

THE APPLICATION OF MOBILE ROBOTS FOR BUILDING SAFETY CONTROL

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Abstract:

In this article we propose the application of service mobile robots for control of building safety parameters. Indoor mobile robots are becoming a reality and their availability and applications are expected to grow rapidly in the near future. Such robots are usually equipped with cameras and laser range finders, which could be used to detect hazardous situations in their operating environment, such as evacuation route obstructions, emergency sign occlusions or accumulation of dangerous materials. We demonstrate how these safety-related augmentations of a mobile robot system can be achieved with few additional resources and validate experimentally the concept using an indoor robot for emergency sign and evacuation route control.

Keywords: *mapping, classification, control, mobile robot, safety*

1. Introduction

The range of potential applications for mobile robots is enormous. However, their current real life usage is limited mainly to: delivery robots [1], guiding robots [2] and cleaning robots [3]. In this article we present a new possible application of an indoor mobile robot for safety control. We discuss a method which integrates different algorithm used in mobile robotics and allows the robot to perform building safety control during day-to-day work, such as cleaning, delivery.

A mobile robot can be perceived as a kind of an agent [4]. It obtains the information about an environment and performs some actions. In order to act in the environment the mobile robot requires navigation module [5].

A typical robotic system consists of the following parts:

- Perception [6] – data obtained from sensors (cameras, laser range-finders) are analysed and represented in a suitable form.
- Mapping [7, 8] allows us to build the representation of the environment. Usually metric maps are built. We can distinguish between occupancy grid and feature-based maps. Occupancy grid represents the environment as a grid of cells. To each cell a numerical value which represents the possibility that the corresponding area is occupied by an obstacles is attached. This kind of a map allows us fast generation of a collision-free path but it requires a huge amount

of memory. In feature-based representations the environment is described as a set of features: lines, corners, etc. Such representation is very useful during process of localization but path-planning based on this kind of map is time consuming. In robotics also non-metric representations of the environment are used. Topological maps [9] represent the environment in the form of a graph. Each node represents the a part of the environment – for example a room or a corridor. Two nodes are connected if there is relation between distinctive parts in the environment. Semantic maps [10], contain data about the meaning and functionality of the detected objects and places.

- Localization [8, 11] allows the robot to determine the position in a given coordinate system. Usually odometry is an important source of information about the robot position. It is inexpensive and provides a good short time accuracy, but if the robot travels for a prolonged period of time errors in determining its position increase so additional methods are used. In the literature Kalman filters or particle filters are used to estimate the robot's position. In these methods, encoder readings are used as an input and sensors measurements as observations.
- Path planning – the aim of path planning is to find optimum collision-free path to the target location [12, 13]. We can distinguish between global and local methods. Global methods require the map of the whole environment and are time consuming. In the case of local methods path is planned on information about nearby obstacles. The method is fast but it can be trapped in local minima.
- Traveling along a planned path the angular and linear velocities of the robot are computed. Usually Dynamic Window Approach (DWA) [14] is used.

During the navigation additional actions can be performed. In the case of safety control the robot has to detect and recognize the emergency-signs and to detect obstacles.

Human safety is a crucial aspect in the design and maintenance of any building. This topic involves multiple risk factors, some of the major being related to fire, explosions and earthquakes. In order to minimize such hazards, building codes are used, which are state-level sets of rules specifying minimum standards of building construction and maintenance [15–17]. Building codes in different countries share many principles regarding human safety, and most importantly, rules regarding hazard prevention and evacuation procedures. These codes (e.g. the ICC Interna-

