Digital Prototyping of a Series Elastic Actuator for Exoskeletons

Antônio Bento Filho, antonio.bento@ufes.br[1]
Rafhael Milanezi de Andrade, rafhael.andrade@ufes.com[1]
Márcio Coelho de Mattos, marcio.mattos@ufes.br[1]

[1] Department of Mechanical Engineering, Universidade Federal do Espirito Santo, Avenida Fernando Ferrari, 514, Goiabeiras, 29075-910 ES, Brazil.

Abstract: *In general, the actuators of the mechanical systems are always rigidly connected to the load to be moved. This can be observed in the hydraulic systems of agricultural, highway construction and mining equipment and in elevation and cargo transportation, among others. Unlike rigid actuators, a series elastic actuator (SEA) contain an elastic element in series with the mechanical energy source. Such an elastic element gives SEA's several unique properties compared to rigid actuators, including tolerance to impact loads, low mechanical output impedance, passive mechanical energy storage, and increased peak power output. These properties align with requirements of robustness, high-power output, and energy efficiency placed on legged actuation systems. As a result, SEA's have been widely adopted in the fields of legged robotics and human orthotics. In the present paper, it is presents the digital prototyping of an actuator with an elastic element inserted in series with the load. Digital prototyping is an efficient approach to product development that lets someone design, visualize, and simulate parts and mechatronic devices. It is possible to make detailed design of the device and get the data for dynamic model simulation. The goal here is virtually create an elastic actuator for applications in mechatronics exoskeletons and prostheses and for robot manipulators in non-structured environments. It is done a digital prototyping of a tubular actuator design which encapsulates the mechanical and electrical components and sensors. The digital prototype dimensions, mass and inertia properties are used to build the dynamic model for simulations and implementation of a controller.*

Keywords*: Elastic actuator, SEA, exoskeletons, digital prototyping.*

1. INTRODUCTION

Series elastic actuator (SEA) has been successfully used in a number of applications for almost 20 years (Pratt and Williamson, 1995). As widely reported by a number of researchers (see (Pratt and Williamson, 1995), (Arumugom et al. 2009), (Paluska and Herr, 2006) and (Paine et al, 2013)) series elastic actuators provide many benefits in force control of robots. Unlike rigid actuators, SEA's contain an elastic element in series with the mechanical energy source. Such as elastic element gives SEA's several unique properties compared to rigid actuators including low mechanical output impedance, tolerance to impact loads, increased peak power output, and passive mechanical energy storage. These properties are well aligned with requirements on legged actuation systems, as a result, SEA's have been widely adopted in the fields of legged robotics and human orthotics (see (Pestana et al., 2010) and (Parietti et al., 2011)).

Fig. 1 shows a linear electric driven SEA (Pratt et al., 2002). The DC motor with gearbox (1) drives the ball screw (4) which moves the ball nut plate (3). Ball nut plate (3) then moves the springs (9) against moving sub assembly (2) which is fixed to the moving rods (8), thus causing the displacement of the load connection terminal (7) and then the movement the load. The guide rods (5) are fixed to the motor flange (10) and to the support plate (6), with plain bearings for the ball screw and for the moving rods (8). They move together with the moving sub assembly (2) in which they are fixed. It follows that all the force exerted by the spindle motor assembly on the load is directly supported by the springs, which are the elastic element purposely inserted to lower the stiffness of the actuator load interface.

