Long-term Activities for Autonomous Mobile Robot - Autonomous Insertion of a Plug into Real Electric Outlet by a Mobile Manipulator -

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Summary. Mobile robots used in the human-robot coexisting environment are required to perform continuous works without human maintenance. On the other hand, they need a rechargeable batteries that require charge, generally. Therefore, an autonomous battery-charging for mobile robots has a big advantage for performing continuous works. However, installation of exclusive use of battery-charging-stations requires much cost.

To improve this situation, we aim to realize an autonomous battery-charging motion for a mobile manipulator using conventional electrical outlets. In this motion, the robot is navigated to a front of an outlet, and a plug attached at the tip of the manipulator is controlled to insert into the outlet. To realize the motion, we implemented "distance transform method" for navigation, and a motion of plug insertion using force feedback control.

In this paper, we explain the above implementations, and we discuss advantages and limitations of such motions.

Key words: battery-charging, navigation, putting a plug into an outlet

1 Introduction

Mobile robots used in the human-robot coexisting environment are required to perform continuous works without human maintenance. Both (1) mounting batteries and (2) mounting power cables are ways to supply electric power to robots in common cases. In the former case, a free-maintenance time for robot is limited by capacity of its batteries. In the latter case, an activity area of robot is limited by length of cables. Therefore, autonomous battery-charging systems for mobile robots has a big advantage to perform autonomous and continuous works. So, in this research, we aim to realize an autonomous battery-charging system for an autonomous mobile robot to enable long term activity of it.

There were several researches that aimed to realize long term activities of autonomous mobile robots. Yuta's work aimed to realize long-term activities for autonomous mobile robot including battery-charging motion [6]. Milo developed a docking station for recharging of autonomous robots [7]. Recently in commercial robots, there are some robots that have an autonomous recharging function, e.g. Roomba [8], AIBO [9]. However, in the above cases, exclusive battery charging stations are used. Usually, an installation of such stations requires cost.

In this research, our final goal is to realize an autonomous battery-charging motion for autonomous mobile manipulators using common electrical outlets in an actual environment. It requires motions of "navigation" and "putting a plug into an outlet". The robot is navigated to a front of an outlet, and a plug attached at the tip of the manipulator is controlled to insert into the outlet. To realize the motion, we implemented "distance transform method" for path planning of a base robot and a motion of plug insertion using force feedback control.

In this paper, we explain implementations of both navigation and plug insertion, and discuss advantages and limitations of such motions.

2 Problem definition and Assumption

To realize long-term activities for autonomous mobile robots, there are many research topics (e.g. re-scheduling tasks, an architecture of operating system and so on). In this research, we focus on a basic function "autonomous battery charging", and we set our objective motions as "(1) autonomous navigation and (2) putting a plug into outlet". Assumptions of these motions are as follows.

- A type of target robot is a mobile manipulator.
- A plug is installed at the center of the manipulator's hand.
- A target environment is our laboratory.
- Location of an objective outlet is known.
- An initial position of the robot is known.
- No marks and guides are installed in the target environment.

These assumptions are proper because the target environment is a human-robot coexisting environment and the cost of altering an environment should be reduced as much as possible. Additionally, an usual mobile robot working in indoor environments can have a map.

A view and a layout of the target environment are shown in Fig.1 and Fig.2. This is one of common office environments, and some outlets exist in walls.

Fig. 1. Photograph of the environment

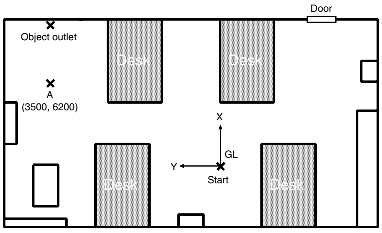

Fig. 2. Layout of the environment

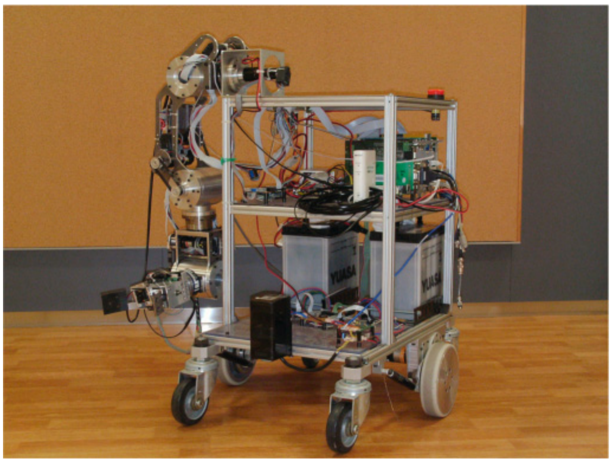

Fig. 3. Target robot (Autonomous mobile manipulator)

3 Target robot

Target robot used in this research is an autonomous mobile manipulator. A view of the robot is shown in Fig.3.

