Long distance outdoor navigation of an autonomous mobile robot by playback of Perceived Route Map

Shoichi MAEYAMA Akihisa OHYA and Shin'ichi YUTA
Intelligent Robot Laboratory
Institute of Information Science and Electronics
University of Tsukuba
Tsukuba, Ibaraki, 305 JAPAN
phone:+81-298-53-5155 fax:+81-298-53-6471
Email: {maeyama, ohya, yuta}@roboken.esys.tsukuba.ac.jp

Abstract: In this paper, we report a development of an autonomous mobile robot for long distance outdoor navigation in our university campus. We propose how to generate a long distance Perceived Route Map (PRM), a position-based navigation algorithm using PRM, and incremental integration of the robot system by multiple processors and multiple agents. Furthermore, we developed an experimental robot system and conducted experiments of autonomous navigation using PRM in our university campus. Finally, from experimental results, we discuss open problems and future work in outdoor navigation.

1. Introduction

We present a research on long distance outdoor navigation of an autonomous and self-contained mobile robot. The objective of this research is the development of a robot to achieve outdoor navigation over a distance of about 2km in our university campus (Figure 1). The target environment is the paved or tiled walkway shown in Figure 2. The walkway can be assumed to be a two dimensional plane along with a wall, a hedge or a tree etc., which can be utilized as landmarks. A walker or a bicycle can be assumed to be a moving obstacle. In response to these moving obstacles, the robot waits for them to go away, because the robot is much slower than the obstacles.

A walkway is a much more unstructured environment than highway, in which the vehicle can be controlled by following white lane. In conventional works, the boundary edge of the road area or the shape of the detected road area is used for navigation control[1][2]. These approaches focus on the road following technique like an autonomous highway vehicle. But, it is difficult to treat a shadow on the road, detect intersections and change the way. On the other hand, positioning is essential for long distance walkway navigation. Position information is also useful for locomotion control, since it is easy to decide a turning point and the goal. However, in conventional works, it has not been actively used.

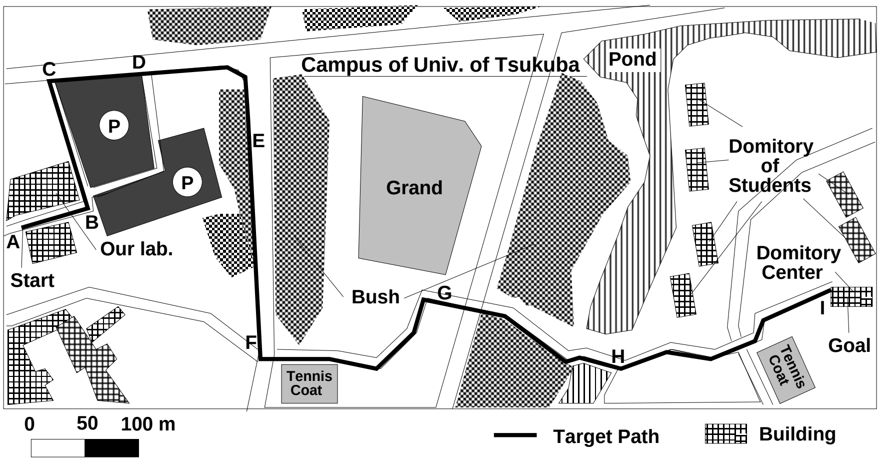


Figure 1. Schematic map of the target environment. (A,B,...,H,I are passing points.)

In this paper, we propose the position-based outdoor navigation using the Perceived Route Map, which includes path from the start to the goal taught by an operator and landmarks acquired automatically by robot itself. Then, we discuss some problems on walkway navigation from experimental results.

2. Navigation using the Perceived Route Map (PRM)

In our basic strategy, while the operator controls the robot from the start to the goal, the robot generates the route map which is perceived by own internal and external sensors (Figure 3). We call such a map the Perceived Route Map (PRM). After that, the position-based autonomous navigation is done by playback of the PRM. On a walkway, the question “what kind of properties in this environment can be utilized for robust navigation” itself is a important problem. If the robot is navigated a long distance using the PRM, it will become obvious what kind of information is needed for walkway navigation.