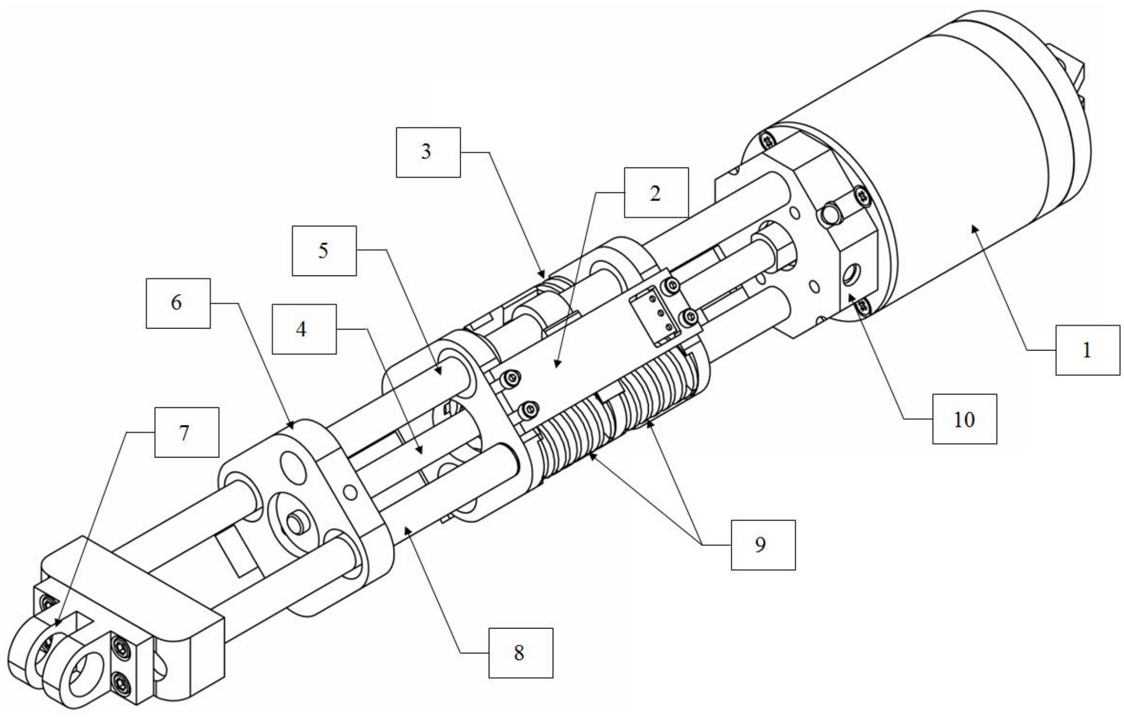

Fig. 1. Electric SEA (1) DC motor with gearbox; (2) moving sub assembly, (3) ball nut plate, (4) ball screw, (5) guide rod, (6) support plate; (7) load connection terminal, (8) moving rod, (9) and springs (10) motor angle and rods plate (Pratt et al., 2002).

The SEA's components can be chosen and configured in many different ways, producing designs with various tradeoffs which affect the power output, volumetric size, weight, efficiency, backdrivability, impact resistance, passive energy storage, backlash, and torque ripple of a SEA. (Curran and Orin, 2008), (Hutter et al.,2009), (Kong et al, 2009), and (Ragonesi et al., 2011) propose rotary designs based primarily on commercially available off-the-shelf components. (Lagoda et al., 2010) and (Diftler et al., 2011) design a compact rotary SEA using a harmonic drive and a high-stiffness planar spring.(Hutter et al. 2011) and (Torres-Jara and Banks, 2004) use linear springs coupled to rotary shafts between the motor and the chassis ground to achieve compact actuator packaging with low spring stiffness. In (Kong et al., 2012) and (Taylor, 2011), the authors place the spring within the reduction phase. This arrangement reduces the torque requirement on the spring compared to designs with the spring at the actuator output. (Edsinger-Gonzales and Weber, 2004), (Gregorio et al., 1997), and (Pratt and Pratt, 1998) propose a prismatic designs which use ball screws as the primary reduction mechanism followed by a cable drive to remotely drive a revolute joint. Ball screws are highly efficient, even for large speed reductions (85–90%), are backdrivable, are tolerant to impact loads, and do not introduce torque ripple. (Paine et al., 2013) is a good review of some recent progress in series elastic actuators. In this paper is presented a different design of a SEA. In order to avoid accidents risks and components contamination, the internal components were encapsulated in a unique hollow tubular structure. That allows substitute the heavy structure of solid steel tubes of the reference model (Pratt et al., 2002), permitting the applications in wearable robots, exoskeletons and prostheses.

Different architectures have been proposed for controlling series elastic actuators. The variation of controller design is related to the different physical characteristics of the hardware. For example, force can be observed either by measuring spring deflection and applying Hooke's law in (Kong et al., 2010), or by measuring change in resistance, as is accomplished using strain gauges, as shown in (Pratt and Williamson, 1995). If friction and backlash are too large, a pure high-gain PID approach can suffer from stability issues. In order to avoid this issue, (Pratt et al., 2004) suggest using position feedback as the innermost control structure for force control. This idea is adopted in others researches (see (Lagoda et al., 2010)), treating force control as a position or velocity tracking problem. In this paper, it was adopted such idea to develop the propose SEA controller.

