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Solving the Narrow Corridor Problem in Potential Field-Guided Autonomous Robots

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Abstract — This paper tackles the issue of converting the guidance signal from the gradient of a potential field into a control signal that can both guide an autonomous robot and effectively manage its dynamics. Particular emphasis is placed on dealing with the "narrow corridor" artifact reported by Koren and Borenstien [1] which the attractor-repeller potential field paradigm proposed by Khatib [2] suffers from. The suggested solution is based on a novel concept this paper introduces called: nonlinear, anisotropic, dampening forces. In addition to eliminating the narrow corridor artifact, improving the quality of the trajectory, the suggested solution significantly increases the speed of the robot. Theoretical development along with simulation results are provided.

I. INTRODUCTION

A planner is the center piece of an autonomous robot. It is what allows the sensory-motor activities of a robot to assume a purposive, context-sensitive, useful form that is able to actualize a high-level goal set by an operator. At first, planners were built in conformity with the classical AI, hierarchical, symbolic reasoning approach. In this approach sensory data is first converted into a symbolic representation of the environment of the robot that is stored in a suitable database. This database is then pruned by a search algorithm to generate a plan which the low-level controllers of the robot have to execute in order to reach the goal. Despite the solid foundations on which this approach stands, it was observed that, in real-life, the approach can, at best, provide a slow shaky performance. In his seminal work that appeared in the mid-eighties [2,3] Khatib suggested that the sensors of a robot be directly coupled to its servo loops. The coupling was achieved via potential fields. The result was a tremendous increase in the speed at which the robot responds to the contents of the environment. Khatib's work marked a turning point in the way planning is approached.

In the early nineties, Koren and Bornestien reported what they referred to as a serious and inherent deficiency in Khatib's method [1]. They found that if an autonomous robot that is guided by the potential field method is operating in a narrow corridor, the robot could behave erratically, oscillating in a sustained manner between the two walls of the corridor. The artifact was called the "narrow corridor effect". The implications of such a finding are significant. Since a service autonomous robot will have to pass through corridors in order to deliver mail in offices, laundry in hospitals, or parts in factories, the use of potential field-based planners is immediately ruled out and alternatives, such as the vector histogram method [4], should be sought.

While the author of this paper agrees with [1] that the narrow corridor effect is a serious artifact, he disagrees with it being an inherent deficiency in the potential field approach. In this paper, it is shown that this artifact is caused by a misunderstanding of the dual role the gradient of a potential field plays as both a control and guidance provider. This misunderstanding led to an improper coupling between the gradient field and the robot's servo loops that, among other things, caused the narrow corridor artifact. A nonlinear conditioning force, called: nonlinear, anisotropic, dampening force (NADF) is suggested in this paper to properly couple the gradient field to the servo loops of a robot. This force is designed to take the dual nature of the field into account. Its use in coupling the gradient field to the servo loops eliminate the narrow corridor artifact and achieve a significant improvement in the speed of response and quality of the robot's trajectory. Moreover, the suggested modification may be used with later, more general forms, of the potential field approach, such as the harmonic potential field approach [5], to enable the planner to both guide a robot and manage its dynamics.

This paper is organized as follows: in section II some background is provided about the attractor - repeller form of the potential field approach and the narrow corridor artifact. Section III contains the proposed solution. Simulation and conclusions are placed in sections IV and V respectively.

II. BACKGROUND

Khatib perceived the need for fast reaction if a robot is to have a reasonable chance of success in a dynamic environment. Speed was attained by removing the intermediate, computationally-expensive modules between the sensors of the robot and its servo loops. Since the servo loops are concerned with generating the forces actuating motion, the sensory signal had to be converted into a compatible format. To achieve this the idea of artificial forces was introduced. There are two types of sensory data whose presence had to be accounted for: sensory data pertaining to how to reach the goal, and data alerting the robot to the presence of obstacles in its vicinity. Khatib used the goal data to generate an attractive potential field (Va) and used the data about the obstacles to generate a repeller field. The negative gradient of the first potential is used to generate the attractor force that would drive the robot to its goal:

$$ug = -\nabla Vg \qquad (1)$$

and the positive gradient of the other field to build the repeller force:

$$uo = \nabla Vo, \qquad (2)$$

where ∇ is the gradient operator. The artificial force (ua) that is used in driving the robot to its target while avoiding the obstacles is simply taken as the sum of the two forces:

$$ua = ug + uo. \tag{3}$$

Figure-1 illustrates the above procedure,

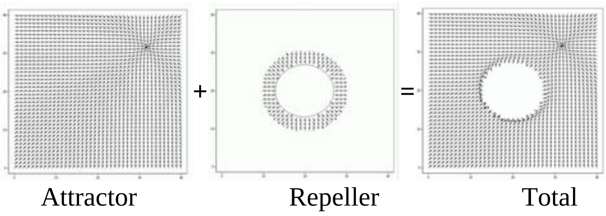

Figure-1: Attractor and repeller forces added to yield the artificial guidance field.