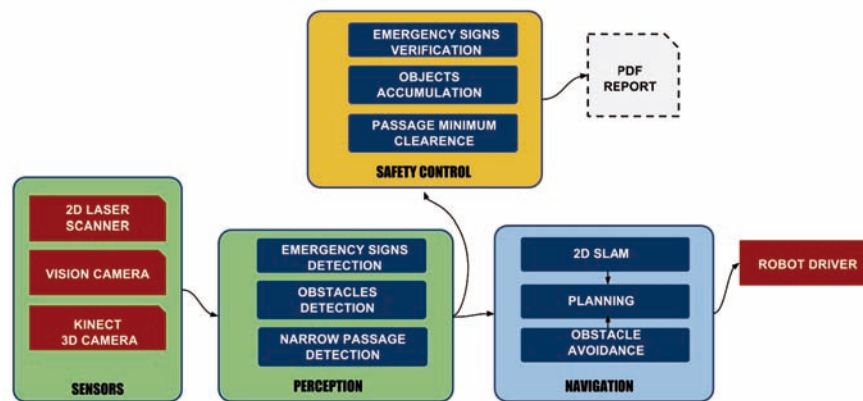


Fig. 1. The system architecture

tional Property Maintenance Code) specify the numbers of exits, exit capacities, visibility of exit signs, emergency escapes, corridor and stairway parameters, accumulation of garbage or other materials in passageways, doors, windows, fire escapes, stairways, accumulation of flammable or hazardous materials, fire detectors, fire alarms, extinguishers, and many other parameters of the building. Failure to fulfill these and other requirements results in conditions which are a potential threat to human safety thus periodic inspections are required. In this work we explore the possibility to use mobile robots for control of various building safety measures. We can recognize three different anomalous situations: the emergency sign is put in the wrong place, the emergency exit is occluded and the emergency exit is encumbered. Autonomous, service mobile robots are used increasingly often in large buildings for such tasks as cleaning floors, transporting items or guiding visitors. According to recent forecasts, within the next ten years mobile robotic assistants are expected to become common in households as well. Most advanced applications of service robots require these machines to be equipped with multiple sensors such as colour cameras, range finders and depth cameras. These sensors are used for self-localization and for performing particular tasks involving objects and places that are recognized by the robot. Modern indoor navigation techniques use an internal map and representation of the current state of the world held in the robot's memory, which is subject to constant updates. Taking these qualities of mobile robots into consideration it would be very convenient to engage them into additional, non-time-consuming, safety-related activities, which could save human labour as well as shorten the reaction time to hazardous conditions and increase overall building safety.

In buildings where mobile robots are already present, many safety control tasks could be automated at virtually no cost and would require only a small fraction of the robots' computational effort. Robots with on-board cameras and localization systems can easily check for the presence or visibility of arbitrary signs and other items at their required position (specified

on the robot's internal map), as well as detect hazardous obstructions of evacuation routes, doors and stairs. Mobile robots operating inside the building on a regular basis could detect such conditions and prompt human reaction in a fast and reliable manner.

In order to test this concept we design a safety control system integrated with the regular software and hardware of an indoor robot. In the experimental section we validate several elements of this system using a large robot for transport tasks operating in the building of Faculty of Mechatronics.

2. The System Architecture

The system architecture is presented in Fig. 1. The system operates on the ROS platform [18]. The Robot Operating System is an open source project that functions as a bridge between hardware and other infrastructure (communication modules, operator panels, different computers), state-of-the-art algorithms and methods developed and used by our team. This high-level software includes: navigation algorithms which allows for autonomous localization, and locomotion of the robot, automatic task and actions planning, communication with the robot by different interfaces (e.g. Graphical User Interfaces, gestures and voice commands recognition etc.), data processing.

2.1. Sensors

The robot (Fig. 2) used in our system is equipped with sensors which allow us to acquire information about the environment without installation of any additional devices in the building. The proposed sensor system includes: Proprioceptive sensors – used in order to estimate (not determine) the robot position relative to a starting location. The laser scanner [19] is an optical, non-contact distance measuring sensor. The method of measurement is based on pointing a laser beams onto the environment and calculating a distance from each received reflection. Typical sensor of this kind is a 2D scanner with 180° or 270° angle range. The rotation of high speed internal mirror enables high (50 Hz) frequency of scanning with the range of 25 m or higher. The industrial laser scanners are reliable and could be used with

concern of the safety regulations (Machinery Directive 2006/42/EC [20]). Laser scanners are designed to operate faultlessly even in harsh environment (direct sunlight or black night, the variety of weather conditions, dynamic objects). Mounting a laser scanner on the tilt mechanism is a common solution to make high accuracy 3D scanning. It provides a dense flat scan in front of the robot, which allows to automatically detect objects in predefined zones. In most cases the two zones are defined: warning zone in which occurrence of an obstacle limits robot velocity and protective zone which forces the robot to stop. The robot continues its task after object disappearance.

