Hyper-Redundant Arm with ER Fluid Based Actuator and Control System

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***Abstract* — Hyper-redundant robots of backbone types are generally driven by traction cables, making different curves for different segments in their body. This paper presents the structure of a hyper-redundant robot of backbone type having an electro-rheologhic system for position control. For proper operation, so for bending, we uses a cables system with DC motor-driven. The control system is made with a PIC microcontroller. Modeling the robot's position is done by bending it with cables, combined with locking the desired elements position through the electro-rheological system. The major advantage of this type of drive lies in the fact that the robot modeling can be done with a system with only three cables, the position lock system of an element or segment is relatively simple. Also presented is a variable width signal system with constant amplitude where the duration of the input signal is the control variable. The control system uses a mixed control. We use this controller for control of robot curvature respectively the control of ER valve.**

Keywords—hyper-redundant arm, electrorheological valve, ER valve PWM control

I. INTRODUCTION

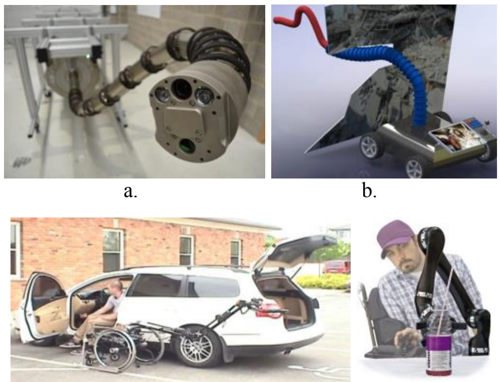
Hyper-redundant robots are inspired by biological structures by trunks, tentacles and snake backbones, these arms are the mechanical structures with continuum elements described by distributed parameter models [1][2][3].

They are robots designed to operate in restricted spaces, used for complex industrial operations (Fig.1.a), for search and rescue in case of natural disasters (ruins) (Fig.1.b), for manipulation and grip for disabled people (Fig.1.c, d), etc.

The robotic arms attached to wheelchair are hyper-redundant robots capable of acting in restricted environments. Some examples of operations performed: taking a container from the refrigerator (Fig.1.d), manipulating and positioning the wheelchair for transferring the person from the car to the wheelchair (Fig.1.c), coupling an electric chair to a rechargeable power system, etc.

Both the position of the grille and the position of the robot body are important, as they operate in movement restriction areas. Hyper-redundant robots with discrete structure are made up of identical, sequenced elements. The link between the elements is a joint with one or more degrees of freedom. The biological correspondent is snake backbone (Fig.2).

The robot body is divided into segments consisting of several successive elements. Changing the angular position of the elements in a segment results in the curvature of the segment or the robot curvature.



a. b.

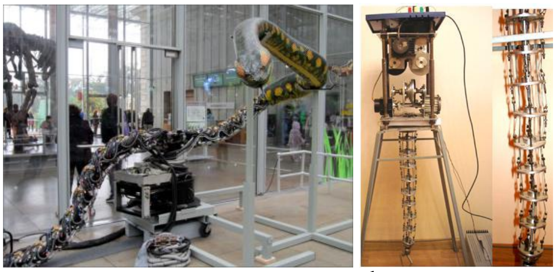
c. d.

Figure 1. Example of hyper-redundant arm. a-industrial arm; b-serch and rescue robot; c-auto wheelchair manipulator; d-7 DOF manipulator for disabilities persons

Figure 2. The biological snake backbone.

Two main types are more important: the actuator in each joint (Fig.3.a), which leads to an increased mobility (in terms of element), the disadvantage would be the weight of the robot and actuators in the base (Fig.3.b), In this case the movement being transmitted by traction cables. The second variant has the advantage of a reduced inertia mass, but it implies the robot curve at the segment level, not at element level.

At least three traction cables are required on the robot's boundary for the actuation of each curve segment. The differential change in their length results in a curved segment. Since at least three drive cables are required for each segment, there is a major disadvantage due to the complexity of the drive system, both constructively and in terms of control.



a. b.

