Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

A Distributed Force and Position Control for Tentacle Manipulator

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Abstract: The grasping control problem for a hyperredundant arm is studied. Frist, dynamic model of the arm is analyzed. The control problems are divided in the subproblems: the position control in a desired reaching area, the control of the arm around the object-load and the force control of grasping. The difficulties determined by the complexity of the non-linear integral-differential equations are avoided by using a very basic energy relationship of this system. First, the dynamic control of the arm for a desired reaching area is inferred. Then, the position controland the force control for grasping are discussed. Numerical simulation are presented.

1. INTRODUCTION

The control of a hyperredundant manipulator is very complex and a great number of researchers have tried to offer solutions for this difficult problem. In (Hemami, 1984) it was analyzed the control by cables or tendons meant to transmit forces to the elements of the arm in order to closely approximate the arm as a truly continuous backbone. In (Gravagne and Walker, 2000), Gravagne analyzed the kinematical model of "hyper-redundant" robots, known as "continuum" robots. Important results were obtained by Chirikjian and Burdick (Chirikjian, 1993), (Chirikjian and Burdick, 1990, 1995), which laid the foundations for the kinematical theory of hyper-redundant robots. Mochiyama has also investigated the problem of controlling the shape of an HDOF rigid-link robot with two-degree-of-freedom joints using spatial curves (Mochiyama et al., 1998). In (Robinson and Davies, 1999, Suzumori, S. Iikura, 1991) it is presented the "state of art" of continuum robots, outline their areas of application and introduce some control issues.

The difficulty of the dynamic control is determined by integral-partial-differential models with high nonlinearities that characterize the dynamic of these systems. In (Ivanescu, 2002) the dynamic model for 3D space is inferred and a control law based on the energy of the system is analyzed.

In this paper, the problem of a class of hyperredundant arms with continuum elements that performs the grasping function by coiling is discussed. The difficulties determined by the complexity of the non-linear integral-differential equations, that represent the dynamic model of the system, are avoided by using a very basic energy relationship of this system. Energy-based control laws are introduced for the position control problem. A force control method is also proposed.

The paper is organized as follows: section 2 presents the basic principles of a hyperredundant structure with continuum elements; section 3 studies the dynamic model; section 4 discusses the both problem of grasping by coiling, the position control and force control; section 5 verifies by computer simulation the control laws.

2. BACKGROUND

2.1. Technological Model

The paper studies a class of hyperredundant arms that can achieve any position and orientation in 3D space, and that can perform a coil function for the grasping. The arm is a high degree of freedom structure or a continuum structure.

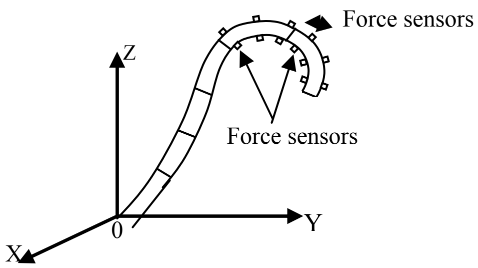

Figure 1. The force sensors distribution

The general form of the arm is shown in Figure 1. It consists of a number (N) of elements, cylinders made of fiber-reinforced rubber. There are four internal chambers in the cylinder, each of them containing the ER fluid with an individual control circuit. The deformation in each cylinder is controlled by an independent electrohydraulic pressure control system combined with the distributed control of the ER fluid (Figure 2).

The last m elements $(m < N)$ represent the grasping terminal. These elements contain a number of force sensors distributed on the surface of the cylinders. These sensors measure the contact with the load and ensure the distributed force control during the grasping.

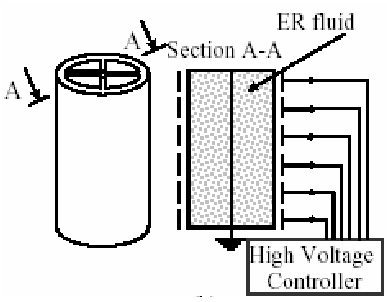

Figure 2. The cylinder structure

2.2. Theoretical model

The essence of the hyperredundant model is a 3-dimensional backbone curve C that is parametrically described by a vector $r(s) \in R^3$ and an associated frame $\phi(s) \in R^{3\times 3}$ whose columns create the frame bases (see Figure 3).

