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Robot Navigation Planning Problems in Dynamic Environments

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Introduction

Planning in dynamic environments is an extension of the basic path planning problem. Dynamic environments may contain stationary obstacles in addition to moving obstacles. This planning includes but is not restricted to navigation planning problems and approaches in partially known dynamic environments, planning in continuous spaces under differential constraints, multi-robot planning, evasion of unpredictable obstacles and planning in repetitive environments. Such enumeration of environment niches is important when identifying the situations where certain planning methods and approaches are more applicable. Moreover, method selection criteria might vary over time and criteria itself can be the composite of inverse factors, like the shortest path and the maximum clearance to obstacles. The purpose of this paper is to discern criteria for selection of individual approaches and their combinations to solve dynamic planning of robot navigation.

The field of mobile robot navigation is continuously evolving, thus approaches presented in this paper serve only as representation of respective categories without premature judgment. Many algorithms can be found in the literature, but not all could have been cited by this paper because of its conciseness.

Planning in unknown environments

Real-time obstacle avoidance requires *reactive* motion planning in unknown dynamic environments. Reactive methods are used when the time to respond is bounded. They build constant time *heuristics* (heuristic algorithms) for making progress toward the goal. The main task is integrating *global* goal reaching and *local* obstacle avoidance.

One of the local obstacle avoidance approaches is dynamic window [1], which is based on steer angle field. The search space consists of aerial and angular velocities reachable by the robot within a short-term or immediate time interval. This approach considers only acceptable velocity shift on which the robot is able to stop safely, i.e. neither hitting the obstacle nor tumbling down. Defining the objective function, which includes a measure of progress towards the goal, forward velocity of the robot and the distance to the next obstacle on the trajectory, is the main task. As an extension to the local planner is *corridor* planning. Corridors consist of *backbone* path on either side of the corridor, where backbone path provides a global direction of motion, and the corridor leaves the room for local deviations from the global path.

Scheduled and real-time planning

Local planning approaches are much faster than global planning. Real time or *online* planner has a limited time for path evaluation. There are different approaches to distribute the processing load. One of them is *Partial Motion Planning* scheme using iterative probabilistic techniques. Typically such *offline* planner overestimates the time period required for path planning and returns the best partial path explored during allocated time. *Anytime* planners have similar features to offline planners. They start from initial or poor quality paths and as long as time has not run out constantly improve path quality. Such sophisticated techniques as prebuilding or preplanning partially known environment, scheduling processing load for idle time or utilizing re-planners [2] for repetitive dynamic environments bring further challenges.

Acceleration and velocity constraints

Another challenge in dynamic environment is velocity, direction shift and acceleration constraints. Normally, agent’s (robot’s) speed shift is restricted by its acceleration. Navigation planning under these constraints is *non-holonomic*. Non-holonomic (kinodynamic) motion is the one which does subject to velocity and direction shift constraints. Direction shift could be represented by parallel parking of a car, which is non-holonomic navigation problem. Not all methods are able to incorporate velocity constraints. Such methods as single-shot method *Randomly Exploring Random Trees* (RRT) is capable of embracing these constraints into the planner. RRT grow a possible path from the start position by sampling randomly in workspace of the robot and applying valid acceleration vectors.

Another approach is sampling time axis and limiting the possible accelerations. Thus sampling velocities too.

Navigation planning for wheeled robots, which can not slide sideways, is the most common case. Planning under these constraints covers but is not limited to unicycle, tricycle, a simple car, differential drive, *Reeds-Shepp car* and *Dubins car* [3]. Differential drive is two-wheeled drive system with independent actuators for each wheel, Reeds-Sheep car is a simple car where velocity can accept three discrete values: forward speed, parking and reverse speed, i.e. $u_S \in [1;0;-1]$. Dubins car is Reeds-Shepp car with reverse direction excluded, i.e. $u_S \in [1;0]$.

The simple car represents car-like robot, where car's configuration is defined by *x*, *y* coordinates and car position angle θ (Fig. 1).

