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A Decentralized, Evolutionary, Hybrid Controller For Directing Traffic Along Two-way Streets

by

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ABSTRACT

This paper tackles the excessive complexity facing the design of traffic controllers. This complexity, which is usually exponential in the number of agents, effectively limits planning to that of a small-size traffic. Here, an evolutionary approach to control design is suggested to free traffic controllers from such a limitation. Guidelines from self-organizing systems are used to derive a mutli-agent motion controller that, among other things, has a computational effort that linearly increase with the number of agents; therefore, making it feasible to manage a large-size traffic. The controller is also required to be "open" in order for any agent to join or leave traffic without the others having to adjust the manner by which they sense, process information, or actuate motion. Along with self-organization, concepts from Hybrid Systems, and the Potential Field Approach to control synthesis are utilized to realize the controller. Theoretical development as well as simulation results are provided.

1. INTRODUCTION

The utilization of common resources by agents seeking different goals is almost always an unavoidable operational necessity. While sharing resources is desirable, let alone necessary, it is nevertheless a potential source of problems. These problems arise when two or more agents attempt to utilize a resource in conflicting manners. To prevent conflict, a controller (a planner) must be utilized to guarantee the proper multiplexing of resources among the interacting agents. There are two approaches for constructing these controllers: a centralized approach, and a decentralized approach. In a centralized approach a supervisory control simultaneously observes the states of all the agents. A search is then initiated in the Hyper Action Space of the group (the HAS houses the spaces of possible, admissible actions that individual agents can project) to generate and fan synchronized sequences of instructions (i.e. the solution) to all the agents in order for them to progressively modify their behavior and reach their respective goals. Due to the above, centralized controllers are:

1- Inflexible, in the sense that any change in the agents or the environment immediately translates into a change in the HAS which in turn necessitates repeating the search of the HAS for a new solution.

2- Has crippling complexity that usually grows exponentially with the number of agents.

3- Prone to problems in sensory communication and action synchronization.

A multi-agent system is considered decentralized if every agent in the group is independent from the others in sensory data acquisition, information processing, and action projection. These requirements, in effect, makes decentralization equivalent to self-organization. Unlike centralized top-down approaches, self-organization is a bottom-up approach [1] where the system designer is only required to supply the individual agents with basic "self-control" capabilities (Geno-type, or G-type). The overall control action that shapes the behavior of the whole group (Pheno-type, or P-type) evolves in space and time as a result of the interpretation of the G-type in the context of a particular environment [2]. In order to construct a proper G-type control:

1- Each agent must individually develop a control action to drive it towards its goal. Such a control need not take into consideration the control actions of the other agents.

2- Each agent must have the ability to generate a control that can resolve any conflict with other agents through bilateral interaction.

Some of the properties of decentralized control:

1- There is no need to construct or search a HAS to generate a solution. For decentralized control, the solution emerges as a result of the agents interacting among themselves and with the environment.

2- No interagent communication is required.

3- Synchronous behavior is an emergent phenomenon that results from asynchronous interaction.

4- The controller's complexity linearly grows with the number of the agents.

5- Decentralized systems form "open" systems that enables any agent to join or leave the group without the others having to adjust the manner in which they process information or project actions.

In this paper a controller is developed for the special case where "space" is the resource that is being shared among the agents. The controlling process is required to provide the agents with the ability to simultaneously participate in reaching an accommodating arrangement that enables all of them to safely reach their targets. The suggested controller is Hybrid in nature [3] (for an extensive survey of Hybrid systems see the paper by Labinaz et. al. [4]). This is a direct consequence of decentralization where the agents are allowed to

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pursue their subjectively constructed, continuous control (in the sequel this component is called the Purpose Field (PRF)) while dealing with the discrete event of a conflict when and where it arises (the continuous control component that is used to resolve conflicts is called the Conflict Resolving Field (CRF)). In order for the control to realize complex pattern configurations, a potential field approach is adopted to generate the control action [5]. In this approach the control field is induced by operating on a potential field surface (a manifold) with the proper vector differential operator. The aim of the above is to generate a multi-agent control that is at least :

1- Complete (i.e. if a solution exist, the controller will find it.)

