Managing the Dynamics of a Potential Field-Guided Robot in a Cluttered Environment

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Abstract-This paper extends the capabilities of the harmonic potential field approach to planning to cover both the kinematic and dynamic aspects of a robot's motion. The suggested approach converts the gradient guidance field from a harmonic potential to a control signal by augmenting it with a novel type of dampening forces suggested in this paper called: nonlinear, anisotropic, dampening forces (NADFs). The combination of the two provides a signal that can both guide a robot and effectively manage its dynamics. The kinodynamic planning signal inherits, fully, the guidance capabilities of the harmonic gradient field. It can also be easily configured to efficiently suppress the inertia-induced transients in the robot's trajectory without compromising the speed of operation. Theoretical results and simulation are provided in the paper.

I. Introduction

The harmonic potential field approach to planning is emerging as one of the most powerful paradigms for the guidance of autonomous agents. Since it was suggested in the mid-late eighties [1,2] the approach is continuously developing to meet the stringent requirements operation in a real-life environment imposes on an agent. Up-till-now, the approach has amassed many attractive properties crucial for enhancing goal reachability. The approach is provably-correct driving the agent to a successful conclusion if the task is manageable and providing an indication if the task is intractable. It can be used to guide the motion of an arbitrarily shaped agent in an unknown environment regardless of its geometry or even topology relying only on the sensory data acquired online by the agent's finite range sensors. The method can also impose a variety of constraints on the agent's trajectory such as regional avoidance and directional constraints [3-8].

A planner may be defined as an intelligent, purposive, context-sensitive controller that can instruct an agent on how to deploy its motion actuators (i.e generate a control signal) so that a target state may be reached in a constrained manner. Traditionally, a planning task is distributed on two stages: a high level control (HLC) stage and a low level control stage (LLC), figure-1. The HLC stage receives data about the environment, the target of the agent, and constraints on its behavior. It then simultaneously process these data to generate a reference plan or trajectory marking the desired behavior of the robot which if actualized leads to the agent reaching its target in the desired manner. The reference plan is then fed to the LLC in order to convert it into a sequence of action instructions to be executed by the agent's actuators of motion. Unfortunately, the HLC-LLC paradigm for planning suffers from serious problems that adversely impact the reliability of operation. An alternative to the above may be achieved by fusing the HLC and LLC modules into one called: the navigation control (NC). An NC attempts to directly convert the environmental data, goal of the robot, and constraints on its behavior into a control signal (figure-1). Khatib potential field (PF) approach may be considered as one of the first methods to cast planning in an NC framework [9]. The PF approach enjoys several attractive features, most significant is the high speed by which a robot can respond to the contents of its environment.

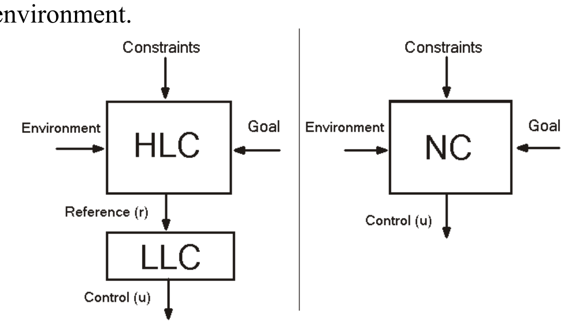


Figure-1: The HLC-LLC and NC control structures.

