A Corridors Lights based Navigation System including Path Definition using a Topologically Corrected Map for Indoor Mobile Robots

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Abstract

This paper proposes an indoor navigation system for an autonomous mobile robot including the teaching of its environment. The self-localization of the vehicle is done by detecting the pose of corridors fluorescent tubes with a camera pointing to the ceiling.

A map of the lights based on odometry and used later for navigation tasks is first built by remote controlling the robot. The map distortion due to positioning errors is corrected to facilitate route definition by detecting and closing open cycles extremities.

Paths defined on the modified map whose geometry differs from the robot one are then converted automatically into the robot map so that the robot can refer to it and cancel odometry errors during navigation.

1 Introduction

When a wheel type mobile robot navigates on a two dimensional plane, it can use sensors to estimate its position by summing elementary displacements provided by incremental encoders mounted on its wheels. The main default of this method known as odometry is that its estimation error increases unboundedly[1]. For long distance navigation, odometry and other dead reckoning solutions may be supported by an absolute localization technique providing position information with a low frequency.

Since absolute localization for indoor navigation using landmarks located on the ground or on the walls is difficult to implement because they can be obstructed, a navigation system based on ceiling landmark recognition can be thought as an alternative to this issue.

The navigation system we developed enables a mobile robot to navigate in corridors by adjusting its pose whenever it observes ceiling lights recorded in a map that it built in advance. This *robot map* is obtained by guiding the vehicle in corridors and is entirely based on odometry. Due to the accumulation of odometry errors it is not topologically correct, but still can be used by the robot to localize itself while navigating.

However, the user needs a better representation of the environment in order to set up a route relatively to the landmarks. An intermediate *user map* which does not preserve the distance between each light is created automatically by matching lights located at open cycles extremities and closing them.

The path defined relatively to this map is then converted with respect to the *robot map*, involving jumps whenever the vehicle gets close to a landmark represented more than once in its map.

Figure 1 is a schematic overview of our approach.

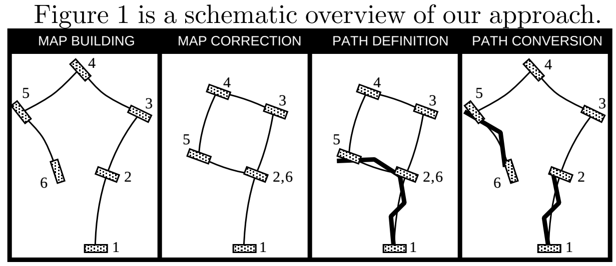

Figure 1: Although a distorted map can be used for navigation, a topologically correct representation of the environment is required to define new routes.

2 Related work

The idea of using lights as landmarks for indoor navigation is not new. In 1994, Hashino[2] developed a fluorescent light sensor in order to detect the inclination angle between an unmanned vehicle and a fluorescent lamp attached to the ceiling. The objective was to carry out the main part of the process by hardware logic circuit. Instead of lights, openings in the ceiling for aeration have also been used as landmarks to track. Oota *et al.*[3] based this tracking on edge detection, whereas Fukuda[4] developed a more complex system using fuzzy template matching. Hashiba *et al.*[5] used the development images of the ceiling to propose a motion planning method.

More recently, Amat *et al.*[6] presented a vision based navigation system using several fluorescent light tubes located in captured images whose absolute pose estimation accuracy is better than a GPS system. A wheelchair navigation system using a library ceiling images mosaic has also been developed by Kami[7].

One advantage of the system proposed here is its low memory and processing speed requirements that make its implementation possible on a robot with limited image-processing capabilities. Moreover, our navigation system includes a landmarks map construction process entirely based on the robot's odometry data and therefore does not require any preparation in advance of the environment.

The issue of odometry errors drift leading to an inconsistent map is solved by providing the user a globally correct representation of the world so that the vehicle path can be defined easily with respect to the landmarks. This is the main difference with the previous works which either assume the knowledge of the ceiling landmarks' exact pose thanks to CAD data of building maps or thanks to an overall picture of the ceiling, or require the absolute vehicle pose to be entered manually and periodically during the landmarks map construction so as to cancel odometry errors.