1. Base robot
   The size of the base robot is 56[cm] in width, 71[cm] in depth and 80[cm] in height. The weight is about 30[kg] which includes two batteries. Controllers and normal sensors are contained in the robot's body to be self-contained robot. It has a power-wheel-steering for locomotion.
2. Manipulator and hand
   The 6 D.O.F. manipulator is mounted at the right of the base robot. It is a PUMA-configuration which was produced in our laboratory (made by aluminum). At the tip of the manipulator, a two finger hand is installed

Fig. 4. 2-D Range sensor

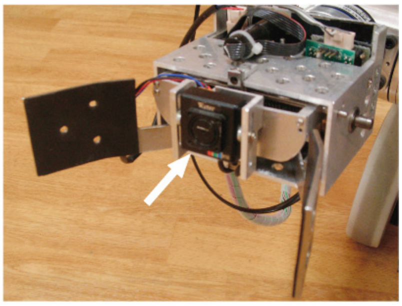

Fig. 5. Vision sensor and hand

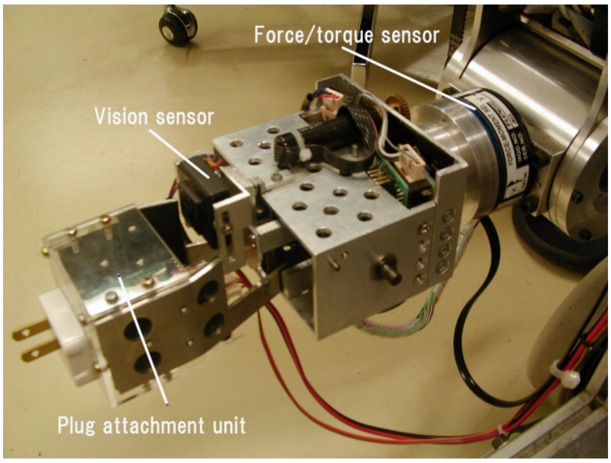

Fig. 6. Plug attachment unit and force/torque sensor

shown in Fig.5. A force/torque sensor is installed between the manipulator and the hand shown in Fig.6.

3. Plug attachment unit
   A plug attachment unit for battery charge is installed at the center of the hand (Fig.6). It contains a tilt sensor ADXL202AE (ANALOG DEVICES corporation) to adjust the unit's posture. Currently, the plug is a dummy.
4. Force/torque sensor
   The force/torque sensor is IFS-67M-25A 25-1 (Nitta corporation) which can detect 3 dimensional force and 3 dimensional torque. It is used for (1) force feedback control of manipulator and (2) detection of plug insertion in this research.
5. Vision sensor
   A small CCD camera WAT-230 (Watec) is installed in the center of the hand as a vision sensor. It is used to recognize the relative position of the

objective outlet to adjust hand's position. The vision sensor is lifted up mechanically to keep its view area when the finger is closed. The function can be seen in Fig.5 and Fig.6.

6. Range sensor
   Two dimensional range sensor PB9-11 (Hokuyo automatic corporation) is installed in front of the base robot (Fig.4). It scans 81 steps of half-circle area to measure length to objects using LED beam. It is used for acquiring environment information and position adjustment for the base robot.

4 Autonomous navigation

The robot should move to the closest outlet when it requires battery charging. In our assumption, the robot can have a map of the target environment and information of outlet locations in advance. However, because of movable chairs and other obstacles, sensor based navigation is necessary. In this section, we introduce an implementation of sensor-based path planning using a range sensor.

4.1 Path planning

The start position and the outlet position (goal position) are assumed to be known. On the other hand, we assume that a map of the environment is unknown because of movable chairs and other obstacles. Considering these assumptions, we apply distance transform method [3][4] for a sensor based path planning to navigate the robot to the goal position.

Usually, the method assumes that the environment is fully known. Instead, we use a range sensor to detect local environment information to plan local path. A concrete procedure of distance transform method is shown as follows.