To integrate the artificial force into the robot's servo loops, first the dynamics of the robot have to be inverted resulting in the decoupled second order system:

$$\ddot{X} = u \tag{4}$$

where $X = [x\ y]^t$ and $u=[u_x\ u_y]^t$. The artificial forces are then augmented with a dampening component and used as the control input of the robot

$$\begin{bmatrix} u_x \\ u_y \end{bmatrix} = -\mathbf{B}\cdot\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} + \begin{bmatrix} ua_x \\ ua_y \end{bmatrix} \tag{5}$$

where B is a positive constant and $ua = [ua_x\ ua_y]^t$.

Koren and Borenstien observed that a mobile robot utilizing the above procedure behaves normally in an empty corridor (figure-2). However, its behavior changes dramatically if an obstruction is present along its way. The presence of the obstruction seems to ignite sustained oscillations in the trajectory of the robot (figure-3).

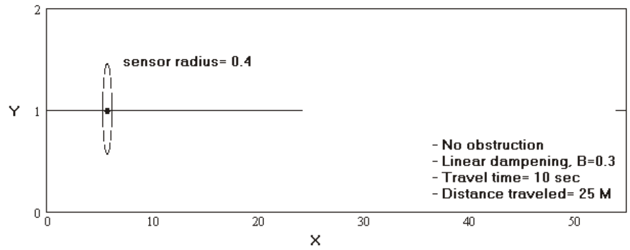

Figure-2: A well-behaved trajectory of a robot guided by an artificial potential in an empty corridor.

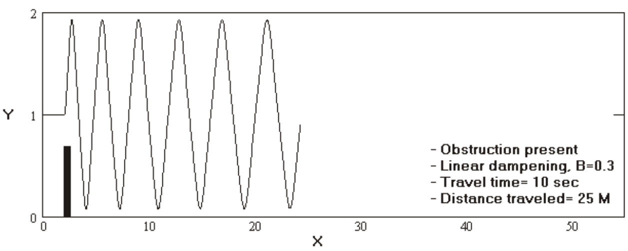

Figure-3: Obstruction-induced oscillations, the linear dampening case.

The corridor width used in the above simulation is two meters, the radius of the sensor is 0.4 meter, and the radius of the robot is assumed to be too small. The obstruction is made to occupy the rectangular region: 0.8 ≥y≥0, and 3≥x≥2. The goal force ug is:

$$ug(x,y) = \begin{bmatrix} 1 \\ 0 \end{bmatrix}. \tag{6}$$

The obstacle force is:

$$uo(x,y) = \begin{bmatrix} 0 \\ \{100\cdot[-(y-1.6)\Phi(y-1.6)-(y-.4)\Phi(-y+.4)]+ \\ \mathrm{Kp}\cdot(\Phi(x-2)-\Phi(x-3))(-(y-1.3)\Phi(-y+1.3)\} \end{bmatrix}$$

where Kp=1 if an obstruction is present in the corridor, and Kp=0 if the corridor is empty. **Φ** is the unit step function, and B=0.3 is used in the simulation.

III. THE SUGGESTED SOLUTION

The artificial gradient field that is to be fed to the servo loops of a robot consists of a dense group of vectors. At each point in the robot's workspace one and only one vector belonging to this group will be found guiding the robot to the direction along which it has to proceed if the target is to be reached. This guidance is transmitted to the robot by treating the gradient field as a force acting on the robot's mass. Since the inertial forces will prevent the trajectory from heading along the direction marked by the gradient field, the gradient field is augmented with another component proportional to the velocity of the robot. This component acts as viscous dampening whose job is to marginalize the effect of the inertial forces and make the robot's trajectory more responsive to the guidance of the artificial vector. It also stabilizes the dynamic equation of the robot:

$$\begin{bmatrix} \ddot{x} \\ \ddot{y} \end{bmatrix} = -\mathbf{B}\cdot\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} + \begin{bmatrix} ua_x(x,y) \\ ua_y(x,y) \end{bmatrix}. \tag{7}$$

Unfortunately, it was already shown that this approach has problems.

