

USING HYBRID VECTOR-HARMONIC POTENTIAL FIELDS FOR MULTI-ROBOT, MULTI-TARGET NAVIGATION IN A STATIONARY ENVIRONMENT

BY
Ahmad A. Masoud

Electrical Engineering Department, Queen's University,
Kingston, Ontario, Canada K7L-3N6

ABSTRACT

In this work, Hybrid Vector-Harmonic potential fields are suggested for building a path planner for multi-robot, multi-target navigation in a stationary environment. The suggested method is complete provided that the workspace satisfies a lenient geometrical condition. The operation of the planner is based on the bottom-up approach to behavior synthesis (instead of the common top-down approach). Such an approach proves effective in limiting the complexity of planning. The approach also enjoys significant flexibility, enabling the addition or removal of any number of robots from the workspace without having to adjust the manner in which the rest of the robots behave. Theoretical development, proofs, as well as simulation results are provided for a number of different robot workspace configurations.

I. INTRODUCTION

A daily act of planning which people engage in with little, if any, attention to its complexity is the simple trip from home to work and back. In a metropolitan city, such a process involves thousands, if not millions, of participants, each of which is only aware of the path that he/she is going to follow. No considerations are given or, in my opinion, can be given to whether a path that is selected by an individual conflicts with the ones selected by others. Any planner that attempts to derive a priori known conflict-free paths (a top-down approach to motion synthesis) faces serious difficulties. The complexity of attempting to carry out the necessary checks, is more than enough to cripple such a planner. Roughly speaking, a planner of such a form has to do N^N performance satisfaction checks ($(N-1)^N$ conflict evasion checks, and N goal satisfaction checks). This is prohibitively large even for a medium size group. In general, a top-down approach to planning has a wholistic nature where a central decision making unit simultaneously observes the states of all the participants, processes all the acquired information, and provide synchronized sequences of instructions to all the individuals in order for them to progressively modify their course and safely reach their respective destinations.

Planning in an environment that is shared by more than one purposive agent has attracted the attention of many researchers. The suggested techniques may be divided into two main classes: a class that is concerned with planning motion for one robot with the rest of the robots not reactively adjusting their paths to accommodate the presence of that robot; the second class in which all the robots simultaneously participate in reaching an accommodating arrangement that enables all of them to safely reach their respective destinations. Examples of the first class of techniques can be found in [1-5]. On the other hand, Techniques of the second class that simultaneously tackle planning for all the robots [6-12] are, in general, more difficult to design than the previous ones. To the best of the author's knowledge, the only method with a provably complete planner is that of Parson's and Canny [6]. However, the method suffers

from an exponential complexity that effectively limits its usability to a small number of robots.

The fact that the above planning process successfully takes place with no central planner observing and/or controlling the movements of the participants, or any a priori restrictions on the number of the participants or shapes of the paths they follow, provides a new look at the problem that is fundamentally different from previous approaches. A careful examination of the manner in which a path is generated by such a process seems to strongly advocate a bottom-up approach to planning. In contrast to the top-down approach, a bottom-up approach to motion synthesis has a local nature where the participants are assumed to have local sensory and decision making capabilities. The capabilities of the individuals are, in general, simple and not adequate, on their own, to handle the planning task at hand. The solution's (i.e. a sequence of instructions that is generated for each participant to direct its motion along a safe and conflict-free path toward its target) complexity far exceeds what the capabilities of an isolated individual can achieve. In a bottom-up approach the solution globally emerge as a result of constructive interaction among the members of the group.

In this work, a Hybrid Vector-Harmonic potential field is suggested for constructing a path planner for multi-robot, multi-target navigation in a stationary environment. The suggested planner is complete provided that the narrowest passage in the workspace is wide enough to allow the two largest robots of the group to pass at the same time. The planner may be divided into two components: a component that is constructed for each robot, in isolation of the others, to drive it to its respective target. This part is constructed with the aid of Harmonic Potential fields [13,14] and is referred to here as the Purpose Field (PRF). The other component is constructed from an underlying Vector Potential field [15,16]. The function of this component is to prevent collision among the different robots and to guarantee that any conflict which may arise due to the PRF's disregard to one another is resolved. Therefore, this field component is called the Conflict Resolving Field (CRF). The suggested planner is decentralized. In other words, the planning action can be broken down into reasoning and execution procedures which each robot can perform in isolation of the reasoning and execution processes of other robots yet still meet the global objective of successful, safe, conflict-free motion to the targets. The suggested planner enjoys significant flexibility in the sense that any addition or removal of robots to or from the group can be done without altering the manner in which the remaining robots individually behave. The suggested planner requires each robot to have only local sensing capabilities (i.e. a robot has to only be aware of the other robots in its immediate neighborhood). Another attractive feature of the planner is the emergent nature of the solution that it produces. While the planner equips the individual members of the group with elementary, a priori known, programmed actions to affect their immediate environment, the resulting

patterns of behavior which are responsible for the resolution of a conflict and satisfaction of the purpose are a priori unknown, very flexible, highly adaptive and responsive to the global state of the group, and far exceed in complexity what the separate actions of the individuals can produce. Finally, the complexity of the planner is significantly less than that of others in its class. In particular, for N robots in a 2-D environment, the computational burden of planning is equal to that of planning N paths to the respective targets of the robots and at most, depending on how crowded the workspace is, the evaluation of 6·N simple functions at each time step during the evolution of the solution.

This paper is organized as follows: in section II the navigation problem is formulated and the suggested planner is presented. Section III, contains motion analysis. Results and conclusions are placed in section IV and V respectively.

II. THE SUGGESTED PLANNER

In the following the problem is formulated and the structure of the suggested planner is provided.

