OBSTACLE AVOIDANCE FOR REDUNDANT MANIPULATORS USING ARTIFICIAL POTENTIAL METHOD

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Abstract: The control problem using artificial potentials is analised for two cases: first case we'll consider that the redundant manipulator moves without restriction in a free-obstacle workspace, and in the second one the redundant manipulator moves in a workspace with obstacles. Numerical simulation for 3D model are presented in order to emphse the eficiency of the method.

Keywords: redundant manipulators, obstacle avoidance, artificial potential method, dynamic control.

1. INTRODUCTION

Research in the area of obstacle avoidance can be broadly divided into two classes of methodologies: global and local.
Global methodologies rely on description of the obstacle in the configuration space of a manipulator (Rimon and Koditschek, 1989; Udupa, 1977). Local methodologies rely on description of the obstacles and the manipulator in the cartesian workspace (Khatib, 1986; Krogh, 1984, Andrews and Hogan, 1983). However both methodologies used artificial potential technique to generete the paths the robotic system should take in order to get its goal. In the global method case the artificial potential technique surrounds the configuration space obstacles with repulsive potential energy functions, and places the goal point at an global energy minimum (Rimon and Koditschek, 1989; Newman, 1989; Okutomi and Mori, 1986). The point in configuration space representing the manipulator acted upon by a force equal to the negative gradient of this potential field, and driven away from obstacles and to the minimum.
In the local methodologies, instead, local potential are expressed in the cartesian workspace of the manipulator. Obstacles to be avoided are surrounded by repulsive potential function and the goal point is surrounded by an attractive well. These potentials are added to form a composite potential which imparts forces on a model of the manipulator in cartesian space. Torques equivalent to these forces cause the motion of the real manipulator.
On the other hand, when we control the global motion of redundant manipulators, we are confronted with their nonlinear dynamics in many degrees of freedom. However, convergence to target solution position has not been sufficiently investigated for these kind of structures whose so complex dynamical model. Most of the work about redundant and hyperredundant manipulators control problem was donne from kinematic poin of view. In this paper we analyse two control problems of a redundant manipulator in order to get the target position. We will analyse the control problem using artificial potentials for two cases: first case we'll consider that the manipulator moves without restriction in a free-obstacle workspace, and in the second one the manipulator moves in a workspace with obstacles.

2. ARTIFICIAL POTENTIAL FIELD APPROACH

As we emphased earlier most proposed potential function are based upon the following general idea: the robot should be attracted toward its goal configuration, whilw being repulsed by obstacles.

The field of artificial forces $\vec{F}(q)$ in $\Gamma = R^N$ (N=2 or 3) is produced by a differentiable potential function $\Pi : \Gamma_{free} \to R$, with:

$$\vec{F}(q) = \vec{\nabla}\Pi(q) \qquad (1)$$

Where $\vec{\nabla}\Pi(q)$ denotes the gradient vector of Π at q. In $\Gamma = R^N$ $\Gamma = R^N$ (N=2 or 3), we can write q=(x,y) or (x,y,z), and:

$$\vec{\nabla}\Pi = \begin{pmatrix} \partial\Pi/\partial x \\ \partial\Pi/\partial y \end{pmatrix} \text{ or } \begin{pmatrix} \partial\Pi/\partial x \\ \partial\Pi/\partial y \\ \partial\Pi/\partial z \end{pmatrix} \qquad (2)$$

In order to make the robot be attracted toward its goal configuration while being repulsed from the obstacle, Π is constructed as a sum of two more elementary potential functions:

$$\Pi(q) = \Pi_{att}(q) + \Pi_{rep}(q) \qquad (3)$$

Where Π_{att} is the attractive potential associated with the goal configuration q_{goal} configuration and Π_{rep} is the repulsive associated with the Γ-obstacle region. Both potentials are independent one each other.
There are a varity of potential functions defined in the literature for attractive potential and repulsive anes as well. We have chossen for our work the following potential functions:
The attractive potential field Π_{att} can be simply defined as a parabolic well, i.e.:

$$\Pi_{att}(q) = \frac{1}{2} k d_{goal}^2(q) \qquad (4)$$

Where k is a positive scaling factor and $d_{goal}(q)$ denotes the Euclidean distance $\|q - q_{goal}\|$. The function Π_{att} is positive or null, and attains its minimum at q_{goal}, where $\Pi_{att}(q_{goal}) = 0$.
The function d_{goal} is differentiable everywhere in Γ. At every configuration q, the artificial attractive force $\vec{F}_{att}$ deriving from Π_{att} is:

$$\begin{aligned} \vec{F}_{att}(q) &= -\vec{\nabla}\Pi_{att} \\ &= -k d_{goal}(q) \vec{\nabla} d_{goal}(q) \\ &= -k(q - q_{goal}) \end{aligned} \qquad (5)$$

The main idea underlying the definition of the repulsive potential is to create a potential barrier around the Γ-obstacle region that cannot be travesed by the robot's configuration, as well as the fact that the repulsive potential not affect the motion of the manipulator when is sufficiently far away from the Γ-obstacle. In order to achieve these constraints a definition of repulsive potential function could be as follows:

$$\Pi_{rep}(q) = \begin{cases} \frac{1}{2}\eta\left(\frac{1}{d(q)} - \frac{1}{d_0}\right)^2 & \text{if } \mathrm{d(q)} \le \mathrm{d}_0 \\ 0 & \mathrm{d(q)} > \mathrm{d}_0 \end{cases} \qquad (6)$$

3. REDUNDANT MANIPULATOR CONTROL USING ARTIFICIAL POTENTIAL APROACH

3.1 Dynamic system

We consider a redundant mechanical system which in general case could have n degrees of freedom. The motion of the system is describe by generalized coordonates, the set $p = [\theta \quad q]^T$ such as (Ivanescu, 1984) describ an ideal tentacle arm, with a uniformly distributed torque.
Further more the redundant manipulator model is consider as a distributed parameter system defined on a fixed spatial domain (Wang, 1965) and the spatial coordonate. Thus the dynamic model of this redundant manipulator can be obtained, in general form, from Hamilton partial differential equation (Ivanescu, 2002; Takegaki and Arimoto, 1981; Wang, 1965) of distributed parameter control. The Hamiltonian is expresed as $H = E_{kin} + E_{pot}$ and the ecuation of motion are:

$$\frac{\partial p(t,s)}{\partial t} = \frac{\partial H}{\partial v(t,s)} \qquad (7)$$

$$\frac{\partial v(t,s)}{\partial t} = -\frac{\partial H}{\partial \omega(t,s)} + F(t,s) \qquad (8)$$

where p generalized coordinates, v momentum densities.
In the paper we use the dynamical model expressed only as a function of general coordonates, developed for infinite dimensional system using Lagrange equation (Ivanescu, 1984).

$$\frac{\partial}{\partial t}\left(\frac{\partial E_{kin}}{\partial \dot{\theta}(t,s)}\right) - \frac{\partial E_{kin}}{\partial \theta(t,s)} + \frac{\partial E_{pot}}{\partial \theta(t,s)} = F_\theta \qquad (9)$$

$$\frac{\partial}{\partial t}\left(\frac{\partial E_{kin}}{\partial \dot{q}(t,s)}\right) - \frac{\partial E_{kin}}{\partial q(t,s)} + \frac{\partial E_{pot}}{\partial q(t,s)} = F_q \qquad (10)$$

Where $F = [F_\theta \quad F_q]^T$ force vector which assures the manipulator control.
E_{kin} represents kinetic energy of the system and has the form as fallows:

$$E_{kin} = \frac{1}{2}\rho\int_0^l \{[\int_0^s (-\dot{q}' \sin q' \sin\theta' + \dot{\theta}' \cos q' \cos\theta')ds']^2 +$$

$$+[\int_0^s (-\dot{q}' \sin q' \sin \theta' - \dot{\theta}' \cos q' \sin \theta')ds']^2 +$$

$$+[\int_0^s \dot{q} co\, sq' ds']^2 \Big\} ds \qquad (11)$$

E_{pot} represents potential energy of the system with the form:

$$E_{pot} = \rho g \int_0^l \int_0^s \sin q' ds' ds \qquad (12)$$

A sintezed form of the dynamical model of 3D spatial redundant manipulator is given (Ivanescu, 2002) as fallows:

$$\int_0^s \int_0^s G_q(\ddot{q}, \ddot{\theta}, \dot{q}, \dot{\theta}, q, \theta) ds' ds'' = F_q \qquad (13)$$

$$\int_0^s \int_0^s G_\theta(\ddot{q}, \ddot{\theta}, \dot{q}, \dot{\theta}, q, \theta) ds' ds'' = F_\theta \qquad (14)$$

where G_q, G_θ are nonlinear functions of the motion parameters. As we presented so far, is obviusly that in the case of redundant manipulators it is dealing with a great number of parameters and nonlinear terms. However, from these reasons, to derive a control law using classical methods is very difficult.

In the next sections, the artificial potential method is extended to the control problem of this kind of manipulators. We will analyse the control problem using artificial potentials for two cases: first case we'll consider that the manipulator moves without restriction in a free-obstacle workspace, and in the second one the manipulator moves in a workspace with obstacles.

3.2 Control problem in a free-obstacle workspace

The control problem means the motion control by forces F_θ, F_q, from initial position described by $\Gamma_0 : (\theta_0(s), q_0(s))$, $s \in [0, l]$ to the target position $\Gamma_T : (\theta_T(s), q_T(s))$. The target vector is denoted $p_T = [\theta_T \quad q_T]^T$. As we mentioned from literarure it can be considered the assuption that, regarding mechanics, position p_T is asmptotically stable, if the potential function of the system has a minimum at $p = p_T$ and the system is completely damped in the sense that it has a positive definite dissipation function ( ). In fact, the artificial potential function of the system has great effect on both dynamic and static mechanical proprieties so it is natural to attempt to improve the caracteristic of the system by modifying the potential function.

Let's denotes $\Pi_{att}(p)$ as a artificial potential fuction properly chosen to accomplish the goal of control for free-obstacle case. For this case we need only the attractive potential function to reach the target.

The attractive potential field Π_{att} can be simply defined as a parabolic well, i.e.:

$$\Pi_{att}(p) = \frac{1}{2} k d_{target}^2(p) \qquad (15)$$

Where k is a positive scaling factor and $d_{target}(p)$ denotes the Euclidean distance $\|p - p_T\|$. The function Π_{att} is positive or null, and attains its minimum at p_T, where $\Pi_{att}(p_T) = 0$.

Further more, if we consider the control forces vector, $F = [F_\theta \quad F_q]^T$, with the form by its components:

$$F_\theta(t,s) = \frac{\partial E_{pot}}{\partial \theta(t,s)} - \frac{\partial \Pi_{att}}{\partial \theta(t,s)} - F_{\theta T} \qquad (16)$$

$$F_q(t,s) = \frac{\partial E_{pot}}{\partial q(t,s)} - \frac{\partial \Pi_{att}}{\partial q(t,s)} - F_{qT} \qquad (17)$$

and it is substitued in Lagrange ecuations (9), (10) of the dynamic model , by canceling the terms $\frac{\partial E_{pot}}{\partial \theta(t,s)}, \frac{\partial E_{pot}}{\partial q(t,s)}$ the chosen potential function, $\Pi_{att}(p)$, becames the potential function of the system.

From (15) the second terms of (16), (17) are actually:

$$\frac{\partial \Pi_{att}}{\partial \theta(t,s)} = (\theta(s) - \theta_T(s))$$
$$\frac{\partial \Pi_{att}}{\partial q(t,s)} = (q(s) - q_T(s)) \qquad (18)$$

The terms $F_{\theta T}, F_{qT}$ assure the damping control (Ivanescu, 2004; Takegaki, 1981; Wang, 1964) and for practical reasons it can be used the derivative component of the control with the particular form:

$$F_{\theta T}(s,t) = K_\theta(s)\dot{\theta}(s,t) \qquad (19)$$

$$F_{qT}(s,t) = K_q(s)\dot{q}(s,t) \qquad (20)$$

3.3 Control problem in a restrictioned workspace

For this case, in order to make the robot be attracted toward its goal configuration while being repulsed from the obstacle, Π is constructed as a sum of two more elementary potential functions:

$$\Pi(p) = \Pi_{att}(p) + \Pi_{rep}(p) \qquad (21)$$

Where Π_{att} is the attractive potential associated with the target configuration p_{target} configuration and Π_{rep} is the repulsive associated with the Γ-obstacle region. Both potentials are independent one each other.