2. DIGITAL PROTOTYPING DESIGN

Over the years, digital prototyping has been successfully applied in engineering and manufacturing allowing virtually explore a complete product before it's built. As reported by (Johansson et al., 2004) the digital prototyping has been important to development of industrial robots, reducing the time robot programming phase. According to the authors, the robot task can be simulated in a virtual model of the work cell when still only a digital prototype of the workpiece exists and the risk of technical failure for a transition can be reduced. In this way, before manufacture of the proposed serial elastic actuator, is presented in this paper its digital prototyping.

2.1. First Design

The characteristics desired for the actuator are:

a) Enclosed internal components, to avoid component contamination and accidents risks;
b) Size adequate for wearable robots, exoskeletons and prostheses applications, emulating natural muscles;
c) Aesthetically suited to applications in wearable robots, exoskeletons and prostheses;
d) And smart enough for applications in unstructured environment.

The first prototype design is shown in Fig. 2. There are two ball nuts (2) bolted to plates with a tab and grooved flanges for o'rings (9) installation. The flanges have a central hole and are connected by means of an extender, which is a tube with external male thread at both ends. The springs (4 and 5) slide around the extender and press on both sides a plate fixed to the tube base (7) of the retractable arm (3).

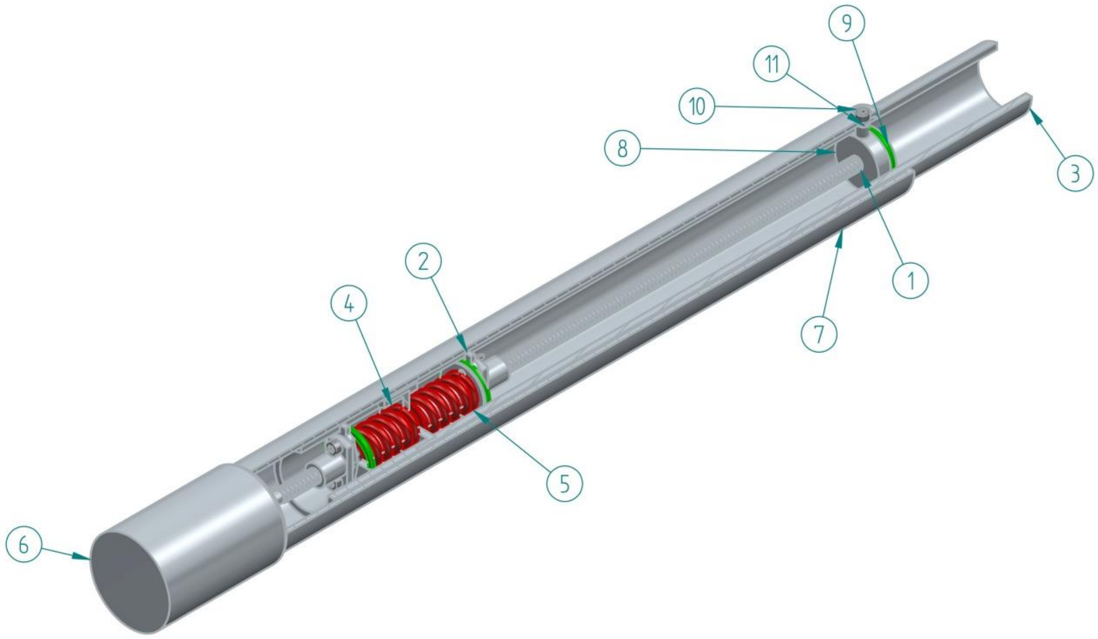

Fig. 2. First prototype showing internal actuator components: ball screw (1);ball nuts (2); movable arm (3); springs (4, 5); motor & gearbox (6); base tube (7); bearing screw (8);o'ring (9); allen screws (10); guide ring (11).

2.2. The moving sub assembly

Fig. 3 shows the exploded view of the moving sub assembly, a set of pieces that behaved as a single device after assembled. The ball nut (1) is enclosed by two bolted flanges (4, 3). Tubes (2) are used to grip a flange on the nut (1). The flange (4) has threaded holes for Allen screws (5) and flange (3), countersunk holes for these screws and thread. In the central bore of each flange is a threaded guide tube (6), with the pre stressed springs. Over the flanges is fixed the circuit board (7) with the sensor for acquiring the deformation of the spring against the linear encoder attached to the flanges (3) and (4).

