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Review

Optimal path planning of mobile robots: A review

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Mobile robots are increasingly used in automated industrial environments. There are also other applications like planet exploration, surveillance, landmine detection, etc. In all these applications, in order that the mobile robots perform their tasks, collision-free path planning is a prerequisite. This article provides an overview of the research progress in path planning of a mobile robot for off-line as well as on-line environments. Commonly used classic and evolutionary approaches of path planning of mobile robots have been addressed. Review shows that evolutionary optimization algorithms are computationally efficient and hence are increasingly being used in tandem with classic approaches while handling Non-deterministic Polynomial time hard (NP-hard) problems. Also, challenges involved in developing a computationally efficient path planning algorithm are addressed.

Key words: Path planning, mobile robot, off-line environment, on-line environment, classic, evolutionary algorithms.

INTRODUCTION

Mobile robots are increasingly being employed in many automated environments. Potential applications of mobile robots include a wide range such as service robots for elderly persons, automated guided vehicles for transferring goods in a factory, unmanned bomb disposal robots and planet exploration robots. In all these applications, the mobile robots perform their navigation tasks using the building blocks (Siegwart and Nourbakhsh, 2004) as shown in Figure 1.

Navigation of a mobile robot involves perception of environment, localization and map building, cognition and path planning and motion control. While perception refers to understanding its sensory data, finding its pose or configuration in the surroundings is localization and map building. Planning the path in accordance with the task by using cognitive decision making is an essential phase before actually accomplishing the preferred trajectory by controlling the motion. As each of the building blocks is by itself a vast research field, this paper reviews path planning approaches.

Apart from robotic applications, path planning finds use in planning the routes on circuit boards, obtaining the hierarchical routes for networks in wireless mobile communication (Manousakis et al., 2005), planning the path for digital artists in computer graphics and in computational biology to understand probable protein folding paths (Choset et al., 2005).

The objective of this paper is to provide an overview of path planning algorithms used in mobile robots. This article provides an overview of the research progress in path planning of a mobile robot for off-line as well as on-line environments. Commonly used classic and evolutionary approaches of path planning of mobile robots have been addressed. Further scope and challenges involved in developing computationally efficient path planning algorithms are also identified.

CATEGORIES OF PATH PLANNING ALGORITHMS

Path planning of a mobile robot is to determine a collision-free path from a starting point to a goal point optimizing a performance criterion such as distance, time or energy, distance being the most commonly adopted criterion. Based on the availability of information about environment, there are two categories of path planning algorithms, namely off-line and on-line. Off-line path planning of robots in environments where complete information about stationary obstacles and trajectory of

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移动机器人越来越多地用于自动化工业环境,还有其他应用,如行星探索、监视、地雷探测等。 在所有这些应用中,为了让移动机器人执行任务,无碰撞路径规划是一个先决条件。本文章概述了移动机器人在离线和联机环境中的路径规划方面的研究进展。对移动机器人路径规划通常采用的传统和进化方法已经得到解决。审查表明,进化优化算法在计算上效率很高,因此越来越多地与经典方法同时使用,同时处理非决定性的多时(NP-硬)问题。此外,还解决了制定计算高效路径规划算法的挑战。

Key 单词:路径规划、移动机器人、离线环境、在线环境。经典的,电子演算RITHMs。 ionary
algo

INTRODUCTION

移动机器人正在许多自动化环境中越来越多地被使用,移动机器人的潜在应用包括多种用途,例如为老年人自动导航飞行器提供服务机器人,供人使用,在工厂中转让货物,无人驾驶炸弹处理机器人和行星探索机器人。如图1所示,在所有这些应用中,移动机器人利用建筑块(Siegwart和Nourbakhsh,2004年)执行导航任务(Siegwart和Nourbakhsh,2004年)。

移动机器人的导航包括环境感知、定位和地图建设、认知和宣誓规划以及运动控制,虽然认知是指了解其感官数据,但发现其在周围的构成或配置是定位和地图建设。通过使用认知决策来根据任务规划路径是一个关键阶段,然后才能通过控制运动真正实现首选轨迹。 由于每个构件本身都是一个庞大的研究领域,本文件审视了路径环绕方法。

除了机器人应用之外,路径规划还发现使用NN来规划电路板上的线路,以获得

网络无线移动通信网络网路(Manousakis等人,2005年),规划计算机图形和计算生物学数字艺术家的宣誓,以了解可能的蛋白质老化路径(Cheste等人,2005年)。

移动机器人使用的宣誓计划算法。 本文概述了在为离线和不在线环境中的移动机器人进行宣誓规划方面的研究进展。 通常使用的移动机器人路径规划的经典和进化方法已经得到解决, 并确定了制定计算高效路径规划算法所涉及的进一步范围和挑战。

CATEGORIES OF PATH PLANNING ALGORITHMS

从起点到目标点的最优化性能标准,如距离、时间或能量,距离是最常用的标准。 根据环境信息的可得性,有两类路径规划算法,即离线算法和联机算法。在完全了解静止障碍物和轨道的环境里,机器人的离线路径和轨道

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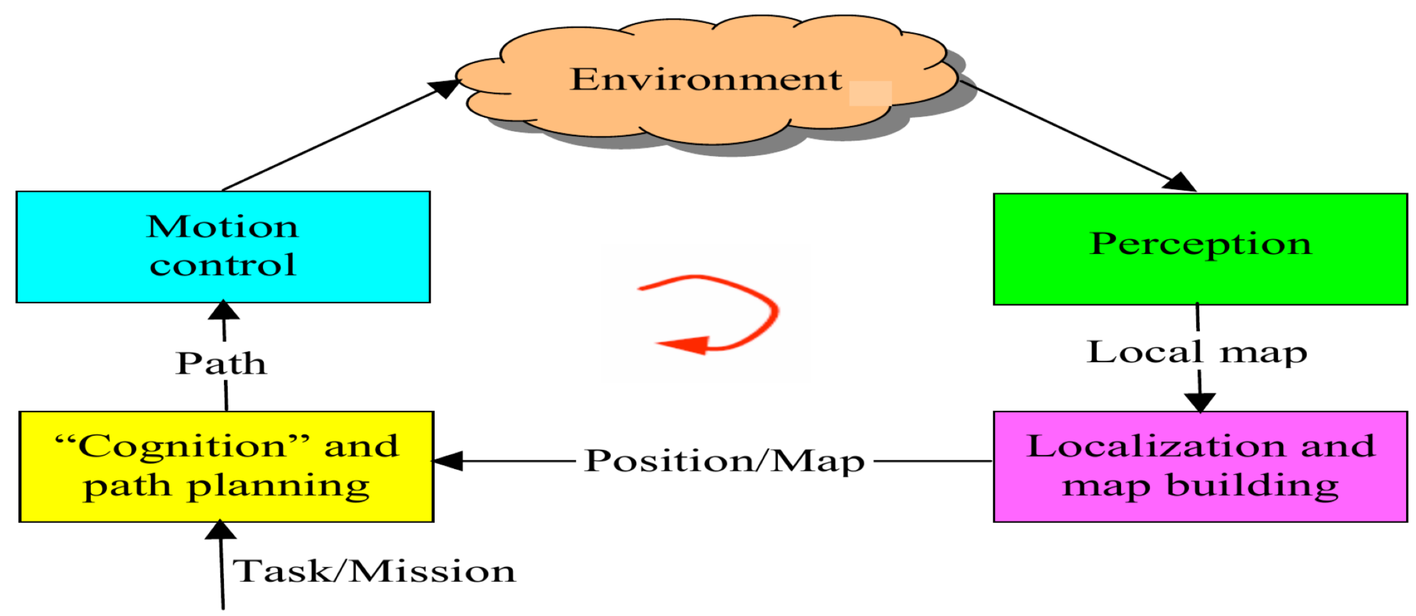

Figure 1. Building blocks of mobile robot navigation.

moving obstacles are known in advance is also known as global path planning. When complete information about environment is not available in advance, mobile robot gets information through sensors, as it moves through the environment. This is known as on-line or local path planning. Essentially, on-line path planning begins its initial path off-line but switches to on-line mode when it discovers new changes in obstacle scenario.

