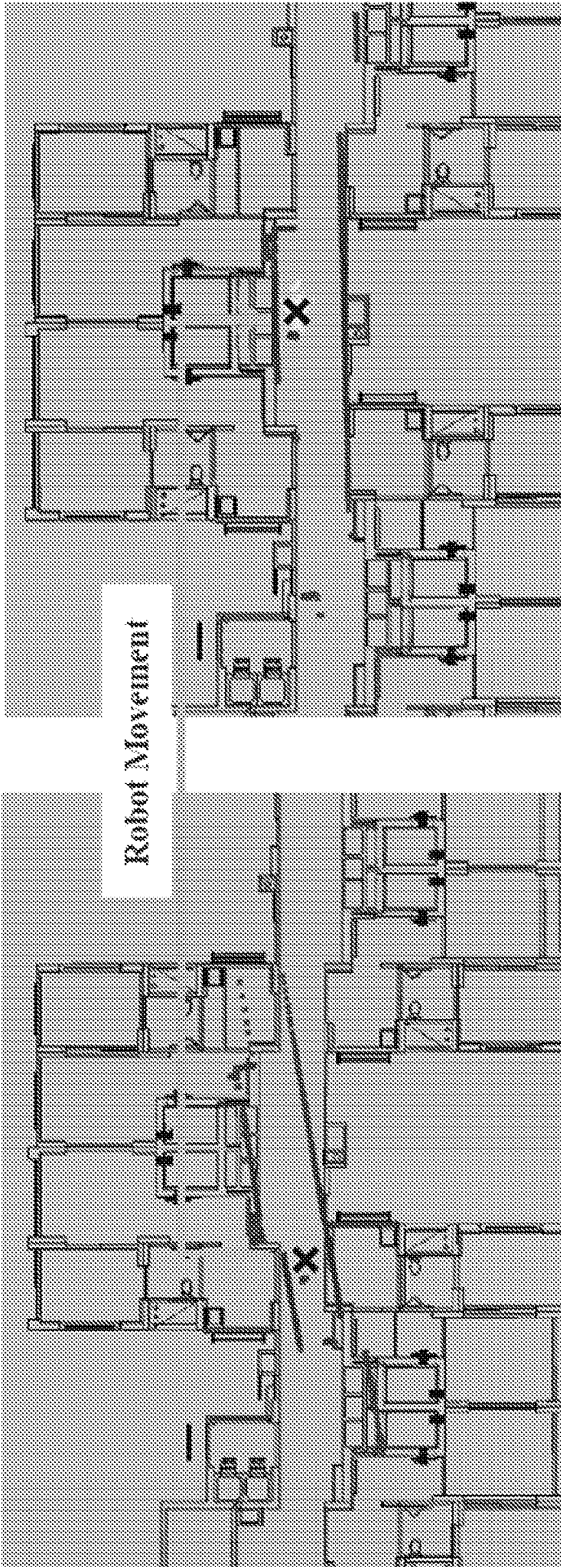


FIG. 48D

FIG. 48C

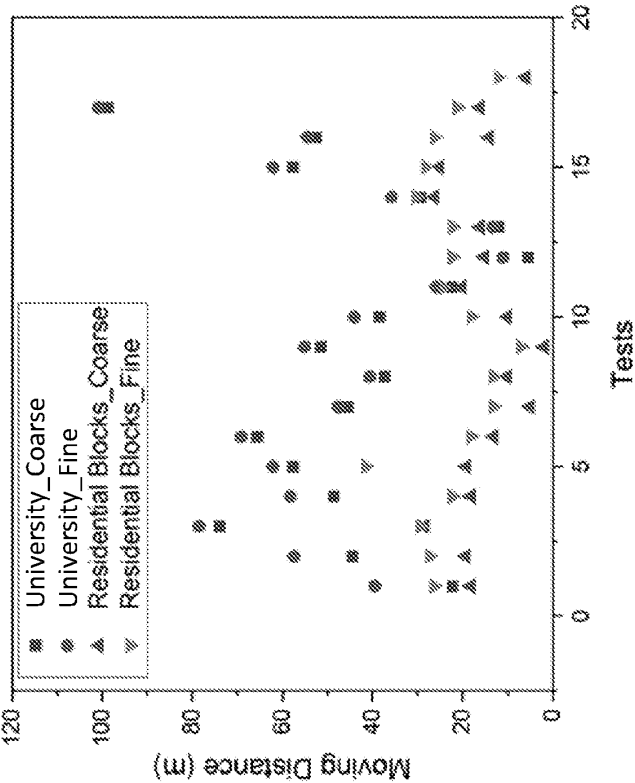


FIG. 49B

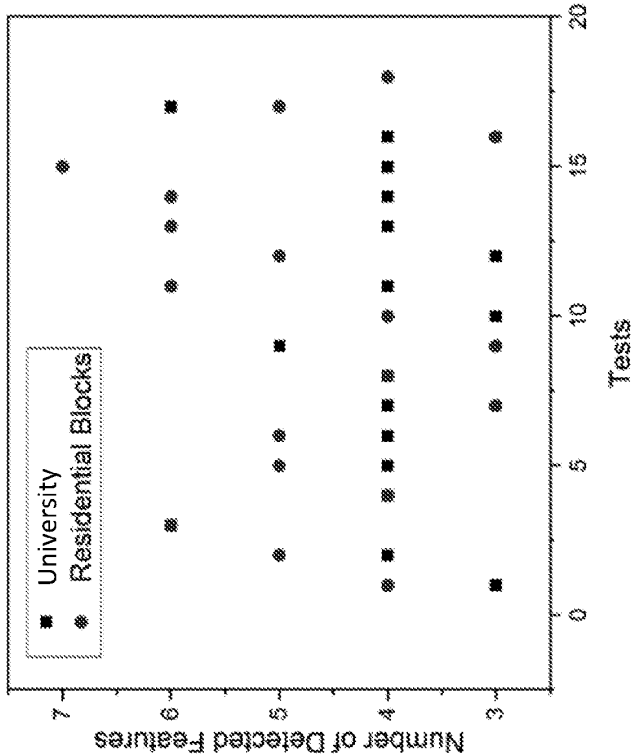


FIG. 49A

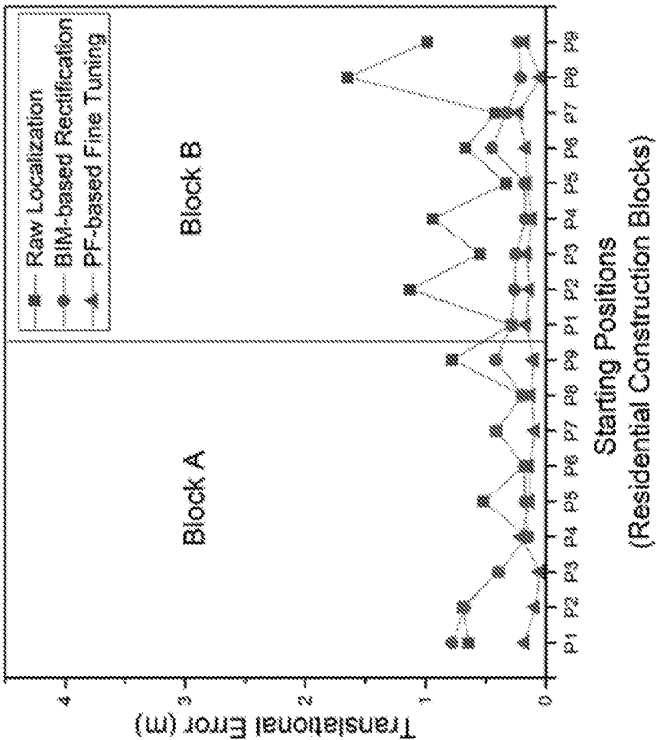


FIG. 49C

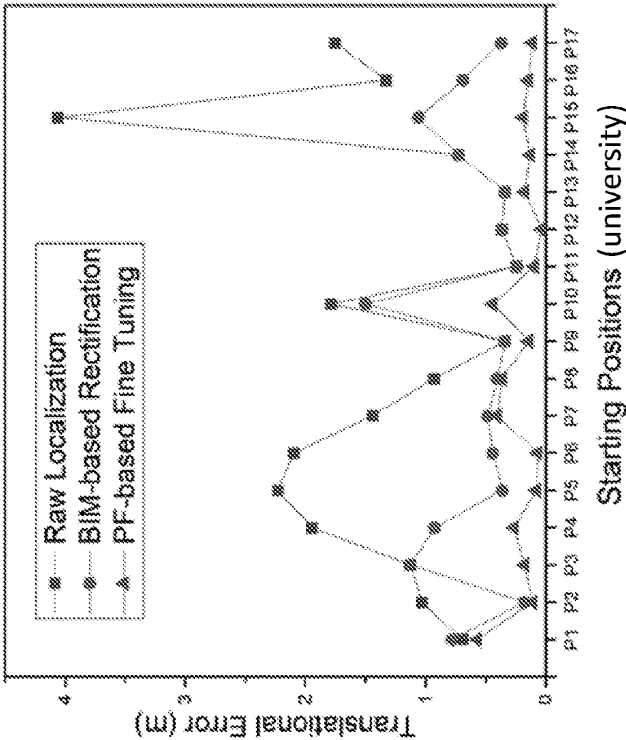


FIG. 49D

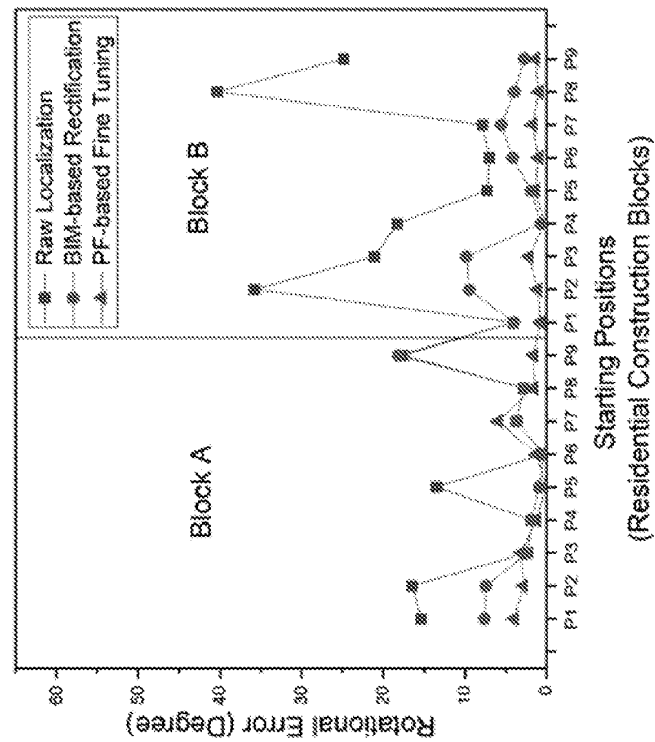


FIG. 49F

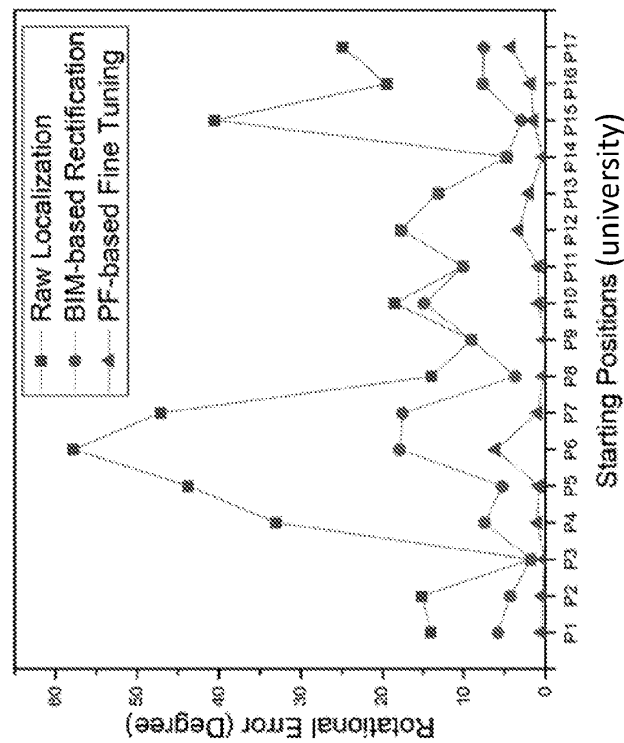


FIG. 49E

Table 10

| Block      | Average No.<br>of features | Average<br>distance (m) | Average BIM-based<br>rectification error |               | Average total<br>distance (m) | Average PF-based fine<br>tuning error |               |
|------------|----------------------------|-------------------------|------------------------------------------|---------------|-------------------------------|---------------------------------------|---------------|
|            |                            |                         | Position (m)                             | Direction (°) |                               | Position (m)                          | Direction (°) |
| University | 4                          | 44.88                   | 0.61                                     | 8.91          | 50.32                         | 0.21                                  | 1.47          |
| BlockA     | 4                          | 14.81                   | 0.37                                     | 5.00          | 21.99                         | 0.12                                  | 2.39          |
| BlockB     | 5                          | 16.61                   | 0.26                                     | 4.69          | 22.76                         | 0.15                                  | 1.18          |

FIG. 50