Proceedings of the 1998 IEEE
ISIC/CIRA/ISAS Joint Conference
Gaithersburg, MD • September 14-17, 1998

Integrating Directional Constraints in Motion Planning Using Nonlinear, Anisotropic, Harmonic Potential Fields

by

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Abstract

This paper addresses an important problem that has remained, to the best of the author's knowledge, neglected in the motion planning literature. That is the incorporation of directional constraints along with obstacle avoidance in steering a robot to a target zone. The available motion planners deal exclusively with isotropic workspaces that place no restrictions on the direction of motion in their interior. Unfortunately, realistic workspaces do not support the above behavior. Instead, they impose a priori known restrictions on the direction of motion inside a workspace (e.g., ENTER and EXIT signs, direction of traffic along a one-way street). In this paper Harmonic field motion planners which can only deal with isotropic workspaces are generalized to incorporate anisotropic workspaces with preimposed directional constraints. Theoretical developments along with simulation results are provided.

1. Introduction

Despite the diversity of motion planning methods [1-3], all existing techniques, to the best of the author's knowledge, are unified in considering isotropic workspaces in which a mobile agent is required to reach a target zone while avoiding undesired regions. Such class of workspaces places no restrictions on the direction the agent can assume inside the admissible region of the workspace. Unfortunately, realistic workspaces are highly likely to impose directional constraints on the behavior of an agent. Such constraints may appear in the form of ENTER or EXIT signs requiring the agent to restrict its direction of motion at a door in accordance with the posted instructions. They also appear in traffic flow restricting the direction of motion of a vehicle at a certain street lane. As can be seen it is imperative for a realistic motion planner to be able to incorporate such constraints in its effort to safely steer the agent to its target. While there are many planning approaches from which one may choose a candidate to modify in order to incorporate directional constraints, this author believes that the Harmonic Potential Field approach to motion planning [4-25] is an ideal candidate for such a choice. Harmonic planners are a subset of a more general class of planners that are called Hybrid PDE-ODE motion planners (Figure-1). When set to operate in the context of a Hybrid Discrete-time Continuous-time system this class of planners transforms into an interesting and powerful class of motion planners that is called Evolutionary, Hybrid, PDE-ODE motion planners [26,27] (Figure-2). Evolutionary, Hybrid, PDE-ODE planners are situated, embodied, intelligent, and emergent mechanisms for behavior generation. They require no a priori knowledge of their multidimensional environment to guarantee that a mobile agent with an arbitrary shape will converge to its target from the first attempt (First Attempt Completeness). Moreover, in such class of planners the range of the sensors has no influence on convergence where even local sensing such as tactile sensing or a bumper switch can guarantee convergence in a multidimensional environment. The range of the sensors only controls the rate of convergence. Figure-3 shows three attempts of a point agent to reach its target in a maze. Despite the total lack of a priori knowledge about the maze and the use of proximity sensing the agent managed to reach its target every attempt, each time enhancing its performance till it

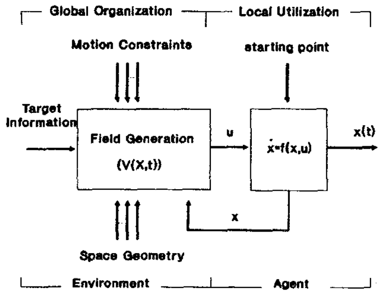

Figure-1: A Hybrid PDE-ODE Motion Planner.

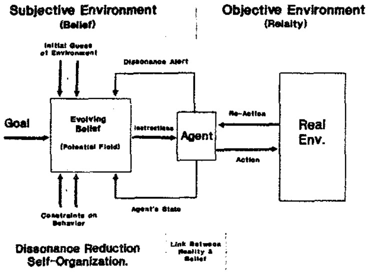

Figure-2: An Evolutionary, Hybrid PDE-ODE Planner.

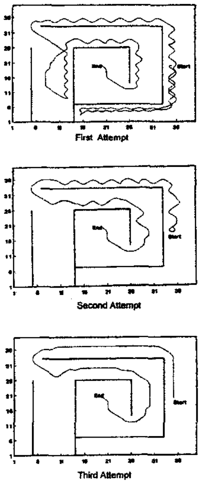

Figure-3: Three attempts of a point agent to reach its target With no a priori knowledge of the environment using local sensing only.

converged to an optimal path to the target. Figure-4 shows an arm manipulator that is utilizing the above class of planners to reach its target. As can be seen the manipulator was able to reach its target from the first attempt despite the total lack of a priori knowledge about its environment and the use of local proximity sensing.

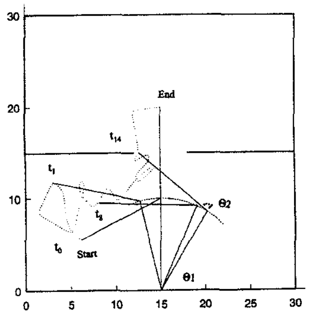

Figure-4: An arm manipulator reaching its target from the first attempt. No a priori knowledge of the workspace is available, local sensing used.