Figure 3. Discreet hyper-redundant actuators. *a-joint actuators; b-base actuators*

In [4][5][3], the authors propose a robot architecture that combines the advantages of the two constructive types, using an electro-pneumatic blocking system of the element joints, which reduces the drive system to a single traction cable system no matter the number of robot's curvature segments.. So the result: low inertial mass and element-level curvature with a single traction system. The major disadvantage is low speed positioning considering that a single element of curvature can be operated at a certain time.

Figure 4. Hybrid hyper-redundant arm HHR 2

In the present paper a similar conceptual solution is presented; it uses an element locking with electorhoheological fluid. This constructive solution controls the dynamics of the blocking of the elements and eliminates the impediment of the low positioning speed, since it is possible to operate as many segments simultaneously (respecting the plane and the direction of movement). Bigger loads can be manipualted due to the efficiency of this system. The positioning shocks disappear because the blocking or unlocking of the elements is gradual, controlled, not on / off as in the case of pneumatic pistons from the previous variant. We can also control movement dynamics by controlling the dynamics of partial or total blocking of the elements.

II. THE ROBOT ARHITECTURE

A. General presentation

The proposed structure is a hyper-redundant robot driven by traction cables. Each joint has a blocking element (motion control) that is controled with electrorheological fluid valve (Fig.5). The robot curvature is provided by the angular positioning of an element relative to the neighboring elements. Every element is cinematically and dynamically controllable. To achieve the desired curvature, a four-cable system combined with an electrorheological blocking system for each joint is used.

Between each two successive elements along the traction cables are positioning springs are placed wich combined with the action of the traction cables and the locking elements impose the angular position of the elements for the desired curvature of the segment (fig. 10).

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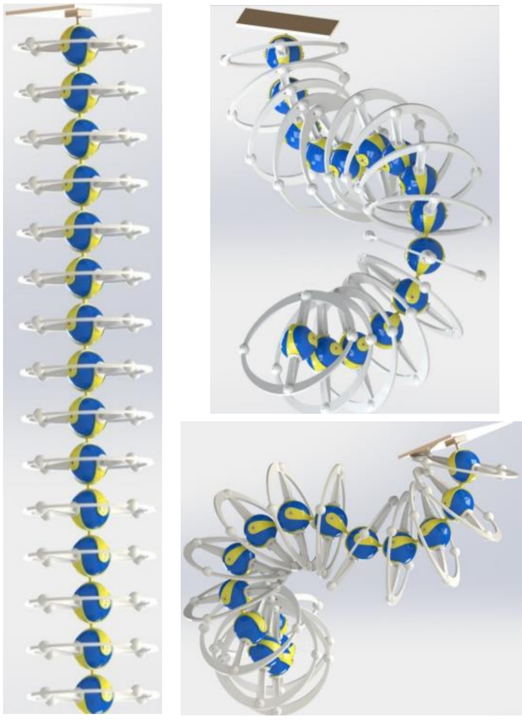

Figure 5. Hyper-redundant arm actuation with electrorheological control system

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For the bending of a robot segment is acting by traction cables are operated on the elements involved in the segment, the rest being blocked by means of the locking elements. *By segment of curvature we mean one or more successive elements that move in the same plane, making the curvature of a part of the robot.* Since each element can be controlled independently, the curve segment is determined by the motion desiderate both as a position along the robot body and as a number of elements. Figure 5 illustrates three bent segments, each consisting in five elements, for different positions, including relaxation.

Controlling the positioning dynamics of each element in the segment is possible by acting the traction cables and using the electrorheological blocking system, when bending a segment. Thus, different angular increments for elements of the same segment of curvature can be obtained. So we get the planarly spline segment curvature and not a circle arc.

To achieve the desired position, repeat the following operations are repeated: 1-Using the electrorheological blocking system locks the position for all robot elements is locked, except for those we want to change their position. 2-Changes the position of the free elements using the cable drive system, controlling the dynamics of movement of element-level. 3-New curve segments are considered and process is repeated until the final position is achieved.

B. Element description

The robot construction element consists in a 4th grade spherical joint, similar to the cardan cross joint, which allows two rotations around a two axis perpendicular to each other, in the section plane which is perpendicular to the joint (Fig 6 - Fig10).