OFF-LINE PATH PLANNING ALGORITHMS

Examples of path planning in off-line environments are service robots operating during maintenance period of a nuclear power plant, automated guided vehicles in a factory, etc. where there may not be any change in the captured environment map.

Classic approaches

A fundamental approach for formulating and solving the path planning problem is the configuration space (C-space) approach (Lozano-Perez and Wesley, 1979). Though the idea was also exercised by Udupa (1977) in his doctoral thesis, it was Lozano-Perez who extensively used this in the perspective of path planning. The central idea of this approach is the representation of the robot as a single point. Thus, the C-space of the mobile robot path planning problem is reduced to a 2-dimensional problem. As robot is reduced to a point, each obstacle is enlarged by the size of the robot to compensate. The path planning literature was united around this approach by Latombe's book (1991). Using C-space as the fundamental concept, there are many classic path planning approaches like roadmap approach, cell decomposition approach, etc. In roadmap approach, networks of collision-free paths are constructed connecting start and target points. The well known roadmap methods are visibility graph and Voronoi diagram.

Visibility graph (Lozano-Perez and Wesley, 1979) is drawn by joining two vertices of mutually visible polygonal obstacles that are present between start and target points. The shortest path is then identified through the roads obtained from the visibility graph. The method is efficient in sparse environments as the number of roads is dependent on the number of polygonal obstacles and their edges (Li et al., 2002; Siegwart and Nourbakhsh, 2004). Another roadmap approach, the Voronoi diagram (Dunlaing and Yap, 1985) is constructed using via points which are equidistant from two or more obstacles. As a result, the obtained path is safer but normally not shorter (Masehian and Amin-Naseri, 2007; Garrido et al., 2011).

The cell decomposition approach (Lozano-Perez, 1983) computes the C-space of the mobile robot decomposes the resulting space into cells and then searches for a route in the free space cell graph. Grid method (Brooks and Lozano-Perez, 1983; Zhu and Latombe, 1989; Payton et al., 1993; Likhachev et al., 2005; Hachour, 2008a, b) is a popular cell decomposition approach where grids are used to generate the map of the environment. The main difficulty is how to find the size of the grids, the lesser the size of grids, the more accurate will be the representation of the environment. However, using lesser grids will result in exponential rise in memory space and search range (Zheng et al., 2007).

Evolutionary approaches

Classic approaches though found to be effective, take more time in the determination of feasible collision-free

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地方地图路径“地方化和地方化”以及定位地图路径和位置地图路径规划地图建设任务

Figure 1. Building blocks of mobile robot navigation.

预知移动障碍也被称为全球路径规划。 当无法事先获得关于环境的完整信息时,移动机器人通过感应器获得信息,当它通过环境移动时。这被称为在线或本地路径旋转。 基本上,在线路径规划在发现障碍情景出现新变化时开始脱机,但开关到在线模式。

OFF-LINE PATH PLANNING ALGORITHMS

离线环境中路径规划的例子包括核电厂维修期间运行的服务机器人、工厂的自动制导车辆等,所捕捉的环境图在这些方面可能没有任何变化。

Classic approaches

制定和解决路径规划问题的一个基本办法是配置空间(C-空间)方法(Lozano-Perez和Wesley,1979年)。 虽然Udupa(1977年)在其博士论文中也采用了这一想法,但Lozano-Perez从路径规划的角度广泛使用了这一想法,这一方法的中心思想是将机器人作为单一点。因此,移动机器人路径的C-空间问题将缩小为二维问题,因为机器人被降低到一个点,每个障碍都扩大为机器人的大小,以弥补机器人的大小。路径规划文献是Latombe's oook(1991年)围绕这一方法联合起来的。使用C-空间作为基本概念,有许多经典路径规划方法,如oadmap 方法、细胞分解方法等。

路线图方法、无碰撞路径网络是连接起点和目标点的网络,众所周知的路线图方法为可见度图和Voronoi图。

可见度图(Lozano-Perez和Wesley,1979年)通过结合在起始和目标卵液之间存在的两个相互可见的多边形障碍的顶端绘制,然后通过从可见度图中获得的道路确定最短路径,这种方法在稀少环境中是有效的,因为道路数量取决于多边形障碍的数量及其边缘(Li等人,2002年;Siegwart和Nourbakhsh)。另一种路线图方法,即Voronoi图Dunlaing和Yap(1985年),是通过两个或两个以上障碍的等距点建造的,作为一个河口,所获得的道路更安全,但通常不会缩短Masehian和Amin-Naseri,2007年;Garrido等人,2011年。

电网法(Brooks和Lozano-Perez,1983年;Zhu和Latombe,1989年;Payton等人,1993年;Likachev等人,2005年;Hikhachour,20o8a,b)是一种流行的电网分解法,其中电网被用来绘制环境地图。主要困难是如何找到网格的大小,网格越小,对环境的描述就越准确,但是,使用较小的网格将导致记忆空间和搜索范围的指数上升(Zheng等人,2007年)。

Evolutionary approaches

传统的办法虽然被认为有效,但需要更多的时间才能确定可行的无碰撞办法

path. Also, classic approaches tend to get locked in local optimal solution which may be far inferior to the global optimal solution. Moreover, path planning of a mobile robot in the presence of multiple obstacles is found to be non-deterministic polynomial time hard (NP-hard) problem (Canny and Reif, 1987). It becomes even more complicated when the environment is dynamic. These drawbacks make the classic approaches to be incompetent in complex environments (Sugihara and Smith, 1997). Hence, evolutionary approaches such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), etc. Similarly, Ant Colony Optimization (ACO) and Simulated Annealing (SA) are employed to solve the path planning problem quickly.

GA is an optimization tool based on the mechanics of natural genetics and selection (Holland, 1975; Goldberg, 2000). The first step in path planning using GA is random generation of population containing alternative paths. Dozier et al. (1997) from NASA presented a hybrid planner which makes use of visibility-based repair approach and evolutionary technique. The visibility-based repair approach is used to quickly transform the ones which interfere with the obstacles (invalid paths) into valid paths and then subject to binary coded GA. GA with binary string is computationally costly for the reason that before each evaluation of function, chromosomes are transformed to phenotypes (Ripon et al., 2007). Xiao et al. (1997) proposed an evolutionary planner for path planning. This planner has comparatively simple genotype structures that can represent valid paths, but necessitates complex decoders and fitness functions to obtain the optimal path. Moreover, there may be loss of accuracy in transforming to binary mode.