2- Flexible (i.e. the addition or removal of agents from the group will not disturb the operation of the planner.)

3- Computationally feasible for a large group.

This paper is organized as follows: in section 2 the problem is formulated, in section 3 the construction of the controller is outlined. Section 4 contains results, and section 5 conclusions. On going work is briefly outlined in section 6.

2. PROBLEM FORMULATION

An agent is assumed to be an M-D hyper sphere (D_i) with a radius d_i and a center x_i ($x_i \in R^M$),

$$D_i(x) = \{x: |x-x_i| \le d_i\} \qquad i=1,..,L \quad (1)$$

where L is the number of agents in the workspace. The workspace (Ω) is assumed to contain stationary forbidden regions {O} with boundary $\Gamma \in R^N$ ($\Gamma=\partial O$, $M \ge N$). Each agent has a target zone T_i which is also an M-D hyper sphere with a fixed center c_i, where

$$D_i(x) \subset T_i(x) \qquad x_i = c_i. \quad (2)$$

The target zones are assumed not to intersect each other or the obstacles,

$$T_i(x) \cap T_j(x) \equiv \phi, \qquad i \ne j \quad (3)$$
$$T_i(x) \cap O \equiv \phi \qquad i=1,..,L.$$

The suggested controller assumes the form of the first order nonlinear dynamical system

$$\dot{X} = H(X,\Gamma,C) = U_1(X,\Gamma,C) + U_2(X,\Gamma,U_1), \quad (4)$$

where $X \subset R^{ML}$ ($X^t=(x_1^t \ldots x_L^t)^t$), $C \subset R^{ML}$ ($C^t=(c_1^t \ldots c_L^t)^t$), also $H: R^{ML} x R^{ML} x R^N \rightarrow R^M$. The U_1 component of H continuously act to drive the state X to C. On the other hand, U_2 remains inactive till a constraint is about to be violated or a deadlock situation is about to form. Once such a situation transpire, U_2 acts as a "behavior modifier", to U_1 in order to prevent a constraint from being violated, and/or to resolve a deadlock situation. The activities of U_2 dissipates once the conflict is resolved. As can be seen, U_1 is independent of U_2, while U_2 is dependent, among other things, on U_1. In the sequel this dependence is made implicit, and U_2 is referred to as $U_2(X,\Gamma)$. In general the controller is required to :

$$\lim_{t\to\infty} x_i \rightarrow c_i \qquad i=1,..,L \quad (5)$$
$$D_i(x) \cap D_j(x) \equiv \phi \qquad i \ne j, \ \forall t,$$

and

$$D_i(x) \cap O \equiv \phi \qquad i=1,..,L.$$

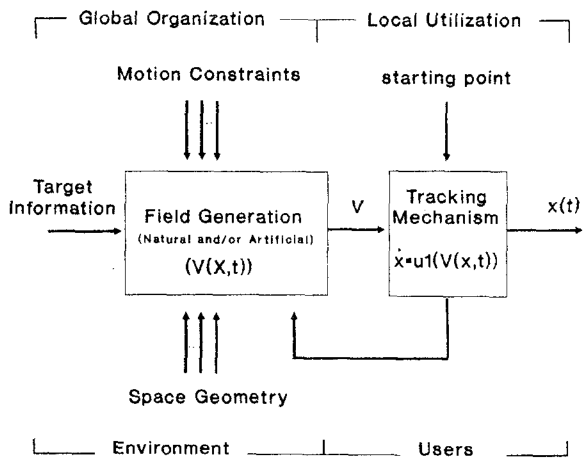


Figure-1: Basic Structure of reflexive potential-based Path planning techniques.

