Autonomous Battery Recharging for Indoor Mobile Robots

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Abstract

This paper describes a method for automatically recharging the batteries on a mobile robot. The robot used in this project is the Nomadic Technologies? Nomad XR4000 mobile robot. The battery recharging system was implemented using the robot's built-in sensors to control docking with a simple recharging station. The recharging station has an AC power plug, an infra-red beacon and a target designed for detection by the Sick Laser Range Finder. The robot's IR sensors perform the beacon detection. The robot moves towards the beacon until the laser target pattern is visible to the Sick laser. The system is currently under development and undergoing its performance testing.

1 Introduction

A mobile robot is being prepared at the Australian National University for teleoperation using a Web-browser fom the Internet. It is intended that the robot will be available to operators continuously with only occasional local intervention required. With a battery life of approximately 6 hours the requirement for occasional intervention can only be achieved if the robot is provided with a method for automatic recharging. This paper describes the development of the required automatic recharging system.

1.1 Background

In the late 1940's, Grey Walter developed the first autonomous recharging mobile robots, named "Tortoises" [Walter, 1953]. These robots had light following behaviour that is used for his neurological research. An important feature of these robots was autonomous recharging. Walter had created a recharging hut that contains a light beacon and a battery recharger that makes contact with the robot when the robot enters the hut.

More recently, University of Tsukuba have been implementing an autonomous recharging mobile robot, named Yamabico-Liv [Yuta, 1998]. Its robust navigation system that includes error adjustment and environment map, guides the robot into its recharging station. The robot has special hardware that enables the electric contact to the battery recharger.

Another tour-guide robot was developed at the Robotics Institute of Carnegie Mellon University. The robot named Sage is a modified Nomad XR4000 which provides tours around the Carnegie Museum of Natural History [Nourbakhsh, 1998]. It is also capable of autonomous recharging by using a CCD camera and a 3-D landmark placed in the environment. The landmark is located directly above the plug and it guides the robot's position for reliable docking.

1.2 Concept

An example of navigation used for our system is similar to an aircraft landing. When the aircraft approaches an airport for landing, it does not begin to align to the runway until it enters the primary control zone nearby the airport. Within the zone, the air traffic controller will nominate a runway and guide the aircraft direction for alignment with the runway. A similar concept is applied to robot recharge docking. The robot approaches the recharging station and begins to align itself to the AC power plug when the alignment guidance is visible. Therefore, the solution to this project is divided into two sections, long distance approach, and close approach for an accurate alignment.

1.3 Robot

Although there are many possible solutions towards autonomous recharging of a robot, the constraint of minimum hardware modification to the robot restricts the range of solutions. For a mobile robot that is capable of autonomous recharging must have following hardware characteristics:

?? An on-board battery recharger if it is powered by rechargeable batteries. Alternatively, battery connectors those link to a stationary recharger at a recharging station;

?? ability to move with accuracy;

?? and sensors to guide its position with accuracy.

Figure 1: The Nomad XR4000 indoor mobile robot

Nomadic Technologies? Nomad XR4000 mobile robot has met the criteria for self-recharging. It has an on-board battery recharge to support four heavy-duty 12VDC lead-acid batteries, hardware controlled holonomic-drive system, and a number of different sensors for navigational applications. It weighs 150kg, diameter of 62cm and height of 85cm. The plug used in the recharging is the standard IEC plug. The AC socket for the Nomad XR4000 robot had been moved directly below the Sick laser range finder to simplify the positioning problem.

1.4 Sensors

The sensors used are the 48 short-range infra-red proximity sensors surrounding the robot, and a Sick LMS-200 laser range finder fitted as a manufacturers option in the body of the robot with a 180? viewing angle, as shown in Figure 2.

Figure 2: Nomad's Door-mounted - Bumper, IR and Sonar sensors, and the Sick LMS-200 laser range finder.

It was found that the IR sensors can detect change in infra-red lights up to 7m away, hence they were used for long distance beacon detection. The Sick laser range finder has range up to 120m at the lowest resolution. However, for our application shorter range of 8m with high resolution of 0.5? in angle and 1mm in distance, was used as the short-range alignment sensor.

1.5 Recharging Station

The recharging station has targets for robot's sensors and the power plug. Using the properties of the sensors, targets were designed to create a unique landmark. The recharging station, as shown in Figure 3, consists of an IR beacon for the IR sensors, and a "Grid" as a target for the Sick laser. Software was developed for detection of these targets. The algorithm consists of detection of the target and moving towards the target to position the robot at the required accuracy of ?1mm before the plug insertion.

Figure 3: The recharging station

A generic IEC power plug holder was designed to provide flexibility in the plug insertion, reduce in sparking, and compliance for the accuracy required. It is also designed to adjust plug height, and to fit varieties of plug designs.