Further, Sugihara and Smith (1997), Gallardo et al. (1998), Nagib and Gharieb (2004) and Al-Taharwa et al. (2008) used fixed-length path consisting of binary strings. A fixed-length path gives a quick solution for environments with few obstacles and it takes hours to evolve a solution for a complex environment. In order to reach the target in a complex environment, variable length chromosomes are needed. Tu and Yang (2003) presented variable length binary coded GA in which gene indicates the subsequent movement direction and distance. The main limitation of such algorithms is that they direct to some invalid results like paths that may not reach to the target point at all (Shahidi et al., 2004).

Wang et al. (2006) presented a genetic based path planning algorithm, in which populations are generated including the ones which interfere with the obstacles (invalid paths also). Later such invalid path sequences are subjected to penalty function evaluation. This increases computation load resulting in higher execution time (Raja and Pugazhenthi, 2008, 2009a, b, 2011).

PSO is another very widely used evolutionary algorithm in path planning. It is an evolutionary computation technique inspired by social behavior of bird flocking or fish schooling. Years of study on the dynamics of bird and fish resulted in the possibilities of utilizing this behavior as an optimization tool. Compared to GA, the advantages of PSO are that PSO is easier to implement and there are fewer parameters to be adjusted (Kennedy and Eberhart, 1995). Qin et al. (2004) proposed an algorithm which finds out shortest path using graph based approach and PSO. They used graph based approach to obtain the collision–free paths in static environments and then PSO along with mutation operator to arrive at the shortest path.

Zhang and Gu (2008) used variable path length which depends upon number of vertices of polygonal obstacles. Binary PSO along with genetic like mutation operator is used to optimize the path. Nasrollahy and Javadi (2009) presented a PSO based planner for dynamic environments in which populations are generated containing invalid paths and then they are subjected to penalty function evaluation. Recently, Gong et al. (2011) proposed a model which uses a multi objective PSO and genetic like mutation operator. The multi objectives are shortest distance and danger of path from the obstacles. The mutation operator is used to repair the invalid paths.

The other optimization algorithms which have been used in path planning to a smaller percentage are ant colony optimization (ACO) and simulated annealing (SA) algorithms (Masehian and Sedighizadeh, 2007). ACO is inspired by the foraging behavior of ants for finding the shortest path to the food source. A method for optimal path planning based on improved Dijkstra algorithm and ACO is proposed by Guan-zheng et al. (2006). The improved Dijkstra algorithm consists of the standard Dijkstra algorithm and removal of unnecessary path nodes algorithm to get the sub-optimal paths. ACO is used to obtain the global optimal path from the sub-optimal paths. Garcia et al. (2009) presented simple ACO – distance memory (SACO-dm) algorithm for global path planning among static and moving obstacles. In SACO-dm, optimal path is influenced by current distance between robot and target nodes and the memory capability of ants remembering the visited nodes. Results show that optimal paths are achieved with lesser computation time compared to SACO.

SA is a type of heuristic random search method and it resembles the cooling process of molten metals through annealing. A method employing SA for collision-free path amid static polygonal obstacles in C-space setting is presented in Martinez-Alfaro and Gomez-Garcia (1998). Binary setting is used which may result in non-optimal path when shorter computation time is desired. Miao and Tian (2008) developed SA algorithm based approach for dynamic environments. Their approach uses vertices of the static and dynamic obstacles as search space. Then the SA algorithm is used to find the optimal path.

ON-LINE PATH PLANNING ALGORITHMS

In recent times, on-line path planning has received more

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路径。此外,经典方法往往被锁定在地方最佳解决方案中,而这种解决方案可能远远低于全球最佳解决方案。 此外,在多重障碍面前对移动机器人进行路径规划被认为是非决定性的多元时间硬(NP-硬)问题(Canny和Reif,1987年)。 当环境是动态的时,它变得更加复杂。这些缺陷使得传统方法在复杂环境中无能(Sugihara和Smith,1997年),因此,进化方法,如遗传高理学(GA)、粒子最优化(PSO)等。 同样,Ant 殖民地优化(ACO)和模拟安纳林(SA)也被用来迅速解决路径流动问题。

GA是一种基于自然遗传学和选择机制的优化工具(Holland,1975年;Goldberg,2000年)。 利用GA进行路径规划的第一步是随机生成含有替代路径的人口。来自美国航天局的Dozier等人(1997年)介绍了一个混合规划师,该规划师利用了以可见度为基础的修复方法和进化技术。以可见度为基础的修复方法被用来迅速将干扰障碍(无效路径)的功能转换成有效路径,然后接受二元编码的GA。 使用Oinary 字符串的GA在计算上成本很高,因为在每次对功能进行评估之前,染色体会转换成苯型(Ripon等人,2007年); Xiao等人(1997年)提出了路径规划的进化规划员。这个规划器拥有相对简单的基因型结构,可以代表有效路径,但需要复杂的解码器和健身功能才能获得最佳路径。 此外,转换成二进制模式可能会失去准确性。

此外,Sugihara和Smith(1997年)、Gallardo等人(1998年)、Nagib和Gharrieb(2004年)以及Al-Taharwa等人(2008年)使用了由二进制字符串组成的固定长度路径;固定长度路径为没有障碍的环境提供了快速解决方案,为复杂的环境制定解决方案需要几个小时;为了在复杂的环境中达到目标,需要变异的酵染色体。Tu和Yang(2003年)提出了可变的二进制密码GA,其中基因表示随后的移动方向和距离,这种算法的主要限制是,它们直接导致一些无效的结果,如可能根本达不到目标点的路径(Shahidi等人,2004年)。

Wang等人(2006年)提出了一个基于遗传路径的巡回算法,在算法中,产生人口,包括也干扰障碍的无效路径。 之后,对无效路径序列进行惩罚功能评估,从而增加计算负荷,增加执行时间(Raia和Pugazhenthi,2008年、2009年a、b、2011年)。

Pso是另一个在路径规划中广泛使用的另一个进化算法。 它是一种进化计算技术,其灵感来自鸟群捕鸟或鱼类教育的社会行为。 多年来对鸟类动态的研究。

与GA相比,PsO的优点是,PsO更容易执行,需要调整的参数较少(Kennedy和Eberhart,1995年)。 Qin等人(2004年)提出了一个算法,用图表法和PsO法找到最短路径。他们利用图表方法在静态环境中获得无碰撞路径,然后与突变操作员一起到达最短路径。

Zhang和Gu(2008年)使用了视多边形障碍的顶部数量而定的可变路径长度。二进制 PsO 和像突变操作员这样的遗传操作员被用来优化路径。Nasrollahy和Javadi(2009年) 和 Javadi(2009年) 用于人口产生含有无效路径的动态环境的PsO型规划员,然后进行阴道功能评估。使用多目标Pso和基因如突变操作器的模型,多观察器距离最短,有障碍路路的危险。 突变操作器用来修复无效路径。

在路径规划中使用的其他优化算法的比例较低,其他优化算法是蚂蚁聚居优化(AcO)和模拟Annealing(SA)算法(Masehian和Sedighizadeh,2007年)。A受到蚂蚁为寻找食物来源最短路径而施用诱因行为的启发。Guan-zheng等人(2006年)提出了基于改进Dijkstra算法和AcO的最佳宣誓规划方法。设置的Dijkstra 算法包括标准的 Dijkstra 算法和删除不必要的路径节点算法以获取亚最佳路径。 Aco 用于从亚喜马拉雅路径获取全球最佳路径。 Garcia等人(2009年)为静态障碍和移动障碍间全球路径流动提供了简单的 ACO 距离内存(SAcO- dm) 算法。在 SAco- dm 中,最佳路径受机器人与目标节点之间目前距离的影响,以及蚂蚁回忆所访问节点的记忆能力的影响。 结果显示,最佳路径的计算时间比SAco要短。