The general view among researchers attributes the corridor artifact to flaws in the potential field approach. However, this author believes that the source of the deficiencies is the manner by which the inertial forces are managed and the trajectory of the robot is made to yield to the guidance from the artificial force. As it stands, the potential field method relegate this task to the viscous dampening forces. This component exercise omniscient attenuation that discourages 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. Commonsense dictates that 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-4).

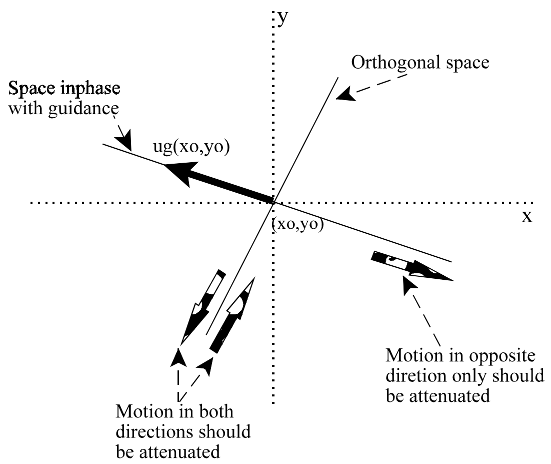

Figure-4: Guidance-dependant dampening forces.

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 would behave in the above manner is:

$$\mathbf{ud} = -\mathbf{Bd}\cdot[(\mathbf{n}^t\,\dot{\mathbf{X}})\,\mathbf{n} + (\frac{\mathbf{ug}^t}{|\mathbf{ug}|}\cdot\dot{\mathbf{X}}\cdot\Phi(-\mathbf{ug}^t\,\dot{\mathbf{X}}))\frac{\mathbf{ug}}{|\mathbf{ug}|}] \quad (8)$$

where **n** is a unit vector orthogonal to ug, and ud represents the dampening force. This force is given the name: nonlinear, anisotropic, dampening force (NADF).

For the two dimensional case, an NADF has the form:

$$\mathbf{ud} = \frac{-\mathbf{Bd}}{\mathbf{ug}_x^{\,2} + \mathbf{ug}_y^{\,2}}\left[(\mathbf{ug}_x\,\dot{\mathbf{y}} - \mathbf{ug}_y\,\dot{\mathbf{x}})\cdot\begin{bmatrix}-\mathbf{ug}_y\\ \mathbf{ug}_x\end{bmatrix} + (\mathbf{ug}_x\,\dot{\mathbf{x}} + \mathbf{ug}_y\,\dot{\mathbf{y}})\cdot\Phi(-\mathbf{ug}_x\,\dot{\mathbf{x}} - \mathbf{ug}_y\,\dot{\mathbf{y}})\begin{bmatrix}\mathbf{ug}_x\\ \mathbf{ug}_y\end{bmatrix}\right] \quad (9)$$

The attractor-repeller paradigm of the potential field approach represents an early form of such techniques. It is well-known that guidance provided by this paradigm was not adequate and suffered from what is known as the local minima problem in which the guided robot stops somewhere in the workspace short of reaching its target. More advanced forms of the potential field approach later appeared [6,7,8] solving the local minima problem and adding significant capabilities to this class of planners. Most notably is the Harmonic potential field (HPF) approach to planning [5,9,10,11]. This approach is provably-correct, complete (i.e. if a solution exist it will find it; other wise, it will give an indication that the planning problem is unsolvable), it can plan in unknown environments, it exhibits evolutionary and self-improvement capabilities, and has a remarkable ability to jointly handle a variety of constraints on the trajectory of the robot (e.g. directional and regional avoidance constraints [9]). A basic setting of the HPF approach is: solve the boundary value problem (BVP)

$$\nabla^2 V(x) \equiv 0 \qquad x \in R^N - \Gamma$$

subject to: $$V = 0|_{X=X_T} \;\&\; V = 1|_{X\in\Gamma}\;. \quad (10)$$

to obtain the potential V, where x_T is the target point the robot want to head for and Γ is the boundary of the obstacles the robot needs to avoid. A vector guidance field is then constructed using the negative gradient of the harmonic potential:

$$\mathbf{ug} = -\nabla V(x, x_T, \Gamma)\;. \quad (11)$$

Without any consideration given to dynamics, a first order, gradient dynamical system is constructed to mark an obstacle-free constrained path to the target point:

$$\dot{x} = \mathbf{ug}\;. \quad (12)$$

If dynamics are considered, the trajectory of the robot has to be generated using a second order dynamical system such as:

$$\ddot{x} = \mathbf{ug}\;. \quad (13)$$

For this case, there are no guarantees that the constraints will be upheld even if dampening is added to ug.

Although the NADF approach was developed to solve the narrow corridor problem faced by the attractor-repeller form of the potential field approach, it has a generic nature that makes it possible to directly apply the method to the case of the harmonic potential field approach to enable it to deal with the robot's dynamics. All what needs to be done is to simply augment ug with the NADF. This yields the dynamic system equation:

$$\ddot{x} = \mathbf{ug} + \mathbf{ud}\;. \quad (14)$$

The ability of NADF to enable the harmonic potential field approach to carry out kinodynmic motion planning instead of only tackling the kinematic issues of planning is demonstrated in the next section.

IV. SIMULATION RESULTS

The narrow corridor effect was demonstrated in figures-2,3. An argument, however, could be raised that in order to get rid of the oscillations one needs only to increase the coefficient of viscous dampening. Unfortunately, this straight-forward solution will not work. While increasing the dampening coefficient does get rid of the sustained oscillations, violent transients do remain. Moreover, significant slowdown of motion occur. In figure-5 the coefficient of dampening is increased three times (B=1). Remaining strong transients are very clear. In the previous case, the robot was able to travel 25 meters in 10 seconds. The increase in dampening cut the travel distance by more than half to 10 meters in 10 seconds.

With the hope of eliminating the overshoot, the dampening was increased more to B=3, ten times its original value (figure-6). As can be seen, significant overshoot still remain and the robot became impractically slow.

The linear viscous dampening force is replaced with NADF. The dampening coefficient used is Bd=5 (figure-7). As can be seen the robot responded well to the presence of the obstruction with little overshoot taking place. Not only a significant improvement in transients was achieved, the robot, despite the large value of the dampening coefficient, became more agile covering more than twice the distance in the linear dampening case (figure-2).

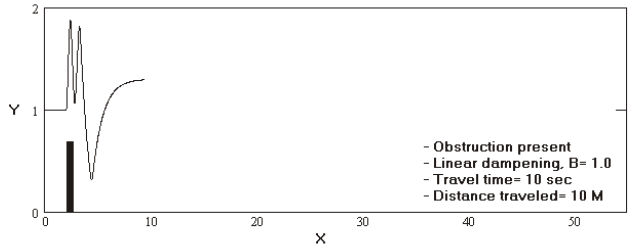

figure-5: Coefficient of linear dampening increased, strong transients are still present.

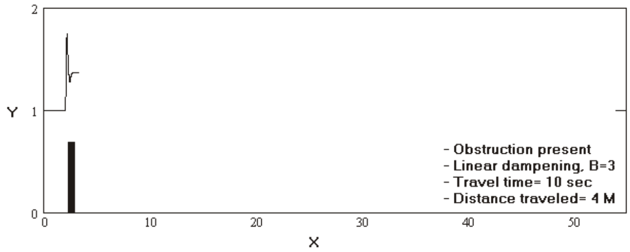

figure-6: Increase in linear dampening didn't eliminate overshoot and significantly slowed-down the robot.

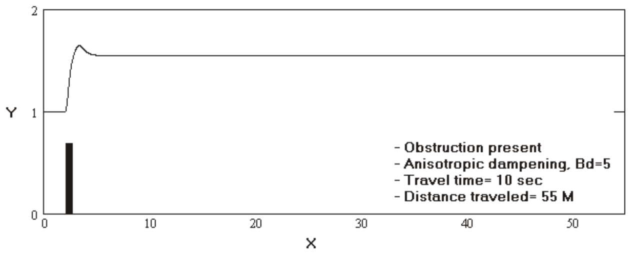

figure-7: The NADF brought transients under control and maintained an agile behavior.