Formulation

A robot is assumed to be a massless, M-D hyper sphere (D_i) that has a radius d_i and a center $x_i \in R^M$,

$$D_i(x) = \{x: |x - x_i| \leq d_i\}, \quad i=1, \dots, L, \quad (1)$$

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

$$D_i(x) \subset T_i(x) \quad \text{when } x_i = c_i.$$

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

$$T_i(x) \cap T_j(x) = \emptyset, \quad i \neq j$$

$$\text{and } O \cap T_i(x) = \emptyset \quad i = 1, \dots, L. \quad (2)$$

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

$$\dot{x} = H(x(t), \Gamma, C), \quad (3)$$

where $x \in R^{ML}$ ($x^t = [x_1^t \dots x_L^t]^t$), $C \in R^{ML}$ ($C^t = [c_1^t \dots c_L^t]^t$),

also $H: R^{ML} \times R^{ML} \times R^N \rightarrow R^M$. The planner is required to ensure that

$$\lim_{t \rightarrow \infty} x_i(t) \rightarrow c_i \quad i = 1, \dots, L, \quad (4)$$

$$\text{and } D_i(x) \cap D_j(x) = \emptyset, \quad i \neq j, \quad \forall t$$

$$\text{and } O \cap D_i(x) = \emptyset \quad i = 1, \dots, L, \quad \forall t.$$

The H vector consists of three functionally distinct steering actions. In the following, each component is discussed for a single robot. The full planner is then supplied.

The Navigation Actions on One Robot

In the following the steering actions experienced by one robot are first examined. To drive a robot (D_i) to its target (c_i), a point force is applied on its center (x_i). This force changes in magnitude and direction depending on the location of the robot making it an element of a force field spanning the entire workspace. The structure of this field encodes the plan that the robot has for reaching its destination. The static environment (Γ) and the target point (c_i) are used to generate this navigation action using a harmonic potential field (v_i) [13,14] where the guidance vector field is taken as the negative gradient flow of such a potential

$$\dot{x}_i = -\nabla v_i(x_i, c_i, \Gamma), \quad (5)$$

such that $\lim_{t \rightarrow \infty} x_i(t) \rightarrow c_i$, and $x_i(t) \cap O = \emptyset \quad \forall t$.

The second component of the navigation action acts to prevent collision of the robots with one another. To generate this component each robot is surrounded with a repulsive field that is strictly localized to its vicinity (D_i), where D_i is a hyper sphere with a center x_i , and a radius d_i

$$D_i(x) \subset D_i(x) \subset T_i(x) \quad \text{when } x_i = c_i.$$

Such a force field can be easily generated as the gradient flow of a spherically symmetric scalar potential field $v_r(x, x_i)$:

$$v_r(x, x_i) = \begin{cases} \xi(|x - x_i|) & |x - x_i| \leq d_i \\ 0 & |x - x_i| \geq d_i \end{cases}, \quad (6)$$

where d_i is the radius of D_i , and ξ is a monotonically decreasing function with

$$d\xi(r)/dr = 0 \quad r \geq d_i,$$

where r is the radial distance from the center. The force field that is responsible for the steering action of this component ($f_r(x)$) is taken as the gradient flow of v_r

$$f_r(x) = \nabla v_r(x). \quad (7)$$

Besides the f_r 's, another component that is defined on the same zone surrounding the robots is needed. This component runs tangent to the surface of the robots (f_t). The f_t 's circulate the robots in the same direction and, like the f_r 's, are strictly localized to their respective D_i . This kind of field is generated from an underlying vector potential field with a divergence that is identically zero

$$f_t(x) = \nabla \times \Lambda(x) \quad \nabla \cdot \Lambda = 0, \quad (8)$$

where Λ is a vector potential with zero divergence. The requirement that all the tangent fields circulate the robots in the same direction is crucial for ensuring that the individual vector fields can also be a part of a larger vector field that is connecting all the robots together (Figure-1). As will be shown in the sequel, such a requirement is crucial for the collective cooperation of the f_t 's to resolve any conflict that may arise (remove any deadlock in motion). Finally, a field fencing the obstacles ($v_o(x_i)$) is used to guarantee that as a result of interaction, no collision will occur between any of the robots and the static obstacles. Although this can be guaranteed by carefully designing the Harmonic fields, it is more convenient to have it as a separate component. These barrier fields can be easily derived as the gradient flow of a scalar potential field (v_o),

$$\dot{x}_i = \nabla v_o(x_i, \Gamma) \quad i=1, \dots, L. \quad (9)$$

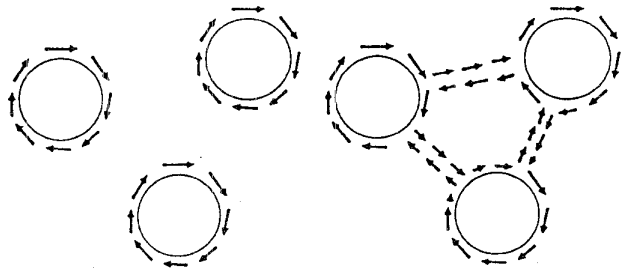


Figure-1: Same direction circulation guarantees that the individual circulating fields are parts of a larger one circulating in the same direction.