Building geometrically correct maps has received considerable attention in the mobile robotics community and lead to complex and computationally expensive approaches sometimes involving simultaneous localization and map building (SLAM/CLM)[8][9][10]. Providing the robot a representation of the environment as close as possible to the reality so that it can be used directly for navigation is the leitmotiv of these approaches. The system we propose proves that map building and navigation in large-scale corridors can be performed without modifying the perception the robot has of its own environment.

3 Lights Map Building

A robot equipped with a camera pointing to the ceiling (Fig.2) is guided under each light and adds landmark information to the map whenever a new light appears above it. We suppose that no more than one light at a time can be seen by the robot.

Lights are detected by computing an appropriate histogram-based threshold for each captured image and checking whether the number of pixels brighter than the threshold is bigger than a given value. If the considered pixels are enough, they correspond to a light and its pose in the image is computed using its moment-based features after correcting the image distortion and checking that the binarized shape does not touch the image borders [11]. Figure 2 shows the different image processing steps.

Since the distance between the camera and the ceiling is unknown, two images of the same light taken from different places are used in order to convert the light position in the image into the robot referential. The estimated robot pose in the map being entirely based on odometry, the landmark will be recorded with an error which grows as the vehicle keeps moving.

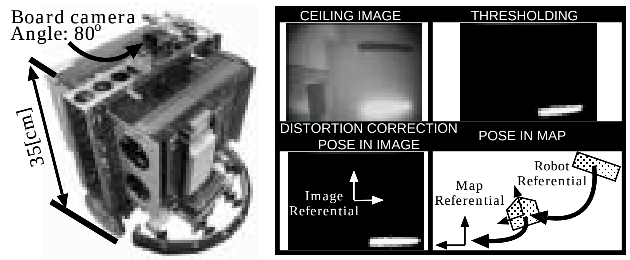

Figure 2: "Yamabico" mobile robot equipped with a camera pointing to the ceiling and map building process steps.

4 Path Definition

4.1 Map Pre-processing

4.1.1 Necessity

Although the *robot map* geometry does not correspond to the real world, it is possible to set up directly a route as a succession of segments whose extremities can be defined relatively to the lights and obtain satisfactory navigation results. However, in the case of long cyclic corridors, odometry errors are such that the same light is recorded in the *robot map* at different places, which can be confusing when defining the robot trajectory.

Fig.3.c shows the map built by a robot guided in corridors schematized in its center. The map distortion does not allow setting up a route different from the one followed by the vehicle when the map was built. For example, E and D are not connected whereas the navigation task may consist in moving from E to D through C without going through A and B.

4.1.2 Algorithm

Free route set up is made possible by creating a topologically correct *user map* thanks to an algorithm that closes open cycles in the order they appeared when the map was created. Cycles extremities lights L_s, L_e can be specified with a GUI or detected automatically if the list of corridors crossings lights is known. No hypothesis is made concerning the corridors shape but we suppose that the orientation of corridors junction lights can be computed modulo π, i.e. their shape is rectangular. Each loop is closed in two steps:

1. Match L_e's orientation with L_s by rotating each loop odometry segment. The orientation error for a displacement of length dl along the cycle is modeled by $d\theta = Kdl$ where $K = \frac{\theta_s - \theta_e + p \cdot \pi}{l}$, l being the cycle length, $(\theta_s, \theta_e) \in [-\frac{\pi}{2}, \frac{\pi}{2}]^2$ L_s and L_e's orientations modulo π and $p \in \mathbb{Z}$ a value to cope with