The hardware for the recharging station costs under $300 and is designed for ease of manufacturing, with readily available materials.

Other compliance mechanisms or electrical contacts were considered. However, it is required to be well-insulated for the safety, since 240VAC is used for the recharging.

1.6 Paper Outline

In this paper, Section 2 discusses the relationship between the sensors and their target designs. The details of the short-range target alignment, long-range beacon detection and their performances are presented in Section 3, followed by concluding remarks.

2 Long Range Approach

The Nomad's built-in IR sensors are used to detect the IR navigational beacon. A long-range navigational beacon is designed to exploit the IR sensor characteristics.

2.1 Long Range Beacon

The IR sensors on the Nomad are used to sense proximity within the range of approximately 0.5m. The robot emits IR radiation that is reflected from nearby objects. The IR sensor detects change in IR intensity. A value of 0 to 255 is returned depending on the intensity of the IR signal detected. While it is normally used as a short-range proximity detector, we found that by using reflective tape, IR radiation is reflected at greater distances up to 5m.

The detection can be achieved at a longer distance of 7 metres using IR spot-lights that are used for CCD camera's for night vision. An oscillator circuit is added to create flashing IR beacon for the IR sensors to detect. The IR spot-lights are arranged to illuminate the 180? of its surrounding, as shown in Figure 4.

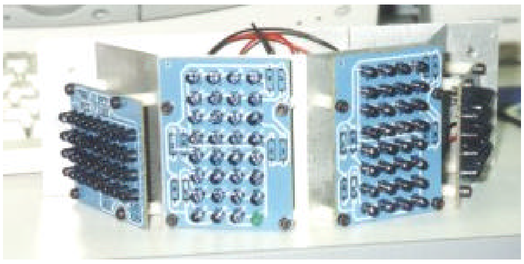

Figure 4: The long-range IR beacon. It consists of four IR "spot-light" LED arrays and an oscillator circuit.

2.2 Long-Range IR Beacon Detection

The IR sensors alone cannot distinguish between the IR beacon and nearby objects. The IR detection is performed using combination of the Sick laser range finder, Sonar sensors and the IR sensors, as shown in Figure 5.

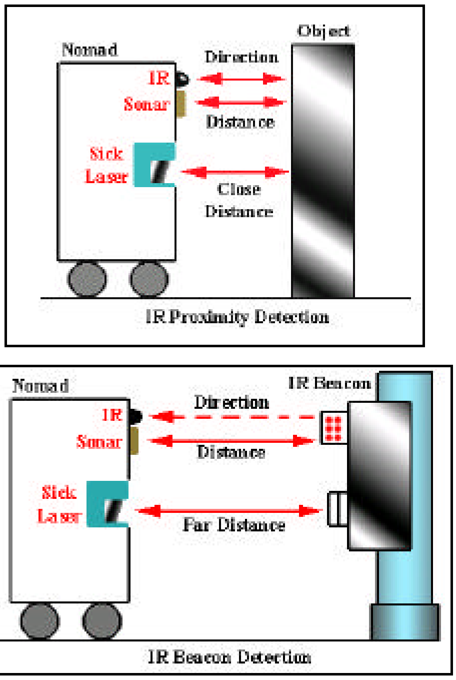

Figure 5: The distinction between the IR proximity detection and the IR beacon detection using the Sick laser range finder and Sonar sensors.

The distinction between the beacon and nearby objects is their proximity that is made by the Sick laser range finder. The beacon must be sufficiently far away from the robot so that the distinction is clear. Therefore the IR beacon cannot be identified at a close range of approximately 1m. The obvious assumption is that the sizes of close-by objects are tall enough to return close proximity by the Sick laser and the IR sensors. Using this method, the robot is able to move within approximately 1m radius away from the recharging station and thus enter the short-range region.

3 Short Range Approach

When the Nomad enters the short-range region, the Sick laser range finder will be able to detect the grid pattern. The grid pattern is designed to generate a pattern that is distinguishable from the rest of the environment. The grid pattern is used to guide the robot align to the power plug prior to the insertion.

3.1 Short-Range Target: Grid

As the robot approaches the recharging station, the Sick LMS-200 laser range finder is used to provide 2-dimensional view of the environment with 180? coverage at 0.5? angular and 1 millimetre distance resolution. To identify the grid from the rest of the environment, a distinctive pattern was designed. The target also provides guidance information for the robot at accuracy of ?1mm position error perpendicular to the plugging direction. Figure 6 shows the Grid target that is used for guiding the robot's position during the docking.

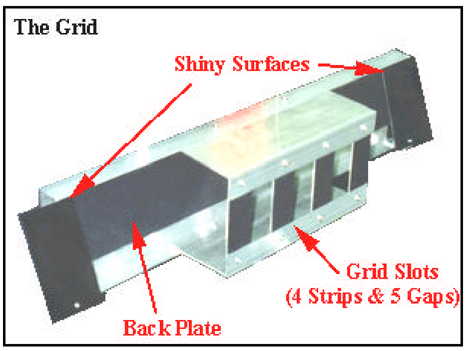

Figure 6: The Grid is used for position guidance and alignment of the robot using the Sick laser range finder.