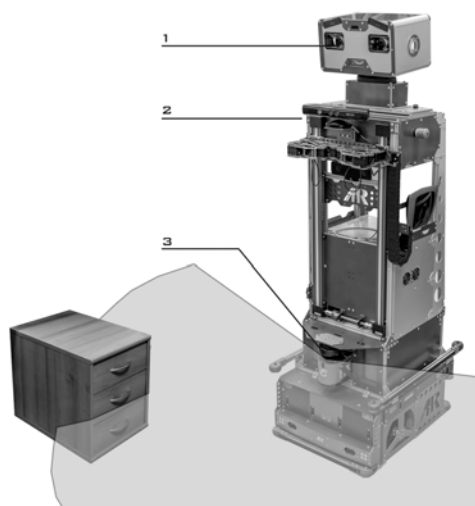


Fig. 2. The robot Kurier with sensors: 1 – Vision camera, 2 – Kinect 3D camera, 3 – Laser scanner

The Kinect [21] is a motion controller designed for the Xbox 360 console. This inexpensive device is a very good replacement for costly advanced laser scanners. The device includes a vision camera and depth sensor. With the use of this one device it is possible to gather visual information and 3D point cloud which contains a set of points, laying on surfaces around, with defined 3D coordinates and RGB values. Such information allows to reproduce a 3D digital model (with colour information) of a scene seen by the sensor. Vision cameras are used to detect and recognize flat visual signs placed on the walls.

The robot is also equipped with communication link with building network and simple Human-Robot interface (HRI).

2.2. Mapping

In our system we assumed that the map of the environment is known. It is obtained based on documentation of the building [22]. The map is defined as graph $G = \{N, E, M, P, L\}$, where: N is a set of nodes, each node represents some area (room) in the building, E is a set of edges, M is a set of grid-based maps of the areas (nodes), L is a set of landmarks. A grid-based map is attached to each node (room). Fig. 3 presents the idea behind our approach.

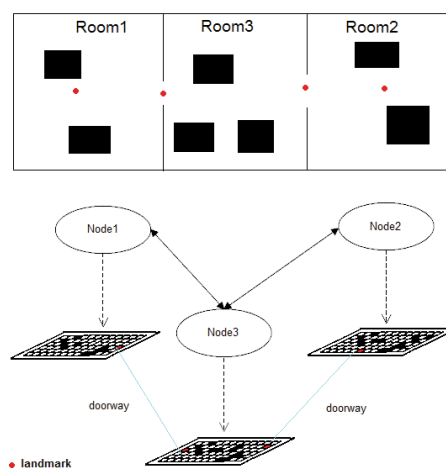


Fig. 3. The map of the environment [23]

2.3. Path Planning

Our hybrid path planning system works in the following steps: A start node (the initial position of the robot) is defined; The goal node is indicated; The topological path between the start and goal nodes is planned; The metric path between nodes is generated; Details of the mapping and path planning modules are described in our articles [23, 24].

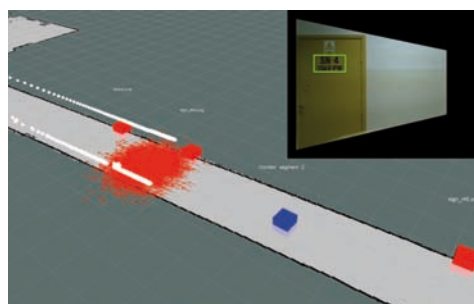


Fig. 4. Example of visual localization on a metric map.