2.1. Acquisition of the PRM

For position-based navigation, a precise route map must be given to the robot in advance. However, it is difficult for a human to make a route map over a distance of about 2km in outdoor environment. So, we want that the robot makes the route map by itself. But, exploration by the robot itself in outdoor consume much time. Our interest is not map building by exploration. Therefore, We propose route map generation by natural landmark acquisition through human route teaching. In this method, a human operator controls the robot to the goal at first. Then, the robot remembers its own trajectory as a path and the location of landmarks to correct its position on the way to the goal. The operator teaches only the path from the start to the goal with a manual controller. The robot generates the route map which is perceived by own internal and external sensors. As the result, the route map is generated

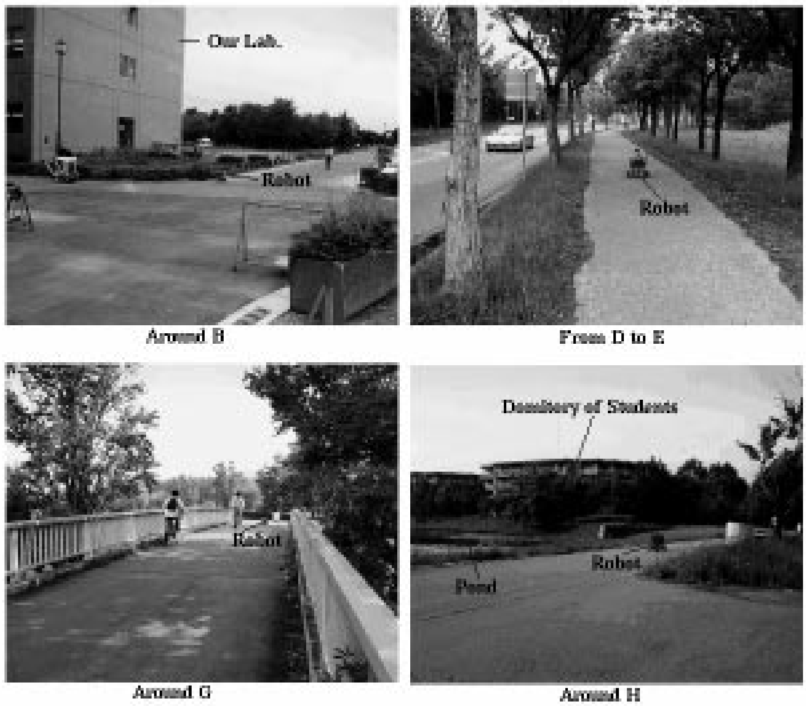


Figure 2. Target environment which has a paved road along with trees and hedges. (B, D, E, G and H are some passing points shown in Figure 1.)

with the expression suitable for the robot. The relative location between path and landmarks is recorded in the route map.

A landmark is the mark to confirm the position. Therefore, the objects for landmarks must satisfy the requirements, that they can be detected at the same location with the same characteristics even if the robot has displacement. The robot must detect the objects which satisfy with such conditions. But, of course the robot does not know where such objects are in advance. So, we propose the PRM generation by parallel execution of multiple agents (Figure 4). At first, we suppose that the robot has the functions of the sensors to measure the distance or/and direction of the objects. Furthermore, the robot should have a locomotion controller and position estimator. Then, we prepare Landmark Agent, Path Agent and Radio controller Agent. The Landmark Agent is the agent to detect the landmark candidate from the measurements by sensors and store the sensing point and landmark location and so on when it is repeatedly detected at the same landmark position even if the robot travels over a distance. The Path Agent is the agent to store the passing point of the robot. The Radio controller Agent is the one to interpret the human operation and to send the control command to the locomotion controller. In this system,

