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An algorithm for safe navigation of mobile robots by a sensor network in dynamic cluttered industrial environments☆

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ABSTRACT

Mobile robots have been widely implemented in industrial automation and smart factories. Different types of mobile robots work cooperatively in the workspace to complete some complicated tasks. Therefore, the main requirement for multi-robot systems is collision-free navigation in dynamic environments. In this paper, we propose a sensor network based navigation system for ground mobile robots in dynamic industrial cluttered environments. A range finder sensor network is deployed on factory floor to detect any obstacles in the field of view and perform a global navigation for any robots simultaneously travelling in the factory. The obstacle detection and robot navigation are integrated into the sensor network and the robot is only required for a low-level path tracker. The novelty of this paper is to propose a sensor network based navigation system with a novel artificial potential field (APF) based navigation algorithm. Computer simulations and experiments confirm the performance of the proposed method.

1. Introduction

The implementations of industrial mobile robots in manufacturing domains have been an important and necessary part of industrial automation. Industrial robots are used to replace human in many types of works, such as transportation, assembly and welding. In smart factory, various industrial mobile robots travel on the factory floor with different destinations and tasks. This requires a fundamental problem of robotics, which is the safe navigation of ground mobile robots; e.g. [1–3].

Safe navigation is normally implemented in many military and commercial applications, such as search and rescue in high-risk environments, planet development and mapping. Especially in the industrial automation and smart factory, the collision-free navigation is an important feature for industrial mobile robots; see e.g. [4–6]. An industrial mobile robot should be capable of moving to a destination and avoiding collisions with obstacles. In the industrial environments, the obstacles include static objects, such as walls, equipments and machines, and moving objects such as people and other robots. To avoid these static and dynamic obstacles, a large number of local navigation algorithms and approaches were proposed in previous research works, such as [1,7–11]. As a typical example of local navigation methods, a positioning-orientation switching controller for the parking problem is proposed in the work [10]. In local navigation approaches, the robots are equipped with some sensors, like camera and sonar, to detect the obstacles surround it and execute the navigation algorithms to avoid the detected obstacles.

However, with the acceleration of industrial automation development, many different types of industrial mobile robots are implemented and work cooperatively in a smart factory to complete complicated tasks in many manufacturing domains, such as electronics and automotive. It involves a significant demand for a simple, efficient and integrated robot navigation system in the workspace. In this paper, we propose an integrated sensor network based global navigation algorithm to replace the local navigations for all the mobile robots in the smart factory. The sensor network has emerged as one of the most promising technologies for the future [12]. A sensor network can obtain environment's and obstacles' information more efficiently and extensively than local sensors on the robots. In the past few years, there are a lot of implementations of sensor networks combined with mobile robots; e.g. [13–17]. In this paper, we focus on the problem of ground industrial mobile robot navigation in dynamic cluttered industrial environments based on a range finder sensor network deployed on the floor of smart factory.

This topic, sensor network based ground robot navigation, has attracted some researchers' attention in last decade. The basic problem statement in their researches is considering sensor network that each sensor node indicates whether the surrounding environment is safe to

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navigate a sensor-free mobile robot along the safe trajectory to the target. In the work [18], a roadmap based navigation algorithm with a novel WSN query protocol called Roadmap Query is proposed to avoid dangerous area in the 2D area; see another work [19]. In the work [20], the authors considered a ceiling camera to detect the obstacles on the ground and used the remote computer to generate Bézier curve based pathes for the non-holonomic mobile robot. In another work [21], a dynamic priority based path planning algorithm was proposed for multiple robots formation with obstacle avoidance. As the advantages of this algorithm, an efficient path planner for the multiple mobile robots was proposed and a dynamic priority strategy for cooperation of robots in formation was developed. In the following researches, the navigation problem without localization was considered and there are some works focusing on it. For example, in the work [22], received signal strength indication (RSSI) technology is used to assist the navigation without robot localization; also see work [23] on the same problem. Along with the development of this field, the path planning algorithms are also improved a lot. For example, the ant colony optimization method [24], genetic algorithm [25] and potential field method [26] are applied on the path planning problem; see other path planner [27–29]. The path planning also has been an important part of the sensor network based navigation methods.

