CONSTRAINING THE MOTION OF A ROBOT MANIPULATOR USING THE VECTOR POTENTIAL APPROACH

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ABSTRACT

In a recent work [1] the authors suggested an approach based on Artificial Vector Potential Fields to drive a robot along a safe path to a desired destination. In this paper the approach is extended to place constraints on both the position and velocity of the path. Placing a priori known constraints on both position and velocity of a robot is of considerable practical significance for system operation. Previous results are briefly stated, and simulation results are also provided.

I INTRODUCTION

Since its introduction in the mid eighties the popularity of the potential-based approach to path planning has been steadily rising [2]-[5]. The reason behind such an interest is due to the ability of such an approach to transform path planning into a task that can be performed by the low level controller of the robot. This meant great reduction in computational complexity enabling the planner to attain real time capabilities. The key element in the operation of a potential-based technique is the navigation control. Such a control function to tie the internal environment of the robot which constitute the system dynamics and the dynamics of the motion actuators to its external environment which is represented by the workspace, the obstacles in it, and the desired target.

In a recent paper [1] the authors suggested a new approach for designing the navigation control. The proposed approach take into consideration the distinct function of the navigation control and the need for it to accommodate the requirements of both environments of the robot. As a consequence the control is required to be bounded and smooth to suit the dynamics of the robot. As for the workspace which is unstructured and subject to change, it is required that the amount of effort spent in adjusting the control be proportional to the amount of change in the workspace. To meet the above requirements it was found necessary to generate the control from an underlying vector potential field (VPF) instead of a scalar potential field (SPF). Such choice is due to the ability of a VPF to generate a force that can arbitrarily direct motion in an N-D space, while a force that is generated from an underlying SPF can only project force along one degree of freedom.

In a practical situation it is most likely that the robot will be required to proceed to a target while requiring the speed not to exceed a certain value. This work extend the approach in [1] to incorporate constraints on both the robot speed.

This paper is organized as follows: In section II the previous results are briefly reviewed. Section III and IV discuss the generation of the constraining control in both velocity space and the position-velocity space. Results are reported in V, and conclusions are placed in section IV.

II PREVIOUS WORK

A planning technique navigates the system

$$D(q)\ddot{q} + c(q,\dot{q}) + g(q) = u \qquad (1)$$

where q is the position in the natural coordinates of the robot, D is the inertia matrix, c is a vector containing the coriolos and centripetal torques, g is a vector containing the gravity torques, and u is the torque needed to drive the position to a target set {T}, while avoiding the obstacles {A}. Current potential-based planning techniques construct the control from the gradient flow of a SPF

$$u = -\nabla V$$

This flow vanishes along the equipotential contours (tangent space). With the loss of control over the tangent subspace which spans N-1 degrees of freedom of an N-D space, controllability is expected to deteriorate with an increase in space dimensionality. To remove this deficiency and to synthesize a complete set of force fields an underlying VPF (**A**) must be used to generate the navigation control

$$u=-(\nabla V+\nabla\times\mathbf{A}) \qquad \nabla\cdot\mathbf{A}=0. \qquad (2)$$

The Proposed Navigation Strategy

The navigation control has two parts

$$u = u_g + u_l \qquad (3)$$

where u_g properly controls the robot in the obstacle-free space, and drives the motion to the desired target. u_l is called the steering control, and is strictly localized to the vicinity of the obstacles such that the controls from different obstacles do not intersect. u_l is designed in the local coordinates of the obstacles then transformed to the natural coordinates of the robot. It smoothly deflect the motion away from the obstacles in a manner that prevent collision and allow u_g to sweep the robot to the target. By shifting the task of managing the obstacles to u_l (u_g is independent of u_l; while, u_l is dependent on u_g and the geometry of the corresponding obstacle) great flexibility is achieved in the sense that the addition or deletion of an obstacle affects only the corresponding steering control.

u_l is divided into two distinct components. The first component is radial to the obstacle surface. It acts to prevent the robot from penetrating the region occupied by the obstacle (u_{ln}). It is called the Penetration Prevention Control (PPC), and it occupies a region $A\delta_d$ around Γ. The function of the other component is to align the robot on the right part of the obstacle surface to allow u_g to sweep it to the target (u_{lt}). This component acts tangent to the obstacle surface, and is called the Local Alignment Control (LAC). For smooth diversion of the motion away from the obstacle, the steering control is made to occupy a surrounding finite region ($A\delta$). The control on the outer boundary ($\Gamma\delta$) is set to zero. The generation of u_l inside $A\delta$ is treated as a Vector Boundary Value Problem which was reduced to solving four scalar boundary value problems.