3. THE CONTROLLER

A self-controller for agent-i assists in laying a path to c_i by modifying its state (x_i) under the influence of u_{1i} and u_{2i}, where the vectors u_{1i} and u_{2i} (both $\in R^M$) are the i'th elements in U_1 and U_2 respectively,

$$\dot{x}_i = u_{1i}(x_i,\Gamma,c_i) + u_{2i}(X,\Gamma). \quad (6)$$

The u_{1i} component is a vector field that encodes the agent's plan to reach c_i. As for u_{2i} it consists of two components

$$u_{2i}(X,\Gamma) = u_{2oi}(x_i,\Gamma) + u_{2di}(X),$$

where

$$u_{2di}(X) = \sum_{j=1}^{L} u_{2ij}(x_i,x_j) \qquad i \ne j. \quad (7)$$

u_{2ij} is a local vector field that encodes a plan for the corrective action released by agent-i to avoid a conflict with agent-j. As for u_{2o}, this component provides extra guard against colliding with the static obstacles; its presence is convenient not necessary. In the following the construction of these components is outlined.

3.1 the PRF Component (u_{1i})

It is required that u_{1i} be constructed so that for the dynamical system

$$\dot{x}_i = u_{1i}(x_i,\Gamma,c_i), \quad (8)$$
$$\lim_{t\to\infty} x_i \rightarrow c_i,$$

and

$$x_i \cap \Gamma \equiv \phi \qquad \forall t.$$

The control field u_{1i} is induced by a vector differential operator that is acting on a potential field (V_i). This field has one unique stable equilibrium point at c_i and a structure that steers xi away from Γ. Figure-1 show the block diagram describing the field generation process; more details may be found in [5]. Two examples of synthesis techniques are the Harmonic [6] and Biharmonic field approaches [7]. In the first the differential properties of the potential manifold are constrained by solving Laplace equation

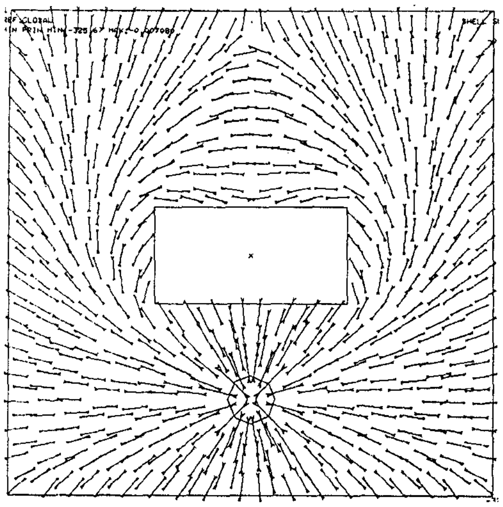


Figure-2: A PRF (Biharmonic Potential)

$$\nabla^2 V_i(x_i) = 0, \qquad (9)$$

subject to the proper boundary conditions on Γ and c_i. The PRF is generated as

$$u_{1i} = -\nabla V_i.$$

As for the second method, the potential manifold is constrained by solving

$$\nabla^4 V_i(x_i) = 0, \qquad (10)$$

subject to the proper conditions on Γ and c_i. The PRF is generated as

$$u_{1i} = -\nabla\nabla^2 V_i.$$

Figure-2 show an example of a PRF that is generated by the second method. Success was also encountered in generating PRF's for the moving target case [8].

3.2 The CRF component (u_{2i})

This component is strictly localized to the vicinity of the robots and the obstacles. u_{2di} is restricted to D_i, where D_i is a hyper sphere with a center x_i and a radius d_i such that :

$$D_i(x) \subset D_i'(x) \subset T_i(x) \qquad x_i = c_i. \quad (11)$$

On the other hand u_{2oi} is restricted to a thin strip O' that is surrounding O. Each subcomponent of u_{2di} (u_{2ij}) has two components, a radial one (u_{2ij_r}), and a tangent one (u_{2ij_t})

$$u_{2ij} = u_{2ij_r} + u_{2ij_t}. \qquad (12)$$

The radial component is generated from the gradient flow of a spherically symmetric scalar potential field (v_{ij}) [9]