Thus, for the second case the Lagrange equations (9), (10) of de dynamic model became:

$$\frac{\partial}{\partial t}\left(\frac{\partial E_{kin}}{\partial \dot{\theta}(t,s)}\right)-\frac{\partial E_{kin}}{\partial \theta(t,s)}+\frac{\partial \Pi}{\partial \theta(t,s)}=F_{\theta T} \qquad (22)$$

$$\frac{\partial}{\partial t}\left(\frac{\partial E_{kin}}{\partial \dot{q}(t,s)}\right)-\frac{\partial E_{kin}}{\partial q(t,s)}+\frac{\partial \Pi}{\partial q(t,s)}=F_{qT} \qquad (22)$$

As we mention in paragraf 2 the repulsive potential acts like a potential barrier around the Γ-obstacle region that cannot be travesed by the robot's configuration, as well as the fact that the repulsive potential not affect the motion of the manipulator when is sufficiently far away from the Γ-obstacle. In order to achieve these constraints a definition of repulsive potential function could be as follows:

$$\Pi_{rep}(p)=\begin{cases}\frac{1}{2}\eta\left(\frac{1}{d(p)}-\frac{1}{d_0}\right)^2 & \text{if } d(p)\le d_0\\ 0 & d(p)>d_0\end{cases} \qquad (23)$$

where d_0 represents a minimum admisible distance from obstacle.

The potential Π can be defined in terms of position coordonates (x,y,z) and obstacle coordonates (x_R,y_R,z_R).

$$x(s,t)=\int_0^s \sin\theta(s',t)\cos q(s',t)ds'$$

$$y(s,t)=\int_0^s \cos\theta(s',t)\cos q(s',t)ds' \qquad (24)$$

$$z(s,t)=\int_0^s \sin q(s',t)ds',\; s'\in[0,\quad s]$$

$$d(p)=\sqrt{(x-x_R)^2+(y-y_R)^2+(z-z_R)^2} \qquad (25)$$

4. SIMULATIONS

In this section, some numerical test are performed, for both cases discused in the paper.

4.1 Numerical test for redundant manipulator working in a free-obstacle workspace

Test1. We consider a spatial redundant manipulator that operates in OXYZ space. Mechanical parameters of the system are $\rho = 0.07kg/m$, the diameter of the link *D=0.05*, the lenght of each link $l_i = 0.2m$, and lenght of the manipulator *l=0,8m*.

The initial curve Γ_0 is assumed to be orizontal (OY-axis),

$$\Gamma_0 : \theta(s,0)=0; \quad q(s,0)=0; \quad s\in[0,\ 0.8] \qquad (26)$$

And the target shape of manipulator is represented by a curve Γ_T in OXYZ frame, with the following parameters of motion:

$$\Gamma_T : \quad \theta_T(s)=\frac{\pi}{4}s; \quad q_T(s)=\frac{\pi}{4}s \qquad (27)$$

According with (15) the arficial potential function used for free-obstacle case is defined as fallows:

$$\Pi_{att}(\theta,q)=\frac{1}{2}k\int((\theta(s)-\frac{\pi}{4})^2 + (q(s)-\frac{\pi}{4})^2)ds \qquad (28)$$

The control law is chosen as (Ivanescu, 2002)

$$F_\theta(s,t)=-k_\theta^1(s)e_\theta(s,t)-k_\theta^2(s)\dot{e}_\theta(s,t) \qquad (29)$$

$$F_q(s,t)=-k_q^1(s)e_q(s,t)-k_q^2(s)\dot{e}_q(s,t), \quad s\in[0,l] \qquad (30)$$

where the proportional and derivative coefficients are selected as

$$k_\theta^1(s)=k_q^1(s)=12.5$$
$$k_\theta^2(s)=k_q^2(s)=1.58 \qquad (31)$$

The numerical simulation of dynamical model (16), (17) was carried out using Matlab framework.