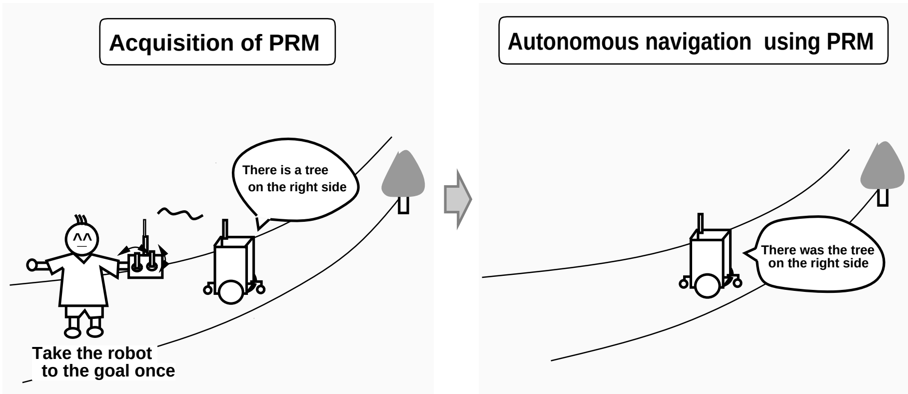


Figure 3. Outdoor navigation using Perceived Route Map (PRM) : PRM generation by natural landmarks acquisition and autonomous navigation using the PRM.

agents work in parallel to cope with the process which has a different time constant. Then, the PRM can be generated without missing the landmarks in the target environment.

2.2. Position based navigation using the PRM

If the robot has a path from start to goal and can estimate the precise position, the robot can arrive at the goal by feedback control of the estimated position. So, the position estimation is the dominant subject for navigation. From recent work of position estimation of mobile robots, the Kalman Filter (KF) is well known for the good performance. KF has a reasonable redundant sensor data

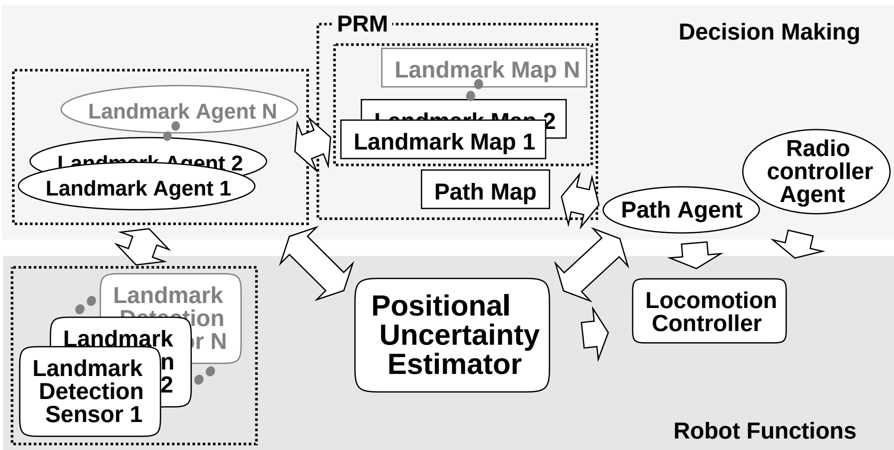
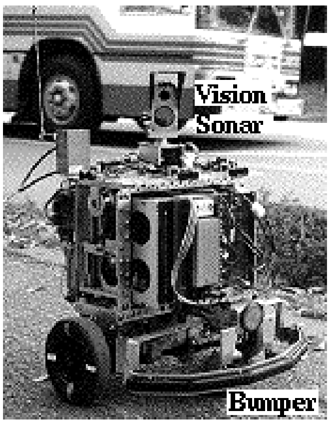


Figure 4. Parallel execution of multiple agents for autonomous navigation using PRM.

fusion with low calculation and small amount of saving data, step by step, and utilizes the low dimensional observation with the correlation of the position parameters [3][4][5][6][7][8]. We also confirmed the performance of this position estimation technique in outdoor application[9][10].

So, we use this technique for navigation using PRM. The PRM data includes the robot inherent errors such as wheel diameter, tread and the other off set. Therefore, if the robot can compensate the un-repeatable error such as the interaction from the road surface by observing landmarks, navigation using the PRM will succeed.

Position based navigation using PRM is also done by multiple agents, shown in Figure 4. The Path Agent gets the path to be followed from the Path Map and sends the command to the locomotion controller. Each Landmark Agent gets the set of sensing points and landmark locations, from each Landmark Map. If the robot crosses the sensing point of a landmark, the Landmark Agent searches the landmark. If the Landmark Agent finds the landmark, the information of observation is sent to the positional uncertainty estimator. Then, the estimated robot position and the error covariances are corrected by Kalman Filter[10]. The threshold for identification of the observed landmark and the landmark in Landmark Map is determined based on the value of the covariance of the estimated position. If the difference of the location of the observed landmark and the map's landmark is less than the threshold, the Landmark Agent decides that they are the same one. Thresholding is very useful to avoid the misunderstanding of landmarks. Each Landmark Agent works independently. But, through the resulting covariance of the estimated position, each Landmark Agent communicates with each other implicitly. More reliable navigation system can be developed by adding more Landmark Agent incre-



