Control of Snake Type Biomimetic Structure

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Abstract. Robotic cooperative tasks impose, in many cases, a grasping action. Grasping by coiling it is one of the most versatile action. The present article propose a frequency stability criterion based on the Kahman – Yakubovich – Popov Lemma for the hyper-redundant arms with continuum element that performs the grasping function by coiling. Dynamics of the biomimetical robot during non-contact and contact operations, for the position control, is studied. An extension of the Popov criterion is developed. The P control algorithms based on SMA snake-type robot actuators are introduced. Numerical simulations and experimental results of the snake type robot motion toward an imposed target are presented.

Keywords: biomimetics, control, robot,snake-type robot.

1 Introduction

Snake type robot and continuum robot represents "state of art" for robotics specialist. The medical robots which allow minimal invasive medical techniques (surgery in the throat, inside the heart, in the stomach) is one of the strongest and actual application of this structure. Ingenious snake type robots consist of multiple miniaturized stages that are connected in series, or flexible links that function as both link and joint. Developing any of these robots poses a common set of problems: design optimization, choice of sensing, kinematic modeling, procedure planning and real-time control. This is the reason that remarkable studies are reported regarding:

- kinematics - Gravagne [2] analyzing the kinematic model of "hyper-redundant" robots, set up term of continuum" robots, Chirikjian and Burdick introduce "backbone curve" of hyper-redundant robot, that captures the robot's macroscopic geometric features),

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- control - Mochiyama investigated the problem of controlling the shape of an HDOF rigid-link robot spatial curves [7], in [8], the "state of art" of continuum robots, their areas of application and some control issues are presented)
- technological implementation - [9, 10] deal with several technological solutions for actuators used in hyper-redundant structures and with conventional control systems.

Control problem of snake-type biomimetic robotic structure presented in the current paper has as target robot grasping function by coiling.

2 Proposed Technological Implementation

In this paper a 2D model for snake-type robot is discussed. The assumption is correct be cause even the serpentine technological robots operate in 3D space, the grasping function of these arms is, generally, a planar function.

The technological proposed implementation is presented in Fig.1. It consists of layered structures that ensure the flexibility, driving and position measuring. The high flexibility is obtained by an elastic backbone rod. The driving layer is made up of two antagonistic SMA actuators, A and B, each of them having a number of SMA fibers that are connected to the ends of the beam and determine its bending by current control. These SMA fibers are well suited for grasping force control due to their high strength to weight ratio.

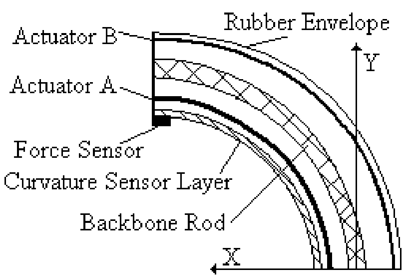

Fig. 1. The segment layer structure

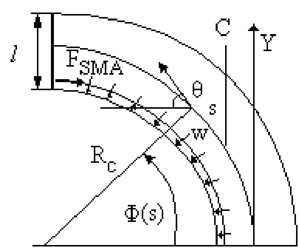

Fig. 2. The body robot parameters

The measuring layer is represented by an electro-active polymer curvature sensor. This sensor is placed on the boundary of the beam and allows for its curvature measuring by the resistance measuring. The sensor system is completed by a number of force sensors placed at each terminal of the beam segment. A rubber envelope protects and isolates this layer structure from the operator environment.

The general form of the body snake-type robot consists of a number (N) of segments and the last m segments $(m < N)$ represent the grasping terminals.

As a theoretical model, we shall consider the beam in Fig.2 with the length L and the thickness l. This beam has been deflected into a circular arc by a SMA fiber. The beam is composed of concentric arcs. The neutral arc defines the curvature of the beam,

$$c_V = \frac{d\phi}{ds}, \quad \phi = \frac{s}{R_c} \tag{2.1}$$

where ϕ represents the angle of the current position, s is the arc length from the origin, and R_c is the radix of the arc.

We denote the equivalent force developed by the SMA actuators at the end of the beam $(s = L)$ by χ, the force density and the distributed force along the beam exercised by the SMA fibers on the beam surface by w and F, respectively, and τ is the equivalent moment of the beam.