$$u_{2ij_r} = \nabla v_{ij}(x_i, x_j), \qquad (13)$$

$$v_{ij}(x_i,x_j) = \begin{cases} \xi(|x_i - x_j|) & |x_i - x_j| \le d_i' \\ 0 & |x_i - x_j| \le d_i' \end{cases}$$

where ξ is a monotonically decreasing function with $d\xi/d\rho = 0$ for $r \ge d_i$, and r is the radial distance from x_j. As for u_{2ij_t}, its flow lines run tangent to D_i. This component requires a vector potential (A_{ij}) to be generated [10,11],

$$u_{2ij_t} = \nabla \times A_{ij}(x_i, x_j) \qquad \nabla \cdot A_{ij} \equiv \phi, \qquad (14)$$

where $\nabla\times$ is the curl operator and $\nabla\cdot$ is the divergence operator. All the tangent components has to circulate the agents in the same direction (Figure-3). This is a necessary condition to prevent a deadlock situation from forming [12]. As for u_{2oi} it is constructed from the gradient of a scalar potential field ($V_o(x_i,\Gamma)$) that is confined to O

$$u_{2oi} = \nabla V_o(x_i, \Gamma). \qquad (15)$$

3.3 The Overall Controller:

While the behavior of a single agents is generated by the system in equation-6, the group behavior is described by the hyper system :

$$\begin{bmatrix} \dot{x}_1 \\ \cdot \\ \dot{x}_L \end{bmatrix} = \begin{bmatrix} u_{11}(x_1, c_1, \Gamma) \\ \cdot \\ u_{1L}(x_L, c_L, \Gamma) \end{bmatrix} + \begin{bmatrix} u_{2o1}(x_1, \Gamma) \\ \cdot \\ u_{2oL}(x_L, \Gamma) \end{bmatrix} + \sum_{\substack{j=1 \\ i \ne j}}^{L} \begin{bmatrix} u_{21j}(x_1, x_j) \\ u_{i1j}(x_i, x_j) \\ u_{2Lj}(x_L, x_j) \end{bmatrix} \qquad (16)$$

This system evolves in dimensionality as agents join or leave the group; hence it satisfies the openness property. Also the structure of the control field keeps mutating under the influence of the G-type controllers and the environment to guarantee that the whole control field reach a sufficient level of in-formation that would enable the projection of a successful control action.

It can be shown that the above system can be made globally, asymptotically stable [12] if:

1- for $\dot{x}_i = u_{1i}(x_i, c_i, \Gamma) \qquad i=1,..,L \qquad (17)$

$\lim_{t\to\infty} x_i \to c_i$, and $x_i \cap \Gamma \equiv \phi$,

2- $D_i(x) \cap D_j(x) \equiv \phi$, and $O \cap D_i(x) \equiv \phi \qquad i \ne j$,

3- $\forall x' \in \Omega$, $\exists x_k \therefore x' \in \{x : |x - x_k| \le \rho\} \subset \Omega$,

where ρ is the sum of the diameters of the two largest agents. This condition simply requires the smallest passage in Ω to be wide enough to allow the largest two agents to pass at the same time.

4. RESULTS

In this section several simulation experiments are conducted to explore the decentralized, self-organizing, nature of the controller. Each example is presented as a sequence of frames with each frame depicting the state of the robots at different instants of the solution.

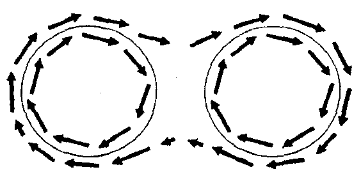


Figure-3a: Rotation in the same direction produces a singularity-free rotating global field.

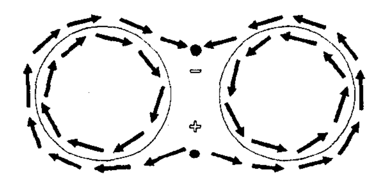


Figure-3b: Opposite circulation produces singularties in the circulating field.