The Dynamic Equation of a Single Robot

Since a robot is a rigid circular disc, its motion can be fully described by the motion of its center (linear velocity \dot{x}_i) and the angular velocity (ω_i). Instead of a robot having to actively monitor its surroundings, measure the interaction forces, then project them back to its center, the following procedure is suggested to automatically accomplish the above and enable the transfer of the geometrical problem into a nonlinear dynamical system. It is well known that for rigid bodies, any force can be transferred from one point to another. However, the force at the new point has to be augmented with the proper moment. Such a procedure can be incorporated in the navigation differential system by shrinking the radius of the robot under consideration to zero, therefore turning it into a point robot. As for the other robots, their radius is augmented by that of the robot under consideration. The boundaries of the obstacles are also advanced by a distance equal to the radius of the robot under consideration (Figure-2). The dynamic equations that describe translation and rotation for the i 'th robot are

$$\dot{x}_i = -\nabla v_1(x_i) + \nabla v_0(x_i) + \sum_j f(x_i, x_j) \quad j=1, \dots, L, i \neq j$$

where $f(x_i, x_j) = f_r(x_i - x_j) + f_t(x_i - x_j)$. (10)

It is important to note that all the force fields in the right side of (10) are designed for the enlarged robots and environment.

As for the dynamic equation governing rotation (ω_i), it is easy to see that only the f_t 's can cause such a motion. Assuming that $d_i \approx d_i$, the rotation equation is approximated as

$$\omega_i = d_i \cdot \sum_j f_t(x_i - x_j) \quad j=1, \dots, L, i \neq j$$

Since the robots have spherical symmetry, rotation about their center will not contribute to the conflict resolving effort; therefore, it is discarded.

The Complete Navigator Equation

The dynamic equation describing the motion of the group of robots is

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \vdots \\ \dot{x}_L \end{bmatrix} = \begin{bmatrix} -\nabla v_1(x_1, c_1, \Gamma) \\ -\nabla v_2(x_2, c_2, \Gamma) \\ \vdots \\ -\nabla v_2(x_L, c_L, \Gamma) \end{bmatrix} + \begin{bmatrix} \nabla v_0(x_1, \Gamma) \\ \nabla v_0(x_2, \Gamma) \\ \vdots \\ \nabla v_0(x_L, \Gamma) \end{bmatrix} + \begin{bmatrix} \sum_j f(x_1, x_j), \quad j \neq 1 \\ \sum_j f(x_2, x_j), \quad j \neq 2 \\ \vdots \\ \sum_j f(x_L, x_j), \quad j \neq L \end{bmatrix}$$

or in a more compact form (12)

$$\dot{X} = H(X, \Gamma, C) = -V(X, \Gamma, C) + V_0(X, \Gamma) + F(X)$$

Since V is the only term that has the target vector (C) in its argument, it is called the Purpose Field (PRF) term. On the other hand, since V_0 and F are only active when a constraint is about to be violated or when a group of robots is in a state of deadlock, this term is called the Conflict Resolving Field (CRF).

III. MOTION ANALYSIS

While it is not hard to see that the ability of the robots to avoid collision with each other and with the obstacles can be guaranteed by making the barrier fields (∇v_0 , f_r 's) strong enough (some techniques set the magnitude of these fields to infinity at the boundary [17]), their ability to reach their respective destinations needs careful examination. In the following it is shown that the first order nonlinear dynamical system in (3) is potentially capable of driving the robots from anywhere in the workspace to their respective destinations provided that the

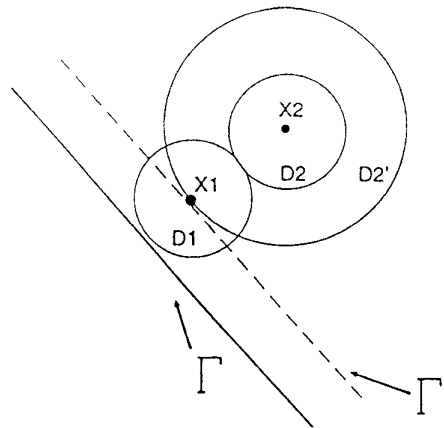


Figure-2: To compute the forces on a robot, the boundaries of the other robots and obstacles are enlarged.

narrowest passage in the workspace is wide enough to allow the largest two robots to pass at all times.

Convergence

Here, it is shown that under certain conditions, the solution of the system in (3) is globally asymptotically stable. The proof is dependent on a theorem by LaSalle (Theorem-3, [18], pp. 524) which is restated below with minor modifications to the notation.

Theorem: Let $E(X)$ be a scalar function with continuous first partials with respect to X . Assume that

- 1- $E(X) > 0$ for all $X \neq C$, (14)
- 2- $E(X) \leq 0$ for all X .

Let E be the set of all points where $E(X) = 0$, and M be the largest invariant set contained in E . Then every solution of the system

$$\dot{X} = H(X, \Gamma, C) \quad (15)$$

bounded for $t \geq 0$ approaches M as $t \rightarrow \infty$.

Proposition: There exist a set of f_t 's which guarantee

$$\lim_{t \rightarrow \infty} X(t) \rightarrow C \quad (16)$$

provided that

- 1. For the gradient dynamical systems

$$\dot{x}_i = -\nabla v_1(x_i, c_i, \Gamma)$$

$$\lim_{t \rightarrow \infty} x_i(t) \rightarrow c_i \quad i=1, \dots, L.$$
- 2.

$$D_1(x) \cap D_j(x) = \emptyset, \quad i \neq j,$$

$$0 \cap D_i(x) = \emptyset \quad i=1, \dots, L.$$
- 3. $\forall x' \in \Omega, \exists x_k$ such that

$$x' \in \{x: |x - x_k| \leq \rho\} \subset \Omega, \quad (17)$$

where $\rho = d_1 + d_2$, d_1 and d_2 are the two largest elements in the set $\{d_i\}$, and Ω is the workspace.

The third condition guarantees that no where in Ω will the geometry of the environment prevent the agents from resolving the conflict and instead forces them to project motion along environmentally determined degrees of freedom (Figure-3) that may not lend itself to the resolution of the conflict. By guaranteeing that there always exist a local, simply connected region that is large enough to enable any two robots to interact, guarantees that whatever pattern of motion which the agents arrive at to resolve the conflict can be realized.