SA是一种脂质随机搜索方法,类似于通过Annealing熔融金属的冷却过程:Martinez-Alfaro和Gomez-Garcia(1998年)二进制使用SA在C-空间环境中的静态多边形障碍中采用无碰撞路径的方法,在需要较短的计算时间时,这种方法可能会导致非最佳宣誓。Miao和Tian(2008年)开发了以SA算法为基础的动态环境方法。 他们的方法使用静态和动态障碍的顶点作为搜索空间。 然后,他用SA算法找到了最佳路径 。

ON-LINE PATH PLANNING ALGORITHMS

In recent times, on-line path planning has received more

attention from researchers (Masehian and Katebi, 2007) since autonomous mobile robots must be capable of operating in dynamic environments. Applications of path planning in on-line environments include planet exploration, mine industry, reconnaissance robots, etc. (Hachour, 2008a). On-line path planning approaches like potential field approach and collision-cone approach have been traditionally followed. Nowadays, evolutionary approaches are increasingly being used along with classic approaches.

Classic approaches

Pioneering works have been initiated by Khatib (1986) who proposed Artificial Potential Field (APF) approach which is popular in mobile robotics. By this approach, a point robot in C-space moves under the influence of an APF in which obstacles are assumed to generate repulsive forces and the target is assumed to generate attractive forces. The robot moves as per the resultant of these forces. This approach is known for its mathematical elegance and simplicity as path is found with very little computation. However, the drawback of this algorithm is that robot may become stagnant or trapped when there is a cancellation of equal magnitudes of attractive and repulsive forces. One solution to overcome this problem is to complement with influential algorithms to escape from trap (Latombe, 1991) and till date many variants of potential field approach like escape-force algorithm (Vadakkepat et al., 2000, 2001), trap recovery model used by Lv and Feng (2006), adaptive virtual target algorithm (Luh and Liu, 2007, 2008), etc. have been proposed.

Path planning problem can also be solved by vector field histogram approach (Borenstein and Koren, 1991). At every instant, a polar histogram is generated to represent the polar density of obstacles around a robot. The robot's steering direction is chosen based on the least polar density and closeness to the goal. In a given environment, the polar histogram must be regularly regenerated for every instant and hence the method is suited for environments with sparse moving obstacles.

Another commonly used on-line approach is based on collision cone concept (Chakravarthy and Ghose, 1998; Qu et al., 2004). Collision of robot can be averted if the relative velocity of robot with regard to a particular obstacle falls exterior to the collision cone. Fiorini and Shiller (1998) proposed a velocity obstacle approach, which is in resemblance to collision cone approach. It consists of choosing avoidance maneuvers to avoid static and moving obstacles in the velocity space. They used basic heuristic strategy for prioritizing objectives such as averting collisions, attaining the goal or accomplishing trajectories with preferred topologies.

Another on-line approach for obstacle avoidance is dynamic windows approach (Fox et al., 1997; Brock and Khatib, 1999). The dynamic window contains the feasible linear and angular velocities taking into consideration acceleration capability of robot. Then the velocity at the next instant is optimized for obstacle avoidance, subject to vehicle dynamics.

Evolutionary approaches

Although classic approaches are found to be effective, computation time is crucial for the success of any on-line path planning algorithms. But, with classic approaches, optimum result can hardly be achieved in quick computation time owing to incomplete information of the environment. Further, due to NP-hard complexity of path planning problem, classic approaches are often combined with evolutionary approaches like GA, PSO, etc. to overcome their drawbacks.

Vadakkepat et al. (2000, 2001) proposed evolutionary APF (EAPF) algorithm to derive optimal potential field functions using GA. When the robot is trapped, a separate algorithm named escape-force is introduced to recover from trap. Potential field immune network proposed by Luh and Liu (2008) used velocity obstacle method to identify the most imminent collision of the obstacle. Potential field approach coupled with biologically inspired immune network is used to avoid the most imminent obstacle. The overall response of the immune network is calculated using GA. Adaptive virtual target algorithm is proposed to direct the robot out of the trap. It was assumed that robot is being trapped if it moves beyond 90° off-target.

Min et al. (2005) employed a mathematical model using collision cone approach and PSO for on-line path planning. To facilitate reduction of computational burden, they ignored instantaneous changes in obstacle velocities in the motion model. Therefore, their algorithm is suited to sparse environments having obstacles with slow velocities. Also, PSO in combination with binary coded genetic operators is used as optimization tool without considering dynamic constraints. Nevertheless, recent studies show that real coded evolutionary algorithms execute better than the binary coded.

Hu et al. (2007) addressed an approach to steer the mobile robot in static or dynamic environments based on PSO and stream functions (or potential flows). Stream functions, derived from hydrodynamics, are engaged to steer an autonomous robot to avoid the obstacles. However, their model also does not consider instantaneous changes in obstacle velocities. Park and Kim (2008) proposed a PSO algorithm based on the potential field approach. The potential field is mathematically modeled by particles' fitness value. The PSO particles are designed to move with Newtonian dynamics. Lu and Gong (2008) proposed an on-line path planning algorithm using PSO technique for unknown environments. Their algorithm is entirely based on

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来自研究人员的注意(Masehian和Katebi,2007年,因为自主移动机器人必须能够在动态环境中运作,在线环境中的路径流动应用包括行星探索、采矿业、侦察机器人等,2008年a)。 在线路径规划方法,如食用实地方法和碰撞锥子方法,传统上一直采用。如今,在采用传统方法的同时,越来越多地采用渐进式方法

Classic approaches

最初的工程由Khatib(1986年)发起,他提出了移动机器人中流行的人工潜力场(APF)方法。 通过这一方法,C-空间中的点机器人在APF的影响下移动,其障碍被假定为产生令人厌恶的力量,目标被假定为产生有吸引力的力量。根据这些力量的结果,机器人移动。这一方法以其数学优雅和简洁而著称,因为路径的计算很少。 然而,这一算法的缺点是,当有同等规模的吸引力和令人厌恶的力量被取消时,机器人可能会陷入停滞或困住状态。克服这一问题的一种解决办法是补充有影响力的算法,以摆脱陷阱(Latombe,1991年),迄今为止,提出了许多可能的实地方法的变种,如逃生力算法(Vadakkepat等人,2000年、2001年)、Lv和Feng使用的陷阱回收模型(2006年)、适应性虚拟目标算法(Luh和Liu,2007年、2008年)等。

路径规划问题也可以通过矢量场直方图方法(Borenstein和Koren,1991年)来解决。 每时每刻,都会产生极直方图,以代表机器人周围障碍物的极密度。机器人的方向是根据东极密度和接近目标的距离选择的。在特定环境中,极地直方图必须定期为每一瞬间再生,因此这种方法适合移动障碍很少的环境

另一种常用的在线方法以碰撞锥形概念为基础(Chakravathy和Ghose,1998年;Qu等人,2004年)。 如果与碰撞锥形相对快的机器人在特定障碍方面的相对速度落在碰撞锥形之外,则可以避免机器人的碰撞。 Fiorini和Shiller(1998年)提出了一个与碰撞锥形方法相似的速度障碍法。它包括选择避免在速度空间中避免静态障碍和移动障碍的避险策略,它们利用基本超常战略确定目标的优先顺序,如避免碰撞、实现目标或以首选地形完成轨道