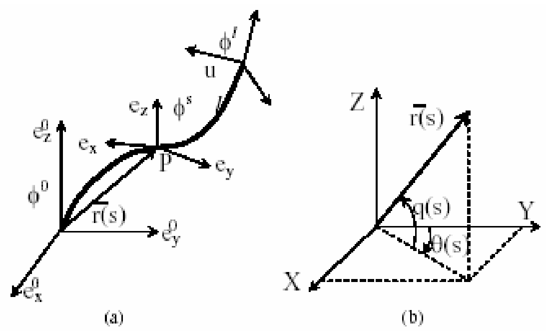

Figure 3. (a) The backbone structure; (b) The backbone parameters

The independent parameter s is related to the arc-length from the origin of the curve C, $s \in [0, \quad L]$, where $L = \sum_{i=1}^{N} l_i$, where l_i represent the length of the elements i of the arm in the initial position.

The position vector on curve C is given by

$$r(s,t) = [x(s,t) \quad y(s,t) \quad z(s,t)]^T \tag{1}$$

where

$$x(s,t) = \int_0^s \sin\theta(s',t)\cos q(s',t)ds' \tag{2}$$

$$y(s,t) = \int_0^s \cos\theta(s',t)\cos q(s',t)ds' \tag{3}$$

$$z(s,t) = \int_0^s \sin q(s',t)ds', \; s' \in [0, \quad s] \tag{4}$$

For an element dm, kinetic and gravitational potential energy will be:

$$dT = \frac{1}{2} dm\left(v_x^2 + v_y^2 + v_z^2\right), \; dV = dm \cdot g \cdot z \tag{5}$$

where $dm = \rho ds$, and ρ is the mass density.

The elastic potential energy will be approximated by the bending of the element:

$$V_e = k\frac{d^2}{4}\sum_{i=1}^{N}\left(q_i^2 + \theta_i^2\right) \tag{6}$$

We will consider $F_\theta(s,t)$, $F_q(s,t)$ the distributed forces on the length of the arm that determine motion and orientation in the θ-plane, q-plane. The mechanical work is:

$$L = \int_0^l \int_0^t \left(F_\theta(s,\tau)\dot{\theta}(s,\tau) + F_q(s,\tau)\dot{q}(s,\tau)\right) d\tau ds \tag{7}$$

The energy-work relationship will be

$$\begin{aligned}&\left[T(t) + V^*(t)\right] - \left[T(0) + V^*(0)\right] = \\ &= \int_0^l \int_0^t \left(F_\theta(s,\tau)\dot{\theta}(s,\tau) + F_q(s,\tau)\dot{q}(s,\tau)\right) d\tau ds\end{aligned} \tag{8}$$

where $T(t)$ and $T(0)$, $V^*(t)$ and $V^*(0)$ are the total kinetic energy and total potential energy of the system at time t and 0, respectively.

3. DYNAMIC MODEL

In this paper, the manipulator model is considered a distributed parameter system defined on a variable spatial domain $\Omega = [0, \quad L]$ and the spatial coordinate s.

From (5), (6), (7), the distributed parameter model becomes,

$$\rho\int_0^S\int_0^S\Big(\ddot{q}'\big(\sin q'\sin q''\cos(q'-q'')+\cos q'\cos q''\big)-$$
$$-\ddot{\theta}'\cos q'\sin q''\sin(\theta''-\theta')+$$
$$+(\dot{q}')^2\big(\cos q'\sin q''\cos(\theta'-\theta'')-\sin q'\cos q''\big)+ \tag{9}$$
$$+(\dot{\theta}')^2\cos q'\sin q''\cos(\theta'-\theta'')-$$
$$-\dot{q}'\dot{q}''\sin(q''-q')\Big)ds'ds''+\rho g\int_0^S\cos q'ds'+k^*q=F_q$$

$$\rho\int_0^S\int_0^S\Big(\ddot{q}'\sin q'\cos q''\sin(\theta''-\theta')+$$
$$+\ddot{\theta}'\cos q'\cos q''\cos(\theta''-\theta')-$$
$$-(\dot{q}')^2\cos q'\cos q''\sin(\theta''-\theta')+ \tag{10}$$
$$+(\dot{\theta}')^2\cos q'\cos q''\sin(\theta''-\theta')-$$
$$-\dot{\theta}'\dot{q}'\sin q'\cos q''\cos(\theta''-\theta')\Big)ds'ds''+k^*\theta=F_\theta$$