Unfortunately, the attractor-repeller setting Khatib used to generate the potential field has some problems. The most serious one has to do with convergence where it was observed that a robot guided by such a method may stop somewhere in the workspace before reaching its target; the problem was termed the local minima problem. Many methods later appeared to generate potential fields that do not suffer from this problem [10-12]. Koditschek diffeomorphism approach [13] was among the first methods suggested to remedy this shortcoming in the PF approach. To convert the gradient guidance field from the potential surface ($-\nabla V$) into a control signal (u), a viscous dampening force that is linearly proportional to speed is added:

$$\mathbf{u} = -\mathbf{B} \cdot \dot{\mathbf{x}} - \nabla \mathbf{V}(\mathbf{x}) \tag{1}$$

This combination will only work provided that the initial speed of the robot is lower than an upper bound S(x):

$$\nu(\mathbf{x}) \leq \mathbf{S}(\mathbf{s}) \qquad \mathbf{x} \in \Omega \tag{2}$$

where ν(x) is the initial speed of the robot at the location x, and Ω is the workspace of the robot [14]. Practical application of the above faced two difficulties: first, no method was provided to compute the upper bound S. Even if a method is devised for doing so, there is no guarantee that in a practical situation the initial speed of a robot can be made to lie below the admissible upper bound. The second difficulty has to do with the fact that the satisfaction of the upper speed constraint guarantees only that obstacle avoidance constraints will be upheld and convergence to the target will be achieved. In potential field methods transients can be a serious concern that could make it impractical to use these techniques for controlling a robot. One form of these transients, called the narrow corridor artifact, was discussed by Koren and Borenstien in [15].

In its current form the HPF approach can only operate in an HLC mode providing only a guidance signal from the gradient of the potential. This signal has to be converted into a control signal by an LLC. In this paper a method is suggested to utilize the HPF approach in an NC mode. This is accomplished by augmenting the guidance gradient signal with a new type of dampening forces called: nonlinear, anisotropic, dampening forces (NADFs). The paper demonstrates that the sum of the gradient and NADF provides an effective planning control signal that can be easily configured to place the dynamics of a robot under control and make the trajectory yield to the guidance from the gradient of the potential field.

This paper is organized as follows: in section II some background about the potential field approach as well as an attempt to cast it in an NC framework are provided. Section III discusses the proposed solution. Simulation results are in section IV, and conclusions are placed in section V.

II. Background

The HPF approach appeared shortly after Khatib's PF approach was suggested. Although the approach was brought to the forefront of the work on motion planning independently and simultaneously by different researchers [16-20], the first work to be published on the subject was that by Sato in 1986 [1]. The HPF approach eliminates the local minima problem encountered in [9] by forcing the differential properties of the potential field to satisfy Laplace equation inside the workspace of the robot (Ω) while constraining the properties of the potential at the boundary of Ω ($\Gamma=\partial\Omega$). The boundary set Γ includes both the boundaries of the forbidden zones (O) and the target point (x_T). A basic setting of the HPF approach is:

$$\nabla^2 V(x) \equiv 0 \qquad x \in \Omega$$

subject to: $$V = 0|_{X=X_T} \;\&\; V = 1|_{X\in\Gamma} \;. \qquad (3)$$

The trajectory to the target (x(t)) is generated using the HPF-based, gradient dynamical system:

$$\dot{x} = -\nabla V(x) \qquad x(0) = x_0 \in \Omega \qquad (4)$$

The trajectory is guaranteed to:

$$1\text{-}\ \lim_{t\to\infty} x(t) \to x_T \qquad 2\text{-}\ x(t) \in \Omega \qquad \forall \mathbf{t} \qquad (5)$$

Figure-2 shows the negative gradient field of a harmonic potential for the simple environment of a room with two dividers. Figure-3 shows the trajectory, x(t), generated using the dynamical system in (4). It ought to be mentioned that the HPF approach is only a special case of a broader class of planners called: PDE-ODE motion planners where the field is generated using the boundary value problem (BVP): solve:

$$L(V(x)) \equiv 0 \qquad x \in \Omega$$

subject to: $$G(V(x)) = 0 \qquad x \in \Gamma. \qquad (6)$$

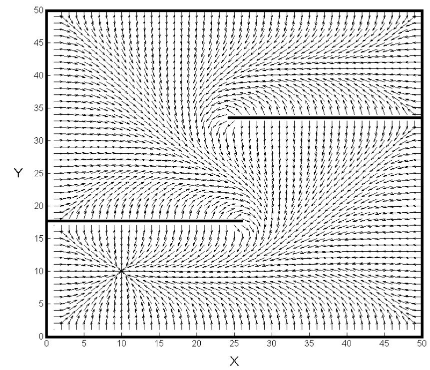


Figure-2: Guidance field of an HPF.