避免障碍的另一个在线办法是动态窗口办法(Fox等人,1997年;Brock和Brock等人,1997年);1999年,Khatib,1999年,动态窗口包含可行的线性速度和角速度,同时考虑到机器人的加速能力。随后,下一瞬时的速度被优化,以避免障碍,但须视车辆动态情况而定。

Evolutionary approaches

尽管传统方法被认为是有效的计算时间,但对于任何在线宣誓计划算法的成功都至关重要。 但是,由于环境信息不全,传统的方法很难在快速计算时间内取得最佳结果。 此外,由于路径环流问题复杂,传统方法往往与渐进方法(如GA、PsO等)相结合。克服他们的缺点

Vadakkepat等人(2000年、2001年)提出了进化APF(APF)算法,以便利用GA获得最佳的潜在实地功能。当机器人被困时,将采用一个名为“逃生力量”的单独算法从陷阱中恢复过来。卢和刘提出的潜在实地免疫网络(Luh和刘2008年)使用速度障碍法来查明障碍最直接的碰撞。利用潜在的实地方法,加上受神学启发的免疫网络来避免最紧迫的障碍。免疫网络的总体反应是用GA计算出来的。建议采用适应性虚拟电磁算法将机器人引出陷阱。假设机器人如果超越9o' 离目标范围,就会被困住。

Min等人(2005年)采用了使用碰撞锥形法的数学模型和用于在线路径的Pso的数学模型,为便利减少计算负担,他们忽略了运动模型中障碍速度的瞬时变化,因此,他们的算法适用于障碍速度缓慢的稀少环境。此外,PsO与二进制编码基因操作员一起被作为优化工具,而没有考虑动态限制。 尽管如此,最近的研究表明,实际的编码进化算法比二进制编码效果更好。

Hu等人(2007年)谈到在基于Pso和流函数(或潜在流)的静态或dvnaic环境中引导移动机器人的方法,流动力学产生的流函数被用来引导自主机器人避免障碍,但其模型也不考虑障碍速度的瞬时变化,Park和Kim(2008年)根据潜在的实地方法提出了PsO算法。潜在字段以粒子的健身价值为数学模型。 Pso粒子设计成与牛顿动态一起移动。 Lu 和 Gong (2008年) 提出了一个使用 Pso 技术对未知环境的在线路径 Olanning 算法。 它们的算法完全基于未知环境。

distance information of the environment without any mathematical model featuring velocity of nearing obstacle. Recently, Hong et al. (2011) presented a model using classic APF considering dynamic model of velocity potential field obtained by a variant of PSO called quantum PSO. Inspired by the nature of motion of microscopic particles (quantum mechanics), quantum PSO updates state of a particle by wave function instead of position and velocity.

Mei et al. (2006) proposed a hybrid algorithm which combines APF and ACO for dynamic environments. ACO is applied to plan the global path and then APF is employed to guide the robot for local route. Lv and Feng (2006) proposed numerical potential field to model the environment and applied ACO to search for optimal path. A trap recovery solution was also discussed by them. The main problem of ACO is difficulty in obtaining the quick solution convergence. Lee et al. (2008) presented improved ACO using potential field approach to get quick solution convergence by tuning the control parameters of ACO. Improved ACO makes use of altered pheromone (a substance secreted by ants) to update the position vector.

Zhang et al. (2004) proposed an APF approach in combination with SA which considers the problems of goal non-reachable with obstacles nearby (GNRON) and local minima in soccer robots. New potential functions have been derived by considering the distance information of start and target points for GNRON problem. Miao (2010) presented a multi operator based SA approach for path planning. Switching, deleting, mutating and repairing operators are introduced along with SA. The parameters of SA are fine tuned for moving obstacles also.

SCOPE AND CHALLENGES

In the domain of path planning, evolutionary methods have proved to yield better results than pure classical approaches (Garcia MAP et al., 2009). Several algorithms have been proposed to overcome the complex nature of NP-hard path planning problem as efficient functioning of mobile robot is influenced by better quality of paths. The review of literature shows that there is still scope for developing more efficient off-line path planning algorithms that will yield better quality paths by addressing some of the issues as follows:

1) Valid paths which do not interfere with the obstacles should alone be considered in the initial generation of population eliminating the use of penalty function evaluation.
2) Optimization techniques with real strings are computationally less expensive because before the evaluation of objective function, details of alternative paths need not be expressed in binary codes.
3) Path containing variable number of segments can be used in generation of population considering the complexity (number of vertices) of environment.
4) Simple decoders and fitness functions can be used to decrease the computational time of algorithms.

Compared to off-line, developing a computationally efficient on-line algorithm is more challenging. One of the difficulties in working with incomplete information of environment is that the path cannot be pre-planned and therefore global optimum solutions can hardly be achieved. However, better quality paths can be achieved by addressing the challenges as follows:

1) More accurate mathematical models can be developed which feature instantaneous velocity of robot as well as nearing obstacles to tackle even cluttered moving obstacles.
2) The influence of other constraining obstacles while negotiating the most imminent obstacle can yield overall better result. Therefore, mathematical model should simultaneously consider the effect of constraining obstacles which may cause further deviation more than avoiding the imminent threat.
3) Avoiding trap of a robot when there exists a path is another vital issue in obstacle avoidance. The need for trap recovery can be eliminated.
4) Any on-line path planning algorithm becomes truly successful if the next instant of the robot is planned within the bounds of the kinematic and dynamic constraints of the mobile robot. So the mathematical models should incorporate the upper bounds for the dynamic constraints in tough time varying environments.

Further, multiple optimization objectives, multiple robot coordination, uncertainties in sensing, prediction, motion control, etc. pose many other challenges in mobile robotics.

CONCLUSION

At present, development in path planning is progressively more inspired by new applications such as circuit board designs, network routings, computer animations, pharmaceutical drug designs, computational biology, etc. The research community puts forward many approaches for solving the path planning problem. This article reflects the research progress that has taken place in path planning of mobile robots, including on-line planning. Although many efficient algorithms have been developed, the diversity of path planning problems has been constantly increasing. Up to 90s, determination of collision-free path remained the main objective. Currently, though collision-free path is a necessary condition, other significant issues such as modeling of dynamic environment, multiple optimal functions, dynamic

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最近,Hong等人(2011年)介绍了一个模型,使用了传统的APF, 考虑由Pso的变体“量子PsO”获得的速度潜在场域动态模型。受微粒运动的性质(量子力学)的启发,量子PsO用波函数而不是位置和速度来更新粒子的状态。

Mei等人(2006年)提出了一个混合算法,将APF和ACO结合用于动态环境,ACO于规划全球路径,然后APF被用于引导机器人进入本地路径。Lv和Feng(2006年)提出了模拟环境的数字潜力字段,并应用AcO寻找最佳路径。他们还讨论了一个陷阱回收解决方案。Lee等人(2008年)指出,改进的AcO利用潜在的实地方法,通过调整AcO的控制参数,实现快速解决方案的趋同。 改进的AcO利用改变后的Felomon(由蚂蚁秘密的物质)来更新定位矢量。

Zhang等人(2004年)与南非议会共同提出了亚太论坛办法,其中考虑到在足球机器人附近有障碍(GNRON)和小球小球中无法达到的目标问题,通过考虑GNRON问题的起始点和目标点的远距信息,产生了新的潜在功能。 Miao(201年)提出了以多运营者为基础的南联盟路径规划办法。与南澳大利亚州一起引入了转换、删除变异和修理操作员,南澳大利亚州参数也根据移动障碍作了细微调整。