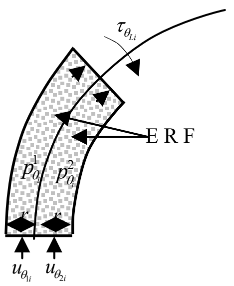

Figure 4. The cylinder driving

The control forces have the distributed components along the arm, $F_\theta(s,t)$, $F_q(s,t)$, $s\in[0,\quad L]$ that are determined by the lumped torques,

$$F_\theta(s,t)=\sum_{i=1}^{N}\delta(s-il)\tau_{\theta_i}(t),\,F_q(s,t)=\sum_{i=1}^{N}\delta(s-il)\tau_{q_i}(t) \tag{11}$$

where δ is Kronecker delta, $l_1=l_2=\ldots=l_N=l$, and

$$\tau_{\theta_i}(t)=\left(p_{\theta_i}^1-p_{\theta_i}^2\right)S\cdot d/8 \tag{12}$$

$$\tau_{q_i}(t)=\left(p_{q_i}^1-p_{q_i}^2\right)S\cdot d/8,\ i=1,2,\ldots,N \tag{13}$$

In (12), (13), $p_{\theta_i}^1$, $p_{\theta_i}^2$, $p_{q_i}^1$, $p_{q_i}^2$ represent the fluid pressure in the two chamber pairs, θ, q and S, d are section area and diameter of the cylinder, respectively (Fig.4). The pressure control of the chambers is described by the equations:

$$a_{ki}(\theta)\frac{dp_{\theta i}^k}{dt}=u_{\theta ki} \tag{14}$$

$$b_{ki}(q)\frac{dp_{qi}^k}{dt}=u_{qki},\ k=1,2;\ i=1,2,\ldots,N \tag{15}$$

where $a_{ki}(\theta)$, $b_{ki}(q)$ are determined by the fluid parameters and the geometry of the chambers and

$$a_{ki}(0)>0,\ b_{ki}(0)>0 \tag{16}$$

4. CONTROL PROBLEM

The control problem of a grasping function by coiling is constituted from two subproblems: the position control of the arm around the object-load and the force control of grasping.

We consider that the initial state of the system is given by

$$\omega_0=\omega(0,s)=[\theta_0,\quad q_0]^T \tag{17}$$

corresponding to the initial position of the arm defined by the curve C_0

$$C_0:(\theta_0(s),\quad q_0(s)),\ s\in[0,\quad L] \tag{18}$$

The desired point is represented by a desired position of the arm, the curve C_d that coils the load,

$$\omega_d=[\theta_d,\quad q_d]^T \tag{19}$$

$$C_d:(\theta_d(s),\quad q_d(s)),\ s\in[0,\quad L] \tag{20}$$

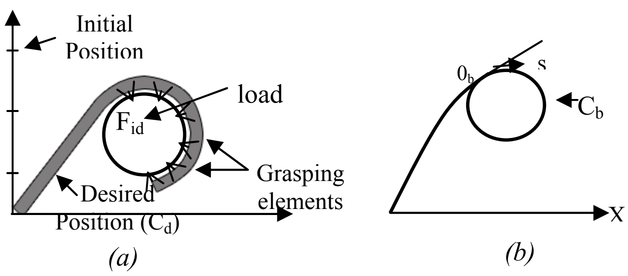

Figure 5. (a) The grasping position; (b) The grasping parameters

In a grasping function by coiling, only the last *m* elements $(m<N)$ are used. Let l_g be the active grasping length, where $l_g=\sum_{i=m}^{n}l_i$.

We define by $e_p(t)$ the position error

$$e_p(t)=\int_{L-l_g}^{L}\big((\theta(s,t)-\theta_b(s))+(q(s,t)-q_b(s))\big)ds \tag{21}$$

It is difficult to measure practically the angles θ, q for all $s \in [0, \quad L]$. These angles can be evaluated or measured at the terminal point of each element. In this case, the relation (21) becomes

$$e_p(t) = \sum_{i=m}^{N} \left(\left(\theta_i(t) - \theta_{bi} \right) + \left(q_i(t) - q_{bi} \right) \right) \tag{22}$$

The error can also be expressed with respect to the global desired position C_d

$$e_p(t) = \sum_{i=1}^{N} \left(\left(\theta_i(t) - \theta_{di} \right) + \left(q_i(t) - q_{di} \right) \right) \tag{23}$$

The position control of the arm means the motion control from the initial position C_0 to the desired position C_b in order to minimize the error.