In this paper Nonlinear, Anisotropic, Potential Fields are suggested for the construction of motion planners that are capable of incorporating directional constraints along with obstacle avoidance in motion planning. In section 2 the equations describing the modified harmonic potential are derived along with the equations that are needed for constructing the planner. In section 3 simulation results are presented, and conclusions are placed in section 4.

2. The Planner

Harmonic motion planners use a gradient dynamical system that is generated from an underlying scalar potential field (V(X)) to safely steer an agent to its target

$$\dot{X} = -\nabla V(X,\Gamma,X_t) \tag{1}$$
$$\text{such that} \quad \lim_{t\to\infty} X(t) \rightarrow X_t, \quad X(t)\cap O \equiv \phi$$

where X and $\dot{X}$ are the N-D position and velocity vectors respectively, Γ is the boundary of the forbidden regions (O, $\Gamma=\partial O$), and X_t is the target state. To accomplish the above, the potential manifold is subjected to a set of differential and state constraints in a process that assumes the form of the boundary Value Problem (BVP) : solve

$$\begin{aligned} \nabla^2 V(X) &= 0 , \qquad X\in\Omega, \\ V(X_t)=0, &\quad V(\Gamma)=1, \end{aligned} \tag{2}$$

where Ω is the workspace of the agent, and ∇^2 is the Lplacian differential operator. The above BVP is not the only setting that may be used to condition V. A set of BVPs that can do the above task may be found in [26]. The Laplacian operator is constructed by forcing the divergence ($\nabla\cdot$) of the gradient of the potential field to be zero inside Ω

$$\nabla\cdot\nabla V(X) \equiv 0 \qquad X\in\Omega. \tag{3}$$

This guarantees the continuity of motion inside Ω (i.e. deadlock is prevented). Implicit in this construction is the uniformity of the workspace as it relates to the behavior of the agent. One way to do away with this uniformity and exercise control over behavior inside Ω is to weigh different locations inside Ω with a proper scaling factor that is a function of the behavior of interest which in this case relates to the direction motion assumes inside Ω. A weighing scheme that serves the above objective is:

$$\nabla\cdot\Sigma(X)\nabla V(X) \equiv 0 \qquad X\in\Omega', \tag{4}$$

where

$$\Sigma(X) = \begin{bmatrix} \sigma_{x_1}(\Psi(X)) & 0 & \ldots\ldots & 0 \\ 0 & \sigma_{x_2}(\Psi(X)) & \ldots\ldots & 0 \\ \cdot & & & \\ 0 & 0 & \ldots\ldots & \sigma_{x_N}(\Psi(X)) \end{bmatrix},$$

Ω' is a subset of Ω ($\Omega'\subset\Omega$), $\Psi(X)$ is a unit vector field that is defined in Ω' to mark the direction along which motion is to proceed, and $\sigma_{xi}(\Psi(X))$ is defined as:

$$\sigma_{x_i}(\Psi(X)) = \begin{bmatrix} \sigma_f & \Psi^t(X)\nabla V(X) > 0 \\ \sigma_b & \Psi^t(X)\nabla V(X) \le 0 \end{bmatrix},$$

σ_f and σ_b are positive constants ($\sigma_f \gg \sigma_b$) depicting the permissibility of the associated part of the workspace along the associated direction.

The modified planner generates a safe, constraints satisfying trajectory to the target using the gradient dynamical system:

$$\dot{X} = -\nabla V(X,\Psi(X),\Gamma,X_t)\ ,\ \ X\in\Omega.$$

$$\underset{t\to\infty}{Lim} X(t)\to X_t,\ X(t)\cap O\equiv\phi,\ and$$
$$\Psi(X)^t\nabla V(x)>0\ \ X\in\Omega'.$$

The Potential field is conditioned for navigation using the BVP: solve

$$\begin{array}{lll} & \nabla^2 V(X)=0 & X\in\Omega-\Omega', \\ and & \nabla\cdot\Sigma(X)\nabla V(X)=0 & X\in\Omega', \\ subject\ to & V(X_t)=0,\ V(\Gamma)=1\ . & \end{array} \quad (5)$$

3. Results

The capabilities of the planner are demonstrated using the simple example shown in Figures 5,6 of a road with two unidirectional lanes. At each lane the agent is required to restrict its direction of motion in accordance with the large arrows shown to mark the admissible direction of motion. Also, the agent can only switch lanes at either the beginning or end of the road and is forbidden from doing so along the solid line separating the two lanes. First, an isotropic, harmonic potential field planner is used for steering motion from an initial starting point in the workspace to the target point (Figure-5a). As can be seen, the planner totally disregarded the constraints on direction and proceeded to target along the shortest path (a straight line). Figure-5b shows the corresponding gradient navigation vector field that is used for steering the agent. In Figure-6a a nonlinear, anisotropic, harmonic potential field planner is used for steering motion. As can be seen, the planner enforced the directional constraints, avoided the obstacles, and drove the agent to its target. Figure-6b shows the corresponding gradient navigation vector field.