The Boundary Steering Control

The control inside $A\delta_d$ and at its boundaries ($u\Gamma_l$) is derived in terms of the normal $e_n(\Gamma)$, and tangent $e_t(\Gamma)$ to Γ and $\Gamma\delta d$. $u\Gamma_1$ has two components, the boundary PPC (BPPC), and the boundary LAC (BLAC).

The BPPC ($u\Gamma_{1n}$)

It can be shown that the control

$$u\Gamma_{1n}(q,\dot{q}) = \alpha_1(q,\dot{q})e_n(\Gamma) \qquad (4)$$

can prevent a robot from entering Γ. α_1 is a scalar positive function

$$\alpha_1(q,\dot{q}) = \alpha_1'(\dot{q},q) + \alpha_1''(\dot{q}_n,q_n).$$

where $\alpha_1''(\dot{q}_n,q_n)=C\dot{q}|\dot{q}_n|\cdot\alpha_{q1}''(q_n)$, $\alpha_1'>0$, and q_n is the radial distance form Γ to the robot position.

The BLAC ($u\Gamma_{1t}$)

The first step in designing the BLAC is to partition Γ into two parts Γ_T, and Γ_o, such that when $u_1=u\Gamma_{1n}$, q satisfies the following

$$q(t_1) \in \Gamma_T \quad \text{then} \quad \lim q(t) \in T \quad t\to\infty$$
$$q(t_1) \in \Gamma_o \quad \text{then} \quad \lim q(t) \in \Gamma_o \quad t\to\infty$$

The second step is to clamp the motion to the obstacle in the Γ_o regions. The final step is to construct the BLAC on Γ to drive the motion from Γ_o toward Γ_T. Let the vector $\xi\in Q$, where Γ is the image of Q, and ξ is a parametric representation of Γ. The proposed control has the form

$$u\Gamma_{1t}(\xi) = -\alpha_2(q)\cdot(\xi - \xi_r)/\|\xi - \xi_r\| \qquad (5)$$

where ξ_r is a point on Γ_T. The details can be found in [1].

The Steering Control

The PPC and LAC components are constructed as

$$u_{1n}(q,\dot{q})=M_n(q,\dot{q})\cdot\mathbf{Q}_n(q), \quad u_{1t}(q,\dot{q})=M_t(q,\dot{q})\cdot\mathbf{Q}_t(q)$$

Where **Q** is the basis phase field, and M is a scalar magnitude field that modulates the strength of **Q**.

The PPC

To generate $\mathbf{Q}_n$, the following SBVP is solved

$$\nabla^2 V_{1n}(q) = 0 \quad \text{subject to} \qquad (6)$$

$$V_{1n}\big|_{\Gamma} = C, \text{ and } V_{1n}\big|_{\Gamma\delta} = 0 \quad C > 0$$

$$\mathbf{Q}_n(q) = \nabla V_{1n}(q)/\|\nabla V_{1n}(q)\|$$

M_n is obtained by solving :

$$\nabla^2 V_{2n}(q) = 0 \quad \text{subject to}$$

$$V_{2n}\big|_{\Gamma,\Gamma\delta d} = 1, \quad \text{and} \quad V_{2n}\big|_{\Gamma\delta} = 0$$

$$M_n(q,\dot{q}) = \begin{cases}\alpha_1(q,\dot{q})\cdot V_{2n}(q) & q\in A\delta d\\ \alpha_1(\Gamma\delta d,\dot{q})\cdot V_{2n}(q) & q\in A\delta\end{cases} \qquad (7)$$

If the PPC is to, as well, clamp the robot to Γ_o, an additional boundary condition is added

$$V_{2n}\big|_{\Gamma_o'} = -1$$

where Γ_o' is the portion of Γ' that corresponds to Γ_o, and Γ' is an equipotential surface inside $A\delta$ chosen equal to C/2.