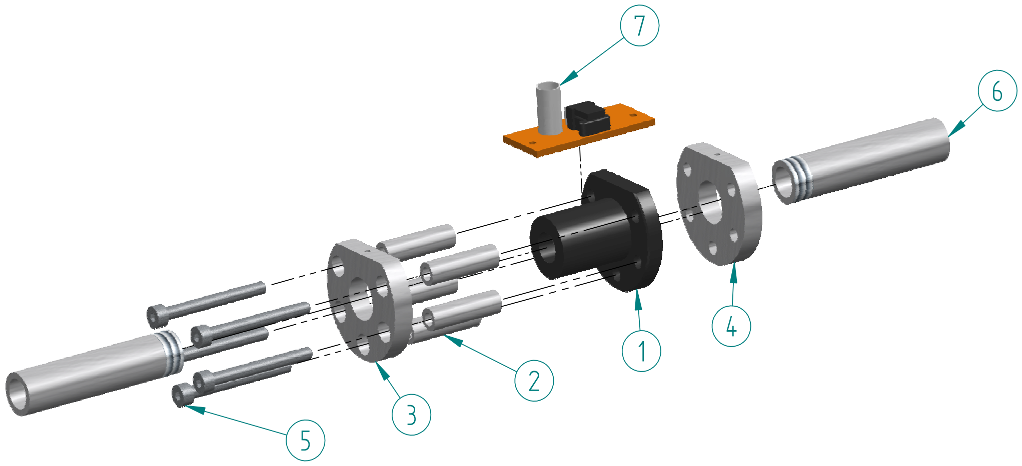

Fig. 3. Exploded view showing action device sub assembly components.

2.3. The DC motor & gearbox

It were chosen based on the forces for actuator operation and for the spring assembly, according to the planetary gearbox, and the ball screw torque force conversion. The DC motor is a 60 mm, brushless, 400 W; the gearbox is a planetary gearhead 62 mm diameter, 8-50 N.m torque and the ball screw is a 10 mm diameter and 3 mm pitch rolled steel.

2.4. Final Design

Fig. 4 shows the actuator final design. The interactive digital prototyping design process done resulted in a set of desirable characteristics for the actuator very similar to those originally intended, as follows:

a) 425 mm long when retracted, with 130 mm range;
b) Maximum diameter of 60 mm;
c) Interchangeability of springs;
d) Maximum load capacity up to 450 N;
e) Standard rolled ball screw 10 mm diameter, 3 mm pitch;
f) Main model structure of drawn carbon steel or aluminium alloy tubes;
g) Estimated final weight of 3,70 kg.;
h) Estimated continuous speed: 13,40 cm/s;
i) Operating voltage : 48 V.

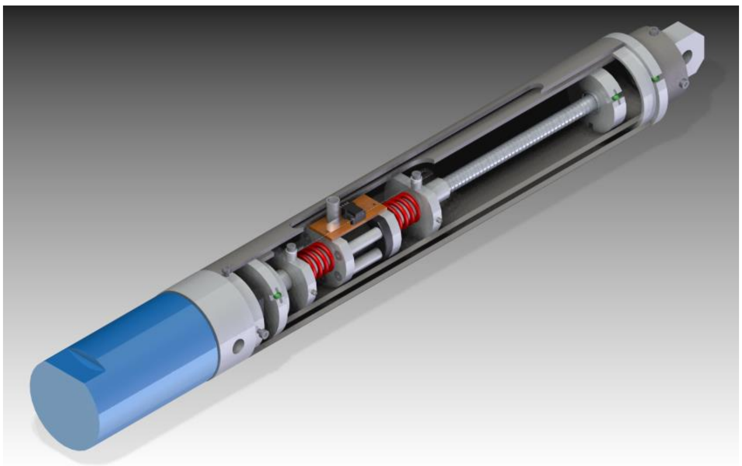

Fig. 4. Actuator final design showing internal components.

3. ACTUATOR'S DYNAMIC MODEL

The dynamic model of the actuator was constructed from the digital prototype data to run a simulation in order to verify its dynamic behavior, bandwidth and validate the project settings, as presented in Fig. 5.