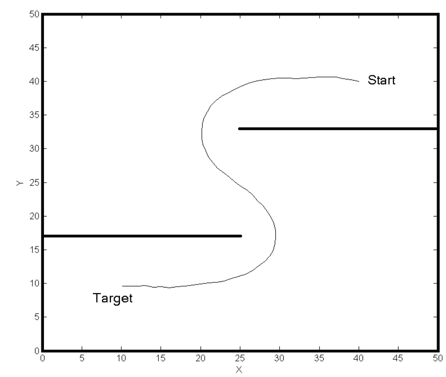


Figure-3: Trajectory generated by the field in figure-2.

The trajectory is generated using the nonlinear system:

$$\dot{\mathbf{x}} = F(V(x)) \qquad x(0) = x_0 \in \Omega \qquad (7)$$

where L is scalar partial differential operator, G is a governing relation restricting the potential or some of its properties at the boundary to a certain value, F is a nonlinear vector function mapping $R \rightarrow R^N$, N is the dimension of x, PDE stands for partial differential equation, and ODE stands for ordinary differential equation. Planners assuming a PDE-ODE setting other than that of the one in (3) may be found in [8].

The trajectory, x(t), generated by the dynamical system in (4) is only a reference trajectory that should be fed to an LLC in order to generate the control signal, u, the robot is using. It ought to be noticed that the PF approach was originally suggested as a high-speed alternative to the HLC-LLC paradigm to planning. The PF method in [9] is in effect an NC. As mentioned before, despite the advantages of Khatib's approach it suffered, among other things, from a convergence problem that was called: the local minima problem.

Koditschek was among the first to tackle the local minima problem . He used a diffeomorphism-based method to generate a potential field that does not suffer from this problem. The planning control signal was generated by adding to the negative gradient of the potential a component that is proportional to the speed of the robot. In figure-4, the negative gradient of the potential in figure-2 is used to navigate a 1kg point mass. The dynamic equation of the system is:

$$\begin{bmatrix} \ddot{x} \\ \ddot{y} \end{bmatrix} = -\mathbf{B} \cdot \begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} - \begin{bmatrix} \partial V(x,y)/\partial x \\ \partial V(x,y)/\partial y \end{bmatrix} \tag{8}$$

where B=0.1. As can be seen, despite the fact that the initial speed of the robot is zero, the trajectory violated the avoidance condition and collided with the walls of the room.

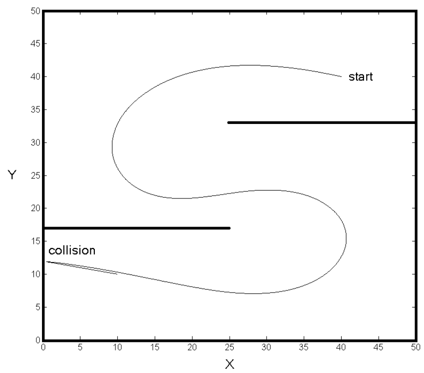
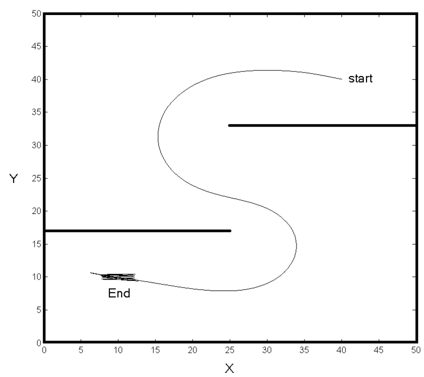


Figure-4: trajectory of a point mass controlled by the field in figure-2.