The LAC

To construct the LAC component

1- Choose ξ_r inside Γ_T, and ξ_n inside Γ_o
2- Construct the following lines

$$\rho_r=\{q:\dot{q}(t)=-Q_n(q),\ 0\le t\le\tau,\ q(0)=\xi_r,\ q(\tau)\in\Gamma\delta\}$$
$$\rho_n=\{q:\dot{q}(t)=-Q_n(q),\ 0\le t\le\tau,\ q(0)=\xi_n,\ q(\tau)\in\Gamma\delta\}$$

3- Solve the following BVP

$$\nabla^2 V_{1t}(q) = 0 \quad \text{subject to} \qquad (8)$$

$$V_{1t}\big|_{\rho_r} = 0, \text{ and } V_{1t}\big|_{\rho_n} = C \quad C > 0$$

$$\partial V_{1t}/\partial n = 0 \quad \text{at } \Gamma,\Gamma', \text{ and } \Gamma\delta$$

$$\mathbf{Q}_t(q) = \nabla V_{1t}(q)/\|\nabla V_{1t}(q)\|$$

4- Compute the magnitude field as

$$\nabla^2 V_{2t}(q) = 0 \quad \text{subject to}$$

$$V_{2t}\big|_{\Gamma,\Gamma'} = 1, \quad \text{and} \quad V_{2t}\big|_{\Gamma\delta} = 0$$

$$M_t(q,\dot{q}) = \begin{cases}\alpha_2(q,\dot{q})\cdot V_{2t}(q) & \text{inside } \Gamma'\\ \alpha_2(\Gamma\delta d,\dot{q})\cdot V_{2t}(q) & \text{outside } \Gamma'\end{cases} \qquad (9)$$

The following formula is used to generate the control its boundary values [6]

$$\frac{\partial V(r)}{\partial X_i(r)} = \oint_s\left(\frac{\partial V(q)}{\partial n}\cdot\frac{\partial G(r,q)}{\partial X_i(r)} - V(q)\frac{\partial}{\partial X_i(r)}\cdot\frac{\partial G(r,q)}{\partial n}\right)ds$$

where S is the surface surrounding $A\delta$, r is a point inside $A\delta$, q is on the boundary, and G(r,q) the proper Green's function.

IV THE PPC IN THE VELOCITY SPACE

It is shown that a feedback of the form

$$u\Gamma_{1n}(q,\dot{q}) = \alpha_2(q,\dot{q})\cdot e_n(\dot{q}) \qquad \alpha_2(q,\dot{q})>0 \qquad (10)$$

can prevent the speed vector ($\dot{q}$) from entering an undesired region ($A_v(\dot{q})$) in the velocity space, where $e_n(\dot{q})$ is a unit vector normal to the surface Γ_v, ($\Gamma_v=\partial A_v$), and $\alpha_2(q,\dot{q})$ is a scalar function. Unlike the PPC in the position space, a bonded PPC in the velocity space that is placed exactly on Γ_v can stop $\dot{q}$ from entering A_v. Let $\dot{q}_n$ be

$$\dot{q}_n = e_n^t(\dot{q})\dot{q} \quad .$$

Let $G(\dot{q}_n)$ be a measure of the distance from Γ_v to $\dot{q}$

$$G(\dot{q}_n) = 1/2\cdot\dot{q}_n \quad .$$

To guarantee that $\dot{q}$ will not enter A_v it is shown that the PPC above can make the time derivative of G always nonegative

$$\dot{G}(\dot{q}_n) = \dot{q}_n\dot{q}_n^{\cdot} = \dot{q}_n[e_n^t(\dot{q})\cdot\dot{q}^{\cdot}] \ge 0 \quad .$$

With the assumption that the initial velocity of manipulator is outside Γ_v (i.e. $\dot{q}_n>0$), the condition for making $\dot{G}$ nonegative reduces to guaranteeing that

$$e_n^t(\dot{q})\cdot\dot{q}^{\cdot} \ge 0 \ .$$

Substituting for $\dot{q}^{\cdot}$ we have

$$e_n^t(\dot{q})[\ f(q,\dot{q}) + D^{-1}(q)u\Gamma_{1n}] =$$
$$[e_n(\dot{q})^t\cdot f(q,\dot{q}) + \alpha_2(q,\dot{q})\cdot e_n^t(\dot{q})D^{-1}(q)e_n(\dot{q})] \ge 0$$

where $f(q,\dot{q})=-D^{-1}(q)(c(q,\dot{q})+g(q)+u_g)$. Since $D^{-1}(q)$ is positive definite, α_2 can be chosen as follow to guarantee the above condition

$$\alpha_2(q,\dot{q}) = \sup_{\dot{q},q}\left|e_n^t(\dot{q})f(q,\dot{q})\right| \Big/ \inf_{\dot{q},q}(e_n^t(\dot{q})D^{-1}(q)e_n^t(\dot{q})) \qquad (11)$$