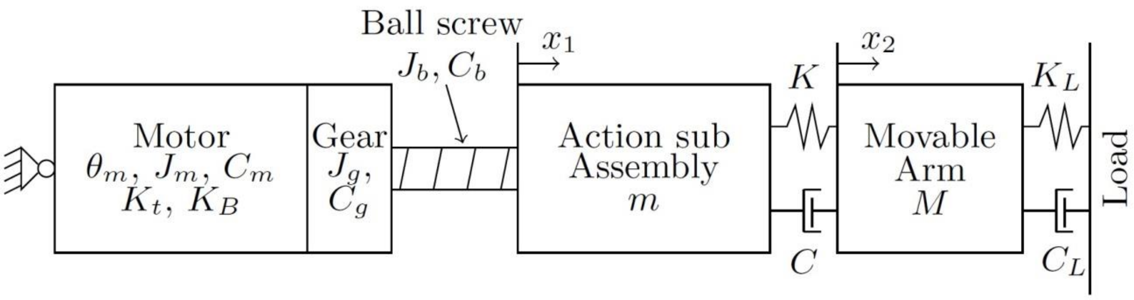

Fig. 5. Actuator's mechanical model.

Referring to Fig. 5, the actuator dynamic model equations are described as follows:

$$ {}_{a}\frac{di_a}{dt} + R_a i_a + K_b \omega = V_a \qquad (1) $$

Where L_a is the armature inductance, i_a is the armature current, R_a is the armature resistance, K_b is the back Electromotive Force (back-EMF) constant, ω is the angular velocity, and V_a is the armature voltage.

$$ \left[J_m + J_g + n^2 J_b + \left(\frac{np}{2\pi}\right)^2 m\right]\ddot{\theta}_m + \left[C_m + C_g + n^2 C_b + C\left(\frac{np}{2\pi}\right)^2\right]\dot{\theta}_m = K_t i_a \qquad (2) $$

Where J_m is the rotor inertia, J_g is the gear inertia, n is the gear ratio, J_b is the ball screw inertia, p is the ball screw pitch, m is the action device sub assembly mass, θ_m is the angular displacement of the motor axis, C_m is the rotor viscous friction coefficient, C_g is the gear viscous friction coefficient; C_b is the ball screw viscous friction coefficient, C is the action sub assembly viscous friction coefficient, K_t is the motor torque proportional constant.

$$ m\ddot{x}_1 + C_b\dot{x}_1 = m\left(\frac{np}{2\pi}\right)\ddot{\theta}_m + C_b\left(\frac{np}{2\pi}\right)\dot{\theta}_m = f \qquad (3) $$

$$ M\ddot{x}_2 + C_L\dot{x}_2 + K_L x_2 = f \qquad (4) $$

Where f is the force between action and movable arm sub-assemblies, M is the movable arm sub assembly mass, C_L is the load interface viscous friction coefficient, and K_L is the load interface elastic constant.

The term $\left(\frac{np}{2\pi}\right)$ is the linear displacement of the movable arm reflected to motor axis rotation and $\left(\frac{np}{2\pi}\right)^2$ is the inertia and viscous friction components of the action device, reflected to motor axis.

Once described the actuator dynamic model equations, the closed loop PID transfer function block diagram in the frequency domain can be made, as shown in Fig. 6.

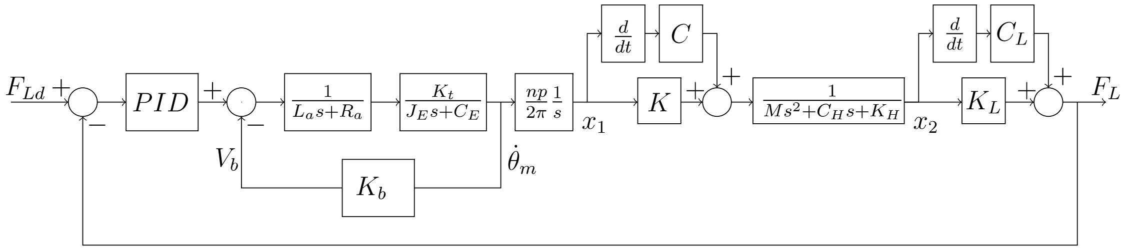

Fig. 6. Actuatos's PID closed loop transfer function block diagram.