Figuer-5: trajectory, point mass, linear dampening increased.

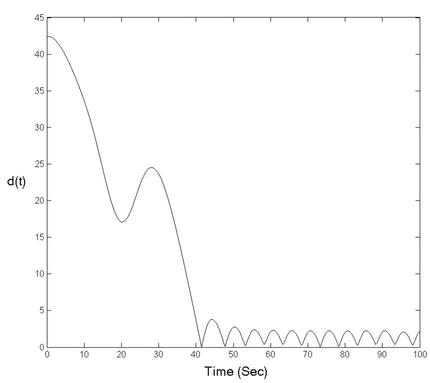


Figure-6: Distance to target versus time.

III. Approach

A straightforward solution to the problem of converting a gradient guidance field into a navigation control signal is to increase the coefficient of the linear velocity term to a sufficiently high level. The linear velocity component acts as a dampener of motion that may be used to place the inertial force under control by marginalizing its disruptive influence on the trajectory of the robot the gradient field is attempting to generate. The following example demonstrates that this solution is impractical. In order to generate a control signal that would satisfy the avoidance constraints (5), the coefficient of dampening of the system is increased to B=0.15. Figure-5 shows the resulting trajectory and figure-6 shows the distance to the target as a function of time. Although the trajectory did converge to the target point (x_T) and did not violate the regional avoidance constraints, unacceptable transients along with significant deviations from the path marked by the gradient field (figure-2) are present. In a second attempt to generate a well-behaved control signal, the dampening coefficient is significantly increased to B=.7. Although a well-behaved trajectory was obtained (figure-7), significant slowdown of motion did occur (figure-8).

The method for converting the gradient field from a harmonic potential into a navigation control signal by simple augmentation with a linear velocity dampening term is incorrect. This approach ignores the dual role the gradient field plays as a control and guidance provider. The field guides a robot to the target using vectors that point out the directions along which the robot has to move if the target is to be reached and the obstacles to be avoided. At the same time these vectors are forces that act on the mass of the robot in order to actuate motion. Obviously the inertia of the robot will have a disruptive influence on motion. The linear dampening term manages the inertial forces in an attempt to make the motion of the robot yield to guidance provided by the gradient field.

A dampening component that is proportional to velocity exercises omniscient attenuation of motion regardless of the direction along which it is heading. This means that the useful component of motion marked by the direction along which the goal component of the gradient of the artificial potential is pointing is treated in the same manner as the unwanted, inertia-induced, noise component of the trajectory. These two components should not be treated equally. Attenuation should be restricted to the inertia-caused, disruptive component of motion, while the component in conformity with the guidance of the artificial potential should be left unaffected (figure-9).

To better manage the effect of the inertial forces, a more carefully constructed dampening component that treats the gradient of the artificial potential both as an actuator of dynamics and as a guiding signal is needed. A dampening force that behaves in the above manner is:

$$\mathbf{ud} = -\mathbf{Bd} \cdot [(\mathbf{n}^t \dot{\mathbf{X}})\,\mathbf{n} + (\frac{\mathbf{ug}^t}{|\mathbf{ug}|} \cdot \dot{\mathbf{X}} \cdot \Phi(-\mathbf{ug}^t \dot{\mathbf{X}}))\frac{\mathbf{ug}}{|\mathbf{ug}|}] \tag{9}$$

where **n** is a unit vector orthogonal to ug, ud represents the dampening force, and Bd is a constant. This force is given the name: nonlinear, anisotropic, dampening force (NADF). For the two dimensional case, an NADF has the form:

$$\mathbf{ud} = \frac{-\mathbf{Bd}}{\mathbf{ug}_x^2 + \mathbf{ug}_y^2}\Bigg[(\mathbf{ug}_x \dot{\mathbf{y}} - \mathbf{ug}_y \dot{\mathbf{x}}) \cdot \begin{bmatrix} -\mathbf{ug}_y \\ \mathbf{ug}_x \end{bmatrix} + (\mathbf{ug}_x \dot{\mathbf{x}} + \mathbf{ug}_y \dot{\mathbf{y}}) \cdot \Phi(-\mathbf{ug}_x \dot{\mathbf{x}} - \mathbf{ug}_y \dot{\mathbf{y}})\begin{bmatrix} \mathbf{ug}_x \\ \mathbf{ug}_y \end{bmatrix}\Bigg] \tag{10}$$