V THE COMBINED POSITION-VELOCITY SPACE

A situation may be contemplated where in addition to avoiding the obstacles, the robot speed is required not to exceed a certain value. Such a situation requires the PPC to act in both the position and velocity spaces

$$u\Gamma_{1n}(q,\dot{q}) = \alpha_1(q,\dot{q})\cdot e_n(q) + \alpha_2(q,\dot{q})\cdot e_n(\dot{q}). \quad (12)$$

Since in the state space representation a surface specified in the position space is orthogonal to that specified in the velocity space, we have

$$\alpha_1(q,\dot{q})\cdot\alpha_2(q,\dot{q}) = 0 \quad (13)$$

when
$q \notin A\delta d$ and $\dot{q} \notin \Gamma v$
$q \in A\delta d$ and $\dot{q} \notin \Gamma v$
$q \notin A\delta d$ and $\dot{q} \in \Gamma v$

However, when $q \in A\delta d$ and $\dot{q} \in \Gamma v$

the above product is not zero. Such a condition occurs at the *intersection* of the two hyper cylinders which are the extension of both $A\delta d$ and Γv along $\dot{q}$ and q respectively (Figure-1). As a result of q and $\dot{q}$ being related by

$$\dot{q} = dq(t)/dt = (q(t) - q(t - dt))/dt$$

and that $u\Gamma_{1n}$ simultaneously actuates motion in both the velocity and position spaces, a special consideration is given to this case in order to guarantee that the specifications in both the velocity and position spaces do not conflict. In the following, the relation between the forces from both spaces is studied for the 1-D case at the intersection of the two surfaces. Based on the analysis restrictions on the M-D case are deduced.

Let Γ be a contour point on the q axis, $en(q+)$ and $en(q-)$ be a PPC pointing in the positive and negative directions of q respectively. Also, let $\Gamma v+$, and $\Gamma v-$ be point contours on the positive and negative parts of the $\dot{q}$ axis respectively. Let $en+(\dot{q}+)$ be a PPC unit vector on $\Gamma v+$ and pointing in the positive direction of $\dot{q}$, $en+(\dot{q}-)$, $en-(\dot{q}+)$, and $en-(\dot{q}-)$ are defined in a similar manner. In the following all possible

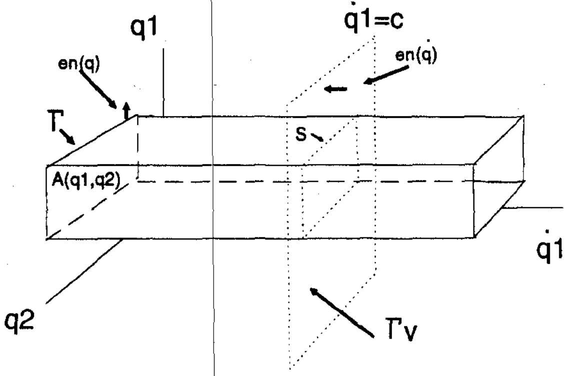

Figure-1: The extended manifolds in the position and velocity spaces, and their intersection S.

combinations of the PPC's in q and $\dot{q}$ are examined to determine the situations of conflict.

1. $e_n(q+)$ and $e_n+(\dot{q}+)$ (Figure-2.1)

Such a situation can not happen, since motion toward Γ means that $q(t)>q(t-dt)$; this forces $\dot{q}$ to be negative. In other words, the PPC's in $\dot{q}$ and q can never be simultaneously active ($\alpha_1\cdot\alpha_2=0$). Such a situation is disregarded as a don't care situation.