SCOPE AND CHALLENGES

在路径规划领域,实践方法已证明比纯经典方法产生更好的结果(GarciaMAP等人,2009年)。 由于移动机器人的高效运行受到路径质量提高的影响,因此提出了若干算法,以克服NP-硬路径规划问题的复杂性质。对文献的审查表明,仍然有余地制定更有效的离线路径规划算法,通过处理下列问题,产生更好的质量路径:

1) 不干预障碍的有效途径应单独在人口最初一代消除使用惩罚功能评估方法时加以考虑。 2) 使用实际字符串的优化技术计算成本较低,因为,在评价强制功能之前,无须在二元法典中表述替代誓言的细节。

4) 简单解码器和健身功能可用于减少算法的计算时间

与脱机相比,开发一种计算效率高的在线算法更具挑战性:在使用不完整的环境信息方面遇到的困难之一是,这条路径不能预先规划,因此全球最佳解决办法几乎无法实现。

(1) 可以开发出更准确的数学模型,其特征是机器人的瞬时速度,以及近乎克服各种障碍的近似障碍,以克服平坦的障碍。 (2) 在谈判最紧迫的障碍的同时,其他限制障碍的影响可以产生总体更好的结果。因此,数学模型应该同时考虑限制障碍的影响,这些障碍可能造成进一步偏差,而不是避免迫在眉睫的威胁。 3)在存在路径的情况下避免机器人的陷阱是避免障碍的另一个关键问题。 回收陷阱的必要性可以消除。(4) 任何在线路径规划算法如果在机器人移动机器人的动力和动态限制范围内规划机器人的下一瞬间,就会真正成功。因此数学模型应该将动态限制的上界纳入到 touah 时间 Varvina 环境的上端。

此外,多重优化双眼、多机器人协调、遥感、预测、运动控制等方面的不确定性等,给移动机器人带来了许多其他挑战。

CONCLUSION

目前,道路规划的发展越来越受电路板设计、网络路由、计算机动画、手工艺药物设计、计算生物学等新应用的启发。 研究界提出了解决道路规划问题的许多办法。本文反映了移动机器人行走路径(包括在线规划)的研究进展。 尽管已经发展了许多高效的算法,但路径规划问题的多样性一直在不断增长。 多达9 %, 确定无碰撞路径仍然是主要目标。目前,虽然无碰撞道路是一个必要条件,但其他重要问题,如动态环境建模。

constraints, etc. are also to be addressed. These constraints craft path planning problems to be more challenging and necessitate more robust and efficient algorithms.

REFERENCES

Al-Taharwa I, Sheta A, Al-Weshah M (2008). A mobile robot path planning using genetic algorithm in static environment. J. Comput. Sci., 4(4): 341-344.

Borenstein J, Koren Y (1991). The vector field histogram – Fast obstacle avoidance for mobile robots. IEEE T. Robot. Autom., 3(7): 278-288.

Brock O, Khatib O (1999). High-speed navigation using the global dynamic window approach. Proceedings of IEEE International Conference on Robotics and Automation, Detroit, USA, pp. 341-346.

Brooks RA, Lozano-Perez T (1983). A subdivision algorithm in configuration space for find path with rotation. Proceedings of eighth International Joint Conference on Artificial Intelligence, Karlsruhe, Germany, pp. 799-806.

Canny J, Reif J (1987). New lower bound techniques for robot motion planning problems. Proceedings of IEEE Symposium on the Foundations of Computer Science, Los Angeles, California, pp. 49-60.

Chakravarthy A, Ghose D (1998). Obstacle avoidance in a dynamic environment: A collision cone approach. IEEE T. Syst. Man Cy. A., 28(5): 562-574.

Choset H, Lynch K, Hutchinson S, Kantor G, Burgard W, Kavraki L, Thrun S (2005). Principles of Robot Motion: Theory, Algorithms, and Implementations. Massachusetts Institute of Technology Press, Cambridge, U.S.A.

Dozier G, Esterline A, Homaifar A, Bikdash M (1997). Hybrid Evolutionary Motion Planning via Visibility-Based Repair. Proceedings of the IEEE International Conference on Evolutionary Computation, Indianapolis, pp. 507-511.

Dunlaing CO, Yap CK (1985). A retraction method for planning the motion of a disc. J. Algorithms, 6: 104-111.

Fiorini P, Shiller Z (1998). Motion planning in dynamic environments using velocity obstacles. Int. J. Robot. Res., 17(7): 760-772.

Fox D, Burgard W, Thrun S (1997). The dynamic window approach to collision avoidance. IEEE Robot. Autom. Mag., 4(1): 23-33.

Gallardo D, Colomina O, Florez F, Rize R (1998). A genetic algorithm for robust motion planning. Proceedings of the Eleventh International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems, Benicassim, Spain, pp. 115-121.

Garcia MAP, Montiel O, Castillo O, Sepulveda R, Melin P (2009). Path planning for autonomous mobile robot navigation with ant colony optimization and fuzzy cost evaluation. Appl. Soft Comput., 9: 1102-1110.

Garrido S, Moreno L, Blanco D, Jurewicz P (2011). Path Planning for mobile robot navigation using Voronoi diagram and fast marching. Int. J. Robot. Autom., 2(1): 42-64.

Goldberg DE (2000). Genetic algorithms in search, optimization and machine learning. Addison-Wesley, Delhi, India.

Gong DW, Zhang JH, Zhang Y (2011). Multi-objective particle swarm optimization for robot path planning in environment with danger sources. J. Comput., 6(8): 1554-1561.

Guan-zheng T, Huan HE, Sloman A (2006). Global optimal path planning for mobile robot based on improved Dijkstra algorithm and ant system algorithm. J. Cent. South Univ. Technol., 13(1): 80-86.

Hachour O (2008a). The proposed genetic FPGA implementation for path planning of autonomous mobile robot. Int. J. Circ. Syst. Sig. Proc., 2(2): 151-167.

Hachour O (2008b). Path planning of autonomous mobile robot. Int. J. Syst. Appl. Eng. Dev., 4(2): 178-190.

Holland JH (1975). Adaptation in natural and artificial systems. University of Michigan Press, Ann Arbor, USA.

Hong Z, Liu Y, Zhongguo G, Yi C (2011). The dynamic path planning research for mobile robot based on artificial potential field. Proceedings of the International Conference on consumer Electronics, Communications and Networks (CECNet), XianNing, pp. 2736-2739.

Hu C, Wu X, Liang Q, Wang Y (2007). Autonomous robot path planning based on swarm intelligence and stream functions. Lect. Notes Comp. Sci., Springer, pp. 277-284.

Kennedy J, Eberhart RC (1995). Particle swarm optimization. Proceedings of the IEEE International Conference on Neural Networks, Perth, Australia, pp. 1942-1948.

Khatib O (1986). Real time obstacle avoidance for manipulators and mobile robots. Int. J. Robot. Res., 5(1): 90-98.

Latombe JC (1991). Robot motion planning. Kluwer Academic Publisher, Boston.

Lee JW, Kim JJ, Choi BS, Lee JJ (2008). Improved ant colony optimization algorithm by potential field concept for optimal path planning. Proceedings of the eighth IEEE-RAS International Conference on Humanoid Robots, Daejeon, pp. 662–667.

Li L, Ye T, Tan M, Chen X (2002). Present state and future development of mobile robot technology research. Robot., 24(5): 475-480.