From [11], we have the following relations

$$w = \frac{dF}{ds}, \quad w = \chi \cdot c_V, \quad \tau = \chi \cdot \frac{l}{2} \tag{2.2}$$

$$dF = \chi \cdot d\phi, \quad dF = -\chi \cdot d\theta \tag{2.3}$$

3 Robot Dynamic Model for Grasping by Coiling

The grasping function control is represented by the force control between the body robot and load. Consider that the robot body has achieved the desired position defined by the surface (object).

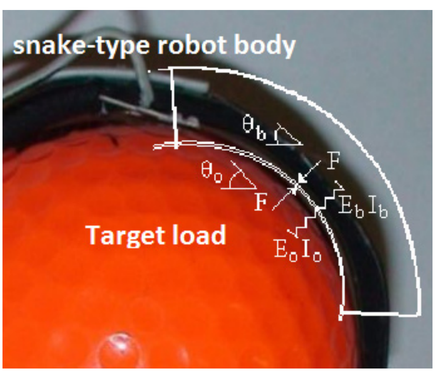

Fig. 3. The grasping model

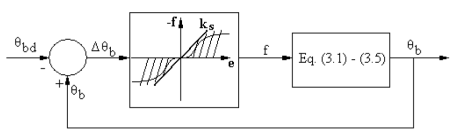

Fig. 4. The grasping control closed loop system

In Fig.3, an object with elastic and damping parameters $E_o I_o$, b_o and c_o, respectively, is grasped by coiling. Using the same procedure as developed in [16], the dynamic model of the two bodies in contact, body and load, is represented by the following partial differential equations,

$$\dot{\tilde{e}} = \tilde{A}\frac{\partial^2 \tilde{e}}{\partial s^2} + \tilde{B}\tilde{e} + \tilde{c}f \tag{3.1}$$

$$\tilde{e}(0,s) = 0;\ \tilde{e}(t,0) = \frac{\partial \tilde{e}(t,0)}{\partial s} = 0 \tag{3.2}$$

$$E_b I_b \cdot \frac{\partial e_b(t,L)}{\partial s} = \tau^* \tag{3.3}$$

$$e_b(t,L) = e_\theta(t,L);\ \frac{\partial e_o(t,L)}{\partial s} = \frac{\partial e_b(t,L)}{\partial s} \tag{3.4}$$

$$\frac{\partial \dot{\tilde{e}}(t,L)}{\partial s} = -\alpha_1 \tilde{e}(t,L) - \alpha_2 \dot{\tilde{e}}(t,L) \tag{3.5}$$

Where $\tilde{e}(t,s) = \left[e_b(t,s),\quad e_o(t,s)\right]^T$,with $e_b(t,s) = \theta_b(s) - \theta_{bd}(s)$; $e_o(t,s) = \theta_o(s) - \theta_{od}(s)$, f is the force error, τ^* is the control variation, and the indices b and o specify the parameters of the beam and object, respectively.

$$\tilde{A} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ \frac{1}{I_{\rho b}}\left(E_b I_b + E_o I_o\right) & 0 & -\frac{E_o I_o}{I_{\rho b}} & 0 \\ 0 & 0 & 0 & 0 \\ -\frac{E_o I_o}{I_{\rho o}} & 0 & \frac{E_o I_o}{I_{\rho o}} & 0 \end{bmatrix};\quad \tilde{B} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -\frac{b_b}{I_{\rho b}} & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -\frac{b_b}{I_{\rho o}} \end{bmatrix};\quad \tilde{c} = \begin{bmatrix} 0 \\ \frac{c_b}{I_{\rho b}} \\ 0 \\ -\frac{c_o}{I_{\rho o}} \end{bmatrix} \tag{3.6}$$

4 Control Algorithm

The grasping force control is the second problem of the grasping control. A force sensor network is used to account for the contact between the robot body and the load. We notice, from (2.2), that the force density w is constant along the robot segment and, in a steady state, w can be approximated to f. A force sensor with the position $s = s^* \in [0, L]$ is used to measure the contact force. The contact force – displacement relation of the sensor is assumed to lie in the positive sector (Fig.4).

$$\Delta F = -\psi(\Delta\theta),\ \psi(\Delta\theta)\cdot\Delta\theta \geq 0 \tag{4.1}$$

$$\psi(0) = 0 \ \text{ for } \ \Delta\theta = 0 \tag{4.2}$$

The nonlinearity $\psi(\Delta\theta)$ is single-valued, time invariant and constraint to a sector bounded by slope k_s which is assumed to meet

$$0 \le \frac{\psi(\Delta\theta)}{\Delta\theta} \le k_s < \infty \tag{4.3}$$

which is the case for most physically realistic elastic contacts.