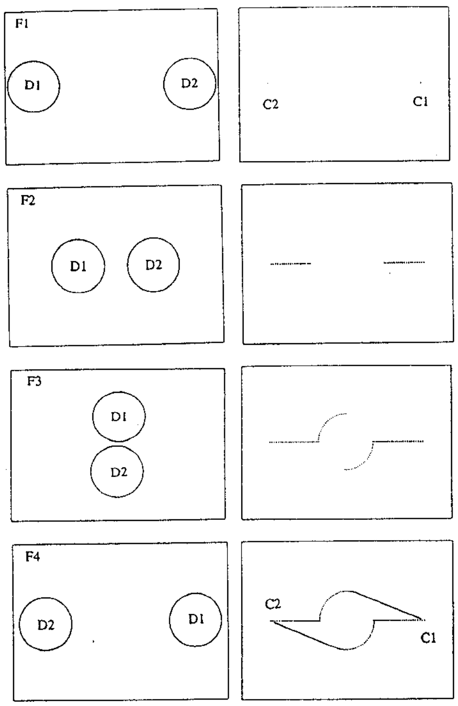


Figure -4a: All Agents Functional.

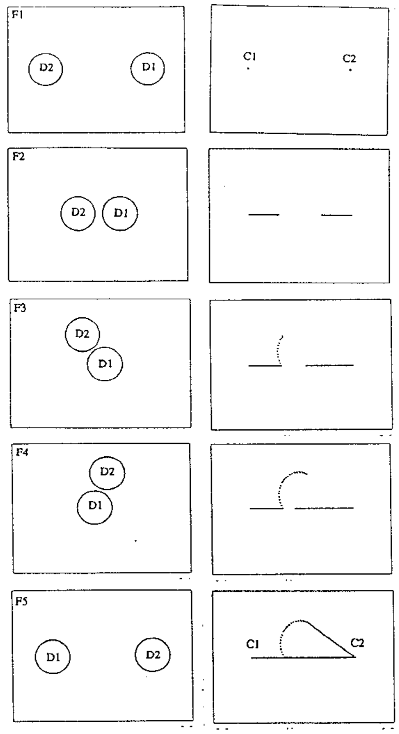


Figure-4b: D1 Malfunction.

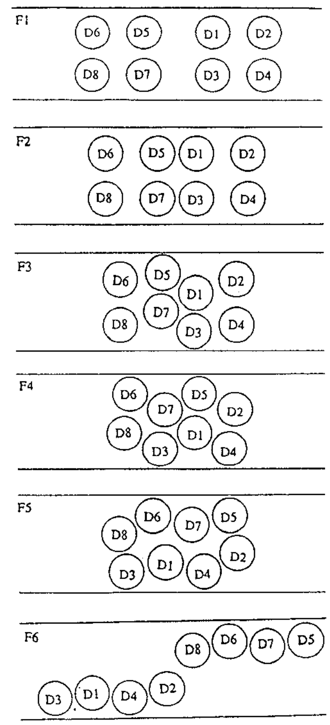


Figure-5: Two Groups passing each other.