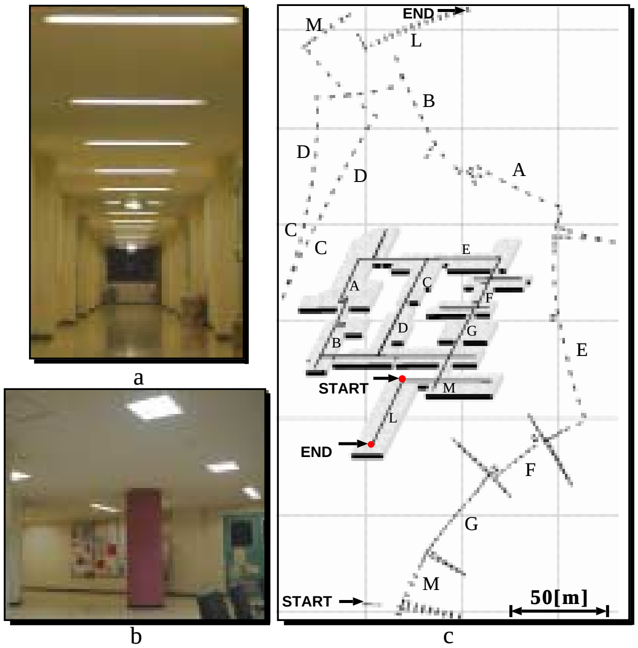

Figure 3: University of Tsukuba 3^{rd} cluster corridors mapped as follows: M→G→F→E→A→B→D→C→D→M→L.

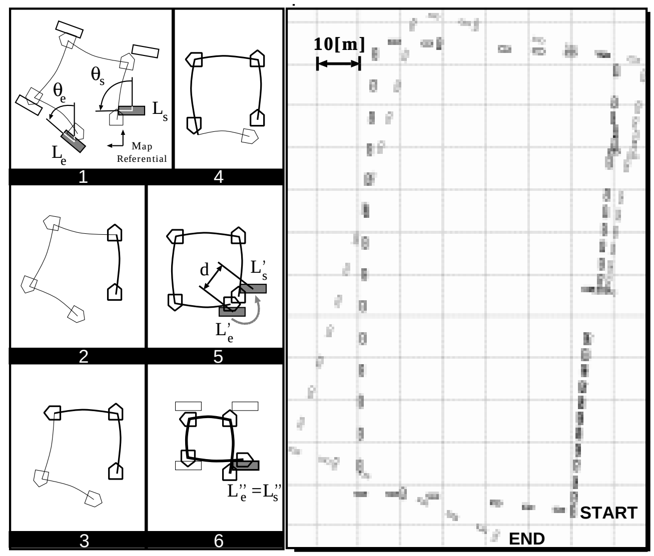

Figure 4: (a) Loop closing steps. (b) Single loop closed.

lights angle ambiguity so that θ_s-θ_e+$p \cdot \pi$ is the exact phase between L_s and L_e (p=0 for short loops). Each segment is modified with respect to the previous one as follows (original odometry segments are written $(\delta X_i, \delta Y_i)$=$(X_{i+1}-X_i, Y_{i+1}-Y_i)$):

for (i=1, θ=0; i<n; i++, θ+=$K\sqrt{\delta X_i^2+\delta Y_i^2}$)

$$\begin{bmatrix} \delta X_i' \\ \delta Y_i' \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \delta X_i \\ \delta Y_i \end{bmatrix} \quad (1)$$

Looking for the p value producing the smallest offset $d = \sqrt{(\sum \delta X_i')^2 + (\sum \delta Y_i')^2}$ between loop extremities lights once their orientation has been matched, provides the exact phase between L_e and L_s.

2. Compensate the remaining offset by shortening or stretching each segment.

for (i=1; i<n; i++)

$$\begin{cases} \textbf{if}\ (\ \delta X_i'>0\ ) & \delta X_i'' = \delta X_i' \cdot [1 - \frac{\sum_{i=1}^{n-1} \delta X_i'}{2\sum_{\delta X_i'>0} \delta X_i'}] \\ \textbf{else} & \delta X_i'' = \delta X_i' \cdot [1 - \frac{\sum_{i=1}^{n-1} \delta X_i'}{2\sum_{\delta X_i'<0} \delta X_i'}] \end{cases} \quad (2)$$

Y-component is modified identically to the X one[†].

Odometry points belonging to a loop that has been closed are marked so that any following open cycle containing parts of already closed loop can be closed without altering the previously corrected parts of the map.

[†]Loops corresponding to corridors dead-ends are detected and post-processed by removing duplicated lights.