4.1. Desired Area Reaching Control

An area reaching control problem is discussed. The desired area is specified by the inequality function:

$$f(\delta r) \le 0 \tag{24}$$

where f is a scalar function with continuous first partial derivates, $\delta r = r_F - r_0$, $r_0 \in R^3$ is a reference point of the desired area and r_F is the position vector (3) of the terminal point.

The potential energy function for the area reaching control has the form (Ceah and Wang, 2005):

$$V_P(r) = \begin{cases} 0, f(\delta r) \le 0 \\ \dfrac{1}{2} k_P f^2(\delta r), f(\delta r) > 0 \end{cases} \tag{25}$$

Theorem 1. The closed-loop control system for the desired reaching area problem is stable if the control forces are

$$\begin{aligned} \tau_{\theta_i}(t) = & -k_{\theta_i} e_{\theta_i}(t) - k_{\theta_i}^* \dot{e}_{\theta_i}^2(t) - \\ & - \max\left(0, \frac{\partial V_P^T}{\partial r} \cdot k_{P_{\theta_i}} a^*(\theta_i, q_i) \right) \end{aligned} \tag{20}$$

$$\begin{aligned} \tau_{\theta_i}(t) = & -k_{q_i} e_{q_i}(t) - k_{q_i}^* \dot{e}_{q_i}^2(t) - \\ & - \max\left(0, \frac{\partial V_P^T}{\partial r} \cdot k_{P_{q_i}} a^*(\theta_i, q_i) \right) \end{aligned} \tag{21}$$

Proof. See Appendix.

4.2. Fluid Pressure Control

Theorem 2. The closed-loop control system of the position (9), (10), (14), (15) is stable if the fluid pressure control law in the chambers of the elements given by:

$$u_{\theta ji}(t) = -a_{ji}(\theta)\left(k_{\theta i}^{j1} \dot{e}_{\theta i}(t) + k_{\theta i}^{j2} \ddot{e}_{\theta i}(t) \right) \tag{28}$$

$$u_{qji}(t) = -b_{ji}(\theta)\left(k_{qi}^{j1} \dot{e}_{qi}(t) + k_{qi}^{j2} \ddot{e}_{qi}(t) \right), \tag{29}$$

where $j = 1,2$; $i = 1,2,\ldots,N$, with initial conditions:

$$p_{\theta i}^1(0) - p_{\theta i}^2(0) = \left(k_{\theta i}^{11} - k_{\theta i}^{21} \right) e_{\theta i}(0) \tag{30}$$

$$p_{qi}^1(0) - p_{qi}^2(0) = \left(k_{qi}^{11} - k_{qi}^{21} \right) e_{qi}(0) \tag{31}$$

$$\dot{e}_{\theta i}(0) = 0 \tag{32}$$

$$\dot{e}_{qi}(0) = 0, \; i = 1,2,\ldots,N \tag{33}$$

and the coefficients $k_{\theta i}$, k_{qi}, $k_{\theta i}^{mn}$, k_{qi}^{mn} are positive and verify the conditions

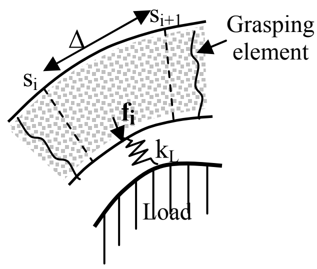

Figure 6. The grasping force

$$k_{\theta i}^{11} > k_{\theta i}^{21}; \; k_{\theta i}^{12} > k_{\theta i}^{22} \tag{34}$$

$$k_{qi}^{11} > k_{qi}^{21}; \; k_{qi}^{12} > k_{qi}^{22}, \; i = 1,2,\ldots,N \tag{35}$$

Proof. See (Ivanescu et al., 2008).

4.3. Force Control

The grasping by coiling of the continuum terminal elements offers a very good solution in the fore of uncertainty on the geometry of the contact surface. The contact between an element and the load is presented in Figure 6. It is assumed that the grasping is determined by the chambers in θ-plane.

The relation between the fluid pressure and the grasping forces can be inferred for a steady state from (Gravagne and Walker, 2000),

$$\int_0^l k \frac{\partial^2 \theta(s)}{\partial s^2} ds + \int_0^l f(s)\widetilde{T}\widetilde{\theta}(s)\int_0^s \widetilde{T}^T \widetilde{\theta}(s) ds = (p_1 - p_2) S \frac{d}{8} \quad (36)$$

where $f(s)$ is the orthogonal force on the curve C_b, $f(s)$ is $F_\theta(s)$ in θ-plane and $F_q(s)$ in q-plane, respectively.