The design features of the Grid are:

?? 4 "wide-enough" strips to generate sufficient data points.

?? 5 gaps to generate 8 edges evenly spaced out.

?? Constant distance between the back plate and the Grid slots.

?? Wide back plate for oblique angle detection.

?? Dull surface to increase diffusion of laser beams for more accurate measurement.

?? Two plastic strips that do not diffuse the laser beam, to mark the start and the end of the Grid.

An algorithm was developed to identify and align the robot to the Grid using the geometrical features. Depending on the robot's position, the Sick laser detects the Grid differently. As the laser beam does not diffuse at the shiny plastic surfaces the maximum range value of 8m is always measured in their direction regardless of the robots distance from them. The algorithm relies on the grid being positioned near a wall so that everything in the Sick laser's view is less than 8 metres away.

3.2 Short-Range Grid Detection

As the robot enters the short-range region there will be sufficient Sick laser data points on each slot and strip of the grid. However, depending on the robot's position relative to the Grid, the laser detects the Grid differently. Figure 8 illustrates how the Grid shape is seen depending on the position of the robot.

By considering the 4 possible cases, a general method was developed to detect the grid. The grid data is broken up into two components, surfaces and gaps, as shown in Figure 7. A gap is the larger distance difference between two adjacent sets of data points. A surface is the sets of points that are close together, and they represent the Grid strips or the back plate. Gaps are used to extract surfaces. The pattern is recognised by counting the occurrence of the surfaces and the difference in distance between front and back surfaces. These conditions must also occur within the width of the Grid.

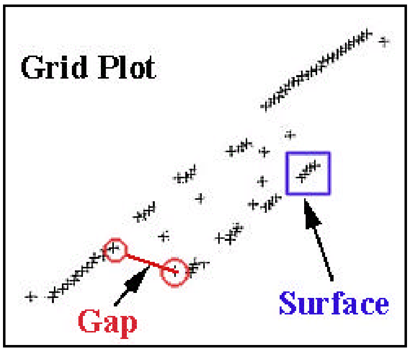

Figure 7: The grid consists of Gaps and Surfaces.

If the conditions are not satisfied, ie, the Grid is not detected, the algorithm will look for the plastic strips that are positioned at the start and the end of the Grid. The maximum range of the Sick laser is returned from the shiny plastic strips. If only one plastic strip is detected, then the distance to surfaces on the left and right the strip is compared. The closer surface is assumed to be the Grid.

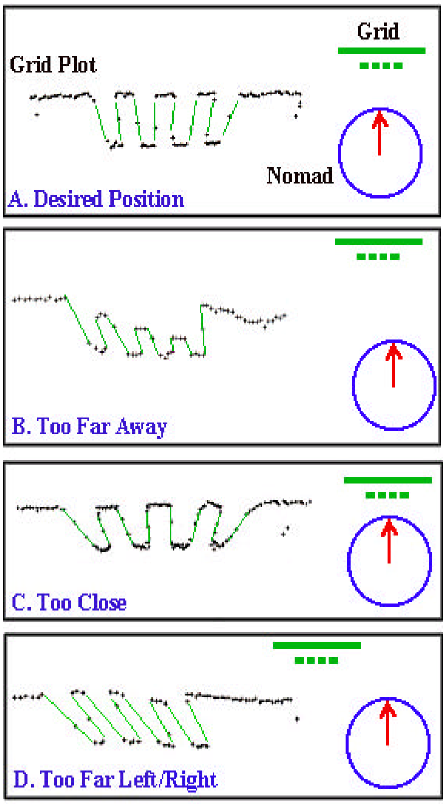

Figure 8: Sick laser data plots of the Grid at different positions of the Nomad. It is categorised into 4 different cases.
Note: The lines are joined at the Grid edges for clarity. The arrow represents the front of the Nomad.

A. The robot is facing the Grid, at a distance of approximately 0.5m. This is the desired position prior to the grid alignment and approach. All grid features are clearly visible.
B. The robot is too far away from the Grid. Back plate points between the slots are incorrect. The IR beacon will "pull" the robot closer. The Grid maybe detected.
C. The robot is too close to the Grid. Too many points are visible at the edges giving curved effect.
D. The robot is too far right to the Grid and is therefore not in the centre of the field of view.

3.3 Grid Alignment and Approach

A number of points on the Grid's front surface are extracted during the Grid detection procedure. A line is fitted to the points to obtain the orientation of the robot relative to the Grid. This allows the robot to move to the position as shown in Figure 8A, by combination of rotation and translation.