Where $_{\mathrm{a}} = 8.200E-04H$, $\mathrm{R_a} = 1.030\ \Omega$, $\mathrm{J_E} = \left[J_m + J_g + n^2 J_b + m\left(\frac{np}{2\pi}\right)^2\right] = 9.510E-05\ kgm^2$, $\mathrm{C_E} = \left[C_m + C_g + n^2 C_b + C\left(\frac{np}{2\pi}\right)^2\right] = 4.594E-05\ \frac{kgm}{s}$, $K_{\mathrm{H}} = 3.336E+06\ \frac{N}{m}$, $K_{\mathrm{b}} = 1.469E-01\frac{Vs}{rd}$, $C_{\mathrm{H}} = C + C_{\mathrm{L}} = 8.160E+01\frac{kgm}{s}$, $K = 3.270E+04\frac{N}{m}$, $C = 8.000E-01\frac{kgm}{s}$, $K_{\mathrm{L}} = 3.303\ +06\frac{N}{m}$.

4. RESULTS AND DISCUSSION

The PID controller was tuned by applying pre-programmed Matlab® routines. The goal was to obtain a robust PID controller with a large frequency band. Hence the PID controller constants were obtained by a interactive process which began with the well known Ziegler-Nichols Method. The tuned PID controller constants are:

$\mathrm{K_p} = 2.915$,$\mathrm{K_i} = 4.153$, and $\mathrm{K_d} = 0.007$.

Fig.7 shows the Bode diagram of the system, where we can see a very good frequency band of 40 Hz, compatible with the Paine's results (Paine et al., 2013). On the other hand, the phase angle is quite high at 40 Hz, greater than 90º. Yet it is possible to apply the actuator in several systems where force control is necessary, as in some robot arms in industrial plants. Resonance frequency is greater than 200 Hz. This implies that the effects due to vibrations will be efficiently filtered into the frequency band of the actuator.

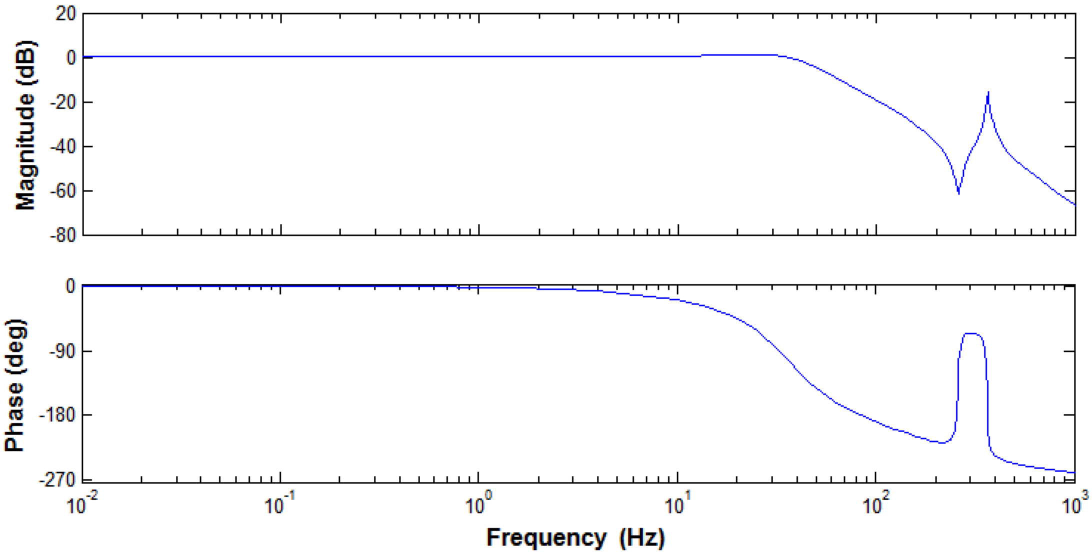

Fig.7. Bode Diagram of the system.

Fig.8 shows the time response for a constant input force. The settling time is less than 0.1 second, a very good result to a force control.

