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Using a wireless visual sensor network to harmonically navigate multiple low-cost wheelchairs in an indoor environment

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ABSTRACT

Harmonic navigation of multiple low-cost robotic wheelchairs in a topology of wireless sensor nodes that are deployed in a dynamic and crowded indoor environment is a Non-deterministic Polynomial-time hard (NP-hard) problem. To address this problem, we propose a distributed multi-wheelchair global harmonic navigation algorithm. The distinguishing features of the proposed navigation algorithm are global search and local conflict resolution abilities. In the proposed algorithm, a travel time prediction method adopts a penalty for potential conflicts based on wheelchairs' priority, velocity and distance between the nodes. Moreover, three harmonic rules are proposed for: (1) giving the highest priority to humans, (2) giving the highest priority to wheelchairs, (3) giving flexible priority to wheelchairs. Through extensive quantitative simulations, we explore the performance of wheelchairs in various floor plan topologies and different values for the system parameters, and demonstrate that the properties of crowded indoor environments have important influence on the performance of global navigation, such as service time. The third harmonic rule establishes the trade-off between the performance of humans and robotic wheelchairs. At the same time, physical prototype wheelchairs are implemented and they verify the proposed global harmonic navigation algorithm. Some suggestions for robotic wheelchair designers, building architects and building owners are provided based on the conclusion of the experimental results.

1. Introduction

Robotic wheelchairs are a type of service robot for indoor applications, such as health care, and will co-exist in the human environment in near future. Autonomous and harmonic navigation is a remarkable feature of robotic wheelchairs. Many applications have focused on developing an integrated wheelchair with a smart 'brain' that can perceive and understand its environment, and respond to changes in that environment (Yuan, 2009; Simpson, 2005). These applications especially emphasize on giving highest priorities to humans (Okorn et al., 2010; Sisbot et al., 2007; Lam et al., 2011) in order to ensure harmonious human–robot coexistence.

Recently, there is a growing research trend in mutual beneficial collaboration (Batalin et al., 2004; Payton et al., 2001; Li and Shen, 2011; Wu et al., 2014) between mobile robots and static sensor networks, as it is believed that in the future, there will be a potential and need for such practical applications (Batalin et al., 2004) in the area of search and rescue and disable assistance. In such applications, neither network nodes nor mobile robots need to know their positions or build any kind of map (O'Hara et al., 2008), and mobile robots are guided autonomously between different locations by the navigation network. These applications also aimed at building an intelligent environment to support the robot navigation, and they preferably find shortest possible paths while avoiding dangers in the environment (Li and Rus, 2005), and collisions with static obstacles (O'Hara et al., 2008), and other mobile objects. Motivated by the characteristic of this kind of network, we have described a solution (Jiang et al., 2011; Tian et al., 2007), in which wireless visual sensor nodes (WVSnode) are distributed in an intelligent environment to support navigation of a robotic wheelchair. The distributed sensors and associated distributed information can release massive robot intelligence in its inhibited environment, which consists of a wireless visual sensor network (WVSN) that detects robots, collects environment information and activates robot behaviors in order to respond to the

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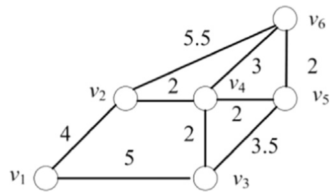

Fig. 1. An example of a weighted graph.

emergent events and help the robots to achieve their goals. But how to use this kind of intelligent environment to harmonically navigate multiple low-cost wheelchairs in an indoor environment is not considered in extant research. This is a challenging problem. Firstly, for current harmonic rules (i.e. designing robotics to serve humans and giving the highest priorities to humans (Okorn et al., 2010; Sisbot et al., 2007; Lam et al., 2011)), some researchers have realized that the situation is quite different for robotic wheelchairs in the sense that wheelchairs may have the highest priorities to move sometime when humans are aware of their existence (Murakami et al., 2001; Kuno et al., 2003). Secondly, current navigation algorithms are not suitable for an indoor environment that is characterized by narrow or crowded aisles. For analyzing this environment, such a class of navigation networks can be considered as a weighted graph, for example as shown in Fig. 1. In which, a shortest path between v_1 and v_6 may be not an optimal solution for two robots running in a opposite direction, when sum of the costs involved in multiple robotic wheelchair travel is considered. Furthermore, a task of planning multi-wheelchair navigation in a crowded and dynamic environment by applying our proposed network can be characterized as a NP-hard problem (Toth and Vigo, 2001). The detailed discussion on Fig. 1 is described in Section 2. Thirdly, current research on harmonic navigation focuses on designing local navigation algorithms. For instance, Sisbot et al. (2007) developed a method of determining how a robot may approach a human by considering safety criteria, visibility criteria, and hidden zones. This kind of research has improved the behavior control method or mechanism of a single wheelchair, but it does not focus on global navigation planner. Some researchers have investigated the harmonic global navigation of multiple wheelchairs. For an instance, Guzzi et al. (2013) implemented a fully distributed algorithm for robot local navigation, as well as a heuristics strategy for mutual avoidance of humans. They also found that the emergent collective behaviors are similar to those observed in human crowds. However, this research did not consider a crowded indoor environment and node topology-based navigation. At the same time, we believe that the wheelchair users have an equal right to access the paths and the quality of serving time, especially when they face emergent situations with time constraints, such as meeting a doctor. This means that the serving time should be considered in the context of global navigation. Moreover, because the distribution of our designed sensor network, the dynamic environment, and limited measuring range of sensors installed on a robotic wheelchair, the central scheduler or planner that persists in global optimal solution is infeasible. In fact, in this kind of real-world environment, it is necessary to design more flexible distributed algorithms for multiple robotic wheelchair navigation to create a harmonic environment for human–robotics collaboration and explore different scenarios and their impact on the algorithms.