Firstly, the local area (within sensing range) is divided into small grids to generate a grid map, and each grid has a binary information (free or occupancy). Basically, each grid's information is detected by range data measured by the two dimensional range sensor. Additionally, the obstacle area is expanded with consideration of the robot's size, and grids in the occluded area from the robot are registered as occupancy. Fig.7 shows an example of this procedure. In this implementation, the local area is set as $3[m]$ in length and $2[m]$ in depth, and each grid size is set as 10[cm] square.

Secondly, distance transform method is applied to the grid map from the goal position to generate the shortest path. If the goal position does not exist in the grid map, a sub-goal is set at the furtherest position in free grids from the robot's position.

Thirdly, the robot navigates along the planned path to the goal (or sub-goal) based on odometry information. The above procedure is repeated until the robot arrives at the goal, as shown in Fig.8.

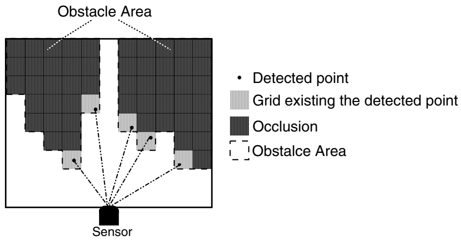

Fig. 7. Registration of grids' property

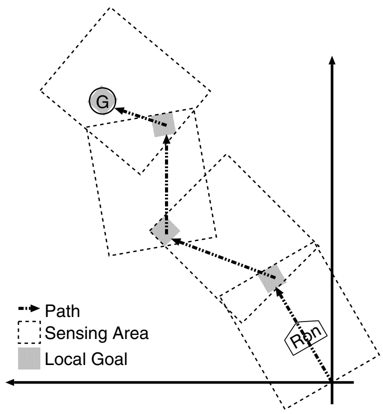

Fig. 8. An overview of repeating procedure

4.2 Adjustment of position and orientation

Theoretically, the robot reaches the goal position exactly if it follows the planned path. Practically in the real environment, it is impossible because a positioning error accumulates due to the error of the wheel diameter, the slippage between wheels and the ground and bumps of the ground. Therefore, an adjustment motion of the base robot's position is necessary for reduction of the error for plug insertion.

In this research, the robot adjusts its position and orientation by detecting distance to the wall and inclination of the wall (using two dimensional range sensor) when the robot arrives at the goal position. Hough transform method is used to abstract the wall's line from the range data (Fig.9).

4.3 Navigation performance in real environment

We implemented the above method on the target robot, and executed the planning and navigation in the target environment. The total length of the path was about 5 [m], and there were some chairs and desks on the way to

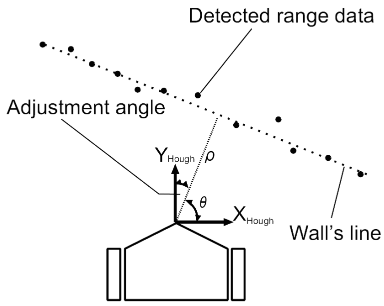

Fig. 9. Adjustment motion using Hough transform method

the goal position in this environment. By repeating the planning and navigation experiment in the same environment, the successful ratio to come to the vicinity of the outlet was about 60%.

4.4 Discussion in failure cases of the navigation

- **Problem of obstacle detection**
  In this research, obstacles are detected by the range sensor, and the sensor (installed at the height of 20[cm]) does not cover obstacles in high position. The lack of the sensing ability causes collision to such obstacles. To solve the problem, additional range sensors can be effective.
- **Problem of local goal selection**
  The algorithm does not guarantee a completion of a path planning of the base robot, even if a path exists. One of the big reasons is that the range sensor is impossible to detect occluded area. We tried to avoid such situations in several heuristic methods, but the navigation sometimes failed because of a selection of useless local goal in some failure cases.
- **Problem of the error of odometry**
  In this implementation, position adjustment of the base robot is performed when the robot arrives at its goal. However, the robot sometimes did not reach the goal position because of the accumulated error. To solve such problems, the robot should adjust its position using some landmarks while it navigates to the goal position.

5 Putting a plug into an outlet

After arrival of the robot in front of the target outlet, it puts a plug into the outlet using the manipulator's motion. In our assumption, the robot knows a position of the outlet, so the insertion can be completed by the pre-planned motion theoretically. However, practically, the adjustment of hand's position and force feed-back control are necessary because of positioning error of the base robot. Therefore, the following element motions are required to realize an autonomous battery charging : (1) position recognition of an outlet, (2) adjustment of hand's position, (3) a motion of plug insertion with force-feedback control and (4) judging completion of the insertion. The element motions are introduced in the following sections.