Likhachev M, Ferguson D, Gordon G, Stentz A, Thrun S (2005). Anytime dynamic A*: An anytime, replanning algorithm. Proceedings of the International Conference on Automated Planning and Scheduling, pp. 262-271.

Lozano-Perez T, Wesley MA (1979). An algorithm for planning collision-free paths among polyhedral obstacles. Commun. ACM., 22(10): 560–570.

Lozano-Perez T (1983), Spatial planning: A configuration approach. IEEE T. Comput. C, 32(3): 108-120.

Lu L, Gong D (2008). Robot path planning in unknown environments using particle swarm optimization. Proceedings of the fourth International Conference on Natural Computation, Jinan, pp. 422-426.

Luh GC, Liu WW (2007). Motion planning for mobile robots in dynamic environments using a potential field immune network. IMechE J. Syst. Control Eng., 221(7): 1033-1045.

Luh GC, Liu WW (2008). An immunological approach to mobile robot reactive navigation. Appl. Soft Comput., 8(1): 30-45.

Lv N, Feng Z (2006). Numerical potential field and ant colony optimization based path planning in dynamic environment. Proceedings of the Sixth World Congress on Intelligent Control and Automation, Dalian, pp. 8966-8970.

Manousakis K, McAuley T, Morera R, Baras J (2005). Using multi-objective domain optimization for routing in hierarchical networks. Proceedings of the International Conference on Wireless Networks, Communication and Mobile Computing, pp. 1460-1465.

Martinez-Alfaro H, Gomez-Garcia S (1998). Mobile robot path planning and tracking using simulated annealing and fuzzy logic control. Expert Syst. Appl., 15(3): 421-429.

Masehian E, Katebi Y (2007). Robot motion planning in dynamic environments with moving obstacles and target. Int. J. Mech. Syst. Sci. Eng., 1(1): 20-25.

Masehian E, Sedighizadeh D (2007). Classic and heuristic approaches in robot motion planning – A chronological review. World Acad. Sci. Eng, Technol.. 23: 101-106.

Masehian E, Amin-Naseri MR (2007). Composite models for mobile robot offline path planning, Mobile robots: Perception and navigation. InTech Publisher, Croatia.

Mei H, Tian Y, Zu L (2006). A hybrid ant colony optimization algorithm for path planning of robot in dynamic environment. Int. J. Inf. Tech., 12(3): 78-87.

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这些制约因素使路径规划问题更具挑战性,需要更有力、更有效率的算法。

REFERENCES

Al-Taharwa I、Sheta A、Al-Weshah M(2008年),利用静态环境中的遗传算法进行移动机器人路径规划,J.Comput.Sci.,4(4):341-344.Borenstein J、Koren Y(1991年),矢量场直方图 -- -- 移动机器人的远方障碍避免,IEEE T.机器人,自动3(7):278-2888.Brock O、Khatib O(1999年),使用Globa动态窗口方法高速导航。美国底特律IEEE机器人与自动化国际会议议事录,第341-346页,Brooks RA, Lozano-Perez T(1983年),《构筑空间中的分类算法,以寻找旋转路径》,第八届德国卡尔斯鲁厄人工智能国际联合会议议事录,第799-806页,Canny J, Reif J(1987年),《强盗运动规划问题新的较低约束技术》。国际电子教育学院计算机科学基础专题讨论会会议记录,洛杉矶,加利福尼亚州,第49-60页。 Chakravarthy A, Ghose D(1998年),《在动态环境中避免障碍:碰撞锥体方法》,国际电子教育学院T. Syst. Man Cy A., 28(5): 562-574。 Choset H, Lynch K, Hutchinson S, Kantor G, Burgard W, Kavraki L Thrun S(2005年),《机器人动力原则:理论、阿尔戈里森和执行》。马萨诸塞州理工学院,剑桥,美国A.Dozier G, Esterline A, Homaifar A, Bikdash M (1997年),《通过以可见性为基础的国际电子EEEE国际会议"进化计算"的《以修复过程为根据的可视性来进行进化规划》,印第安纳波利斯,第507-511页。 Dunlaing CO, Yap CK (1985年),《Dunlaing CO》,Yap CK (1985年),《Agorithms》, J. Algorithms, 6: 104-111。 Fiorini P,Shiller Z (1998年)。动态环境中使用速度障碍进行动态规划。《J.机器人》,第17(7)号决议:760-772 Fox D,Burgard W, Thrun S (1997年),《避免碰撞的动态窗口办法》,IEE 机器人,Autom. Mag.,4(1):23-33 Gallardo D,Colomina O,Florez F,Rize R (1998年)。第十一届人工智能和专家系统人工和工程应用国际会议记录,西班牙,第115-121页。 Garcia MAP、Montiel O、Castillo O、Sepulveda R、Melin P(2009年),《利用蚂蚁聚地优化和模糊成本评估自主移动机器人导航的路径规划》,Appl. Sofi Comput.,9:1102-1110,Garrido S、Moreno L、Blanco D、Jurewicz P(2011年)。利用Voronoi图表和快速行进的移动机器人导航规划路径。J. Robot. Int. J. Autom., 2(1): 42-64;Goldberg DE(2000):用于搜索、优化和机器学习的遗传算法;Addison-Wesley,印度德里;Gong DW, Zhang JH, Zhang Y(2011年);多目标粒子群优化,用于在有危险来源的环境中规划机器人路径。J. Copput., 6(8):1554-1561。Guan-zheng T, Huan He, Sloman A(2006年)。在改进Dijkstra算法和蚂蚁系统算法的基础上,对移动机器人进行全球最佳路径规划。 J. Cent. South Univ. Technol., 13(1) 80-86. Hachour O (2008年a). 拟议的自主移动机器人路径规划的FPGA基因实施器。Int. J. Circ. Syst Sig. Proc., 2(2): 151-167。