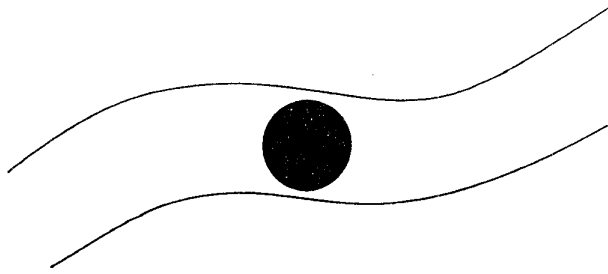


Figure-3: Restrictive environments force an a priori determined spatial pattern on the robot neutralizing its ability to manipulate spatial behavior.

Proof : Consider the following Liapunov Function Candidate (LFC)

$$\Xi = \sum_{i=1}^L v_i(x_i) \quad i=1, \dots, L. \quad (18)$$

It was shown in [19] that Harmonic potential fields satisfying condition (1) in the proposition are suitable LFC's (here, the harmonic fields are denoted by $v_i(x_i)$ instead of $v_i(x_i, c_i, \Gamma)$, and $v_o(x_i, \Gamma)$ is denoted by $v_o(x_i)$). Therefore, their sum is also a valid LFC. The time derivative of Ξ can be computed as

$$\begin{aligned} \dot{\Xi} &= \sum_{i=1}^L \nabla v_i(x_i)^T \dot{x}_i \\ &= \sum_{i=1}^L \nabla v_i(x_i)^T \left[-\nabla v_i(x_i) + \nabla v_o(x_i) + \sum_{j=1, j \neq i}^L f(x_i, x_j) \right]. \quad (19) \end{aligned}$$

The above expression is examined term by term. It is obvious that the term

$$-\sum_{i=1}^L \nabla v_i(x_i)^T \nabla v_i(x_i) \quad (20)$$

is negative definite and is only equal to zero (stable global equilibrium) at $x_i = c_i, i=1, \dots, L$.

As for the second term

$$\sum_{i=1}^L \nabla v_i(x_i)^T \nabla v_o(x_i), \quad (21)$$

it is to be noticed that ∇v_o emanates normal to Γ . Since this flow is restricted to a local, narrow strip surrounding the obstacles ($O\delta = D_i - D_i$), the whole field may be considered orthogonal to Γ

$$\nabla v_o(x_i) \approx \begin{cases} \alpha(x_i)n & x_i \in O\delta \\ 0 & \text{elsewhere} \end{cases}, \quad (22)$$

where n is a unit vector that is orthogonal to Γ , and α is a positive scalar function. The Boundary Value Problem that is used to generate $\nabla v_i(x_i)$ sets the boundary conditions to either [13,14]

$$\frac{\partial v_i}{\partial n} = \nabla v_i(x_i)^T n = 0,$$

or $v_i(x_i) = \text{constant} \quad x_i \in \Gamma$,

$$\text{which in turn makes } \frac{\partial v_i}{\partial n} = \nabla v_i(x_i)^T n < 0 \quad (23)$$

(i.e. the maximum of v_i is achieved at Γ and its value decreases with motion away from Γ). As a result, the

second term of $\dot{\Xi}$ is either

$$\begin{aligned} \sum_{i=1}^L \nabla v_i(x_i)^T \nabla v_o(x_i) &\equiv 0, \text{ or} \\ \sum_{i=1}^L \nabla v_i(x_i)^T \nabla v_o(x_i) &< 0, \quad x_i \in O\delta \quad (24) \end{aligned}$$

which in both cases does not affect convergence, because $c_i \notin O\delta$.

It ought to be noticed that the forces surrounding

the robots have a local, passive nature. This guarantees that no unbounded growth in the magnitude of the x_i 's can occur. The worst case condition is that those forces may cause a deadlock in motion ($x_i - c_i = \text{constant}$). Since, in the worst case, the f 's will bring motion to a halt ($\dot{\Xi}=0$), also taking into consideration the negative definiteness of the first two terms, the derivative of the Liapunov function is always less than or equal to zero

$$\dot{\Xi} \leq 0. \quad (25)$$

If the i 'th robot is in static equilibrium before it reaches its target, the following relation must hold

$$\sum_{j=1, j \neq i}^L f(x_i, x_j) = \nabla v_i(x_i) - \nabla v_o(x_i). \quad (26)$$

Substituting the left hand term of (26) in (19), it can be seen that $\dot{\Xi} = 0$ at the above condition. Therefore the set E is equal to

$$E = E_1 \cup E_2 = \{ x_i : \dot{\Xi} = 0 \}, \quad (27)$$

where $E_1 = \bigcup_i E_{1i}, E_{1i} = \{ x_i : x_i = c_i \}$, and

$$E_2 = \bigcup_i E_{2i}, E_{2i} = \{ x_i : \nabla v_o(x_i) - \nabla v_i(x_i) + \sum_{j=1, j \neq i}^L f(x_i, x_j) = 0, x_i \neq c_i \}, \quad i=1, \dots, L$$

The largest invariant set $M \subset E$ is the subset of E that satisfies the equilibrium condition for (3).