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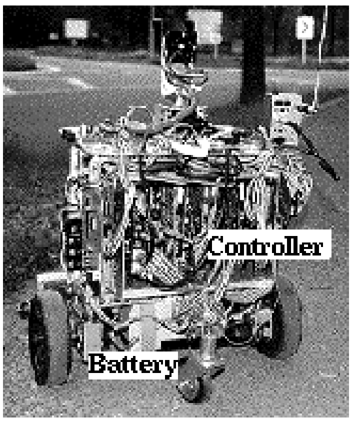

Back

Figure 5. Photographs of the mobile robot YAMABICO NAVI. Dimension (WxHxD) is about 450x600x500 mm. Weight is about 12 kg. Wheel diameter is about 150 mm. Tread is about 400 mm.

mentally. The Radio controller Agent is not used for autonomous navigation.

3. Experimental autonomous mobile robot YAMABICO NAVI

We implemented the proposed navigation system in the experimental mobile robot *YAMABICO NAVI* (Figure 5). Figure 6 shows the system configuration of this robot. The robot has a dead reckoning system by fusion of odometry and gyro[11], SONAVIS [1] to detect landmarks, sonar to detect obstacles, a valve regulated lead acid battery (12V 7Ah) and two DC motors to drive the wheels.

The controller is distributed on multiple CPUs. The *Master* and the other functional modules have a connection like a star with Dual Ported Memory. The *MASTER* is a CPU module to control a total behavior of the robot. Information for decision making is gathered into the *MASTER*. The *MASTER*

[1] SONAVIS is a landmark detection sensor with ultrasonic range sensor and vision mounted on a turn table.

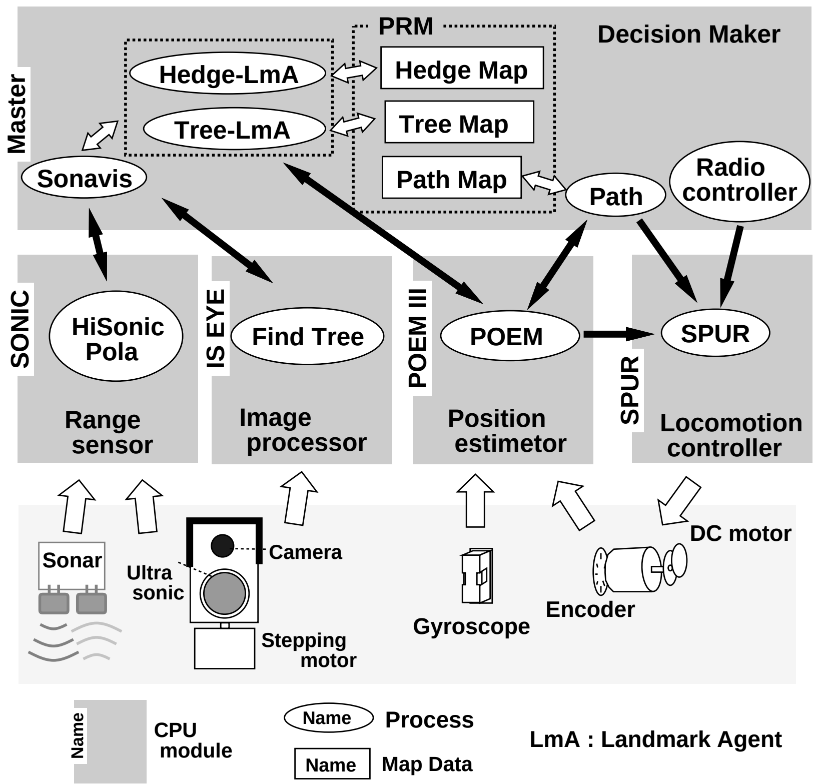

Figure 6. System configuration of YAMABICO NAVI.

decides next motion from these information. Then, the *MASTER* gives the commands to the other functional modules. *YAMABICO NAVI* has functions of Locomotion control (SPUR[12]), Position estimation (POEM III[10]), Image processing (ISEYE) and Ultrasonic range sensing (SONIC).