The simulation results are presented in Figure 1 where it can be seen the initial position, the final one as well as the all intermediaty positions.

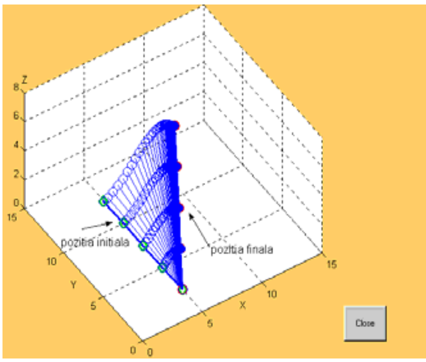

Fig. 1. Motion of the arm towards target position.

We defined the error for global system as

$$e(t)=\int_0^l((\theta(s,t)-\theta_T(s))+(q(s,t)-q_T(s)))ds \qquad (32)$$

and its derivative

$$\dot{e}(t) = \int_0^l \left(\frac{\partial q(s,t)}{\partial t} + \frac{\partial \theta(s,t)}{\partial t}\right) ds \qquad (33)$$

The phase portrait of evolution can be seen in Figure 2 where it can be observed the stability of the motion by error convergence to zero.

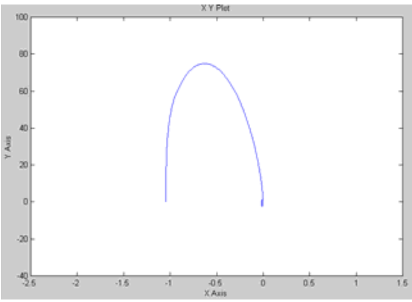

Fig. 2. Phase portrait of the evolution of the system

We also displayed the evolution of generalized coordonates, its derivatives and its accelerations in Figure 3 (a,b,c)

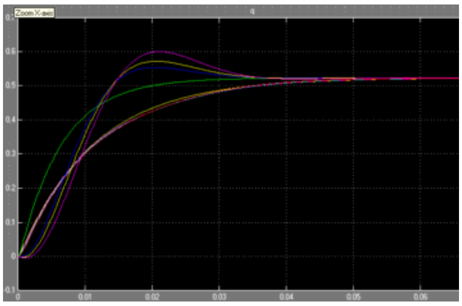

Fig. 3. a. Evolution of the generalized coordinates

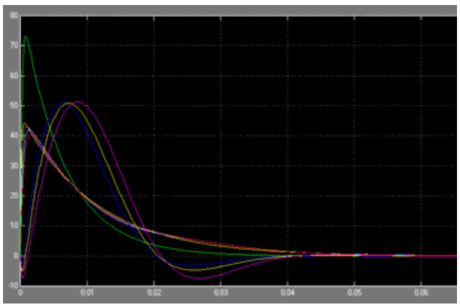

Fig. 3. b. Evolution of their derivatives

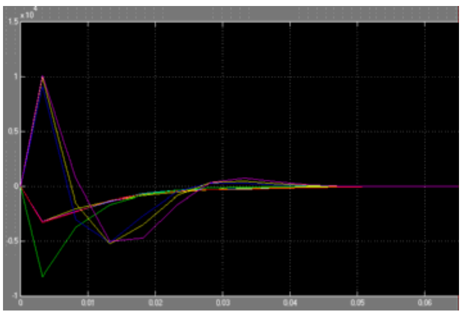

Fig. 3.c. Evolution of accelerations of the model

4.2 Numerical test for redundant manipulator working in a restrictioned workspace

Test2. We consider spatial redundant manipulator that operates in OXYZ space with the same mechanical parameters we defined in the previous paragraf.