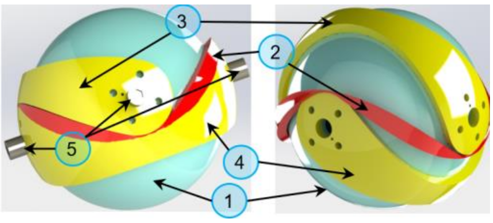

Figure 6. Element joint. Inside detail. *1-spherical inner shirt; 2-frontier of fluid ER; 3-mobile element no.1 (exterior element); 4-mobile element no.2 (exterior element); 5-cylindrical joints*

The element consists of two concentric spherical surfaces, an inner one (1) and an outer one(10). Among these, there is an electrheological fluid, divided into two enclosures through the partition wall (2).

Between the two spherical surfaces, in the ER fluid, move the mobile elements (3) and (4), rotating around the joints (5).

Together with the mobile elements moving through the fluid, we have other two movable elements (7) and (8), with respect to the spherical shirts, which have a rotating motion outside the outer sphere (10). These elements ensure that the element is connected to the arm structure, (6) și (9).

The element is made of plastic and is designed to have a maximum strength / weight ratio.

In Figure 9, various positions of an element are observed, considering the link of attachment with the front element or with the base. The moving element of an element can be rotated by 120º on each axis of rotation. We can see in the figure the operating space of an element.

III. ACTUATING SISTEM

The drive system has two distinct components: the cable actuating system and the positioning springs, respectively the electrorheological blocking system, respectively.

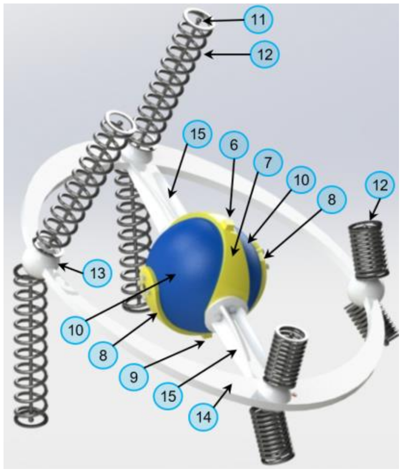

Figure 7. Robot element. Structure details. *6-previous link; 7-element mobile no.1 (exterior element); 8-mobile element no.2 (external element); 9-posterior link; 10-outer spherical shirt; 11-traction cable; 12-spring positioning; 13-ball positioning spring; 14-ring outer element; 15-stiffening arms-Mobile Element no.1*

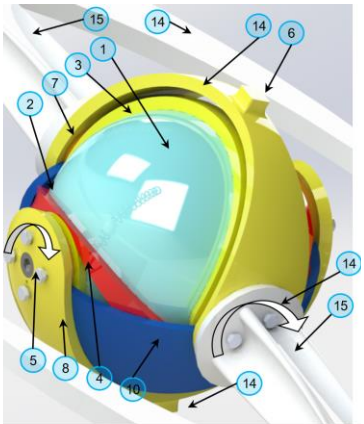

Figure 8. Joint element. Section detail. *1-15 see fig 7 and 9*

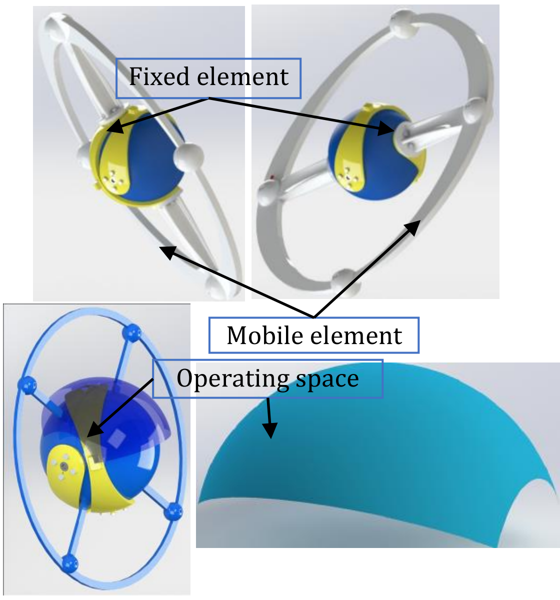

Figure 9. Robot element. Positions detail. Element operating space

A. *Actuating system with traction cables and positioning springs*

Using the cable drive system, the overall arm curve is achieved. For an equal length of cables, the bend curvature is null, this being straight, so in the relaxation position. By varying the cable length in a differentiated way, the arm curvature is obtained. The robotic arm is operated by means of four traction cables, located on its edge, which provide for the bending of the arm.