For small variation $\Delta\theta_i$ around the desired position θ_{id}, in θ-plane, the dynamic model (22) can be approximated by the following discrete model (Ivanescu et al., 2008),

$$\begin{aligned} & m_i \Delta\ddot{\theta}_i + c_i \Delta\dot{\theta}_i + H_i(\theta_{id} + \Delta\theta_i, \ \ \theta_{id}, \ \ q_d) - \\ & - H(\theta_{id}, \ \ q_d) = d_i (f_i - F_{ei}) \end{aligned}, \quad (37)$$

where $m_i = \rho S \Delta$, $i = 1,2,\ldots,l_1$. $H(\theta_{id}, \ q_d)$ is a nonlinear function defined on the desired position $(\theta_{id}, \ q_d)$, $c_i = c_i(\nu, \ \theta_i, \ q_d)$, $c_i > 0$, $\theta, q \in \Gamma(\Omega)$, where ν is the viscosity of the fluid in the chambers.

The equation (37) becomes:

$$\begin{aligned} & m_i \Delta\ddot{\theta}_i + c_i(\nu, \ \ \theta_i, \ \ q_d)\Delta\dot{\theta}_i + h_i(\theta_{id}, \ \ q_d)\cdot\Delta\theta_i = \\ & = d_i(f_i - F_{ei}) \end{aligned} \quad (38)$$

The aim of explicit force control is to exert a desired force F_{id}. If the contact with load is modelled as a linear spring with constant stiffness k_L, the environment force can be modelled as $F_{ei} = k_L \Delta\theta_i$.

The error of the force control may be introduced as

$$e_{fi} = F_{ie} - F_{id} \quad (39)$$

It may be easily shown that the equation (38) becomes

$$\frac{m_i}{k_L}\ddot{e}_{fi} + \frac{c_i}{k_L}\dot{e}_{fi} + \left(\frac{h_i}{k} + d_i\right)e_{fi} = d_i f_i - \left(\frac{h_i}{k} + d_i\right)F_{id} \quad (40)$$

Theorem 3. The closed force control system is asymptotic stable if the control law is

$$f_i = \frac{1}{k_L d_i}\left(\left(h_i + k_L d_i + m_i \sigma^2\right)e_{fi} - \left(h_i - k_L d_i\right)F_{id}\right) \quad (41)$$

$$c_i > m_i \sigma \quad (42)$$

Proof. See (Ivanescu et al., 2008).

5. SIMULATION

A hyperredundant manipulator with eight elements is considered. The mechanical parameters are: linear density $\rho = 2.2\, kg/m$ and the length of one element is $l = 0.05m$. The control problem in the θ-plane will be analyzed. The initial position is the defined by $C_0 : \left(\theta_0(s) = \frac{\pi}{2}\right)$. First, a reaching desired area control is introduced where the area is defined by the circle $\varphi(\delta r) = (r - r_0)^2 - R^2$, $r_0 = (3,2)$, $R = 1$ and the control law (20) is applied. The position error Δr is computed and the phase error is presented in Figure 7. Then, the grasping function is performed for a circular load defined by $C_b : \left(x^* - x_0^*\right)^2 + \left(y^* - y_0^*\right)^2 = \left(r^*\right)^2$, where $\left(x^*, y^*\right)$ represent the coordinates in θ-plane. A discretisation for each element with an increment $\Delta = l/3$ is introduced. A control law (28) is used. The result is presented in Figure 8.