4.2 User map based path definition

The purpose of the *user map* is not to substitute for the *robot map* during the navigation process. This is a fundamental difference with other researches which focus on correcting maps for navigation tasks using SLAM techniques [8][12][13][14] or not[10][9]. The only purpose of the *user map* is to provide the user a general consistent overview of the environment.

As shown in Equ.(2), the map pre-processing algorithm produces a topologically correct *user map* in the detriment of the *robot map* geometry conservation. For this reason, setting up directly a route whose segments extremities would be defined relatively to the *user map* lights and modifying its topology to cope with open loops in the *robot map* would produce a path whose geometry does not fit with the *robot map* one. Topology conversion is not sufficient.

As an alternative to this issue, a local view of the environment is provided to the user in the form of a *user map* scrollable zoom window whose topology contents are based on the *user map* but whose geometry is imported from the *robot map* (See Fig.5,6). Adding a new route segment is done by clicking in the local view window and changing the *user map* observation point is done by scrolling the local view window on the *user map*. Each route segment extremity is represented as a fuzzy point on the *user map* to stress the fact that no precise geometric information is directly available at this level.

Defining route segments relatively to lights whose interval corresponds to the one measured by the robot

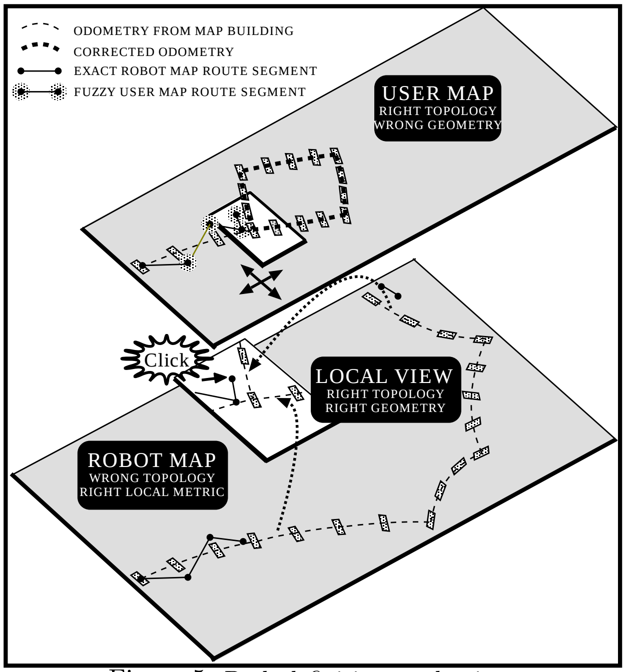

Figure 5: Path definition mechanism.

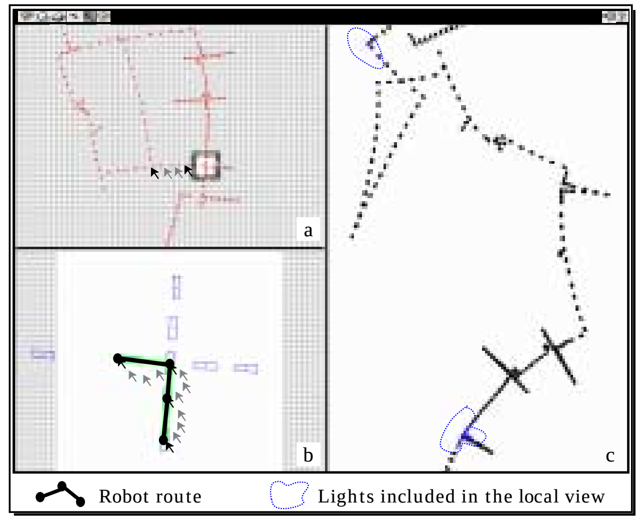

Figure 6: Path definition GUI screenshot.

when it built the map enables the vehicle to reach any place in corridors such as doors with an acceptable precision. Although no scale conversion is required by this method, the existence of open cycles in the *robot map* requires to include jumps between route segments whenever the path goes through corridors intersections that appear to be not connected in the *robot map*.