2. $e_n(q+)$ and $e_n+(\dot{q}-)$ (Figure-2.2)

This situation is similar to the one above and is *disregarded as don't care.*

3. $e_n(q+)$ and $e_n-(\dot{q}+)$ (Figure-2.3)

For this case it is possible for q to be at Γ and $\dot{q}$ at $\Gamma v-$ at the same time. Here, $en(q+)$ attempt to drive q in the positive direction making $q(t) > q(t-dt)$. In other words, $en(q+)$ act to drive $\dot{q}$ in the positive direction, which is in accord with what $en-(\dot{q}+)$ tries to do. Therefore, no conflict can happen and this situation is called admissible.

4. $e_n(q+)$ and $e_n-(\dot{q}-)$ (Figure-2.4)

In this case, while $en(q+)$ attempt to drive $\dot{q}$ in the positive direction $en-(\dot{q}-)$ act to drive $\dot{q}$ in the negative direction. This is a conflict situation that can not be simultaneously enforced by $en(q+)$ and $en-(\dot{q}-)$. By a similar argument it can be shown that

5. $en(q-)$ and $en+(\dot{q}+)$ is a conflict situation.

6. $en(q-)$ and $en+(\dot{q}-)$ is an admissible situation.

7. $en(q-)$ and $en-(\dot{q}+)$ is a do not care situation.

8. $en(q-)$ and $en-(\dot{q}-)$ is, also, a do not care situation.

The admissible situations are

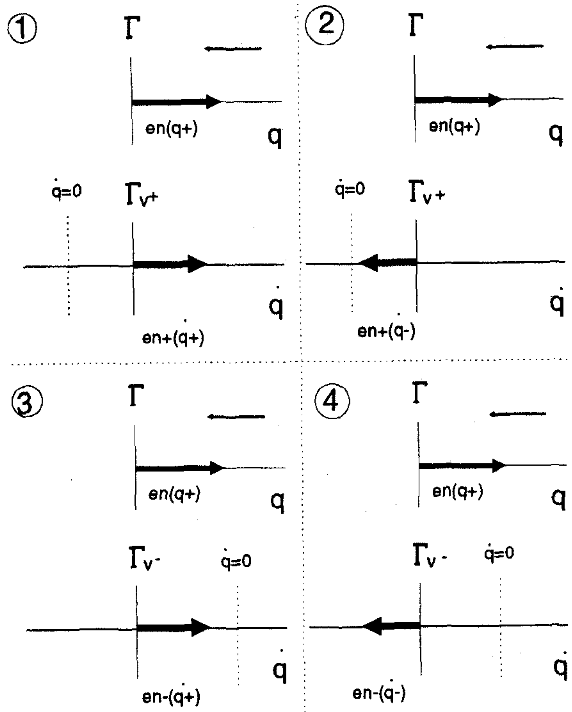

Figure-2: Possible combinations of PPC's in the position and velocity spaces.

a. $e_n(q+)$ and $e_n-(\dot{q}+)$ b. $e_n(q-)$ and $e_n+(\dot{q}-)$.

As can be seen regardless of the direction of $en(q)$, no conflict can arise as long as $en(\dot{q})$ is pointing in a direction that attempts to reduce speed (i.e. $en(\dot{q})$ pointing toward the origin of $\dot{q}$). Such a condition can be separately applied to the the individual components of the M-D $en(\dot{q})$. Therefore, to guarantee that no conflict will arise the following conditions are to be enforced for all $\dot{q}\in\Gamma v$

$$\dot{q}_i e_{ni}(\dot{q}) \le 0 \qquad i=1,..,M \quad (14)$$

where $\dot{q}i$ and eni are the i'th component of $\dot{q}$ and $en(\dot{q})$

In a practical situation it may be required that the motion of the robot be impeded along the flow contours of a vector field in the *positioin space (see example-2)*. The following control can accomplish this task

$$u_d = -V(q)[\dot{q}^t Q(q)]Q(q)$$

where $Q(q)$ is the basis phase vector field which motion is to be impeded along its flow contours, and $V(q)$ is a positive scalar field that controls the strength of the damping.