The multi-agent system for navigation is implemented on the *MASTER*. *Hedge-LmA* is the Landmark Agent to detect hedges as landmarks when the distance measured at the same direction by ultrasonic sensor mounted on SONAVIS is almost same distance while traveling over 90 cm. *Tree-LmA* is one to detect trees as landmarks when the tree is detected at the almost same location by SONAVIS while traveling over 60 cm. *Sonavis Agent* is one to arbitrate *Hedge-* and *Tree-LmA*, since these two Landmark Agents use the same sensor property SONAVIS.

4. Experiments

We conducted some experiments with our robot *YAMABICO NAVI* mentioned above.

At first, the experiment for PRM generation was done. The generated PRM is shown in Figure 7. This is the PRM from A to G in Figure 1 around 5:00 pm in the beginning of May. The weather of these days was fine. The maximum speed of the robot in this experiment was 30 cm/s. Total distance was about 810 m. *Hedge-LmA* detected 95 landmarks which include hedges,

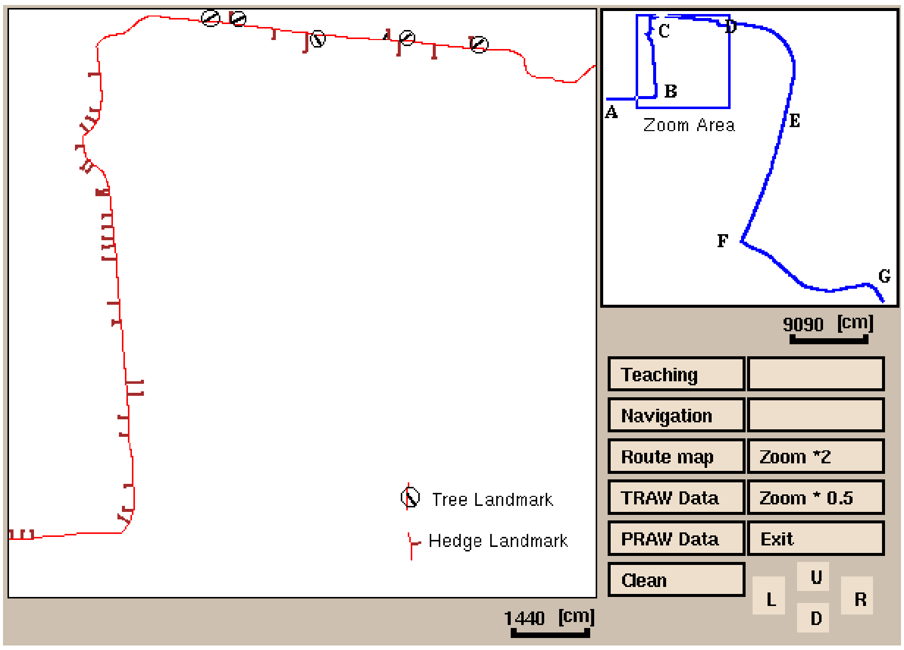

Figure 7. An example of the generated PRM from A to G in Figure 1. (This figure is a window of the debug monitor system.)