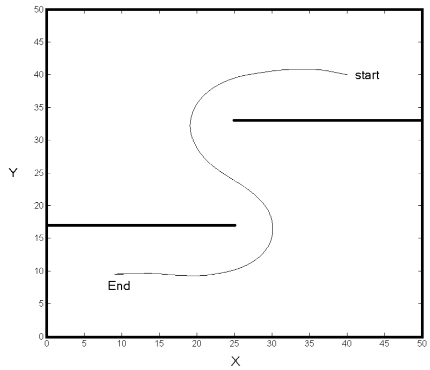


Figure-7: Trajectory, high linear dampening.

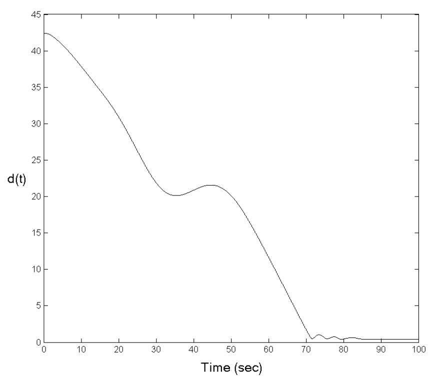
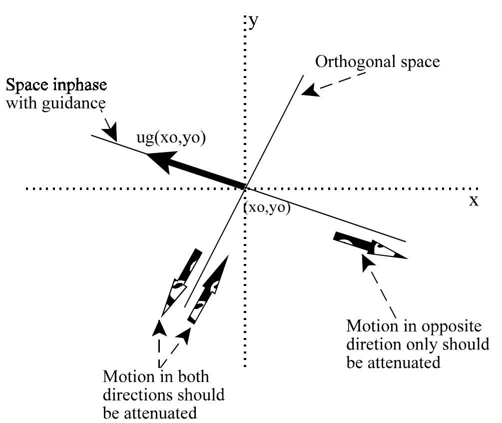
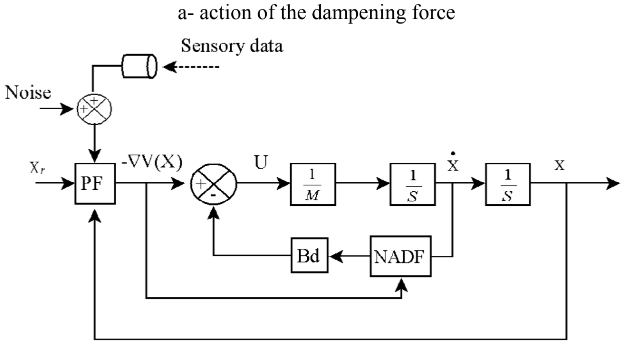


Figure-8: Distance to target versus time.



a- action of the dampening force



b- block diagram

Figure-9: nonlinear, anisotropic, dampening force (NADF).

IV. Results

The gradient field in figure-2 is augmented with NADF dampening forces instead of the linear, viscous, dampening forces. The combination of both gradient field and NADF force are used to steer a 1Kg mass from a start point to a target point. An excessively high dampening coefficient, Bd=10, is used. The trajectory of the mass is shown in figure-10, and the mass distance to the target, D(t), as a function of time is shown in figure-11. As can be seen the kinodynamic trajectory of the mass is almost identical to that marked by the gradient field (kinematics only) in figure-3. Moreover, motion of the mass is almost six times faster than its viscous dampening counterpart shown in figure-7.