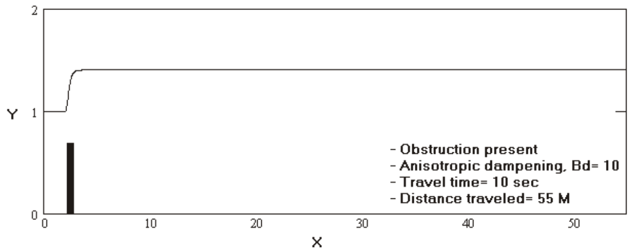

figure-8: Further increase in the coefficient of NADF eliminated overshoot and did not slowdown the robot.

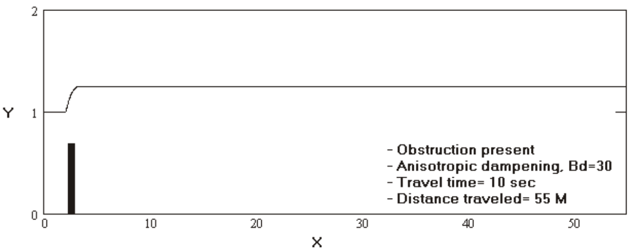

figure-9: Significant increase in the coefficient of NADF did not slowdown the robot.

In figure-8, the dampening coefficient is doubled (Bd)=10. As can be seen, overshoot totally disappeared from the trajectory and a well-behaved response is obtained. While one expect that an increase in dampening should cause a slowdown in the motion of the robot, the robot showed no signs of slowing down with the traveled distance virtually unaffected.

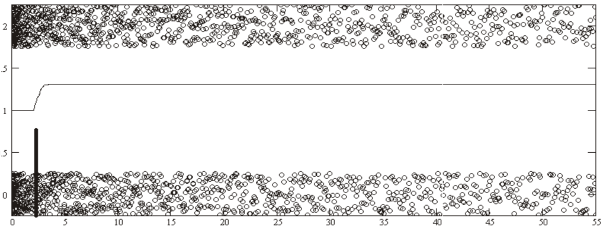

Figure-10: same as figure-9 but with sensor noise added.

To test the effect of the NADF coefficient on the speed of the robot, the coefficient was increased six times to Bd=30 (figure-9). No slowdown in operation was observed. This counter-intuitive property of NADF is important. It simplifies the tuning of the parameters of the controller by giving the designer the freedom to set the coefficient of dampening high enough to effectively control the transients in the trajectory without the risk of slowing down the robot.

The robustness of the approach to the presence of sensor noise is tested. A wideband, noise uniformly distributed between (-0.5, 0.5) is added to the sensor causing uniform jitters in the registered reading of the wall. Same as figure-9, a Bd=30 is used. As can be seen the effect of this relatively large sensor noise is almost negligible on the trajectory of the robot where a steady path was still maintained and the travel distance was not affected.

The approach is tested with the harmonic potential field method. A harmonic guidance potential is generated for a simple rectangular room with a divider in the middle. The negative gradient field is shown in figure-11. In figure-12, the trajectory linking the start point with the end point is generated for the kinematic case using only equation 13.

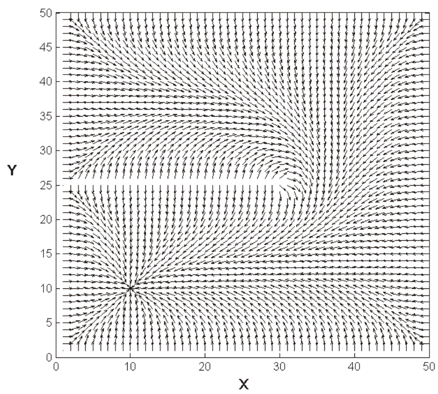

figure-11: Gradient from a harmonic potential.