The contributions of this paper include (1) a multi-wheelchair navigation algorithm based on a WVSN for narrow space scenarios in indoor applications, which is featured as global searching and local conflict resolution, (2) a travel time prediction method that adopts the penalty for potential conflicts based on wheelchair velocity and distance between nodes and various harmonic rules from a perspective of trade-off between travel performance of humans and robotic wheelchairs, and (3) performance evaluation of the proposed algorithm in various topologies of classical floor plans in indoor environments.

The remainder of this paper is organized as follows. Related work is reviewed in Section 2. An overview of our navigation network is described in Section 3. The distributed navigation algorithm with harmonic rules is described and evaluated using various topology simulation scenarios in Section 4. The detailed information of a prototype system based on wireless visual nodes and real-world experiments and their results are introduced in Section 5. Finally, the paper is concluded in Section 6.

2. Related work

Many researchers paid attention to intelligent wheelchair to build a central control unit, such as an agent running on a laptop/remote controller (Lu et al., 2006; Faria et al., 2014; Chen et al., 2013). Trieu et al. (2008) built an intelligent wheelchair that can detect obstacles in front of it using a laser range finder sensor, and produces a real-time map. They have considered the user's intentions via head-movement interface, accessible space of the environment and user safety in their control method. Del Castillo et al. (2006) adopted a sonar approach to detect obstacles for a vision based autonomous wheelchair.

Recently, Radio Frequency Identification (RFID) technology has been introduced into intelligent wheelchair systems, especially for marking global information label (Hamagami and Hirata, 2004; Matsumoto et al., 2006; Tao et al., 2009). Hamagami and Hirata (2004) implemented a software agent to control autonomous behaviors, such as cognising the safety and effectiveness of every move by observing a local real environment by range sensors and acquiring more global and accurate information, such as room number. Matsumoto et al. (2006) built a wheelchair with the ability to accurately determine its position and direction using internal sensors and external assistance from the surrounding environment, including Global Positioning System (GPS) and RFID. Its autonomous traveling controller is a control unit, a board computer and motor amplifiers. Tao et al. (2009) equipped their wheelchair with a main controller (via embedded board 1.5G), where wheel encoders and a ultrasonic sensor are used for obstacle avoidance and a RFID reader is used for detecting the RFID tags on the floor or furniture for location.

With the development of wireless sensor network (WSN) technology, some researchers on robotics have tried to explore a new way of combining WSN and robotics to better serve all kinds of practical applications (Akyildiz et al., 2007; Chen et al., 2013). Some research efforts emphasized on platform implementation and distributed navigation algorithms. O'Hara et al. (2008) presented a hardware platform, the GNATs, to aid in path planning, in which the nodes are equipped with four infrared (IR) emitters and four IR receivers. In the path finding stage a node broadcasts the message between nodes in a similar way to the distributed Bellford algorithm. Simpson (2005) adopted an approach of using embedded nodes to create a 'navigation field', in which mobile robots can find their way around. In this author's approach, transition probabilities between nodes were estimated to compute a best direction to suggest to a mobile robot for moving between a source and a destination. Li and Rus (2005) used number of hops to evaluate the distance between sensors without relying on location information and relying on a reactive task in a sensor network for guiding the movement of a user equipped with a node that can talk to sensors across the field. Bhattacharya et al. (2006) have described a Roadmap Query based navigation method for outdoor and dynamic environment applications. Baeg et al. (2007) and Louloudi et al. (2010) introduced service oriented robots for smart home applications, but both of them do not provide the