J. Syst. Appl. Dev. Int J. Syst. Appl., 4(2):178-190. Holland JH(1975年),密歇根大学出版社自然和人工系统的适应,安阿博尔,美国,Hong Z, Liu Y, Zhongguo G, Yi C(2011年),移动机器人人造潜力领域动态路径规划研究,消费电子、通信和网络国际会议记录(CECNet)XianNing,第39页。2736-2739. Hu C、Wu X、Liang Q、Wang Y (2007年),基于群集智能和流函数的自主机器人路径规划,Lect Notes Comp. Sci., Springer, pp.277-284. Kennedy J, Eberhart RC(1995年),IEEEE国际神经网络会议粒子优化议事录,澳大利亚珀斯,第1942-1948页,Khatib O(1986年),操纵者和移动机器人避免实时障碍,Int. J. 机器人。第5(1)号决议:90-98. Latombe JC(1991年):《机器人运动规划》,Kluwer学术出版社,波士顿,Lee JW、Kim JJ、Choi BS、Lee JJJ(2008年);《通过最佳路径规划的潜在实地概念改进蚂蚁群优化算法》,第八届国际电子环境与遥感协会人类机器人问题国际会议记录,Dajeon,第662-667页。 i, Ye T, Tan M, Chen X (20o2),《移动机器人技术研究的现状和未来发展》。Likhachev M, Ferguson D, Gordon G, Stentz A, Thrun S(2005年) 任何时间动态A*: 随时对自动规划和排期国际会议的算法程序进行重新规划,第26-2271页,Lozano-Perez T, Wesley MA(1979年),规划多面障碍之间无碰撞路径的算法,Comm. ACM., 22(10):560-570。 -ozano-Perez T(1983年),空间规划:配置方法IEEE T(IEEE T)。C, 32(3): 108-120. Lu L, Gong D(2008年),利用粒子群温优化在未知环境中规划机器人路径,第四次自然计算吉南国际会议议事录,第422-426页。Luh GC, Liu WW(2007年)。利用潜在的野外免疫网络规划动态环境中的流动机器人。IMECHE J. Syst. Control Eng., 221(7):1033-1045。Luh GC, Liu WW(2008)。《移动机器人被动导航的免疫学方法》,Appl.Soft Comput.,8(1):30-45.Lv N,Feng Z(2006年),数字潜在领域和在动态环境中基于蚁群优化的路径规划,第六届世界智能控制与自动化大会议事录,Dalian,第8966-8970页,Manousakis K, McAuley T, Morera R, Baras J(2005年)。《无线网络、通信和移动电子计算国际会议议事录》,第1460-1465页。 Martinez-Alfaro H, Gomez-Garcia S (1998)。 使用模拟肛门和模糊逻辑控制的移动机器人路径规划和跟踪,专家Syst. Appl., 15(3): 421-429. Masehian E, Katebi Y (2007)。J. Mech Syst. Sci. Eng. Int. J. Mech Syst. Sci. Eng., 1(1): 20-25; Masehian E, Sediegizadeh D (2007年);机器人运动规划中的经典和惯性方法 -- -- 按时间顺序审查;World Acad. Sci. Eng, Technol. 23: 101-106;Masehian E, Amin-Naseri MR (2007年);移动机器人离线路径规划综合模型;移动机器人:概念和导航。克罗地亚技术出版社,Mei H、Tian Y、Zu L(2006年),《动态环境中机器人路径规划混合蚁群优化算法》,Int.J.Inf. Tech.,12(3):78-87。

Miao H (2010). A multi-operator based simulated annealing approach for robot navigation in uncertain environments. Int. J. Comput. Sci. Secur., 4(1): 50-61.

Miao H, Tian YC (2008). Robot path planning in dynamic environments using a simulated annealing based approach. Proceedings of the tenth International Conference on Control, Automation, Robotics and Vision, Hanoi, Vietnam, pp. 1253-1258.

Min HQ, Zhu JH, Zheng XJ (2005). Obstacle Avoidance with Multi-Objective Optimization by PSO in Dynamic Environment. Proceedings of the IEEE International Conference on Machine Learning and Cybernetics, Guangzhou, pp. 2950-2956.

Nagib G, Gharieb W (2004). Path planning for a mobile robot using genetic algorithms. Proceedings of the International Conference on Electrical, Electronic and Computer Engineering (ICEEC'04), Cairo, Egypt., pp. 185-189.

Nasrollahy AZ, Javadi HHS (2009). Using particle swarm optimization for robot path planning in dynamic environments with moving obstacles and target. Third European Symposium on computer modeling and simulation, Athens, Greece, pp. 60-65.

Park H, Kim JH (2008). Potential and dynamics-based Particle Swarm Optimization. Proceedings of the IEEE World Congress on Computational Intelligence, Hong Kong, pp. 2354-2359.

Payton DW, Rosenblatt JK, Keirsey DM (1993). Grid-based mapping for autonomous mobile robot. Robot. Auton. Syst., 11(1): 13-21.

Qin YQ, Sun DB, Li N, Cen YG (2004). Path Planning for mobile robot using the particle swarm optimization with mutation operator. Proceedings of the IEEE International Conference on Machine Learning and Cybernetics, Shanghai, pp. 2473-2478.

Qu Z, Wang J, Plaisted CE (2004). A new analytical solution to mobile robot trajectory generation in the presence of moving obstacles. IEEE T. Robot., 20(6): 978-993.

Raja P, Pugazhenthi S (2008). Path planning for a mobile robot to avoid polyhedral and curved obstacles. Int. J. Assist. Robotics. Mechatronics, 9(2): 31-41.

Raja P, Pugazhenthi S (2009a). Path planning for a mobile robot using real coded genetic algorithm. Int. J. Assist. Robot. Syst., 10(1): 27-39.

Raja P, Pugazhenthi S (2009b). Path planning for mobile robots in dynamic environments using particle swarm optimization. IEEE International Conference on Advances in Recent Technologies in Communication and Computing (ARTCom 2009), Kottayam, India, pp. 401-405.

Raja P, Pugazhenthi S (2011). Path Planning for a mobile robot in dynamic environments. Int. J. Phys. Sci., 6(20): 4721-4731.

Ripon KSN, Kwong S, Man KF (2007). A real-coding jumping gene genetic algorithm (RJGGA) for multiobjective optimization. Int. J. Inf. Sci., 177(2): 632-654.

Shahidi N, Esmaeilzadeh H, Abdollahi M, Lucas C (2004). Memetic algorithm based path planning for a mobile robot. Int. J. Inf. Tech., 1(4): 174-177.

Siegwart R, Nourbakhsh IR (2004). Introduction to autonomous mobile robot. Massachusetts Institute of Technology press, Cambridge, U.S.A.

Sugihara K, Smith J (1997). Genetic algorithms for adaptive motion planning of an autonomous mobile robot. Proceedings of the IEEE International Symposium on Computational Intelligence in Robotics and Automation, Monterey, California, pp. 138-143.

Tu J, Yang SX (2003). Genetic algorithm based path planning for a mobile robot. Proceedings of the IEEE International Conference on Robotics and Automation, Taipei, Taiwan, pp. 1221-1226.

Udupa S (1977). Collision detection and avoidance in computer controlled manipulators. PhD thesis, California Institute of Technology, California, USA.

Vadakkepat P, Lee TH, Xin L (2001). Application of evolutionary artificial potential field in robot soccer system. Proceedings of the Joint ninth IFSA World Congress and twentieth NAFIPS International Conference, Vancouver, BC, Canada, pp. 2781-2785.

Vadakkepat P, Tan KC, Ming-Liang W (2000). Evolutionary artificial potential fields and their application in real time robot path planning. Proceedings of the 2000 Congress on Evolutionary Computation, Piscataway, New Jersey, pp. 256-263.

Wang Y, Mulvaney D, Sillitoe I (2006). Genetic-based mobile robot path planning using vertex heuristics. Proceedings of the 2006 IEEE International Conference on Cybernetics and Intelligent Systems, Bangkok, pp. 463-468.

Xiao J, Michalewicz Z, Zhang L (1997). Trojanowski K, Adaptive evolutionary planner/navigator for mobile robots. IEEE T. Evolut. Comput., 1(1): 18-28.

Zhang PY, Lu TS, Song LB (2004). Soccer robot path planning based on the artificial potential field approach with simulated annealing. Robotica, 22: 563-566.

Zhang QR, Gu GC (2008). Path planning based on improved binary particle swarm optimization algorithm. Proceedings of the IEEE International Conference on Robotics, Automation and Mechatronics, Chendu, China, pp. 462-466.

Zheng TG, Huan H, Aaron S (2007). Ant Colony System Algorithm for Real-Time Globally Optimal Path Planning of Mobile Robots. Acta. Automatica. Sinica, 33(3): 279-285.

Zhu DJ, Latombe JC (1989). New heuristic algorithms for efficient hierarchical path planning. Technical report STAN-CS-89-1279, Computer Science Department, Stanford University, USA.