VI. RESULTS

Example 1

Here, the PPC is used to constrain both the position and speed of a simple second order system. The navigation control is required to drive a mass (m) along the X-axis from an initial point $X(0)=1$ to a final point $X(\infty)=0$ without crossing the X=0 axis. The control is also required to prevent the speed from exceeding or going below a certain value. The dynamic equation for this system is a simple second order linear differential equation

$$m\cdot\ddot{X} = u \qquad (15)$$

where u is the applied force and $\ddot{X}$ is the acceleration. A PD controller is used to drive the state to equilibrium in the unconstrained state space

$$u_g(X,\dot{X}) = -[\, b\cdot\dot{X} + k\cdot X \,]\quad b>0,\ k>0. \qquad (16)$$

Substituting $u = u_g + u_l$ the system equation becomes

$$\ddot{X} + 2\xi\omega_m\cdot\dot{X} + \omega_m^2\cdot X = \frac{1}{2}\,u_l$$

where $2\xi\omega_m = b/m$ and $\omega_m^2 = k/m$.
For simplicity m and k are taken equal to unity. ξ determine the nature of the response; if $\xi<1$ the system is underdamped, if $\xi=1$ the system is critically damped, and if $\xi>1$ the system is overdamped. The local component of the control (u_l) is

$$u_l(X,\dot{X}) = u_{xl}(X,\dot{X}) + u_{\dot{x}l}(X,\dot{X})$$

$$= M_{xn}(X,\dot{X})Q_n(X) + M_{\dot{x}n}(X,\dot{X})Q_n(\dot{X}) \qquad (17)$$

where u_{xl} constrain the system in the position space, while $u_{\dot{x}l}$ constrains the system in the velocity space. Since $Q_n(X)$ acts along one degree of freedom, and is pointing in the positive direction of X, we have

$$Q_n(X) = 1$$

Also, we have

$$M_{xn}(X,\dot{X}) = \alpha_1(X,\dot{X})V_n(X)$$

where by solving the following

$$\nabla^2 V_n(X) = 0$$

subject to $V_n(0) = 1$, and $V_n(\delta x) = 0 \quad \delta x > 0$

we have

$$V_n(X) = [-1/\delta x\cdot X - 1] \qquad X\in[0,\delta x]$$

Also, we have

$$\alpha_1(X,\dot{X}) = \left(\frac{k}{\delta x}\right)|\dot{X}| \qquad k=1.0$$

The resulting control has the form

$$u_{x_{ln}}(X,\dot{X}) = \begin{cases} \left(\frac{k}{\delta x}\right)|\dot{X}|\cdot\left[\frac{-1}{\delta x}\cdot X - 1\right] & X\in[0,\delta x] \\ \text{zero} & \text{elsewhere} \end{cases} \qquad (18)$$

The PPC along $\dot{X}$ is required to prevent the speed from going below -0.2 (v_c<-.02). As a result $e_n(q)$ is pointing in the positive direction of $\dot{X}$

$$Q_n(\dot{X})=1$$

also,

$$M_{\dot{x}n}(X,\dot{X}) = \alpha_2(X,\dot{X})V_n(\dot{X})$$

$$V_n(\dot{X}) = [-1/\delta\dot{q}\cdot(\dot{X} - v_c) + 1] \qquad \dot{X}\in[v_c+\delta\dot{x}, v_c]$$

$$\alpha_2(X,\dot{X}) = (2\xi\cdot|v_c| + |X|) \qquad \delta\dot{x}>0$$

For the above second order system, it can be shown $|X| \le X(0) = 1$; therefore, α_2 is taken as

$$\alpha_2(X,\dot{X}) = (2\xi\cdot|v_c| + 1)$$

the control component has the form

$$u_{\dot{x}_{ln}}(X,\dot{X}) = \begin{cases} (2\xi\cdot|v_c|+1)\left[\frac{-1}{\delta\dot{x}}\cdot(\dot{X}-v_c)+1\right] & \dot{X}\in[v_c+\delta\dot{x}, v_c] \\ \text{zero} & \text{elsewhere} \end{cases} \qquad (19)$$

In Figure-3.1, the response of the free system (u_l=0) is plotted for ξ=0.3. In Figure-3.2 the response is shown when the speed alone is constrained not to go below v_c=-.2 at all times. Figure-3.3 show the response when both the position and speed are constrained not go below X=0 and $\dot{X}$=-0.2. In Figure-4 the position only is constrained, the response is plotted for different δx, and the critically damped response of the free system (ξ=1) is plotted for comparison. Figure-5 shows the corresponding torques.