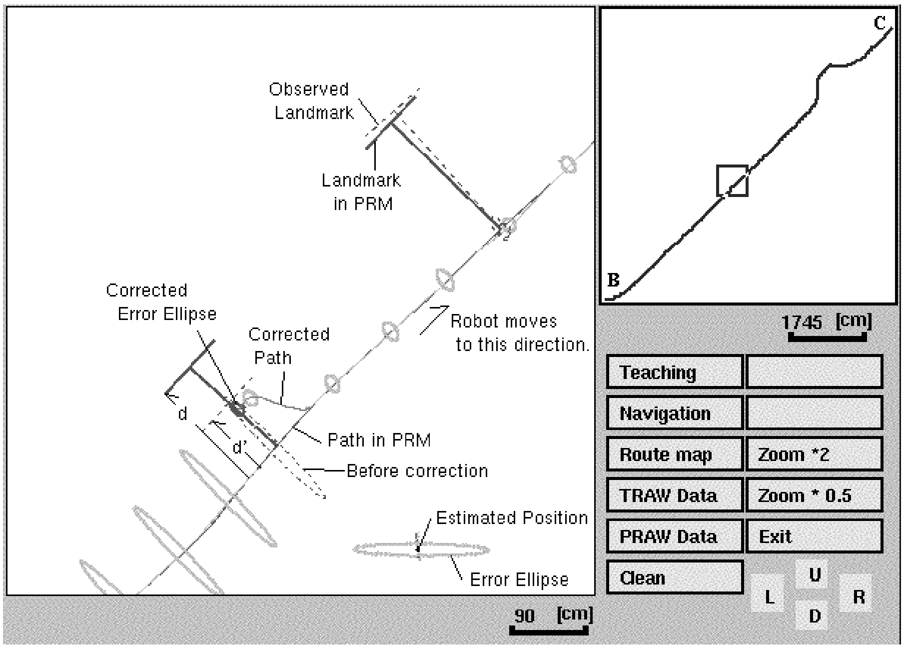

Figure 8. Position correction by hedge landmark.

walls, fences and bushes. 26 trees were detected as landmark by *Tree-LmA*. The maximum distance between landmarks was about 45 m. The average distance between landmarks was about 5 m. From the experiment, we found there are three ramps, which can not be traveled over for the reason of small wheel diameters.

Next, we tried to do some experiments of autonomous navigation using the PRM. Figure 8 shows the position correction by *Hedge-LmA*. In this figure, d is the distance from the robot to the hedge expected from *Hedge Map*, which is included in the PRM. d' is the measured distance of the hedge. So, $d - d'$ is the difference of the map's and the measured distance. If $d - d'$ is smaller than the threshold for the identification, *Hedge-LmA* sends this value to the POEM III function module. The threshold is the deviation 1σ about the estimated position of the sensing direction. The corrected path is automatically generated by the control algorithm of the SPUR function module and the robot returned to the desired path in *Path Map*. The position correction by *Tree-LmA* is similer to *Hedge-LmA*. We reported it in [9].

5. Discussion

The robot sometimes failed in the following cases : (1) Insufficent number of landmarks, (2) Change of sunlight during a day and (3) Dynamic change of environment.

In case (1), when there are insufficent number of landmarks or the robot does not acquire enough landmarks, the robot loses its position. The reason is

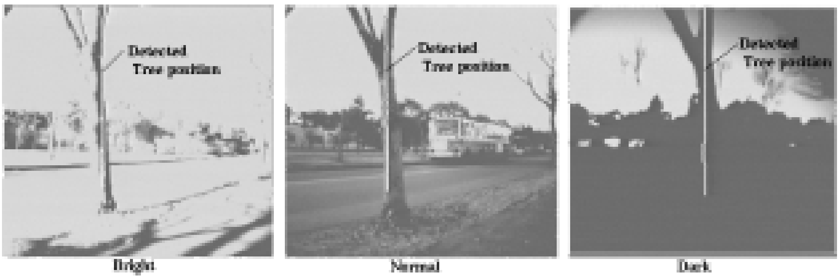

Figure 9. The detected tree position in the case of varying sunlight.

misunderstanding of landmarks or a large error of the estimated direction. As the distance the robot moves without landmark increases, the rate of misunderstandings and missings of following landmarks will be higher, because the positional uncertainty is growing up.

In the next case (2), the sunlight during a day is changing gradually (Figure 9). The tree in the captured image is detected at different positions in varying sunlight. When the measurement error generated from the change of sunlight can not be ignored, the robot must have different a PRM for morning, afternoon and evening.

In the last case (3), unfortunately, the hedge and the bush along the walkway are cut down for maintenance. Some other objects in the environment also move or remove for maintenance or some other reasons. In such cases, the robot must generate this part of the PRM again.

6. Conclusions

We presented a long distance outdoor navigation system for an autonomous mobile robot in this paper. We realized an experimental robot system for generating a long distance Perceived Route Map (PRM) and navigation using the PRM, realized as a multi-agent system. Furthermore, we conducted experiments of autonomous navigation using the PRM in our university campus. Up to now, we have tried to do autonomous navigation using the partial PRMs, which are the PRMs from one passing point to the next. We found some problems such as too few landmarks, the change of environment and the connection of partial PRMs.

In future work, we want to overcome the above stated problems. We will make more various Landmark Agents, robust against the change of environment, and we will connect these partial PRMs.

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