4. Conclusions

In this paper a novel and complete motion planner that is capable of integrating directional constraints along with obstacle avoidance constraints in the navigation process is suggested. The proposed planner is an important addition to the motion planning literature enabling the utilizing agent to enforce the important directional constraints which realistic workspaces often present. It also demonstrates the effectiveness of the harmonic potential field approach to planning, not only as an effective motion planner, but also as a prototype for generating other planning techniques that realistically address the needs of agents operating in a real world environment.

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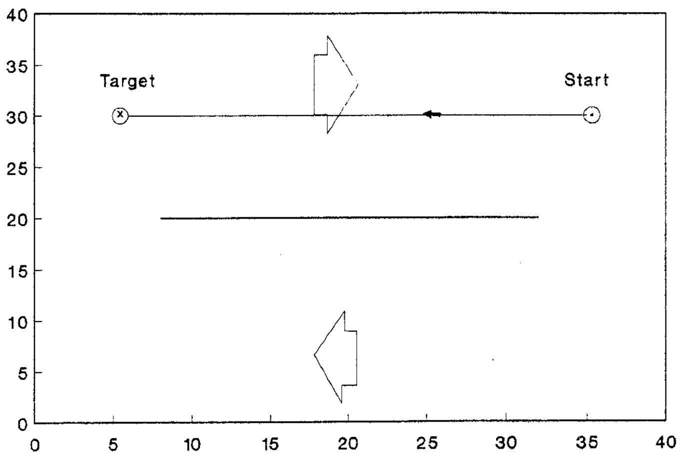

Figure-5a: The generated trajectory, Harmonic planner.

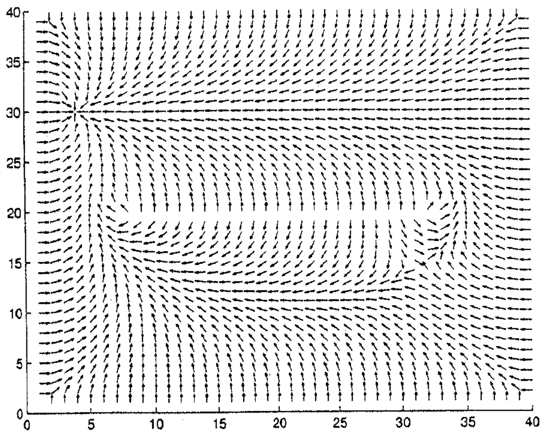

Figure-5b: The gradient navigation field, Harmonic planner.

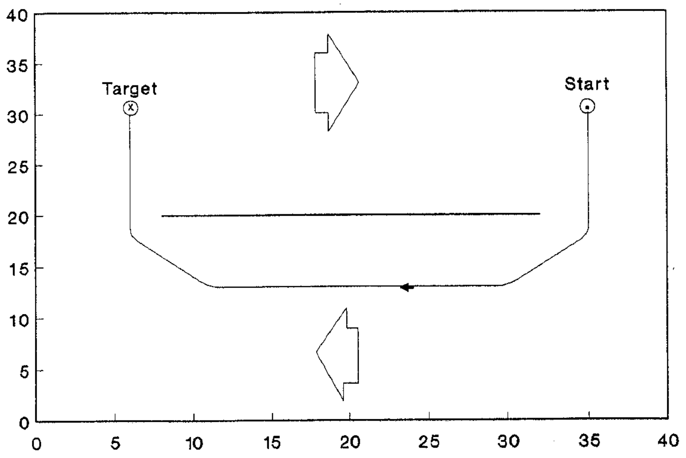

Figure-6a: The generated trajectory, modified Harmonic planner.

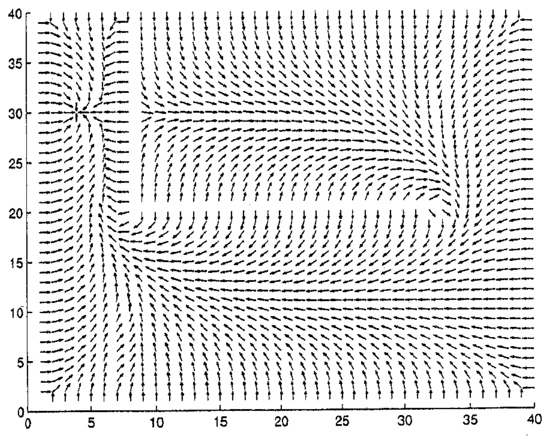

Figure-6b: The gradient navigation field, modified Harmonic planner.