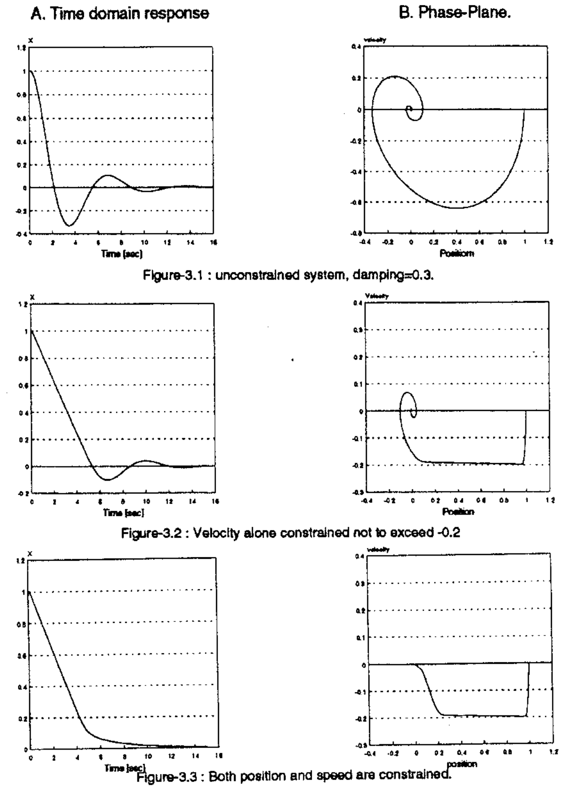

Figure-3.1 : unconstrained system, damping=0.3.
Figure-3.2 : Velocity alone constrained not to exceed -0.2
Figure-3.3 : Both position and speed are constrained.

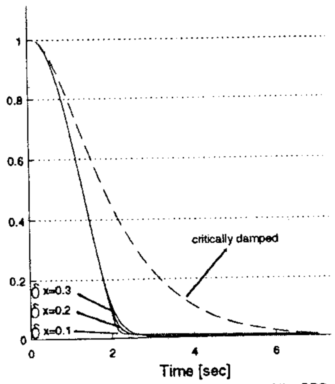

Figure-4 : response for different width of the PPC.

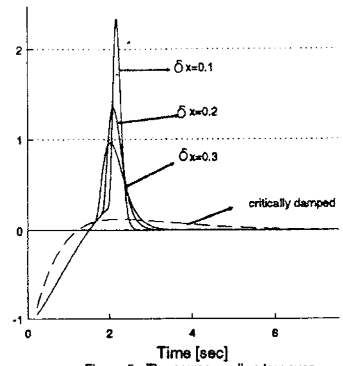

Figure-5 : The corresponding toreques.

Example 2

Simulation is done for a polar manipulator with only its gripper in the workspace. The dynamic equation is

$$\begin{bmatrix} Mr^2 & 0 \\ 0 & M \end{bmatrix}\begin{bmatrix} \ddot{\theta} \\ \ddot{r} \end{bmatrix} + \begin{bmatrix} 2Mr\dot{r}\dot{\theta} \\ -Mr\dot{\theta}^2 \end{bmatrix} = \begin{bmatrix} \tau \\ F \end{bmatrix} \qquad (20)$$

where M is the mass (M=1kg), r is the radial distance, θ is the angle measured from the X-axis. u_g is a PD controller ($\tau=k_p(\theta-\theta_d)+k_d\cdot\dot{\theta}$, $F=k_p(r-r_d)+k_d\cdot\dot{r}$). k_p=.5, k_d=3, $\theta(0)$= 45°, $r(0)=\sqrt{8}$, θ_d=0, r_d=2, $\dot{\theta}(0)=\dot{r}(0)=0$. Figure-6 shows the path of the robot gripper in the free space (u_l=0). In Figure-7 a rectangular obstacle occupying the region ($0.6\le x\le 6, 0.8\le y\le 1.2$) is placed in the path of the arm. To prevent collision a PPC is placed around the obstacle. As can be seen the radial force field successfully prevented the gripper from colliding with the obstacle. However, motion bounced back and forth on the surface till it finally settled short of reaching its target. In Figure-8 an LAC is added between Γ and Γ' with a strength that is set to zero at Γ'. The clamping control as well as the damping control acting along the normal of the surface are present. As can be seen the LAC yanked the arm from the local equilibrium zone and drove it around the obstacle so that u_g was able to sweep it to the target. In Figure-9 the damping along the normal is removed. This results in a shaky path. In Figure-10 the clamping control is also removed. As a result the field from ug pushed the arm outside the region of efficacy of the LAC therefore trapping the robot in a local minima.