The initial curve Γ_0 is assumed to be orizontal (OY-axis),

$$\Gamma_0 : \theta(s,0) = 0; \quad q(s,0) = 0; \quad s \in [0,\ 0.8] \qquad (34)$$

And the target shape of manipulator is represented by a curve Γ_T in OXYZ frame, with the following parameters of motion:

$$\Gamma_T : \quad \theta_T(s) = \frac{\pi}{4} s; \quad q_T(s) = \frac{\pi}{4} s \qquad (35)$$

According with (21) the arficial potential function used for restricted case is defined as a sum of both attractive and repulsive potential as fallows:

$$\Pi(p) = \Pi_{att}(p) + \Pi_{rep}(p) \qquad (36)$$

where

- the attactive potential is calculated by

$$\Pi_{att}(\theta, q) = \frac{1}{2} k \int ((\theta(s) - \frac{\pi}{4})^2 + (q(s) - \frac{\pi}{4})^2) ds \qquad (37)$$

- and the repulsive potential is calculate according with (23) by

$$\Pi_{rep}(\theta, q) = \begin{cases} \frac{1}{2}\eta\left(\frac{1}{d(\theta,q)} - \frac{1}{d_0}\right)^2 & \text{if } d(\theta,q) \le d_0 \\ 0 & d(\theta,q) > d_0 \end{cases} \qquad (38)$$

The numerical simulation result and the phase portret are represented in figure 4 and figure 5, respectivly.

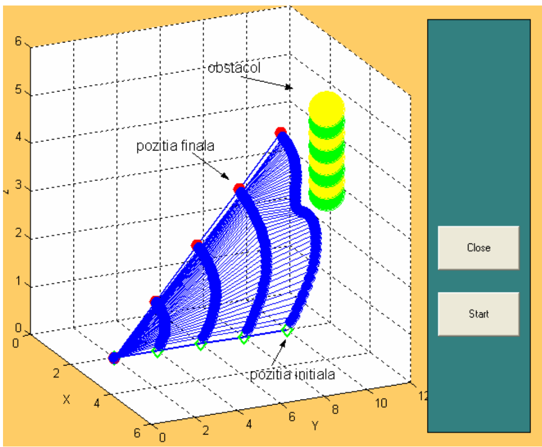

Fig. 4. Motion of the arm towards target position.

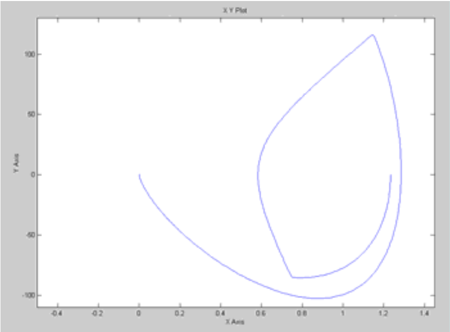

Fig. 5. Phase portrait of the evolution of the system

We also displayed the evolution of generalized coordonates, its derivatives and its accelerations in Figure 6 (a,b,c)

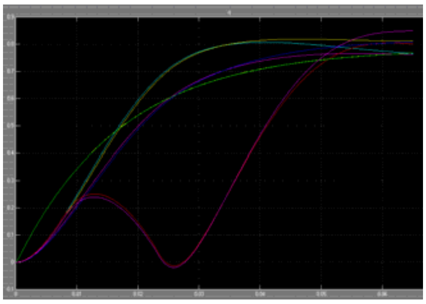

Fig. 6. a. Evolution of the generalized coordinates

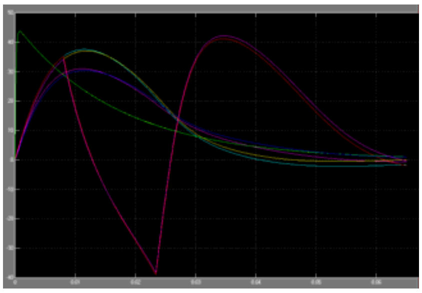

Fig. 6. b. Evolution of their derivatives

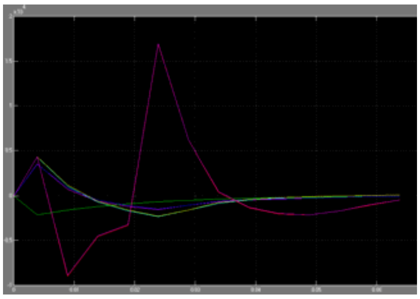

Fig. 6. c. Evolution of accelerations of the model

5. CONCLUSIONS

The control problem using artificial potentials was analised for two cases: first case of movement without restriction in a free-obstacle workspace, and in the second one of the movement in a workspace with obstacles. Numerical simulation for 3D model are presented in order to emphse the eficiency of the method.

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