2.4. Localization

In large buildings there are areas in which the classic approach to metric localization (i.e. based on laser and odometry data) can fail. A good example of such area is a long corridor, where the laser range finder perceives only two parallel walls. Since there are no shapes to be unambiguously matched to the known map, the metric localization system relies exclusively on odometry data. Odometry alone, however, tends to accumulate errors over time, since it can detect only relative displacements of the robot. This accumulated errors increase up to several meters depending on the length of the corridor, which is unacceptable if the robot is supposed to reach some specific point of the corridor (e.g. a selected room door). To prevent this situation, we have developed a localization method that relies on visual data captured with a colour camera. In order to use this method, a semantic map of the building must be provided. It is expected that, at its

lowest level, this map contains qualitative and quantitative information about the spaces or subspaces of the building. Assuming that the robot is equipped with a laser range finder, we first run a conventional Monte Carlo localization algorithm to obtain an approximate metric position, sufficient for localization on the semantic map (based on knowledge of the subspaces boundaries). When the robot navigates inside a known subspace, the algorithm constantly searches the camera input for a set of known visual templates (provided by the semantic map), such as room numbers, emergency signs, boards, wall patterns, etc. Once one of these templates is found, the robot position relative to the template is calculated. Since the templates have fixed positions and orientations, the calculation of the position of the robot in the map is trivial. The position is updated and the conventional localization algorithm continues to run until another template is found.



Fig. 5. The samples of emergency signs

These natural templates can be detected using convolutional matching: We first detect the walls captured in the range finder data data using Hough line detection. Then we apply a perspective transform from the original camera input to a *normalized* viewpoint (i.e. the viewpoint of a virtual camera with its optical axis normal to the wall, positioned at a given distance from it). The resulting image is used for template matching using a fast heuristic algorithm [25].

The presented localization algorithm was tested in a long corridor using a mobile robot equipped with a range finder and a colour camera (with its optical axis deviated 60 degrees from the robot's axis). The corridor was divided into four subspaces, two of them had no characteristic features visible by the laser range scanner. For each of these subspaces, three natural templates were captured. While navigating, on each template detection, the robot's displacement along the corridor was corrected by 0.5–2 m, depending on the magnitude of the accumulated odometry errors. A visualization of the combined localization system has been shown in Fig. 4. The cubes on the walls represent natural templates. The white dots are wall points perceived by the range finder, the cloud of arrows represents possible robot positions randomly spread around the position calculated based on template detection (used by the Monte Carlo metric localization). The attached image (top right) shows the transformed camera input with a bounding box on the detected template.

Beyond localization on a corridor, the proposed algorithm provides, obviously, information about the

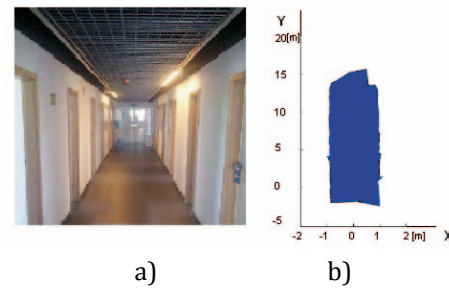


Fig. 6. A corridor with objects blocking the exit. Simple analysis of the data from laser scanner indicates possible evacuation problem.

presence of any known templates of interest. Thus, as presented in the next section, this method can be easily developed to accomplish the task of verification of the visibility of emergency and warning signs, door numbers, information boards and other important flat features of the building.

3. Emergency-routes and Signs Verification

The emergency management significance is unquestionable in all public buildings. The complexity of the emergency routes is rising nowadays, alongside with sophisticated public infrastructures architecture. The design of faultless emergency-routes should be considered as most important. The escape routes verification and its further analysis has to be done to improve building safety. A safety plan is designed and approved by professionals and should not be changed unless the building structure was modified. The verification process should be performed periodically to avoid unauthorized changes. Typically only emergency-signs existence is checked. In most cases, the signs position and quality should also be considered. The accumulation of objects on the escape-path should not occur to prevent clashes during evacuation. Fig. 6a presents the image of the sample environment. The obstacles (a box and bottles) which are placed near the exit door can be easily using a laser range finder (Fig. 6b). It is possible to easily checked if the width of the corridors and emergency exits complies with the safety standards.