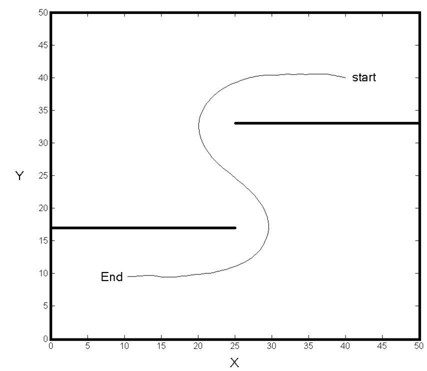


Figure-10: Trajectory, NADF used.

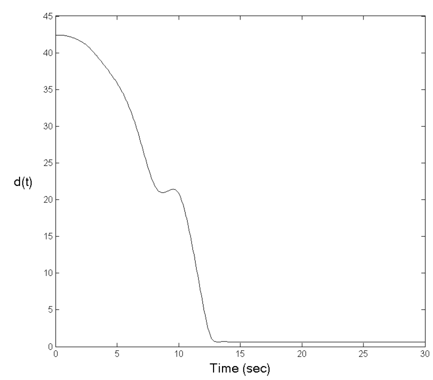


Figure-11: Distance to target versus time.

Compared to the linear dampening coefficient (B), the NADF coefficient (Bd) is much easier to tune. Figures-12 and 13 show the settling time (Ts) for the above case versus B and Bd respectively. As can be seen, the Ts - B profile for the linear case is convex exhibiting only one optimum value for B that yields the minimum Ts. This creates a conflict situation where to minimize the deviation between the kinematic and the dynamic paths one needs a high B; on the other hand, to have an agile response one need to keep B as close to the optimum as possible. The Ts-Bd profile for the NADF case is continuously decreasing. This creates no conflict between having Bd high to reduce the deviation and obtaining the fastest response possible.

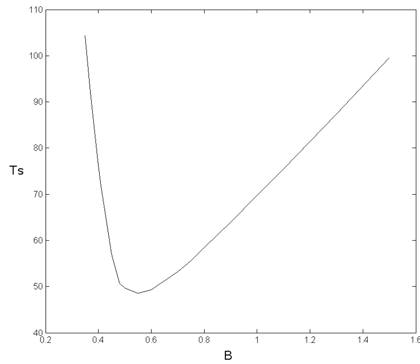


Figure-12: settling time versus the linear dampening coefficient B.

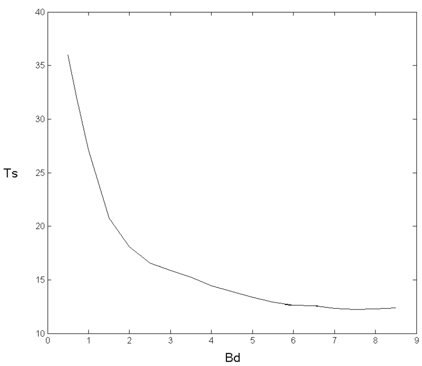


Figure-13:Settling time versus the NADF coefficient Bd.

NADFs have a generic nature that makes it possible to use them in a variety of situations. NADFs may be used to solve a problem in potential field planners known as the narrow corridor effect [21]. NADFs may also be applied directly in the configuration space of a robot in order to control an arm manipulator. It is also possible to use them for the single robot or the multi-robot case. In [22] a complete, decentralized, multi-agent planner was suggested considering the kinematics of the robots only. Figure-14 shows the paths for two massless robots that are trying to exchange positions. When mass is added (1Kg each), the planner totally fails (figure-15).

In figure-16 linear dampening is added to control the inertial forces (B=1). Figure-17 shows the distance to target of robot-1 as a function of time. It took the robot about 13 seconds to reach its target. In figure-18, NADF was used (Bd=10). As can be seen from the distance - time profile in figure-19, it took robot-1 only two seconds to reach its target.