Let us first examine if E_2 is an equilibrium set of system (3). For this case the system forces are

$$h(x_i) = -\nabla v_i(x_i) + \nabla v_o(x_i) + \sum_{j=1, j \neq i}^L \nabla v_r(x_i - x_j) + \sum_{j=1, j \neq i}^L \nabla x_\lambda(x_i - x_j) \quad i=1, \dots, L, \quad (28)$$

where h is the i 'th element in $H, h \in R^M$. It ought to be noticed that if condition 2 in the proposition holds, the magnitude of the radial reaction forces ($\nabla v_o, \nabla v_r$) is determined by the magnitude of the self-forces (∇v_i 's) and the configuration that the set of robots assume during deadlock. On the other hand, the magnitude of the circulating forces (∇x_λ 's) is totally independent of the self-forces and since they are made to rotate in the same direction, such fields contains no singularities (Figure-4). Therefore, their strength can be arbitrarily set by the designer any where in $O\delta$. Since the goal is to eliminate E_2 from M , this freedom is utilized to guarantee that $h(x_i) \neq 0 \forall x_i \neq c_i, i=1, \dots, L$. Since the self-forces are generated from the gradient flow of a harmonic potential, their

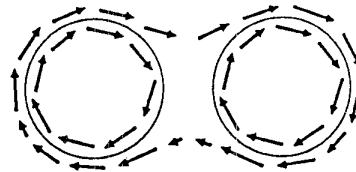


Figure-4a: Rotation in the same direction produces a singularity-free rotating global field.

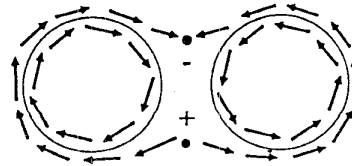


Figure-4b: Opposite circulation produces singularities in the circulating field.

magnitude in Ω is bounded

$$|\nabla v_i(x_i)| \leq K_i \quad x_i \neq c_i \quad i=1, \dots, L, \quad (29)$$

where K_i is a constant. A conservative choice of the magnitude of the circulating fields that would guarantee that E_2 is not an equilibrium set of (3) is

$$|\nabla v_A(x_i - x_j)| \geq \sum_{i=1}^L K_i \quad (30)$$

It ought to be mentioned that if condition 3 on the environment is not satisfied (i.e. there is not enough free space for the largest two robots to move) and the circulating forces have to push against a static obstacle (a static obstacle can be considered as a set of robots (D_0) grouped around the contours marking the boundary of the obstacles and kept in their position with infinitely strong self-fields, $|\nabla v_0| \rightarrow \infty$), there exists no realizable choice of K_i 's that would satisfy condition (30). In other words, whenever the radial forces of one or more robots are in a state of equilibrium, the circulating forces act to push the robots out of that equilibrium by actuating the motion of the robots along the tangent of the contact points. Therefore, E_2 is eliminated from M . Also, since the robots have convex geometry, no equilibrium paths can form trapping one or more robots in a limit cycle.

As for E_1 , the fact that T_i is taken bigger than D_i ($D_i < T_i$) guarantees that once the robots reaches their respective destinations, no interactions among their fields can happen (i.e. $f(x_i, x_j) = 0, \forall v_0(x_i) = 0, \forall i, j$). Also since

$$\nabla v_i(x_i) = 0 \quad x_i = c_i, \quad (31)$$

system (3) is reduced to

$$\dot{x}_i = 0 \quad x_i = c_i \quad (32)$$

making the largest invariant set equal to

$$M = \bigcup_{i=1}^L \{x_i : x_i = c_i\} \quad i=1, \dots, L. \quad (33)$$

Therefore, the robots will globally asymptotically converge to their respective destinations i.e.

$$\lim_{t \rightarrow \infty} x_i(t) \rightarrow c_i \quad i=1, \dots, L. \quad (34)$$

As was mentioned earlier, the suggested planner is complete provided that condition-3 (17) hold. While this condition still covers many practical workspaces, it is, nevertheless, desirable that completeness be achieved for a general workspace that is not restricted by this condition. To examine why imposing this constraint is necessary for the suggested planner to guarantee completeness begins by noting that behavior, in general, has two components: a spatial one that consists of a vector field that assigns to each point in the workspace a direction along which motion should proceed, and a temporal one which consists of a scalar field that assigns a speed to each point in the workspace. Therefore, completeness for a general class of workspaces implies the existence of a spatio-temporal pattern of behavior which, if executed by the agent, leads to the satisfaction of the goal. In general, tractable environments where a solution exist provided that behavior be spatially and temporally manipulated, the environment may at one stage deprive the planner from the ability to fully manipulate spatial behavior by forcing one or more agents to follow spatial behavioral patterns that are set by the geometry of the workspace (Figure-3). If such a situation occurs, the planner can only resolve the conflict by manipulating the temporal component of behavior (i.e. speed up or slow down the movements of the agents, as well as halt motion or reverse it). Since the suggested planner is totally reliant on manipulating spatial behavioral, it may fail if it encounters a situation where both spatial as well as temporal components of behavior are to be manipulated. Condi-

on-3 (17) guarantees that the environment will never be able to prevent the planner from spatially manipulating behavior in order to resolve a conflict.

IV. RESULTS

Several experiments were conducted to explore the behavior of the suggested planner. The following examples are selected to illustrate some of the planner's attributes. Each example is presented as a sequence of frames with each frame depicting the state of the robots at different instants of the solution. The notation used is the same as that in the theoretical development (i.e. D_i represents the i 'th robot, c_i its target and x_i is its center).

In the first example (Figure-5), two robots sharing the same obstacle-free workspace are required to exchange positions. In doing so, each robot makes the naive choice of moving along a straight line to the target. Despite the apparent conflict which such a choice will lead to, each robot proceeds with its plan as if the selected action is conflict-free. Once a conflict is in a phase that is detectable by the narrow domain of awareness which each robot has, corrective actions are taken by each to modify their plans in order to resolve the conflict. The "Behavior Modifiers" may be divided into two distinctive components: a component to prevent collision (this action translates to halting motion along the normal to the robots surfaces), and a component to move the robots out of each other ways (for this case motion is restricted along the tangent of the robots surfaces). Once the conflict is resolved, the behavior modification activities dissipate and guidance is fully transferred to the PRFs. Figure-5a shows the positions of the robots while Figure-5b shows the trajectories followed by the centers of each robot.