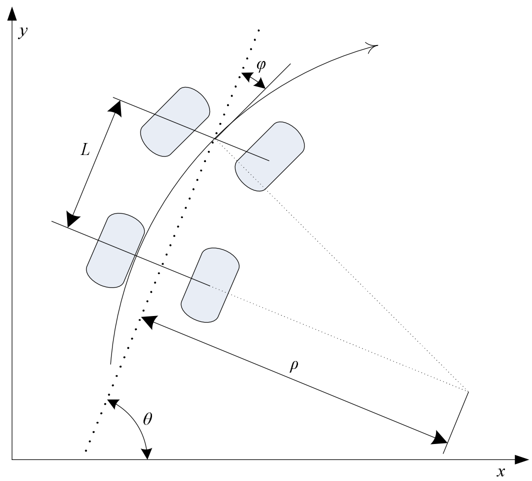

Fig. 1. A four wheeled robot configuration representation

The motion of a wheeled robot can be described by a set of configuration transition equations containing functions of *x*, *y*, θ, speed of a robot *s*, and steering angle φ:

$$\begin{cases} x' = f_x(x, y, \theta, s, \varphi), \\ y' = f_y(x, y, \theta, s, \varphi), \\ \theta' = f_\theta(x, y, \theta, s, \varphi). \end{cases} \tag{1}$$

A question is how fast a robot can move in respect of moving obstacles. This is important because it would allow treating robot motion characteristic as either holonomic or non-holonomic. The faster the obstacle, the higher the reaction is expected from a planner. Fast obstacles practically make robot to become an obstacle avoider.

Interaction with physical world is normally ascertained by designing of feedback control law. Introducing feedback to motion planning yields a closed-loop plan that responds to unpredictable events during an execution. Any errors that might occur during the execution of open-loop plan are ignored. The planner uses feedback control law definition to follow the computed path as closely as possible. Interesting approach is instead of calculating trajectory between initial state and the destination state to compute a vector field over the entire workspace.

Corridor Planning

One of the advantages of corridors is that they make non-holonomic planning more accessible. There were efforts to combine corridor planning with *Probabilistic Roadmap Method* (PRM). PRM does not suffer from local minima and it has been supplied to a wide range of applications. PRM disadvantage is that it generates paths with redundant motions, and that they have little clearance to the hazards. Such planning leads to unnaturally looking motions. Other drawbacks are that any optimizations bring degradation in performance, and that the probability that a random sample will fall into narrow passage is very low. If this passage is the part of solution path that causes problem. On the other side, PRM is suitable for global motion planning, which produces high quality roadmap, and local motions are controlled by other local methods, like potential fields or splines.

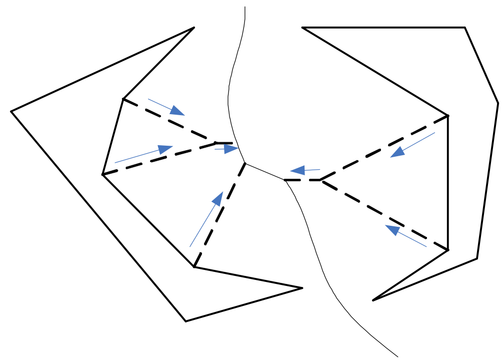

Fig. 2. Partial Voronoi diagram for two non-convex polygons. Voronoi chains originating from the same polygon are drawn with dashed line

The quality of a corridor is determined by the length of the backbone path and the extent to which it was possible to obtain the preferred clearance along the backbone path. When planning the backbone path of a corridor, a trade-off should be made between length and the width of a corridor.

Two approaches are to be taken into account when planning the corridor.

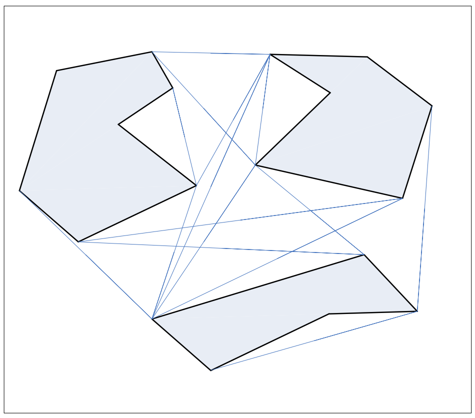

Fig. 3. Visibility graph or vector marks representing shortest-paths

The first is maximizing clearance to the hazards, when generalized Voronoi diagrams (Fig. 2) or cell decomposition methods are applied. There might be exact, vertical and approximate cell decomposition. As long as high-dimensional path planning is computationally intense when calculating explicit C_{free} representations, probabilistic planning might be introduced. Combination of probabilistic planning and cell decomposition results in learning and query stages. Roadmap recalculation is not necessary for static environment.