In Figure-4a, two agents operating in an obstacle-free environment are required to exchange positions. The agents construct the, obviously, conflicting plans that require each to move along a straight line to its target. The agents independently execute their plans till a conflict is detected. Once this situation arise, the agents respond by moving out of each other way till each is in a position where it can can proceed unimpeded along a straight line to its respective target. Although the agents are acting individually in an asynchronous manner, the overall behavior of the group is synchronized (global synchronization without a synchronizer) and coordinated. Moreover, the group was able to augment the informational content of its behavior from the impoverished level that is initially contained in the individual PRF's to a level that enables them to successfully reach their goals. In Figure-4b another interesting property of decentralized controllers is investigated. This property is related to the role individual agents play in assuring that conflict is evaded and purpose is satisfied. In a centralized approach the supervisory control determine these roles by decomposing the overall plan for reaching the target into subplans that are executable in a parallel-distributed manner by the agents. These roles remain fixed after the assignment. Failure of one agent to fulfill its obligation to the group by properly carrying out it role, most likely results in the failure of all the agents to reach their targets. Decentralized systems behave in a different manner. The conflict resolving effort needed for all the agents to reach their targets has a lucid nature in the sense that it dynamically gets reallocated to the agents that are willing and able to participate in the conflict resolution effort. Here, an agent's role keeps adapting to the situation in a manner that would, to the best of the agent's ability, enable all the agents to safely reach their targets. This is clearly demonstrated in Figure-4b. Here a setting similar to the one in Figure-4a is used, except for D1 which refuses to participate in conflict resolution and instead follow the plan encoded by its PRF which requires it to move along a straight line towards its target. As can be seen the other agent adjusted its behavior to compensate for the intransigence of D1. In Figure-5 the evolutionary, self-organizing nature of the controller is clearly demonstrated. Figure-5 shows two groups of four robots each and moving in opposite directions along a confined path. They are blocking each other's way with the goal being the left group to go to the right and vice versa. It is interesting to notice that the groups collectively resolve the conflict by forming right and left lanes and confining the motion of the members of the groups along their respective lane. It ought to be mentioned that lane formation is a high-level, holistic, organizational activity that fundamentally differs from the local, simple, problem-solving activities which the individuals are equipped with. In Figure-6a the importance of the circulating fields for conflict resolution is examined. Here, a group of three agents, each required to hold its position, except for D1 where it is required to move to C1. No circulating fields were used. As can be seen, D1 got trapped in a deadlock situation when it attempted to pass the remaining agents. In Figure-6b, the circulating fields were added. As can be

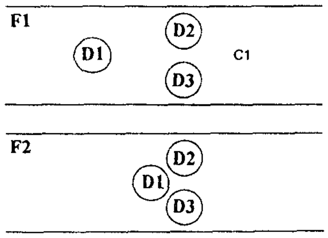


Figure-6a: D2,D3 Hold Position, D1 Moves To C1, No Circulating Fields.

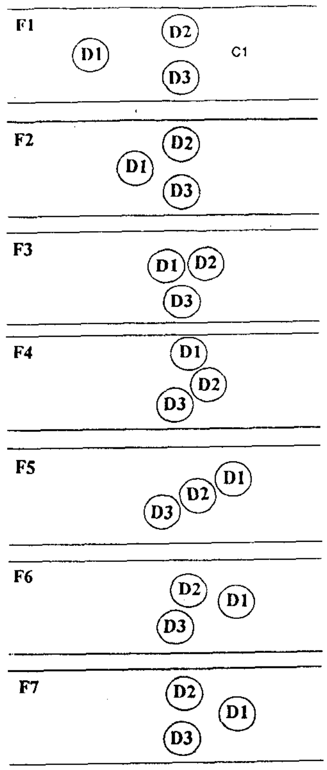


Figure-6b: Circulating Fields Added.

seen D1 was able to successfully reach its target and the remaining agents maintain their original positions. In Figure-7 the importance of the CRFs to circulate along the same direction is demonstrated. Here, a setting similar to the one in Figure-4a is used, except that the CRFs of D1 and D2 circulate in opposite directions. As can be seen instead of avoiding each other, the agents kept blocking each other way. This is due to the singularity which opposite circulation creates in the CRF. Although the agents are in motion as a unit, they are stationary with respect to each other.

5. CONCLUSIONS

This work describes the construction of a complete, decentralized, evolutionary motion controller for agents sharing a workspace with stationary forbidden regions. May be the most