Between any two successive elements there are four repositioning springs, which have the role of keeping the parallelism between the outer rings. They are positioned as following: they are parallel to the curvature of the robotic arm in that area; they are constructively identical; they are positioned on the spherical joints (15) on the support member (14) having an angle of 90° between them.

For connecting and guiding traction cables (11) the element (14), which is stiffened by the joint by means of the arms (15), is used,. This element also ensures the connection of the positioning springs (12) by means of the spherical joints (13). In Fig.7 and Fig.10, it is observed the compression or expansion of positioning springs according to the position of the relative element relative to the robotic arm. For every element rotation, the springs bring it back to the initial position when the force that generated the rotation disappears.

A traction cable passes through the interior of each spring, also passing through the support elements (14), respectively (15). The cables are attached to the outer ring of the last element and pass through the outer rings of the elements to the cable traction system. By actuating the cables, the elements rotate around the joints. The spins are calculated so as to overcome the resistive moments in the system.

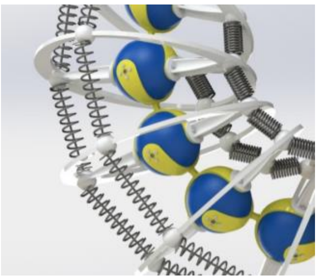

Figure 10. Hyper-redundant arm. Positioning springs and traction cables system detail.

B. *Description of electrorheological lock system for one element.*

It is known that the electrorheological fluid belongs to the category of intelligent materials. The main property of ER fluids used in robotics is to increase the viscosity of the fluid at electrical field exposure, in proportion to field strength. By applying this property to an ER valve, we can control the flow of fluid through the valve. This type of valve-type structure is used to control the blocking of the robot's mobile elements.

Movable elements (3) and (4) are designed to seal the space between the two spherical surfaces. The space between spheres is filled with electrheological fluid. In the presence of ER fluid the motion would be blocked. But these elements are perforated, having a sieve-like structure, thus allowing the fluid flow ER to flow from one side to the other (Fig.11). By controlling the viscosity of the fluid, we control the motion of of the element through the fluid.

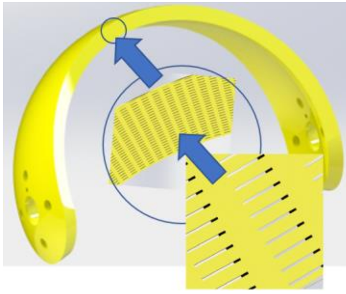

Figure 11. Robot element. Positions detail. Element operating space

As can be seen in the figure, the movable element is perforated having a series of approximately rectangular cross-section slots through which the fluid passes. The excitation electrodes of the fluid are at the top and at the bottom of each slit, the poles of the electric field, respectively. All electrodes are connected in parallel, being connected to the same voltage source simultaneously and generating the same electric field in each slot. Due to the shape of the element, dictated by the strength requirements, the depth of the slots along the element differs, and so from the point of view of fluid locking, some are more efficient by exposure to a longer length in the exciting electric field. The minimum length is at the middle of the element. Moreover, for each slot there is a dynamic pressure due to the movement of the element through the fluid. This pressure is directly proportional to the displacement velocity, and is therefore distributed unevenly across the element, with a maximum value at the half of the element, due to the peripheral speed. Accumulating the two effects we will see a complete, gradual blocking of fluid flow through the slots beginning with the ends of the element, in the middle, proportional to the increase of the electric field of excitation. For this reason the excitation field voltage is calculated for the depth and dynamic pressure of the slot at the half of the element for a complete blocking of fluid flow.