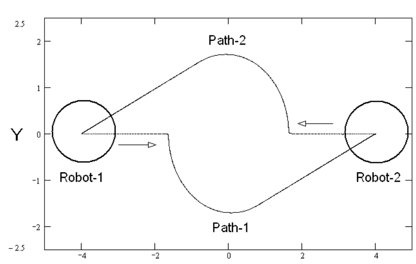


Figure-14:Two robots exchanging positions, kinematics only.

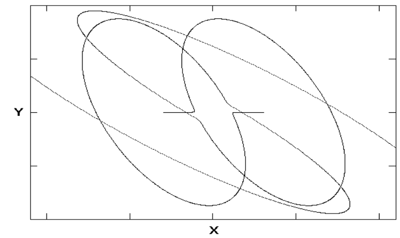


Figure-15: Same as figure-14, but with 1kg mass added to each robot.

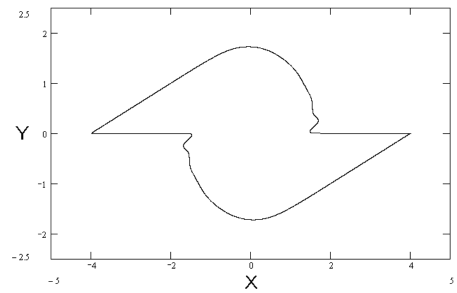


Figure-16: Linear dampening added to manage inertia, B=1.

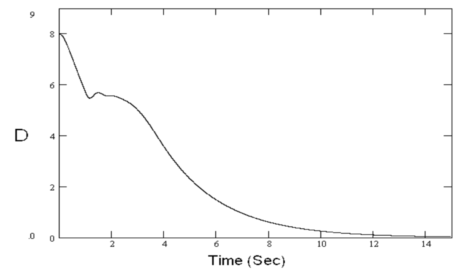


Figure-17: Distance to target versus time for robot-1 in figure-16.

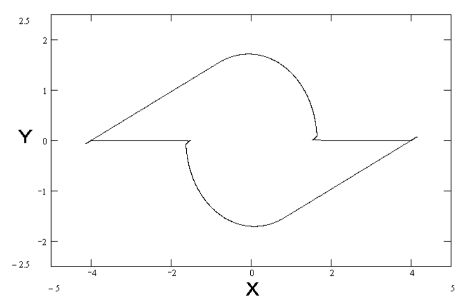


Figure-18: NADF added to manage inertia, Bd=10.

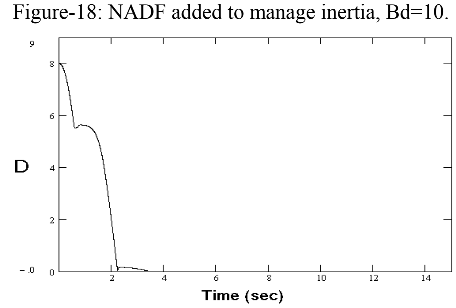


Figure-19: Distance to target versus time for robot-1 in figure-18.

V. Conclusions

In this paper the harmonic potential field motion planning method is cast in a navigation control framework where *a priori* data about a situation is directly converted into a control signal. The gradient of a harmonic potential field, which can only provide a guiding reference, is converted into a control signal by adding to it the NADF suggested in this paper. As was demonstrated, attempting to convert the gradient field into a control signal by adding a linear viscous dampening force (a force proportional to velocity) may be problematic. On the other hand, carrying out such an extension using the NADF approach is straightforward and practical. This is because the NADF approach is developed to take into consideration the dual role the gradient field of an HPF plays both as a control signal and a guidance provider. The simultaneous consideration of these two factors is what enables the control signal to effectively suppress transients without slowing down motion. The work in this paper may be considered as another step towards the HPF approach attaining its full potential.

Acknowledgment
The author would like to thank KFUPM for its support of this work.

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