The second is finding the shortest path, when reduced visibility graphs or vector marks [4] are used (Fig. 3).

There are also published hybrid methods which combine both visibility graph and Voronoi diagram of polygons, and it claims to provide short, smooth and preserving a certain amount of clearance to the obstacles.

Multi-robot planning

Multi-robot planning is one of the planner's applications for known or partially known environments. This approach carries offline characteristic for environment without dynamic obstacles. The task is to bring a set of robots to their destination without mutual collisions and collision with stationary obstacles. We can use offline planner and solve static motion planning problem, because time does not play an intrinsic role. Robotized flexible production systems are more complicated case of multi-agent planning involving dynamic obstacles.

One of the methods is *prioritized* approach [5], where each agent is assigned with a priority and a path for each robot has to be planned in a known dynamic environment, where the previously planned robots are treated as moving obstacles. This approach is fast, but incomplete, because there is no coordination between robots.

Another approach is coordination between *centralized* and *decoupled* planning. When the number of both obstacles and robots increases, the scalability should be considered in the coordination approach. Meanwhile system's intricacy would bring less pressure on performance degradation in prioritized way.

There are situations when each robot has a specific role to accomplish in multiple robots system. Then navigation is stochastic process and static planning approaches are not suitable. Scenarios get even more complicated when robots can switch roles to fill in for critical positions as needed, and switch out of roles that are not being used at that time. To make decisions and to learn how successful robot has been, reward function is to be applied.

Unpredictable moving obstacles

The planner for completely unpredictable moving obstacles is offline in principle. Paths must be found that are guaranteed to be collision-free in the future, regardless of the direction shift of the moving obstacles. The future trajectories of moving obstacles should be estimated conservatively. One of the approaches is when obstacles are assumed to be discs, which grow in time and have a known maximal velocity (Fig. 4).

The goal is to find the shortest paths avoiding those growing disks. Robots motion velocity excelling the velocities of all obstacles is the main prerequisite for such planning. A drawback of this method is that a path to the goal often does not exist. This happens when the goal is covered by a growing disc before it can be reached. Also to minimize error discs should be repositioned and reshaped after each motion advance.

Another approach is iterative short-time planning [6] which consist of two stages: obstacles motion prediction and vehicle motion planning. Motion prediction is carried by probabilistic means and deviations calculation. Vehicle motion planning is iterative process in obstacle velocity space where A* (A-star) routines are applied. A* is a variant of Dijkstra method where admissible heuristic estimate is included in the distance-plus-cost heuristic function. Dijkstra method does not evaluate the distance to the goal.

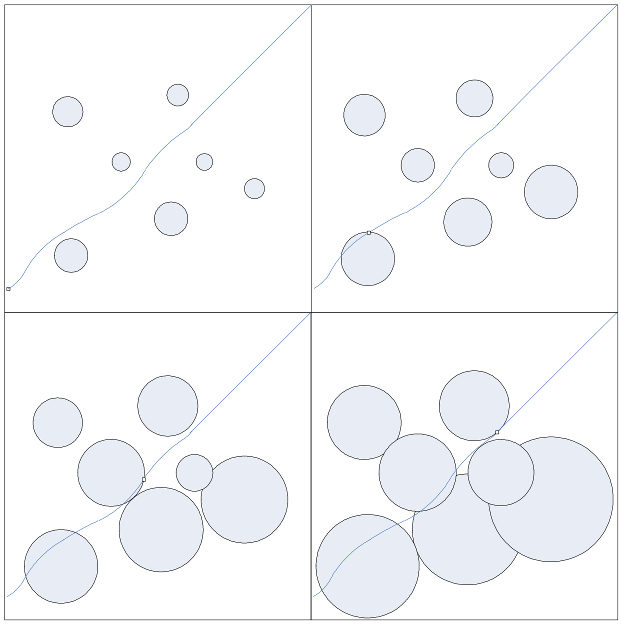

Fig. 4. A trajectory which indicates the shortest path. Each window shows a position of a small square dot at that moment of time

There is another variant of Dijkstra algorithm called D* or Stentz's algorithm. This algorithm can be considered as a dynamic version of the backward variant of A* algorithm. Thus, it maintains cost-to-go values, and the search grows outward from the goal, as opposed to cost-to-come values. D* dynamically updates cost values as the cost terms are learned during execution or problem solving process.