Fig.6 is a screenshot of the path definition GUI. (a) is the *user map* showing the local view window and providing non exact information concerning route segments extremities position. (b) is the local view of the *user map* showing a topologically and geometrically correct representation of the environment. Route segments are defined in this window. (c) Is an optional debug window showing the *robot map* and route segments converted from the *user map* based route. This window is not necessary for the operator in charge of defining robot routes.

5 Navigation

Once a route has been defined via the *user map*, it is uploaded to the robot which tracks each segment. The navigation system consists of :

1. A route segment tracking routine based on odometry which can modify the robot pose components (X, Y, θ) whenever a jump is specified in the route segment list. Jump is performed by first computing the robot pose relatively to the reference frame of the light L_s closest to the jump segment origin (no image processing is reauired for this). This relative pose is then combined with the one of the light L_e closest to the jump segment end in order to obtain the new absolute robot pose in the *robot map* reference.

2. A pose correction system based on ceiling lights. Image processing for light detection is performed whenever the robot understands from its odometry that it is getting close to a landmark recorded in its map. If for any reason no light is found (light switched off), no pose correction is done and the robot keeps moving on using only odometry to localize itself until it will get close to the next light. If the light is detected, the absolute robot pose in the *robot map* referential is estimated from the light pose in the robot reference frame and its pose in the *robot map*. Due to the image processing delay, this data is fused retroactively[15] with odometry and the line tracking control routine cancels the odometry errors.

The distance unit conversion rate defined in Section 3 necessary to convert the light position in pixels in the image into its position in meters in the robot referential is used as a map data, hence avoiding to capture and process two different images of the same light as was done during the map building process.

In order to cope with various lightening conditions, histogram based images thresholds computed during the map building process are ignored and re-computed for each captured image.

6 Experimental Results

Several maps of large cyclic corridors where built and used at different times of the day by the "Yamabico" robot developed in our laboratory. It could navigate on long distances using distorted maps of its environment to cancel odometry errors as long as the distance between each landmark was small enough (typically less than 10[m] for 2.5[m] width corridors). Routes set up via the GUI presented previously were defined relatively to the lights in both corridors directions and successfully tracked by the robot, hence proving that a clockwise made *robot map* can also be used to follow anticlockwise routes. Fig.7 shows how the robot could navigate on 90[m] in the middle of two perpendicular corridors using only odometry and the lights based pose correction system. The distance between each light varied between 4 and 7[m], the corridors width varied between 3 and 2[m] and non-systematic odometry errors occurred several times due to floor imperfections. Ultrasonic data captured by sensors located on the left and right-hand sides of the robot have been plotted in order to improve the legibility of the Figure (robot getting close to the walls or navigating in the middle of the corridor). These data are not used by the navigation system at any time. The main navigation failures were due to the impossibility for the robot to observe fluorescent lights situated close to windows on very sunny days. The sunlight intensity was such that no appropriate threshold could be found to binarize the landmark shape located in a too bright ceiling. We believe higher-level image processing can help to solve this sensing issue.

The *robot map* of Fig.7.c contains 241 lights, 15000 odometry data points and is 1253 meters long. 15 cycles including 13 dead-end loops were closed automatically before path definition, resulting in a map of 170 lights. It took 40[s] seconds on a busy 1GHz PC with 128M of RAM to generate the *user map*. If we keep in mind the map quality generated by our approach relatively to the maps produced by SLAM techniques, we must notice that the time elapsed between the map building and navigation processes is much smaller in our method than in the case of more computationally expensive albeit elegant methods[8].

7 Conclusions

This paper proposed an approach for building and using large-scale corridor lights maps for mobile robots. The robot first collects necessary data concerning corridor lights using raw odometry values. The map is then corrected off-line in order to obtain a consistent data set that will be used later for route definition.

Simplified speaking, the map correction algorithm alternates cycle extremities lights orientation and position matching. No hypothesis is made concerning the corridors shape to correct the map topology.

The route defined on the corrected map is then converted relatively to the *robot map* by including jumping commands when the vehicle reaches corridors crossings. Experimental results in large cyclic environments demonstrate the appropriateness and robustness of this approach.