The excitement of ER fluids requires an electric field of approximately 5KV/mm. The proposed system uses a sieve type with excitation poles for each slot, each slot constituting a ER electrovalve. Considering that the distance between the poles is 0.8mm we need an approximate voltage of 380V, so the average voltage. The immediate benefits consist in widening the scope of this type of robots limited by high voltage. Another advantage is the drastic simplification of the field source and command electronics source, as well as their dimension. An apparent drawback lies in the difficulty of making such an element, difficulty easily overcome by the use of high precision 3D printers with double material deposition, metal and another nonconducting material.

IV. CONTROL SYSTEM

The control system is a mixed one: for the control of 4 ER valves and for the control of the mobile element. The electrorheological (ER) fluids are some fluids with special properties. There are a considerable number of papers [6-8], etc. that describe these properties and the two dominant methods of use the ER effect in practical equipment: valve method and clutch method.

A. Dynamic model

The control system use a variable width rectangular signal and constant amplitude where the duration of the signal is the control variable, respectively u(t) (Fig. 12).

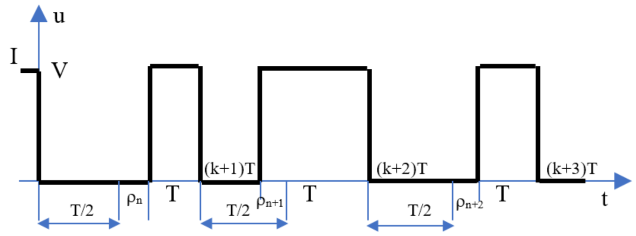

Figure 12. The signal control of the ER valve

The signal u(t) is defined:

$$u(t) = \begin{cases} 0 & kT + \rho_k T < t < kT + \frac{T}{2} + \rho_n T \\ V & kT + \frac{T}{2} + \rho_n T < t < (k+1)T \end{cases} \quad (1)$$

where the variable ρ_k is the control variable and it being a fraction of the time cycle. This signal is suitable for ER fluid control that can provide a steady a steady outflow of fluid for a good preset time and when we have very small time constants.

The main feature of the controller are determined by the dynamic performances of the ER fluid valve. In this paper, a general design with two rectangular electrodes like in Figure 13 is considered.

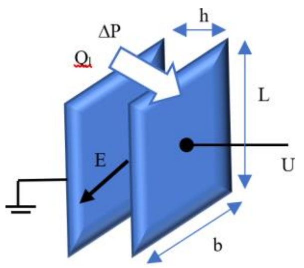

Figure 13. The ER fluid valve

The ER valve is controlled by applying the voltage to the pair of electrodes. We consider this voltage as the control variable (Figure 14).

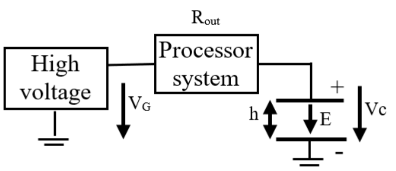

Figure 14. The equivalent circuit of the ER valve

The most used structure contains 4 ER valves known as Wheatstone bridge [6], (Figure 15).

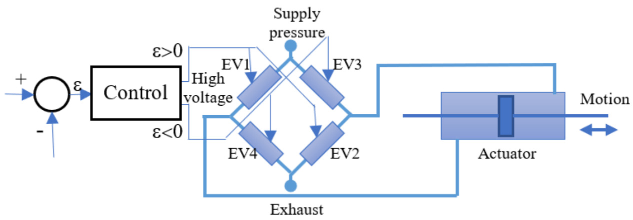

Figure 15. The Wheatstone bridge with 4 ER valves

It is noted that the ER valves are connected in pairs with the same signal source for positive or negative errors. The basic model of the system is a classic form and with the state vector and the input vector.