Recently, there exist many research works on the sensor network based robot navigation with contributions. Among these works, RSSI-based approaches are widely used. In the work [30], the authors proposed a feasible scheme of wireless sensor network (WSN) based mobile robot navigation method. In this method, the sensor nodes of the WSN are deployed as grid pattern. Each sensor node can determine if the nearby cell is safe or dangerous or includes the target. The mobile robot can measure the distance from these sensor nodes by RSSI and can communicate with each sensor nodes. In this work, the robot position estimation algorithm is included and the A-start algorithm is applied to plan a path in the grid-pattern map. With a motion control strategy, the robot tracks the path and reach the target. In another RSSI-based method proposed in [31], sensor network is combined with a radio frequency identification (RFID) system to guide the mobile robot. The sensor nodes deployed in the navigation area in this method provide a vector field indicating the direction to the target. Moreover, the RFID tags are deployed around the obstacles to provide the repulsive vector field. It helps robot avoid the obstacles in the area. In other research works, artificial potential field (APF) method is combined with the RSSI-based WSN. In the work [32], the authors produced an RSSI-based APF in the navigation region and used particle filtering based bearing estimation and interpolated pseudogradient for efficient path planning and navigation; see another method proposed in [33]. In addition, there is a specific method which use the RSSI-based directed radio sensing to build a radio frequency (RF) map for the robot localization and navigation in [34]. In this work, the autonomous mobile robot is guided by a set of inter-connected RF sensor nodes. The particle filtering was used to estimate the robot's localization. The novelty of this work is to use a RF map instead of classic metric map for robot navigation and position estimation. Although the RSSI-WSN based navigation algorithms are widely used, the main disadvantage is that, constrained by the RSSI type sensor network, the RSSI-WSN algorithms do not use a metric map and cannot preform an accurate path planning and navigation. Therefore, in this paper, we propose the algorithm based on metric map built by range finder sensor network.

In addition, in the previous research works, there exist some vision sensor network based navigation algorithms. In these methods, vision sensors are deployed on the ceiling of indoor environment to detect the obstacles and build metric map. For example, in the work [35], the vision sensors localize the wheelchairs and use a navigation protocol to solve the multi-wheelchairs coordination problem with obstacle avoidance. In another work [36], similarly, the vision sensor nodes are deployed on the ceiling to complete the robot localization and obstacle detection. Then a novel path planning algorithm was proposed in this work to plan and re-plan the robot's path in the environment. A model predictive controller was used as a path tracker. Although in these works, the metric map was used for a satisfactory navigation performance, the limitation of the field of view of each vision sensor and the low accuracy of the map building by vision sensors should not be ignored; see other examples [37–39]. Therefore, we consider a 2D range finder based sensor network and design the navigation algorithm based on it. This algorithm avoids the involvement of the image processing with reliable metric map building.

In our method, we take the advantage of the range finder sensor network to navigate all the industrial mobile robots centrally in the workspace. Each range finder sensor node is deployed in dynamic industrial environments, such as factory floor, to detect walls, equipments, moving robots and walking people. Simultaneously, each robot measures its own real-time location and direction by localization, like odometry, and sends the measurements to the sensor network by the wireless communication. With the measurements of environment and robots' position, temporarily safe paths can be dynamically generated and the robots are navigated according to the generated path by the sensor network. Due to the use of the sensor network, the obstacle detection is performed by the sensor network, rather than the mobile robots. It leads a significant advantage that the proposed sensor network based navigation system is flexible for a large amount of mobile robots in applications. It means the number of the sensor nodes is fixed while a different mobile robot can be added into or remove from the workspace.

In this paper, we consider industrial applications of a large number of robots. In this case, if using our sensor network based navigation system, the number of the sensor nodes could be less than the number of robots. Moreover, the sensor quantity will not change along with the increase of the robots' quantity. Comparing with the local navigation methods in which an obstacle sensor is mounted on each robot, our method involves less sensors in this case. The simulation carried out in this paper shows this situation. In addition, it also should be noticed that, in another different case where only few robots work in a large and complex environment, the number of sensors used in our method could be more than the number of sensors in local navigation methods.

Another significant advantage of our method over the traditional methods is that the proposed sensor network based navigation system does not require any changes on both sensors and algorithm when any new robot is added into the system or any old robot is removed from the system.

The main feature of the proposed method is that the navigation tasks for all the mobile robots in the smart factory are completely transferred and integrated into the sensor network. Different types of robots can be navigated simultaneously in the workspace by the sensor network. Each robot is only required to have a low-level path tracking controller and some basic navigation sensors, like inertial navigation sensors or odometry sensors. It does not require any robot sensor for obstacle detection and any other extra navigation algorithm. Moreover, the sensor network based navigation is more flexible in configuration than local navigation in an industrial environment with different types of robots working cooperatively. New robots can be added into the workspace directly without any specialization in navigation. Additionally, a sensor network navigates robots according to the extensive measurements of the environment and perform a shorter and more efficient trajectory than local navigation algorithm. Therefore, this is an efficient, safe and economic navigation system for multiple robots in a dynamic industrial workspace. Furthermore, a practical non-holonomic industrial mobile robot model is considered in our method and dynamic environments with moving obstacles are supposed in our method, unlike other path planning algorithms e.g. [30,37].

The proposed navigation framework can be implemented as one of the most fundamental units in smart factory with various robots working cooperatively. With the arranged sensor network, manufacturers can purchase any types of robots without considering the