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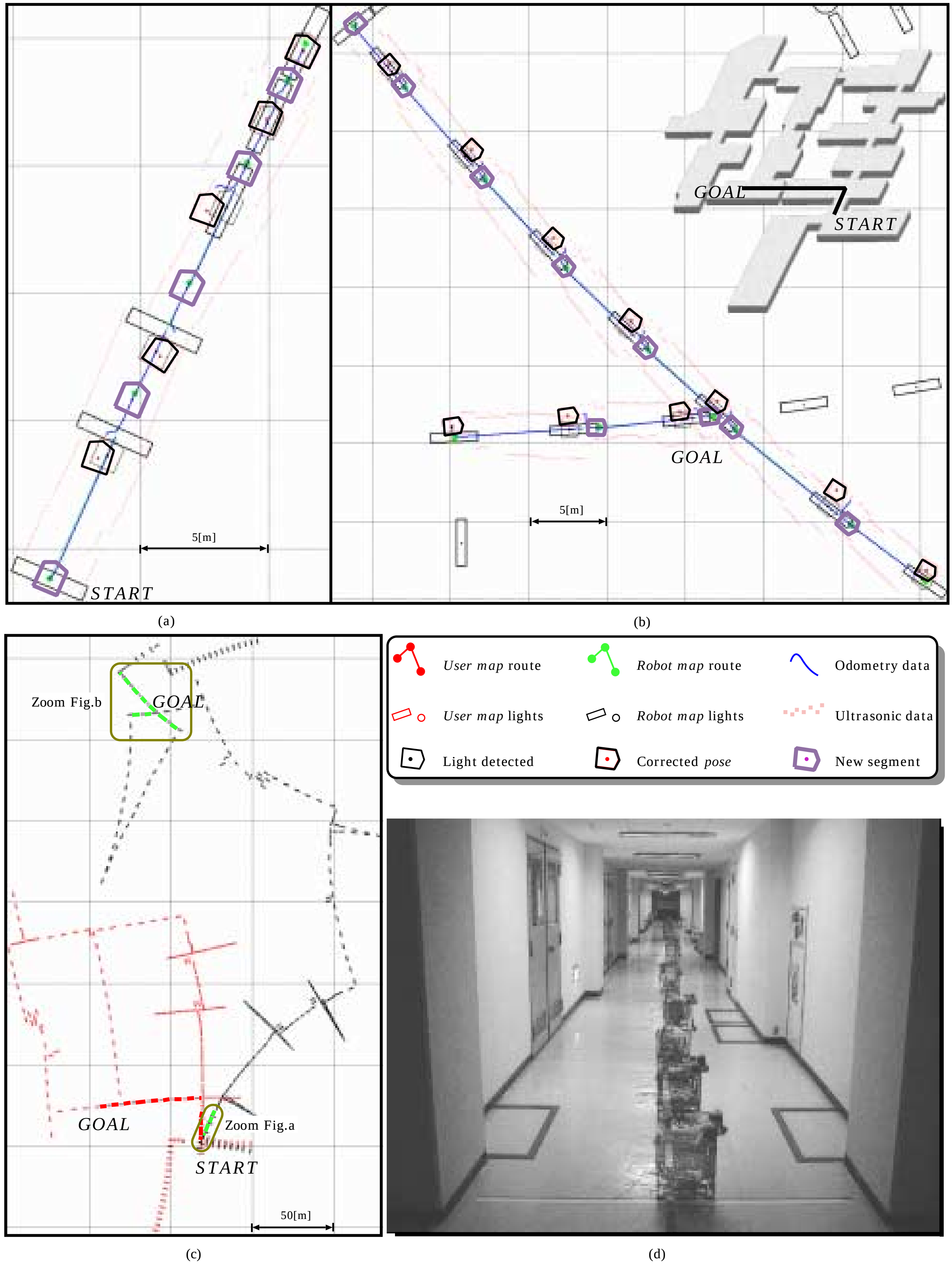

Figure 7: Navigation experimental results. (a),(b) Monitor interface screenshots. (c) *User map* and *robot map* based routes. (d) Robot behavior during an experiment performed in a long corridor with 3[m] separated lights.