In example-2 (Figure-6), three robots operating in an obstacle-free space, and initially positioned on the vertices of an equilateral triangle, are required to proceed towards their symmetric targets. As in the previous example, each robot chooses to proceed along a straight line to its target ignoring the conflict which such a choice leads to. In this case, the response of the robots, once a conflict is detected, exhibits an interesting emergent nature. By reducing the degrees of freedom of the system from three to one, the three robots act as one rotating body to position themselves where each can proceed unimpeded toward its target. It is interesting to notice that without being a priori programmed to do so, the robots choose to cooperate in order to resolve the conflict. This cooperation is manifested as a reduction in the degrees of freedom of the system during the period of the conflict.

In example-3 (Figure-7), the behavior of the robots is explored in the presence of obstacles that are depicted as barriers marking the sides of the road. Two robots occupying the right lane of the road are used. The rear robot is made to be faster than the front one. As can be seen, after the fast robot catches up with the slow one, it decides to temporarily use the other lane to pass the slow robot. Immediately after passing it, the fast robot returns to its original lane.

In example-4 (Figure-8) the evolutionary nature of planning, which is a result of the ability of the group to self-organize, is clearly demonstrated. Two groups of four robots each, moving in opposite directions along a road, blocking each others way with the goal being the left group to get to the right side and vice versa for the right group. It is interesting to notice that the group collectively solves the problem by forming right and left lanes and confining the

motion of each group to one of the lanes. It ought to be noticed that lane formation is a high-level, wholistic, organizational activity that fundamentally differs from the simple, local capabilities which each robot is equipped with to solve the problem.

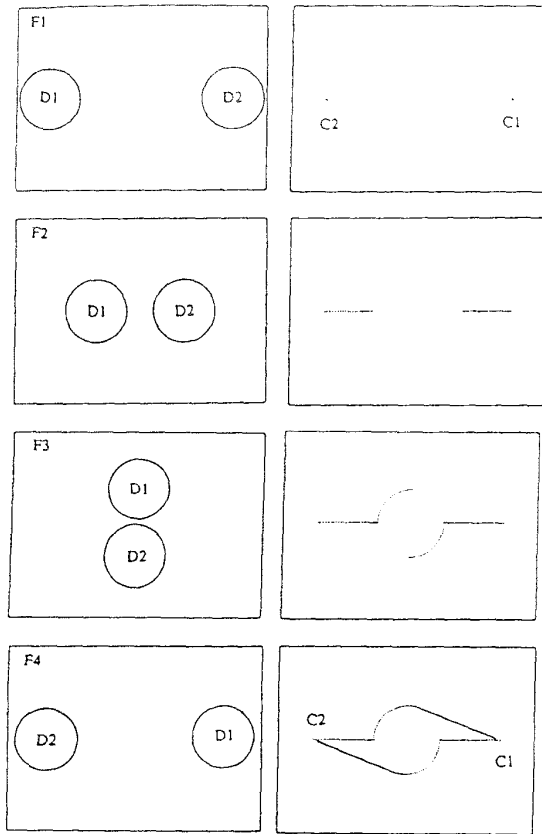
In example-5 (Figure-8) the group is required to perform the difficult planning task of exchanging positions in a confined area. The exchange order is $D_1 \leftrightarrow D_6$, $D_2 \leftrightarrow D_5$, $D_3 \leftrightarrow D_8$, $D_4 \leftrightarrow D_7$. As can be seen, the group successfully carries out the task.

V. CONCLUSIONS

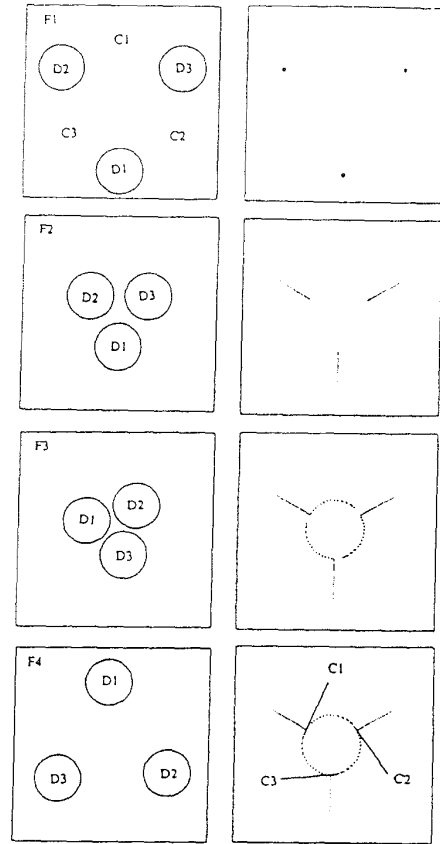
In this work, a complete, flexible, low complexity, path planner is suggested for multi-robot, multi-target navigation in a stationary environment. Perhaps the most interesting feature of the planner is the emergent manner in which the solution is generated. While all that is supplied to the planner in terms of navigational capabilities, is a 'naive' perception of how to go about reaching the target along with some basic maneuvering capabilities, the output far exceeds in complexity, coordination, and overall suitability for navigation each robot's capabilities. This is a direct consequence of not making the manner in which the robots behave, as a whole or as groups in response to a conflict, a priori programmed. Rather, behavior, emerges allowing the planner to convert the simplistic, unsuccessful original plans into workable successful ones. It ought to be mentioned that the PRF's (self-fields) need not be restricted to harmonic fields. It can be shown that any single-agent planning method that guarantee global asymptotic convergence (e.g. [20]) may be used instead. Future work will concentrate on incorporating both the temporal and spatial aspects of behavior in planning as well as modifying the planner so that it becomes possible to incorporate dynamics for the robot as well as nonholonomic constraints.