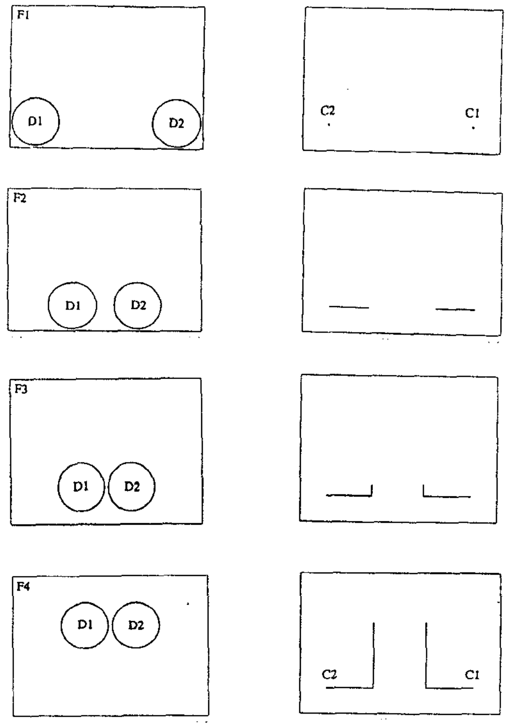


Figure-7: Deadlock Caused by Opposite Circulation.

important property of the controller is its ability to on-line generate the additional information that is needed to execute a successful action. This is due to the controller's ability to construct global useful activities through local interacting activities without the agents, necessarily, being aware of the generated global behavior. The local G-type control that is used by the individual agents does support such a mode of behavior. It is also noticed that the controller exhibits intelligent dispatching capabilities that enables it to redistribute the task of conflict evasion on the properly functioning agents. This is the major cause of the robust performance which the controller exhibits in case of sensor or actuator failure. The work also presents the potential field approach as a powerful tool for generating control fields that are particularly suited for constructing intelligent, decentralized controllers.

6. FUTURE WORK

Ongoing work [13,14] is geared towards removing the need of the agents to a priori know Γ. A PRF for the G-type controller is constructed so that for the system

$$\dot{x}_i = u_i \qquad (18)$$

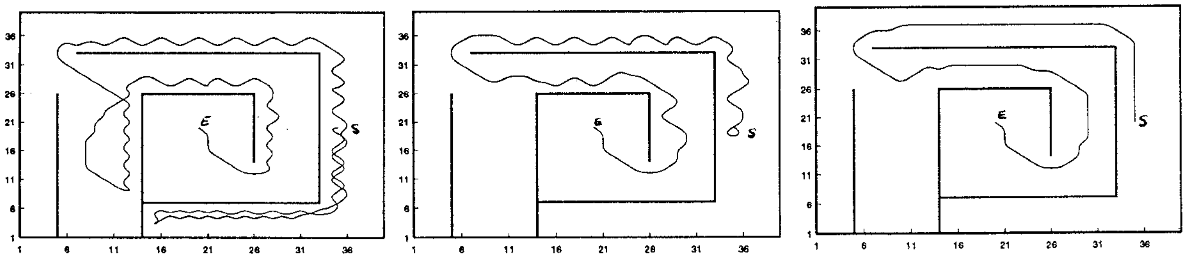
$x_i, u_i \in R^M$, the agent is required to synthesize a finite set of successively dependent f_j's ($\{f_j: j=1, .., k<\infty\}$, $f_j \in R^M$) so that for the system

$$\dot{x}_i = f_j(x_i, c_i, \Omega m, f_{j-1}) \quad x_i(0)=x_{io} \qquad (19)$$

$$f_o = f(x_i, c_i, \Gamma)$$

$$\lim_{\substack{t\to\infty \\ j\to K}} x_i(t) \longrightarrow c_i \qquad \forall x_{io} \in \Omega \quad j=[1,..,k],\ t\in[0,\infty)$$

and $\quad x_i(t) \cap O \equiv \phi,$



a: First attempt. *b: Second attempt.* *c: Third attempt.*

Figure-8: An agent navigating an unknown environment.

where, k is a finite positive integer, $Q \in Z^z$, and f_j maps the hybrid space to the agent's continuous M-D action space $R^M x R^M x Z^z x R^M \rightarrow R^M$. All what is needed to construct the PRF's is an impoverished estimate of Γ (Γ'). Γ' can even be the empty set ϕ ($\phi \subseteq \Gamma' \subseteq \Gamma$). Figure-8a,b,c show the first, second, and third attempts by the agent at reaching its target in a totally unknown environment. As can be seen from zero knowledge of Γ, the agent was able to successfully reach the target at the end of each attempt improving its performance each attempt till an optimal behavior is reached.

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