$$\dot{x} = Ax + bu \quad (2)$$

where $X = \left[\frac{\Delta E}{E_0}\ \frac{\Delta Q}{Q_0}\right]^T$; $u = \frac{\Delta V_G(t)}{V_{Go}}$ (3)

$$A = \begin{bmatrix} -a_3 & 0 \\ a_2 & -a_1 \end{bmatrix};\ b = \begin{bmatrix} a_4 \\ 0 \end{bmatrix} \quad (4)$$

with $a_1 = \frac{Q_0}{\beta^2 bhL} - \frac{12\eta}{bh^3\delta}$; $a_2 = \frac{\alpha cm E_0^m}{\rho h Q_0}$; $a_3 = \frac{1}{RC}$; $a_4 = \frac{V_{Go}}{hE_0RC}$

where η - ER fluid viscosity, Q - the flow, δ - the density, b, L, h are geometric dimension, E - the electrical field, the output resistor of the generator are R and C represent the equivalent capacity of the plates, α, β, m, c are constants.

B. Controller

The controller used in the electro-hydraulic servo system of the robot is mainly by the ER hydraulic semiconductor and the small time constants of the switching process. The system, respectively a variable with pulse system, have the duration of the input signal at constant amplitude, as control variable.
The ER fluid controller of type closed-loop system is presented in Figure 16. A processor computes the pulse width and execute the algorithm. A dedicated circuit provides the voltage variable with pulse signal to control the ER valve.

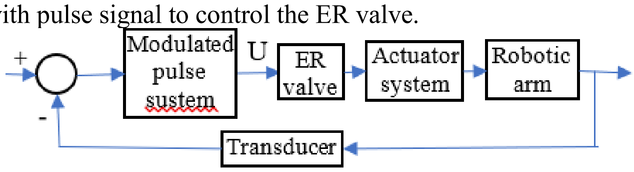

Figure 16. The ER fluid based control system

For a fluid of this type, the observed response times are in the range of milliseconds [8]. Denoting the Laplace transformations of the relative sizes of $\Delta E(t)/E_0$, $\Delta Q(t)/Q_0$ and $\Delta V_G(t)/V_{G0}$ by e(s), q(s) and $v_G(s)$ the transfer functions becomes:

$$Y_{V1}(s) = \frac{e(s)}{V_G(s)} = \frac{k_{v1}}{\tau_1 s+1};\ Y_{V2}(s) = \frac{q(s)}{e(s)} = \frac{k_{v2}}{\tau_2 s+1};$$

$$Y_F(s) = Y_{V1}(s) \cdot Y_{V2}(s) = \frac{k_{v1}}{\tau_1 s+1}\frac{k_{v2}}{\tau_2 s+1} \quad (5)$$

$$k_{v1} = \frac{a_4}{a_3};\ k_{v2} = \frac{a_2}{a_1};\ \tau_1 = \frac{1}{a_3};\ \tau_2 = \frac{1}{a_1} \quad (6)$$

By a correction determined by the response time of the ER fluid, the new transfer function becames:

$$Y_V(s) = Y_{V1}(s)\cdot Y_{V1}^*(s)\cdot Y_{V2}(s) \quad (7)$$

where $Y_{V1}^*(s) = \frac{k_E}{\tau_E s+1}$

and t_E represents the time constant response to the action of electric field on the material, to satisfy the formation of the bridging fibril. the dependence between time constant and particle density is exponential [8].

V. SIMULATIONS

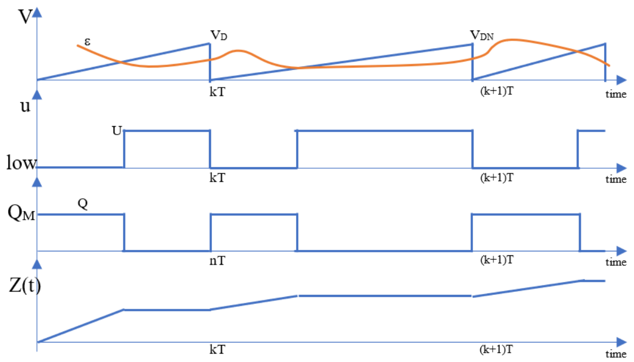

Figure 17. Controller variables - timing diagram

The saw tooth signal V_D with the period T and amplitude V_{DM} is provided by the signal generator. comparing the system error with and ε with V_D we obtained a variable width modulated signal u(t). We use the high-voltage V for valve control and the flow Q.