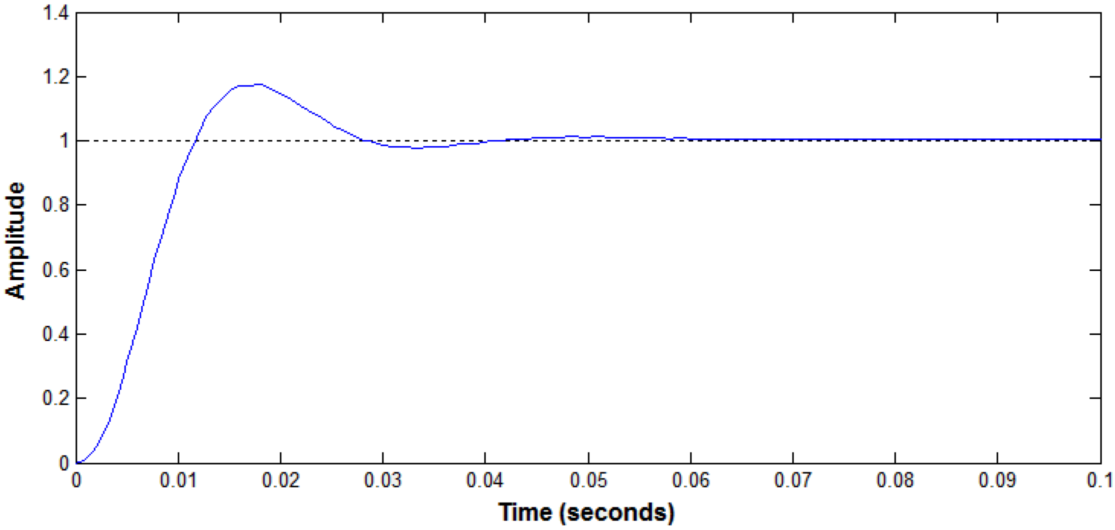

Fig.8. Time response for a 1N step input force

5. FINAL REMARKS

Its presented the digital prototyping of a linear electric SEA for use in exoskeletons, wearable robots and mechatronic devices. It was used a digital prototyping environment for design and assembly of actuators parts, generation of images of section views in perspective and exploded views, and all fabrication drawings of the parts of the actuator. The prototype is driven by a Maxon EC 60 Ø60 mm, brushless 400 W DC motor, with a Planetary Gearhead GP 62 A and a R Series 10 mm diameter rolled steel ball screw.

It's also presented the actuator's performance, evaluated under a PID force controller. Fig.7 shows the frequency response of the magnitude and phase of $\frac{F_L}{F_{Ld}}$. Fig.8 shows the step response to a 1 N force step input. The step response can also be tuned to final displacement or to contact force. Some improvements to the actuator itself will be needed for the next steps of the project, aiming at the fabrication, assembly and testing of the actuator. Future works will be in the construction of a real aluminium alloy based prototype and in testing it's performance in a real time environment for:

a) Evaluating the actuators performance under force, position, velocity and mixed controllers;
b) Verify the effect of spring stiffness and gear ratio in load bandwidth;
c) Development of tuning strategies between the spring stiffness – actuator bandwidth and elastic energy store relationship;
d) Actuator's backslash and viscous friction analysis.

6. ACKNOWLEDGEMENTS

The authors would like to thanks to Federal University of Espírito Santo (UFES), National Petroleum Agency (ANP) and Petrobras for supporting the project.

7. REFERENCES

Arumugom, S., Muthuraman, S., and Ponselvan, V., 2009, “Modeling and application of series elastic actuators for force control multi legged robots,” J. Comput., vol. 1, no. 1, pp. 26–33.
Curran S., and Orin, D., 2008, “Evolution of a jump in an articulated leg with series-elastic actuation,” in Proc. IEEE Int. Conf. Robot. Autom., pp. 352–358.
Diftler, M. , Mehling, M., Abdallah, M., Radford, N., Bridgwater, L., Sanders, A., Askew, R., Linn, D., Yamokoski, J., Permenter, F., Hargrave, B., Piatt, R, Savely, R., and Ambrose, R., 2011, “Robonaut 2—The first humanoid robot in space,” in Proc. IEEE Int. Conf. Robot. Autom., pp. 2178–2183.
Edsinger-Gonzales, A., and Weber, J., 2004, “Domo: A force sensing humanoid robot for manipulation research,” in Proc. IEEE/RAS 4th Int. Conf. Humanoid Robot., vol. 1, pp. 273–291.
Gregorio, P., Ahmadi, M., and Buehler, M., 1997, “Design, control, and energetics of an electrically actuated legged robot,” IEEE Trans. Syst., Man, Cybern. B, Cybern., vol. 27, no. 4, pp. 626–634.
Hutter, M., Remy, C., and Siegwart, R., 2009, “Design of an articulated robotic leg with nonlinear series elastic actuation,” in Proc. 12th Int. Conf. Climb. Walking Robot. Supp. Technol. Mobile Mach., pp. 645–652.
Hutter, M., Remy, C., Hoepflinger, M., and Siegwart, R., 2011, “ScarlETH: Design and control of a planar running robot,” in Proc. IEEE/RSJ Int. Conf. Intell. Robot. Syst., pp. 562–567.