VI CONCLUSIONS

In this work a method is suggested for applying constraints on the state of an arm manipulator using the artificial potential approach with attention focused on the path planning problem. Such a task is performed through a special kind of control called the navigation control which function to tie the external environment in which the robot is operating to its internal environment represented by the robot dynamics and the dynamics of the actuators. The manner in which the control is constructed provide the operator with significant flexibility to dynamically update the workspace. Due to the nature of the steering control it was found necessary to generate the control from a reflexive operator that is applied on an underlying potential function. It is observed that a force field generated from a SPF can only project force along one degree of freedom. In an N-D space this means the loss of N-1 degrees of freedom that could have been used to steer motion. It is also concluded that if an arbitrary force field is to be constructed in order to guarantee full controllability over motion the navigation field has to be generated form an underling vector potential. We strongly believe that the Vector Potential Approach to navigation, yet to be further explored, do have a promising future.

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Figure-6 Robot path in the free space.

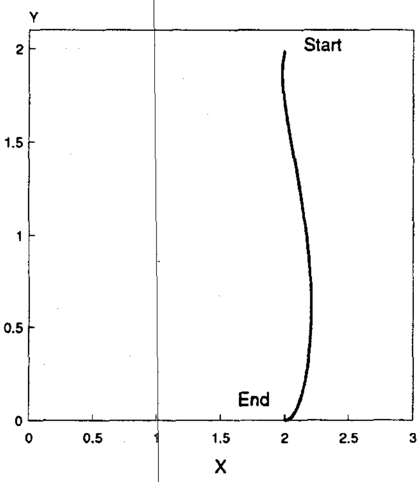

Figure-7 Obstacle added (PPC only).

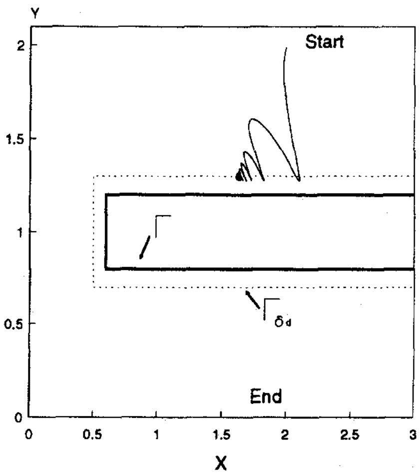

Figure-8 PPC+LAC+Clamp+Damping controls

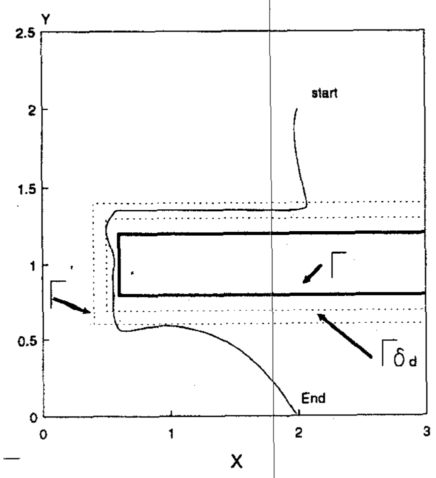

Figure-9 PPC+LAC+Clamp Controls

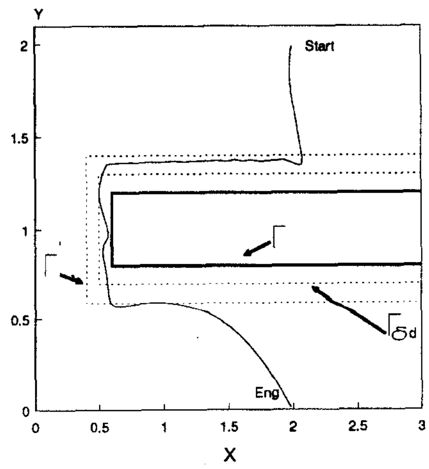

Figure-10 PPC+LAC controls only