In terms of the sensor characteristics, the convergence to zero of the error e_b is equivalent to the convergence to zero of the contact force error f

$$\lim_{t\to\infty} e_b\left(t,s^*\right)=0 \;\Rightarrow\; \lim_{t\to\infty} f\left(t,s^*\right)=0 \tag{4.4}$$

The sensor nonlinearity (4.1) – (4.3) and the dynamic model of the grasping contact described by (3.1) – (3.5) suggest the closed – loop system of Fig.4.

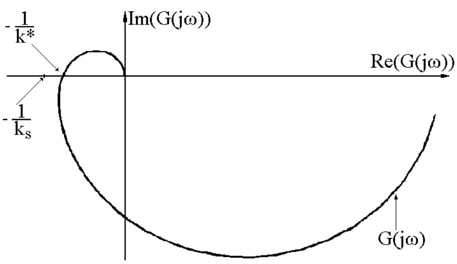

Fig. 5. The plot of $G(j\omega)$ for the grasping control

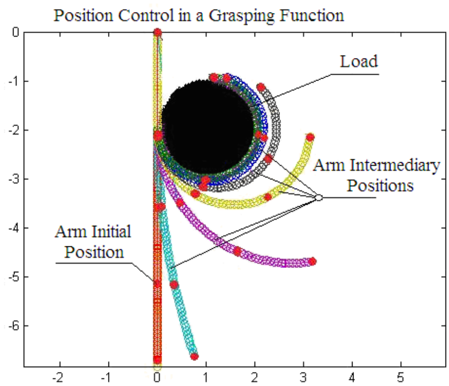

Fig. 6. The simulation of the grasping operation

Theorem. The closed – loop system (Fig.4) is absolutely stable if:

(1) $\left(-\tilde{A}+\tilde{B}\right)$ is a Hurwitzian matrix;

(2) the pair $\left(-\tilde{A}+\tilde{B},\ \tilde{c}\right)$ is completely controllable;

(3) there is a positive definite and symmetrical matrix P such that $\left(\tilde{A}^T P + P\tilde{A}\right)$ is positive definite;

(4) $$\frac{1}{k_s}+\mathrm{Re}\left[\tilde{n}^T\left(j\omega I-\left(-\tilde{A}+\tilde{B}\right)\right)^{-1}\tilde{c}\right]\ge 0 \tag{4.5}$$

(5) the moment of the robot body verifies the relation

$$\tau^* = k_p e_b\left(t,L\right), \qquad k_p > E_b I_b \tag{4.6}$$

Equations (4.1), (4.3) and (3.1) – (3.5) describe the closed loop system (Fig.4), consisting of a partial derivative equation linear system and a nonlinear element represented by the function $\psi(\cdot)$ belonging to the sector $[0,k_s]$. In this case, the condition (4) represents the Popov criterion for this class of systems. According to it, the system will be absolutely stable if the plot of $\tilde{G}(j\omega)$

$$\tilde{G}(j\omega)=\tilde{n}^T\left[j\omega I-\left(-\tilde{A}+\tilde{B}\right)\right]^{-1}\tilde{c} \tag{4.7}$$

crosses the negative real axis at a point that lies to the right of the critical point defined by $-\frac{1}{k_s}$ (Fig.5). For a pair "robot body segment – load" specified, the plot of $\tilde{G}(j\omega)$ has a well-defined characteristic and the intersection with the real axis determines the limit value of k. Let k^* be the corresponding value of the crossing point. The absolute stability is guaranteed if the sensor parameters meet the condition

$$k_s \le k^* \tag{4.8}$$

5 Numerical Simulation and Experimental Results

A hyper-redundant manipulator with 4 segments is considered, Fig.6. The parameters of the robot body were selected run as follows: bending stiffness $E_b I_b = 1$, linear mass density $\rho_b = 0.5\,kg/m$, rotational inertial density $I_{\rho b} = 0.001 kg \cdot m^2$ and damping ratio 0.35. These constants are realistic for long thin backbone structures. The grasping function is exercised by the last three segments of the robot body, the length of each segment is $L = 1$ (Geometrical parameters are scaled.). The load is a cylinder with the radix $R = 1$, bending stiffness $E_o I_o = 0.2$, rotational inertial density and damping ratio 0.22.