5.1 An outlet recognition

To adjust the hand's position, the robot recognizes an outlet position using vision sensor which is installed at the hand. A conventional template matching method is used to recognize the outlet. The matching calculation is performed in IP5000 vision board (Hitachi Corp.) that uses normalized correlation technique.

Fig.10 shows the template image which is acquired in advance, and Fig.11 shows an example of matching result. Once the robot stops parallel to the wall correctly and the target outlet is located in the camera's image, it is almost 100 percent successive ratio for the matching procedure in our experimental setup. That is because the template image includes good texture for template matching.

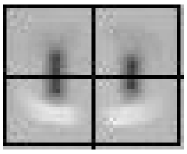

Fig. 10. The template image

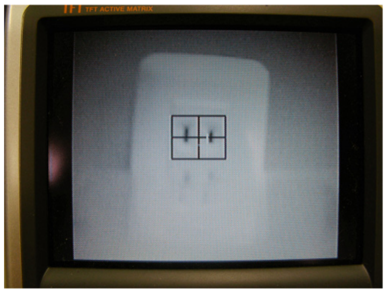

Fig. 11. An example of matching

5.2 Adjustment of hand's position

After the recognition of the outlet, pixel distance between the center of the image plane and the outlet position can be transfered into the actual length as a relative error of the hand's position. It is the unique value because the robot knows the distance from the hand to the outlet. Using the relative error, the robot adjusts the hand's position to align to the target outlet. However, we faced another problem as follows.

In the real motion, the error of the hand's pose still remain due to the backlash of the manipulator and a small tilt of the base robot. Sometimes this error is fatal and the robot can not perform the inserting motion with the error. Fig.12 and Fig.13 shows an example view of this problem.

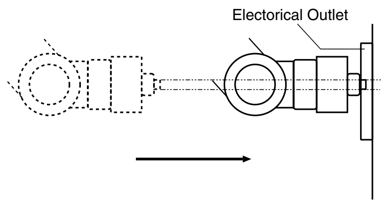

Fig. 12. Insertion without error

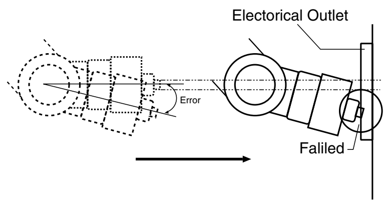

Fig. 13. Insertion with error

Usual approach to solve such problem is to improve accuracy of the hardware. However, such improvement has a limitation, and increases robot's weight that is not suitable for small indoor robot.

Instead of improvement of the hardware, our approach is to install tilt sensor at the plug attachment unit to keep hand's posture parallel to the ground.

5.3 Motion of plug insertion

We separated a plug insertion motion into 2 stages:

Stage 1: Approaching motion of the hand parallel to the ground.
Stage 2: Motion of putting the plug into the outlet.

In the stage 1, the hand is traced along the straight line to the center of the outlet without force-feedback control (Fig.14). When the plug contacts to the outlet, the contact force can be detected by the force/torque sensor, and the robot switches to the stage 2. In this stage, force feed-back control is applied to compensate large contacting force, shown in Fig.15. It is a very simple force-feedback control, the detected force values at the tip of the manipulator are converted into differential angles of joints (calculated by the inverse Jacobian matrix), and the angles are added to the reference angles of the joints.

Since there is a dent around the hole of conventional outlet to make plug insert easy for human, the motion of plug insertion can be performed to slide along the dent, using force-feedback control.

5.4 Judgement of completion of the insertion

In this research, we use force data measured by the force/torque sensor for a judgement of completion of the insertion. We implemented both a passive method and an active method for the judgement, shown as follows.