To enable the guidance field to steer a 1 kg point mass from the start point to the end point, the gradient field is augmented with linear viscous dampening and applied as a force on the mass. The dynamic equation governing motion for this case is:

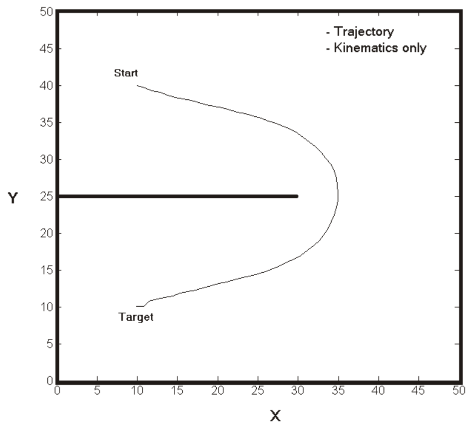

figure-12: Path from the gradient field, kinematics only

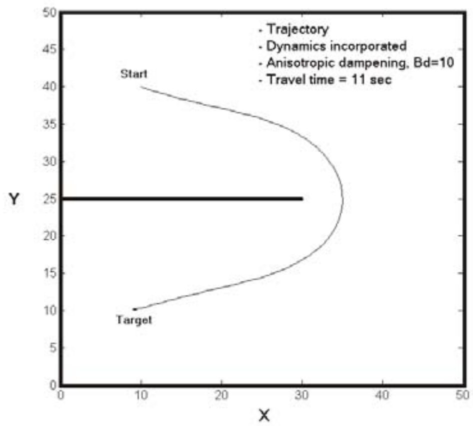

figure-14: Trajectory after adding NADF.

$$\ddot{x} = -\mathbf{B}\cdot\dot{\mathbf{x}} - \frac{\nabla \mathbf{V}(\mathbf{x})}{|\nabla \mathbf{V}(\mathbf{x})|} \tag{15}$$

where B=0.1 . As can be seen in figure-12, the inertia has a pronounced effect on the trajectory that led to the violation of the regional avoidance constraints and collision with the walls of the room.

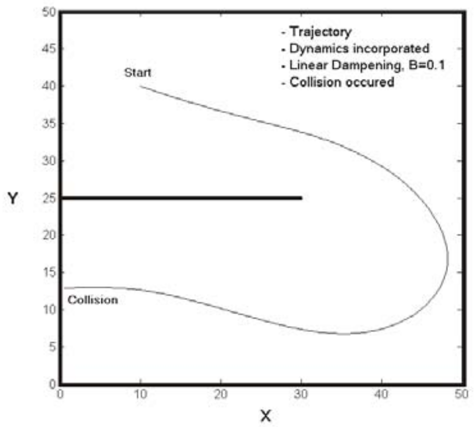

figure-13: The addition of dynamics led to the violation of the avoidance constraints, the linear dampening case.

The viscous dampening force is removed from equation 15 and replaced with NADF. A high dampening coefficient is selected (Bd=10). Figure-14 shows the resulting trajectory. As can be seen, the kinodynamic trajectory follows closely the guidance trajectory that takes into consideration kinematics only. Figure-15 shows the distance of the robot from the target as a function of time. As can be seen, it took the robot about 11 seconds to reach its target. Simulation is repeated for higher values of Bd to examine their effect on time of convergence. Similar to the previous example, the travel time of the robot was virtually unaffected remaining at the value of 11 sec despite significant increases in the value of Bd.

Simulation is repeated for higher values of Bd to examine the effect of the coefficient of NADF on the speed of response. Similar to the previous example, the travel time of the robot was virtually unaffected remaining at the value of 11 sec despite significant increases in the value of Bd.

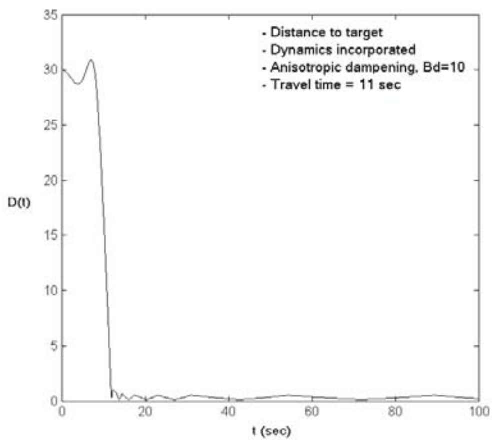

figure-15: Distance to target versus time.

V. CONCLUSIONS

In this paper NADF is suggested as a tool for assisting potential field methods in managing the dynamics of the system they are guiding. It was shown that the potential field method in general and Khatib's method in particular are feasible choices for planning that can effectively, both in terms of the speed of response and quality of trajectory, handle the kinematics and dynamics of planning. This paper demonstrated that the cause of what was thought to be an inherent weakness of the approach is a misunderstanding of the nature of the potential field method which led to an improper coupling of the gradient of the potential to the servo loops of the utilizing robot.

Acknowledgment

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