REFERENCES

- [1] T. Tsubouchi, S. Arimoto, "Behavior of a Mobile Robot Navigated by an Iterated Forecast and Planning Scheme in the Presence of Multiple Moving Obstacles", 1994 IEEE Int. Conf. on Rob. & Aut., May 8-13, San Diego, California, pp. 2470-2475.
- [2] P. Fiorini, Z. Shiller, "Motion Planning in Dynamic Environment using the Relative Velocity Paradigm", 1993 IEEE Int. Conf. on Rob. & Aut., May 2-6, Atlanta, Georgia, pp.560-565.
- [3] M. Hasoun, Y. Demazeau, C. Laugier, "Motion Control for a Car-like Robot: Potential Field and Multi-agent approaches", 1992 IEEE Int. Conf. on Rob. & Aut., July 7-10, Raleigh North Carolina, pp. 1457-63.
- [4] H. Tomigana, B. Bavarian, "Solving the Moving obstacle Path Planning Problem using Embedded Variational Methods", 1991 IEEE Int. Conf. on Rob. & Aut., April, 1991, Sacramento, California, pp.450-455.
- [5] Q. Zhu, "Hidden Markov Model for Dynamic Obstacle Avoidance of Mobile Robot navigation", IEEE Trans. on Rob. & Aut., Vol. 7, No.3, June 91, pp. 390-397.
- [6] D. Parsons, J. Canny, "A Motion Planner for Multiple Mobile Robots", 1990 IEEE Int. Conf. on Rob. & Aut., May 13-18, Cincinnati, Ohio, pp. 8-13.
- [7] J. Ota, T. Arai, "Motion Planning of Multiple Mobile Robots Using Dynamic Groups", 1993 IEEE Int. Conf. on Rob. & Aut., May 2-6, Atlanta, Georgia, pp. 28-33.
- [8] K. Fujimura, "A Model of Reactive Planning for Multiple Mobile Agents", 1991 IEEE Int. Conf. on Rob. and Aut., April, 1991, Sacramento, California, pp. 1503-1509.
- [9] C. Warren, "Multiple Robot Path Coordination Using Artificial Potential Fields", 1990 IEEE Int. Conf. on Rob. & Aut., May 13-18, Cincinnati, pp. 500-5.
- [10] P. Tournasoud, "A Strategy for Obstacle Avoidance and its Applications to Multi-Robot Systems", 1986 IEEE Int. Conf. on Rob. & Aut., April 7-10, San Francisco, California, pp. 1224-1229.
- [11] M. Erdmann, T. Lozano-Pérez, "On Multiple Moving Objects", 1986 IEEE Int. Conf. on Rob. & Aut., April 7-10, San Francisco, California, pp. 1419-24.
- [12] S. Buckley, "Fast Motion Planning for Multiple Moving Robots", 1989 IEEE Int. Conf. on Rob. & Aut. May 18, Scottsdale, Arizona, pp. 322-326.
- [13] J. Decuyper, D. Keymeulen, "A Reactive Robot Navigation System Based on a Fluid Dynamics Metaphor", Parallel Problem Solving From Nature, 1st Workshop, PPSN, Dortmund, FRG, Oct. 1-3, 1990 Proceedings.
- [14] C. Connolly, R. Weiss, J. Burns, "Path Planning Using Laplaces Equation", 1990 IEEE Int. Conf. on Rob. & Aut., May 13-18, Cincinnati, pp. 2102-06.
- [15] A. Masoud, M. Bayoumi, "Constraining the Motion of a Robot Manipulator Using the Vector Potential Approach", 1993 IEEE Regional Conference on Aerospace Control Systems, Westlake Village, CA, May 25-27, 1993, pp. 493-497.
- [16] A. Masoud, M. Bayoumi, "Robot Navigation Using the Vector Potential Approach", 1993 IEEE Int. Conf. on Rob. & Aut., Atlanta, Georgia, May 2-7, 1993 pp. 1-(805-811).
- [17] O. Khatib, "Real-time Obstacle Avoidance for Manipulators and Mobile Robots", The International Journal of Robotics Research, Vol.5, No.1, Spring, 1995, pp. 90-98.
- [18] J. LaSalle, "Some Extensions of Liapunov's Second Method", IRE Transactions on Circuit Theory, CT-7, No. 4, 1960, pp. 520-527.
- [19] A. Masoud, "A Boundary Value Problem Formulation of Pursuit-Evasion in a Stationary Environment: A Potential Field Approach", 1995 IEEE Int. Conf. on Rob. & Aut., May 21-27, Nagoya, Japan, pp.2734-39.
- [20] A. Masoud, S. Masoud, M. Bayoumi, "Robot Navigation Using a Pressure Generated Mechanical Stress Field, The Biharmonic Potential Approach", 1994 IEEE Int. Conf. on Rob. & Aut., May 8-13, 1994 San Diego, California, pp. 124-129.



a. Robots. b. Trajectories.



a. Robots. b. Trajectories.

Figure-5: Two robots exchanging positions.

Figure-6: Three robots moving to their goals.

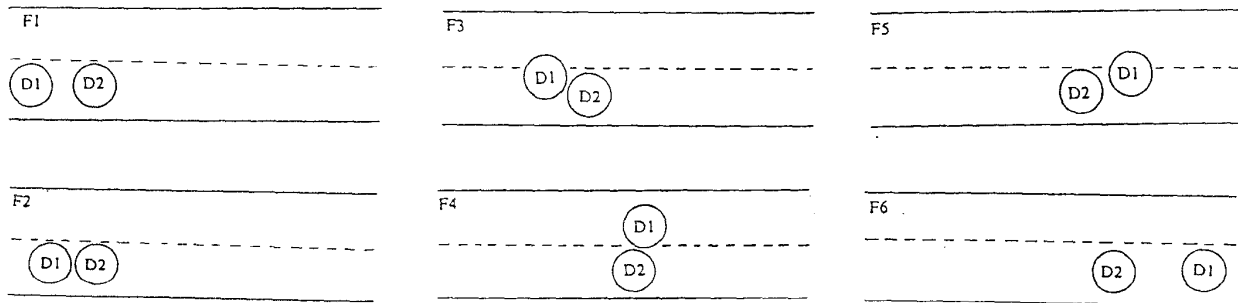


Figure-7: A robot passing a slower one on a two-lane road.