The plot of $G(j\omega)$, Fig.7, crosses the negative real axis at -0.14, which imposes the limit of tension at $T^* = 7.15N$; the plot of $\tilde{G}(j\omega)$ crosses the negative real axis at -0.74, which corresponds to the critical value of the force sector at $k^* = 1.3$.

In Fig .8 force phase portrait for a P – control algorithm (4.5) with $k_p = 24$ is illustrated. Please note the convergence to zero of the force error, but, also, the transient response of the system determined by the P – control law and a low damping factor of the system.

In order to verify the suitability of the control algorithm, a planar continuum terminal robot structure consisting by a layer structure has been employed for testing (Fig.9). The robot body consists of two $(25\times 6\times 4mm)$ continuum segments with an elastic backbone rod. The two antagonistic SMA actuators ensure the actuation system. Each actuator consists of G fibers in parallel. A polymer thick film layer which exhibits a decrease in resistance with an increase of the film curvature is used. Also, a Force Sensing Resistor is used at the end of each segment.

A Quancer based platform is used for control and signal acquisition. The load is represented by a sphere ball with $R_c = 0.02m$. A P-control with $k_p = 2.17$, $T_D = 5\text{s}$, $T_P = 7\text{s}$ is implemented. The contact force in the grasping operation is represented in Fig.10.

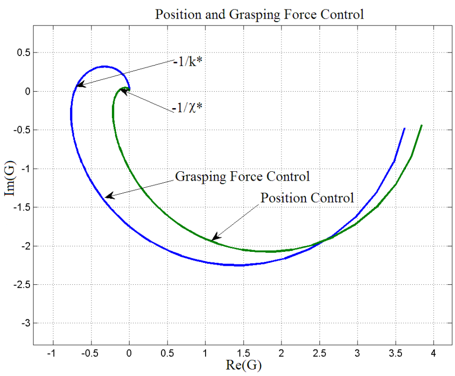

Fig. 7. The plot of $G(j\omega)$ for position and force control

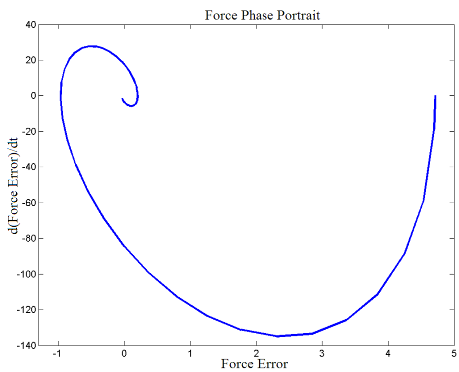

Fig. 8. The force phase portrait

Fig. 9. Experimental platform

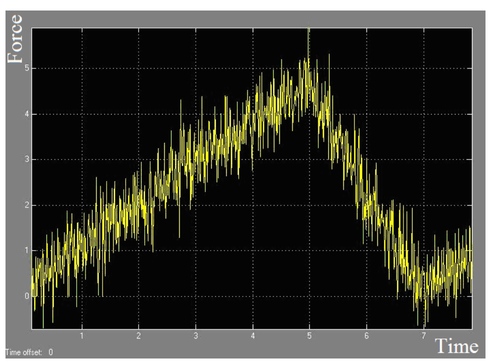

Fig. 10. The contact force diagram

6 Conclusions

In this paper, we have presented a control algorithm for biomimetic snake-type robot with continuum elements that performs the coil function for grasping. First, the dynamic model of continuum robot for the position control during non-contact operations with environment is studied. The P control algorithms are proposed. Then, the grasping control problem for the robot in contact with a load is analyzed. The control algorithms based on SMA actuators are introduced. Proposed approach is validated through simulations and experiments. Our future work is to use for actuation polymer based artificial muscle, in order to improve the robot flexibility and to develop an improved version of biomimetic robotics structure

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