$$u(t) = \begin{cases} 0 & \varepsilon(t) \geq V_D(t) \\ u & \varepsilon(t) < V_D(t) \end{cases};\ Q(t) = \begin{cases} Q_M & \varepsilon(t) \geq V_D(t) \\ 0 & \varepsilon(t) < V_D(t) \end{cases} \quad (8)$$

We neglect the rise and fall times signal in this analysis. We obtain the mobile element position Z(t) by a simple integration of the flow. From Equation (8) we obtain

$$u(t) = \begin{cases} 0 & t \leq \frac{\varepsilon T}{V_{DM}} \\ u & t > \frac{\varepsilon T}{V_{DM}} \end{cases};\ Q(t) = \begin{cases} Q_M & t \leq \frac{\varepsilon T}{V_{DM}} \\ 0 & t > \frac{\varepsilon T}{V_{DM}} \end{cases} \quad (9)$$

The displacement of the robotic arm is

$$\Delta z = a_5 \int_0^{\varepsilon T/V_{DM}} Q(t)dt \quad (10)$$

The general gain of the controller is [8]

$$K_R = \frac{\Delta z}{\varepsilon}\cdot 100 \quad (11)$$

From equation (9)-(11) we obtain

$$K_R = \frac{Q_M\cdot T\cdot a_5}{V_{DM}} 100 \quad (12)$$

We can implement a proportional integration algorithm using this controller. Similarly, the procedure for a integral gain for a component, will be developed.

$$\Delta z = \frac{K_R}{T_I}\int_0^t \varepsilon dt \quad (13)$$

where T_I is integral time constant of the controller.

Using the (10), (12) and (13) equations we obtain $T_I = a_5 \cdot T$

$\tau_E = 7.5 \div 10^2 e^{-14\delta_E}$ where δ_E - the zone particles density. The timing diagram of the variables is presented in Figure 17.

VI. CONCLUSIONS

The robotic stucture presented solves a few problems of this robots category: reduces the drive system to a single group of traction wires for element-level actuating; extends the applicability range by decreasing the valve tension ER: increases the load or the length of the arm by using an ER locking system; simplify the sensing system by using the crosshairs joint types.

The system controller is a modular impulse system where the duration of the input signal is the control variable for a constant amplitude of the signal. A on/off ER hydraulic valve provides modulated pulse width control signal. This valve can be assimilated to a system where we can control the hydraulic semiconductor via the voltage signal. Here are presented for each component the transfer functions wich provide by system dynamic equations. The classical parameters of this controller it's calculated. Using the parameters of the presented model we can simply implement the proportional and integrated coefficients of this controller.

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REFERENCES

[1] Robinson G. and Davies J.B.C., "Continuum Robots – A state of the art", Proc. IEEE Int. Conf. on Robotics and Automation, Detroit, May 1999, pp. 2849 – 2854

[2] Gravagne, Ian A., Walker, Ian D., On the kinematics of remotely - actuated continuum robots, Proc. 2000 IEEE Int. Conf. on Robotics and Automation, San Francisco, April 2000, pp. 2544-2550

[3] Stoian V., Vladu I.C., Vladu I., A New Hyper-Redundant Arm and Control System, Springer Advanced in Intelligent Systems and Computing, vol 371, 2016, pag. 287-296

[4] Vladu I., Strimbeanu D., Ivanescu M., Bîzdoacă N., Vladu C., Florescu M.,– Control System for a Hyper-Redundant Robot – INCOM '12 – Bucharest, may 2012

[5] Vladu I., Ivănescu M., Vladu I. C., "HYPER-REDUNDANT ARM actuation with electro-pneumatic actuation system – part I - Construction", în ICSTCC, Sinaia, 2013.

[6] Brooks, D. A. 1982. "Electro-Rheological Devices", CME, 9: 91-93.

[7] Duclos, T. G. 1988. "Design of Devices Using Electro-rheological Fluids", SAE Technical Paper Series, 881134.

[8] Hill, J. C. and T. H. Van Steenkirte. 1991. "Response Times of Electro-rheological Fluids", J.Appl.Phys., 70 (30) 8: 1207-1211.