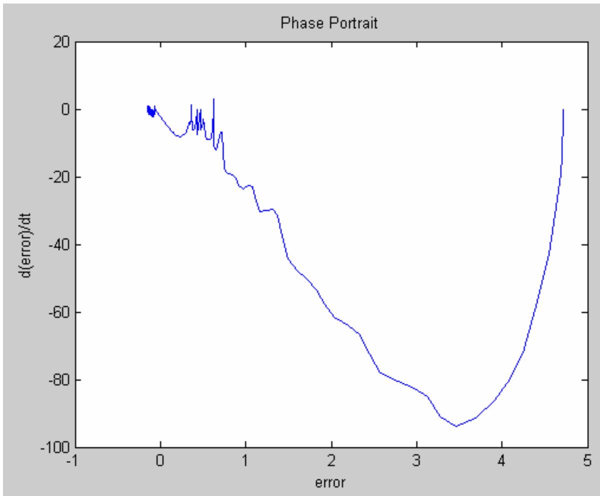

Figure 7. The position error phase portrait

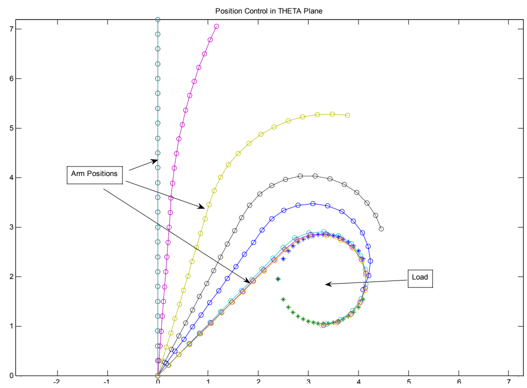

Figure 8. The position control

A force control for the grasping terminals is simulated. The phase portrait of the force error is presented in Figure 9. First, the control (28), (29) is used and then, when the trajectory penetrates the switching line the viscosity is increased for a damping coefficient $\xi = 1.15$.

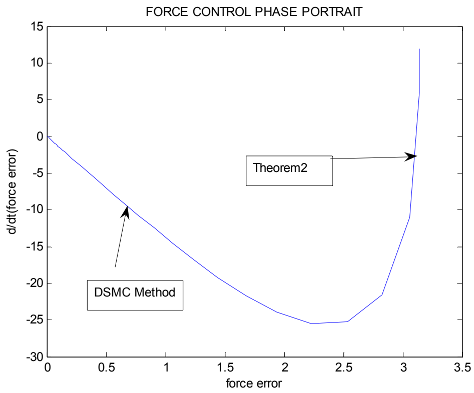

Figure 9. The force control phase portrait

6. CONCLUSION

The paper treats the control problem of a hyperredundant robot with continuum elements that performs the coli function for grasping. The structure of the arm is given by flexible composite materials in conjunction with active-controllable electro-rheological fluids. The dynamic model of the system is inferred by using Lagrange equations developed for infinite dimensional systems.

The grasping problem is divided in two subproblems: the position control and force control. The difficulties determined by the complexity of the non-linear integral-differential equations are avoided by using a very basic energy relationship of this system and energy-based control laws are introduced for the position control problem. Numerical simulations are presented.

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APPENDIX

We consider the following Lyapunov function:

$$W(t) = T(t) + V(t) + \\ + \frac{1}{2} \cdot \sum_{i=1}^{N} \left(k_{\theta_i} e_{\theta_i}^2(t) + k_{q_i} e_{q_i}^2(t) \right) + V_P(r_T(t)) \tag{A.1}$$

where T, V represent the kinetic and potential energies of the system. $W(t)$ is positive definite because the terms that represent the energy T and V are always $T(t) \geq 0$, $V(t) \geq 0$.

By using (19), the derivative of this function will be:

$$\dot{W}(t) = \sum_{i=1}^{N} \left(\begin{array}{l} \left(\tau_{\theta_i}(t)\dot{\theta}_i + \tau_{q_i}(t)\dot{q}_i \right) + k_{\theta_i} e_{\theta_i}(t)\dot{e}_{\theta_i}(t) + \\ + k_{q_i} e_{q_i}(t)\dot{e}_{q_i}(t) + \\ + \max\left(0, \frac{\partial V_P^T}{\partial r} \left(\begin{array}{l} k_{P_{\theta_i}} a^*(\theta_i, q_i) + \\ + k_{\theta_i} b^*(\theta_i, q_i) \end{array} \right) \right) + \\ + \max\left(0, \frac{\partial V_P^T}{\partial r} \left(\begin{array}{l} k_{P_{q_i}} a^*(\theta_i, q_i) + \\ + k_{q_i} b^*(\theta_i, q_i) \end{array} \right) \right) \end{array} \right) \tag{A.2}$$

For a constant desired position θ_{d_i}, q_{d_i}, from (20)-(21), the relation (A.2) can be rewritten as:

$$\dot{W}(t) = -\sum_{i=1}^{N} \left(k_{\theta_i}^* \dot{\theta}_i^2 + k_{q_i}^* \dot{q}_i^2 \right) \leq 0 \tag{A.3}$$

and, from (Ceah and Wang, 2005), the closed-loop system defined by (20) converges to the desired position $\theta_i \to \theta_{d_i}$, $q_i \to q_{d_i}$ and the terminal point r_F converges to the desired area $f(\delta r) \leq 0$ as $t \to \infty$.