3.1. A Proof-of-concept Experiment

We have performed a proof-of-concept experiment using our mobile robot (Kurier). The experiment was planned as follows: the programmed path reflected one of the emergency escape paths from our laboratory to the indicated emergency exit. Alongside this emergency-route a set of safety-signs existence was verified and the width of the corridors or emergency exits was measured. The emergency-routes plan could be presented as a list joint segments whose nodes (vertices) are emergency signs, and the edges are evacuation paths. In the first run, a remotely controlled robot was programmed to record positions of all emergency signs (positions were confirmed by the

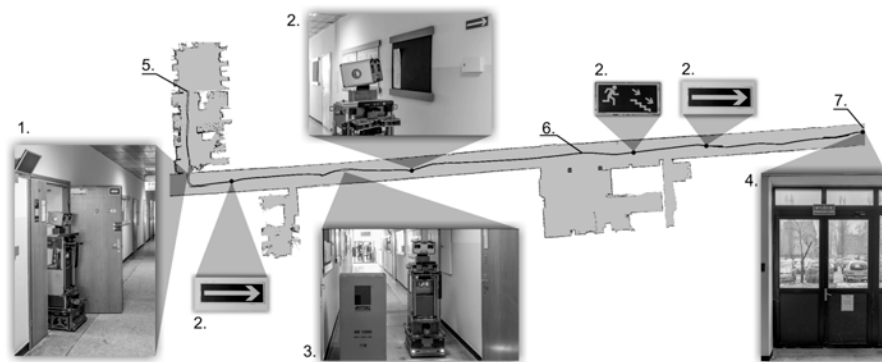


Fig. 7. Emergency-route verification experiment. 1 – narrow passage, 2 – emergency signs, 3 – corridor with obstacle, 4 – emergency-exit, 5 – start position, 6 – recorded path, 7 – EXIT position.

operator). Those recorded templates and their positions became nodes of our representation graph. The experiment goal was an autonomous run to the emergency exit, during which the verification of all signs existence was performed. Before verification experiment, we have occluded one of the signs and put a big obstacle in the corridor. Then an autonomous navigation was executed - starting from our laboratory, heading for the certain emergency exit. In the fig. 8, a solid continuous path leading to the exit is shown. The solid black colour represents positive verification of the actual passage width in the certain space. The width could be set for each space independently (e.g. corridors, doorways, emergency exits). The robot is aware of the room type due to the building representation and its localization. If the width of the measured corridor is lower than a threshold for actual space, a trajectory is recorded with a *warning* label, and denoted in the report as gray dotted line. At the same time, the signs detection algorithm verifies the existence and positions of all emergency-signs recorded previously. If any sign is missing, also a warning label is recorded. In the fig. 7, a positive sign detection is represented with black circles and a negative with black square. Such a generated report could be used as concise aid for professionals. Their focus could be put on most important aspects to check, expediting whole verification process.

3.2. Experimental Results

In the carried experiment, the robot's laser range-finder and odometric sensors were used to localize the robot based on a particle filter method. The range-finder was used to repeatedly measure the corridor width. The 2D template detection program was active during the whole experiment serving 2 functions: providing an additional source of localization (relevant only in the corridor) and reporting the found templates for later off-line emergency sign verification. The template detection algorithm performed well most of the time. All the visible signs were detected. However, we found difficulties detecting templates viewed from a sharp angle (skewed by more than 60 degrees from the frontal view), as well as de-

tecting templates with metal, glass or other reflecting materials (in the experiment no such templates were used). Since the system is designed to work in large buildings with artificial light, we did not intentionally modify the standard lighting during the test - however, it should be noted that this would probably negatively impact performance. The proposed method would present problems for either small robots (with cameras close to the ground) or narrow corridors, since the robot would be too close to the wall, limiting the wall area covered by the field of view. The main difficulties during the experimental run were encountered during autonomous navigation through the relatively narrow laboratory doorway - the limited precision of the drives and control system caused multiple path re-planning iterations, and thus some unnecessary adjusting movements of the robot.

4. Conclusion

When an emergency occurs within a building, it is crucial to guide the people towards exits. It is required that the accumulation of objects on the escape-path does not occur to prevent clashes during evacuation and thus, evacuation signs must be placed along the path. In this article we have presented a new possible application of an indoor mobile robot - safety control. We show that this task can be solve during day-to-day work of a mobile robot such as cleaning or delivery. We strongly believe that a cooperation between Architecture-Engineering-Construction and Mobile Robotics domains could considerably accelerate the development of mobile service robots intended for public buildings.

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