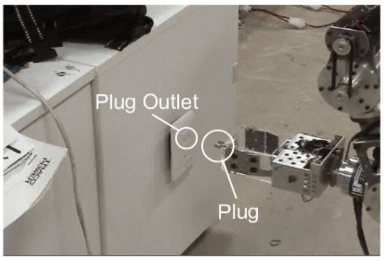

Fig. 14. Adjustment without compliance motion

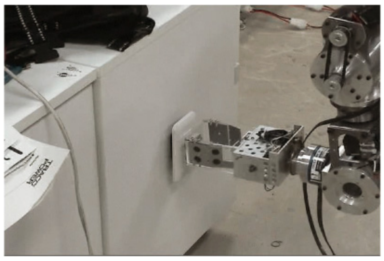

Fig. 15. Insertion with compliance motion

Judgement using passive method

The passive method is to use a log of force data during the motion of plug insertion. Force data log of z axis (the same direction as perpendicular to the outlet) in a typical successful case is shown in Fig.16, and force data log of z axis in a failure case is shown in Fig.16. Both the data were logged when the hand is controlled along a straight line with a manual position adjustment.

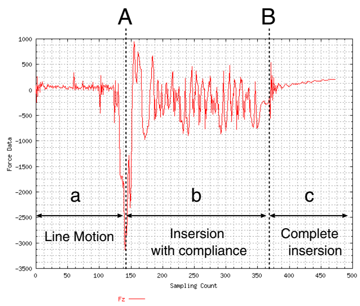

Fig. 16. Force data of successful case

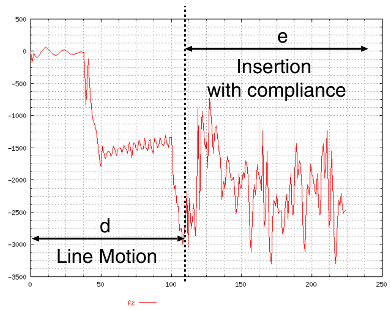

Fig. 17. Force data of failure case

Features of the above cases are shown in the following.

[a :] In the stage 1 of successful case, the swing of the data is not so large.
[b :] In the stage 2 of successful case, the data is oscillated due to force-feedback control.
[c :] After completing insertion of successful case, the change of the force data increases linearly.
[d :] In the stage 1 of failure case, detected force does not exceed the threshold even if the plug contacts to the outlet in this example.
[e :] In the stage 2 of failure case, the force data is continuously increasing in average and the swing of the data does not converge.

The big difference feature is the data in the stage 2 ([b] and [e]). The log pattern in the successful case [b] is oscillated around the initial value, because the plug is inserted correctly. On the other hand, the log pattern in the failure case [e] is oscillated around the offset value, because the plug always push the outlet. Using this feature, the robot can judge completion of the insertion.

Judgement using active method

In our experiences, the passive judgement using force sensor sometimes gives a wrong answer. To confirm the plug insertion, we implemented the active method which uses additional motion of the hand.

If the plug is inserted correctly, the plug and the outlet are united. Therefore, when the robot tries to rotate the hand, the large torque can be detected at the wrist of the hand because the plug can not move. It is performed when the robot finishes inserting motion.

It is very simple and powerful method for judgement of completion of the insertion.

5.5 Plug insertion performance in real environment

We implemented the above method on the target robot, and executed the plug insertion motion in the target environment. The initial position of the base robot was set by eye measurement. By repeating the motion, the successful ratio to insert the plug was about 40%. Note that we counted failure case when the robot detected a failure of plug insertion.

5.6 Discussion in failure cases of the plug insertion

- **Problem of the recognition of the outlet**
  When the robot recognized the outlet, sometimes the template matching method was not succeeded in. We guess that the brightness in the environment was changed. (The normalized correlation technique did not work well in this case.) To solve the problem, installing a flashlight at the hand is effective to keep brightness constantly.
- **Problem of a lack of the stiffness at the manipulator base**
  When the manipulator is stretched (or the manipulator is overhanged from the base), a physical deformation of the base of the manipulator occurs due to the lack of the stiffness at the base part. This is a peculiar problem of our hardware, and it affects to successful ratio in large. A part of the problem can be adjusted by the tilt sensor shown in the section 5.2, but we will improve the part of the manipulator base.

6 Conclusion

In this research, we assume our research objective as "autonomous battery charging using common outlets" to realize the long activity for a mobile robot. We separated the motion into two sub-motions, "autonomous navigation" and "motion of plug insertion", and reported each implementation and performance using a real robot. Currently, the two motions are performed separately, and the integrated motion is very low level in the successful ratio. One of the reasons is that the positioning error of the base robot in navigation disturbs the start of motion of plug insertion.

Although the successful ratio is currently not enough practically, we guess that the ratio can be increased very much by fixing the problems shown in this paper. Therefore, our future work is to search and to fix problems by using a real robot in a real environment. Finally we aim to realize long term activity for mobile robot.

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