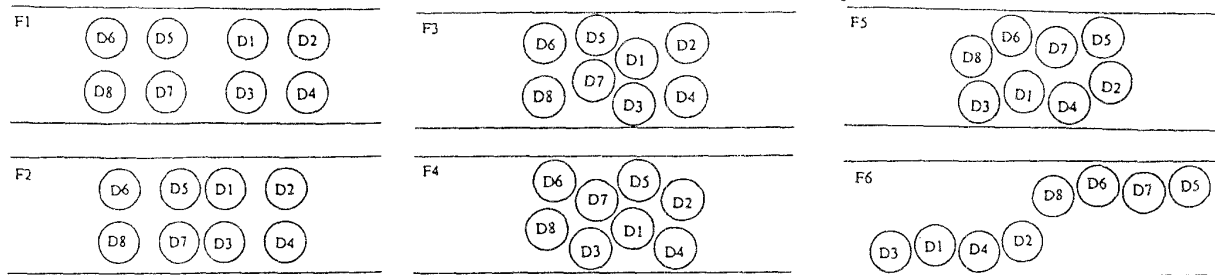


Figure-8: Two groups of robots passing each others in a confined space.

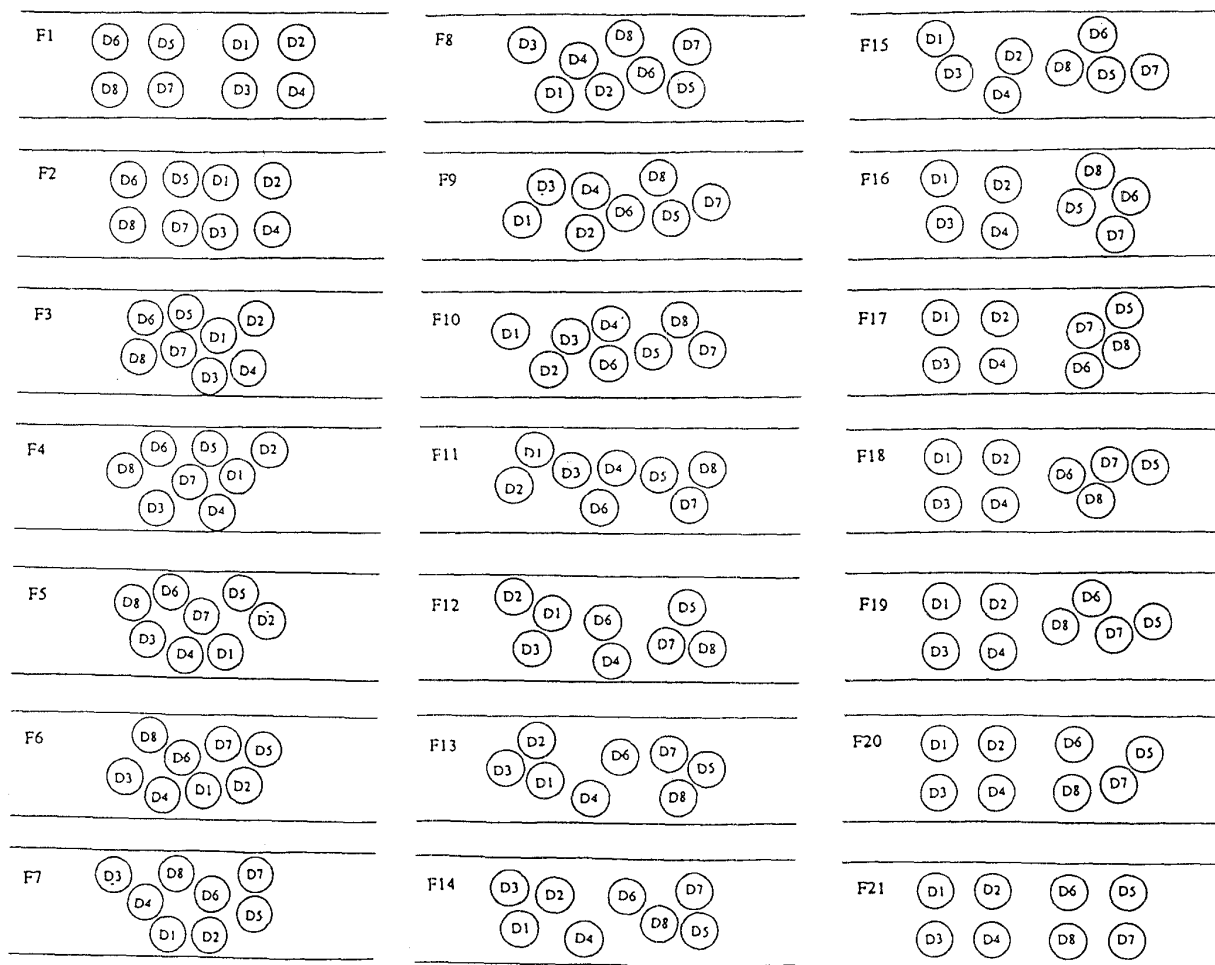


Figure-9: A group of robots exchanging positions in a confined space.