Johansson, R., Robertsson, A., Nilsson, K., Brogårdh, T., Cederberg, P., Olsson, M., Olsson, T., Bolmsjö, G., 2004, "Sensor integration in task-level programming and industrial robotic task execution control", Industrial Robot: An International Journal, Vol. 31 Iss: 3, pp.284 – 296

Kong, K., Bae, J., and Tomizuka, M., 2012, "A compact rotary series elastic actuator for human assistive systems," IEEE/ASME Trans. Mechatronics, vol. 17, no. 2, pp. 288–297.

Kong, K., Bae, J., and Tomizuka, M., 2009, "Control of rotary series elastic actuator for ideal force-mode actuation in human-robot interaction applications," IEEE/ASME Trans. Mechatronics, vol. 14, no. 1, pp. 105–118.

Kong, K., Bae. J., Tomizuka, M., 2010, "A compact rotary series elastic actuator for knee joint assistive system," in Proc. IEEE Int. Conf. Robot. Autom., pp. 2940–2945.

Lagoda, C., Schouten, A., Stienen, A., Hekman, E., and van der Kooij, H., 2010, "Design of an electric series elastic actuated joint for robotic gait rehabilitation training," in Proc. IEEE 3rd RAS and EMBS Int. Conf. Biomed. Robot. Biomechatron. 2010, pp. 21–26.

Pestana, J., Bobin, R., Arevalo, J. C., and Garcia., E., 2010, "Characterization of emerging actuators for empowering legged robots," presented at the 13th Int. Conf. Climbing and Walking Robots Support Technologies Mobile Machines, Nagoya, Japan.

Paine, N., Oh, S., and Sentis, L., 2013, "Design and Control Considerations for High-Performance Series Elastic Actuators" IEEE/ASME Trans. Mechatronics, vol. PP, Issue. 99, pp. 1–12.

Paluska, D. and Herr, H., 2006, "Series elasticity and actuator power output," in Proc. IEEE Int. Conf. Robot. Autom., pp. 1830–1833.

Parietti, F., Baud-Bovy, G., Gatti, E., Riener, R., Guzzella, L., and Vallery, H., 2011, "Series viscoelastic actuators can match human force perception," IEEE/ASME Trans. Mechatronics, vol. 16, no. 5, pp. 853–860.

Pratt J., and Pratt, G., 1998, "Intuitive control of a planar bipedal walking robot," in Proc. IEEE Int. Conf. Robot. Autom., vol. 3, pp. 2014–2021.

Pratt, G. and Williamson, M., 1995, "Series elastic actuators," in Proc. IEEE/RSJ Int. Conf. Intell. Robot. Syst. Human Robot Interact. Cooper. Robot., vol. 1, pp. 399–406.

Pratt, G., Willisson, P., Bolton, C., and Hofman, A., 2004, "Late motor processing in low-impedance robots: Impedance control of series-elastic actuators," in Proc. Amer. Control Conf., vol. 4, pp. 3245–3251.

Pratt, J., Krupp B., and Morse C., 2002, "Series elastic actuators for high fidelity force control", Industrial Robot: An International Journal, vol. 29, no 3, p. 234-241.

Ragonesi, D., Agrawal, S., Sample, W., and Rahman, T., 2011, "Series elastic actuator control of a powered exoskeleton," in Proc. IEEE Annu. Int. Conf. Eng. Med. Biol. Soc. pp. 3515–3518.

Taylor, M. D., 2011, "A compact series elastic actuator for bipedal robots with human-like dynamic performance," Master's thesis, Robotics Inst., Carnegie Mellon Univ., Pittsburgh, PA, USA.

Torres-Jara, E., and Banks, J., 2004, "A simple and scalable force actuator," presented at the Int. Symp. Robot., Paris, France.

8. RESPONSIBILITY NOTICE

"The authors are the only responsible for the printed material included in this paper".