Planning in known environments

Offline planner can be used for known dynamic environments like PRM planner. Practically planning follow decoupled approach, where first stage is dedicated for defining the *collision free configuration space* C_{free} of the robot. The second stage assures that moving robot does not collide with any of the moving obstacles. At the local level depth-first search coordination is performed. The global level A* search is used.

Repetitive environments are variation of known dynamic environments where motions of the moving obstacles are periodic or repetitive. The advantage of planning in repetitive navigation is that relatively expensive preprocessing stage of generated roadmap can be reused multiple times. Mostly probabilistic approaches are used for repetitive environments and more importantly multiple shot approaches can be used for prebuilding the roadmap, like PRM.

Conclusions

Recent works on robot navigation planning in dynamic environments are studied and basic approaches are presented for corresponding use cases. The planner has to work efficiently in adverse dynamic conditions, consisting of, but not being limited to

a) severe dynamic constraints on the motion of the robot,
b) moving obstacles,
c) time delays and uncertainties inherent to physical environment,
d) coordination between multiple robots.

The planner has to demonstrate its effectiveness, performance and scalability both in simulation and experiment, in particular when obstacle trajectories are not known in advance. Navigation planning has to be suitable for any robot with any number of degrees of freedom in two or three dimensional workspaces. The objective function should consist of avoiding any immediate collisions and determining the path to the destination. Any conflicts between these two subtasks should be resolved taking into account the kinematics of the robot.

As further work it is important to continue looking for new ways of analysis to have better understanding on performance of the algorithms and to try combining different methods and determining their precedence. Such real life applications as flexible production systems and mission tasked robot teams trigger further investigation.

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Main robot navigation planning methods and approaches of the dynamic environment are discussed. While considering approaches, performance, the possibility of redundant motions and optimal path existence are taken into account. During path planning the compromise between maximum clearance to obstacles and the shortest path to the destination is discussed. Multi-robot planning is viewed as an offline planning problem with prioritized approach. Planning for unpredictable obstacles and probabilistic routines for known environments including repetitive motions is reviewed. Ill. 4, bibl. 6 (in English; summaries in English, Russian and Lithuanian).

Р. Урнежюс, С. Барткевичюс. Проблемы планирования навигации роботов в динамической среде // Электроника и электротехника. – Каунас: Технология, 2008. – № 6(86). – С. 93–96.

Обсуждены основные методы и подходы планирования навигации роботов в динамической среде. Рассматривая подходы взяты во внимание бистродействие, возможности избыточных движений и существования оптимальной траектории. В течение планирования обсужден компромис между максимальным разрешением к препятствиям и самой короткой траекторией. Планирование навигации многих роботов рассматриваются как оффлайновое планирование с использованием системы приоритетов роботов. Рассмотрено планирование непредсказуемых препятствий и вероятностные процедры для известных сред, включая повторные движения. Ил. 4 , библ. 6 (на английском языке; рефераты на английском, русском и литовском яз.).

R. Urniežius, S. Bartkevičius. Robotų navigacijos dinaminėje aplinkoje planavimo problemos // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2008. – Nr. 6(86). – P. 93–96.

Diskutuojama apie pagrindinius robotų navigacijos dinaminėje aplinkoje planavimo metodus ir būdus. Svarstant metodus yra kreipiamas dėmesys į greitaveiką, perteklinių judesių ir optimalaus kelio buvimą. Planuojant kelią aptariamas kompromisas tarp maksimalaus atstumo nuo kliūčių laikymosi ir trumpiausio kelio iki siekiama tikslo. Apžvelgtas keleto robotų planavimas aproksimuojant neoperatyviuoju planavimo metodu, atsižvelgiant į prioritetus. Aptariamos aplinkos su nenuspėjamomis kliūtimis bei žinomos aplinkos su pasikartojančiomis būsenomis. Il. 4, bibl. 6 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).