Once this position is reached, the Sick laser can accurately extract all the features on the Grid. Another line is fitted along the front surface points to correct rotational orientation, and edges are detected to achieve accurate translational position.

Figure 9 shows the differential plot of the Grid pattern generated from the Sick laser range finder.

The edges (or gaps) of the Grid can easily be detected by determining the magnitude of the peaks and its occurrence. However, when the robot is positioned at an undesired position, as shown in Figure 8, some of the peaks may not be detected due to distortion in the Grid shape. The algorithm was developed to guess the Grid and roughly position the robot to the desired position, shown in Figure 8A.

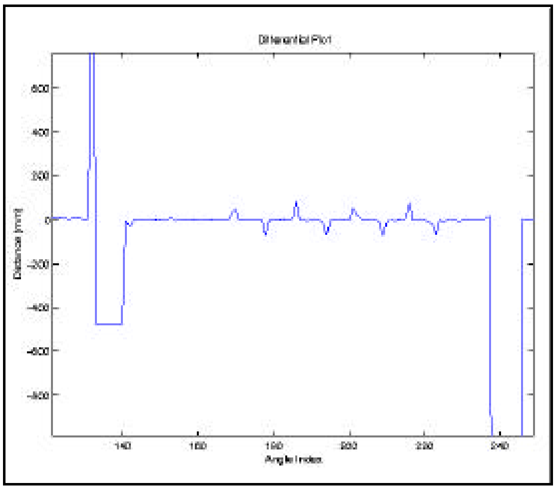

Figure 9: Plot of differential of the Grid pattern with respect to the Sick laser sensor's angle index, showing regular peaks at the edges of the Grid.

The robot slowly approaches towards the power plug as it corrects its position using the Grid edges along the way until it is ready to dock into the power plug. It was found that accurate positioning can be performed by applying a short delay of 1 second in between each movement command. The delay also helps the Sick laser sensor to scan the environment more accurately by taking an average of samples.

Once the robot is docked, it checks the battery voltage levels. If the voltages are increased then the docking is successful, otherwise the robot moves backwards and retries the Short-range docking sequence.

3.4 Performance

The robot's path is shown in Figure 10 with the three main even points. At the starting point, the robot starts to search for the IR beacon using the IR sensors, Sonar sensors and the Sick laser range finder. Once the beacon is found, the robot approaches towards the beacon, until it reaches the short-range region. Then the robot performs transition from long-range approach mode to short-range approach. At this stage, the robot identifies the grid and performs the alignment. Once aligned the robot approaches towards the grid, and the plug is inserted at the docking point. The time taken at each event is tabulated in Table 1. Figure 11 shows video frame captures of the docking sequence.

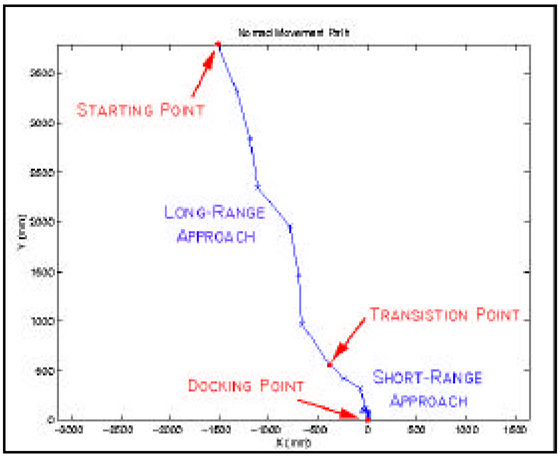

Figure 10: The Nomad's path to the recharging station.

Event Description	Distance to Recharging Station	Accumulated Time
Starting Point	4 metres	0
Long range approach	---	58 seconds
Short range Approach Transition	0.5 metres	1 minute
Short Range Approach	---	1 minute 21 seconds
Plug insertion	0	2 minutes 30 seconds Total

Table 1: Time taken for the Nomad's recharge docking

Figure 11: Video captures of the recharge docking, showing long-range and short-range approach and close-up of the docking.

There were 6 failures occurred out of 30 tests performed. The failures were mainly due to undetected targets. One of the most common failures is due to an undetected IR beacon. This can be caused by reflection of the IR emission from other nearby objects. Another common failure is due to undetected Grid, which can be overcome by moving the robot to the desired position.

4 Conclusion

This paper has introduced how hardware targets for sensors can be generated using the sensor properties for determining the robot's destination. Addition of more features to the target, such as the shiny plastics on the Grid, had increased probability of the target detection.

Future work will involve replacement of the IR beacon with a reflective tape. Since the Sick laser range finder can measure reflectivity at a much longer range, hence the IR beacon will no longer be required. The hardware cost of the system will be reduced to approximately $100. Addition of wandering and searching behaviour is to be added to the system.

The system is currently under development with focus on the reliability.

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