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Pneumatic muscle actuated parallel asymmetrical gripper system with one mobile jaw

Tudor Deaconescu*, and *Andrea* Deaconescu

Transilvania University of Braşov, Department of Industrial Engineering and Management, 500036,
29 Bd. Eroilor, Braşov, Romania

Abstract. The paper pertains to the field of the current global endeavours in industrial robot construction, the presented research being oriented towards identifying innovative constructive solutions for gripper systems. The utilisation of the linear pneumatic muscle as actuator of the gripper system ensures a construction that is light, highly compliant, and that meets the safety requirements related to interaction with humans. The paper further presents and discusses such a system of asymmetrical construction with a single mobile jaw.

1 Introduction

Besides the more or less evolved mechanisms mimicking human motions developed by the end of the 19th century, it was the 20th century industrialisation of global economy that brought about the invention of the modern means of computing and their deployment in the control of working equipment, eventually leading to the invention of robots.

According to the International Federation of Robotics (World Robotics 2016), worldwide robot sales peaked in 2015 with a total of 253,748 units, recording a 15% increase over the previous year. Figure 1 illustrates the 12-year dynamics of worldwide robot sales [1].

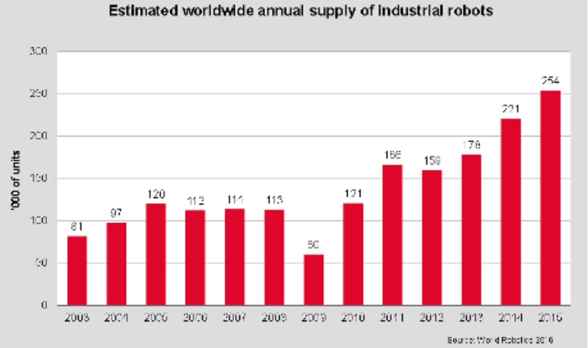

Fig. 1. Worldwide annual supply of industrial robots.

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* Corresponding author: tdeacon@unitbv.ro

The main driver of the growth in 2015 was the general industry with an increase of 33% compared to 2014, in particular the electronics industry (+41%), metal industry (+39%), the chemical, plastics and rubber industry (+16%) [1]. A similar dynamic is forecasted for the next years, as shown by the prognosis in Figure 2 [1]:

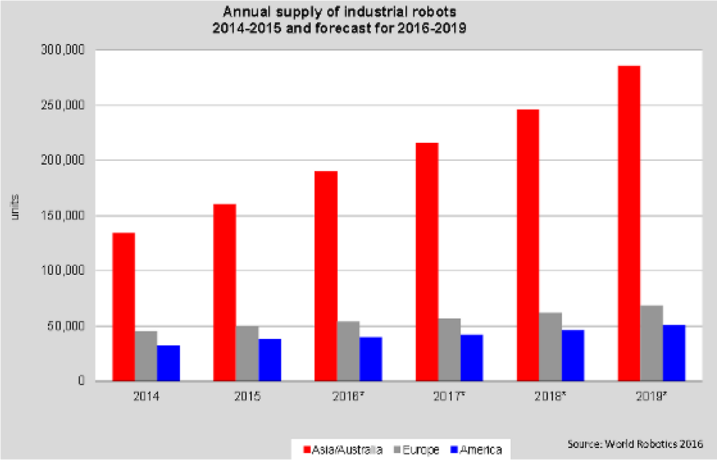

Fig. 2. Forecast of worldwide industrial robot supply.

The future increase in industrial robot demand is determined, *i.a.* by the implementation of the Industry 4.0 concept, linking the real-life factory with virtual reality, which is bound to play a key role in global manufacturing. From 2017 to 2019, robot installations are estimated to increase by at least 13% on average per year: 8% in the Americas and in Europe and 15% in Asia/Australia. Total global sales will reach about 413,000 units in 2019 [1].

Within this context, the gripper system, an essential component of any robot, needs to adapt to the new market requirements, such as to improve its energy efficiency, to be compact and easy-to-use – feature ensured by novel and light materials used for its manufacturing, and to allow optimum human-robot collaboration.

The construction of such gripper systems, satisfying the above requirements, is obtained by analogy-based design, a powerful tool meant to widen the horizon of inspiration in engineering. Nature is the obvious and generous source of inspiration for developing new products. Numerous scientific papers discuss the transfer of knowledge from natural sciences, and in particular from biology to engineering and coin the term of bionic design (bio-mimetics) emphasizing its enormous potential for developing new products and technologies [2].

This paper aims at presenting and discussing an innovative solution for such a bio-inspired, self-adaptive, light and environment friendly gripper system, endowed with a pneumatic muscle as the motion generator.

2 Construction of the gripper system

Grippers are those components of robot systems that facilitate the temporary contact with the manipulated object, ensuring its position and orientation during transport and assembly. The most important characteristics of an industrial gripper are the developed force and its structural rigidity – with a significant impact on the positioning accuracy. A small number of degrees of freedom allow a good reliability of such a gripper, and also contribute to its lower price [3].

Gripping is achieved by mechanical contact forces. While in natural systems such forces are developed by muscles, in artificial grippers it is motors that generate the forces. The motor proposed for the new gripper system discussed in this paper is the pneumatic muscle. The pneumatic muscle is a contracting membrane-based system that under the action of compressed air increases its diameter and shortens its length proportionally with the magnitude of the fed pressure. Due to the cumulated benefits of pneumatic muscle's special technical characteristics (shock absorbing capacity, light weight, small overall dimensions, reduced mass by power unit and compliance), they can be deployed successfully in the construction of gripper systems [4, 5].

With a pneumatic muscle as motor element and a power transmission mechanism based on gears, a parallel asymmetrical gripper system with one mobile and one fixed jaw was conceived, with the structural and block diagrams shown in Figure 3.

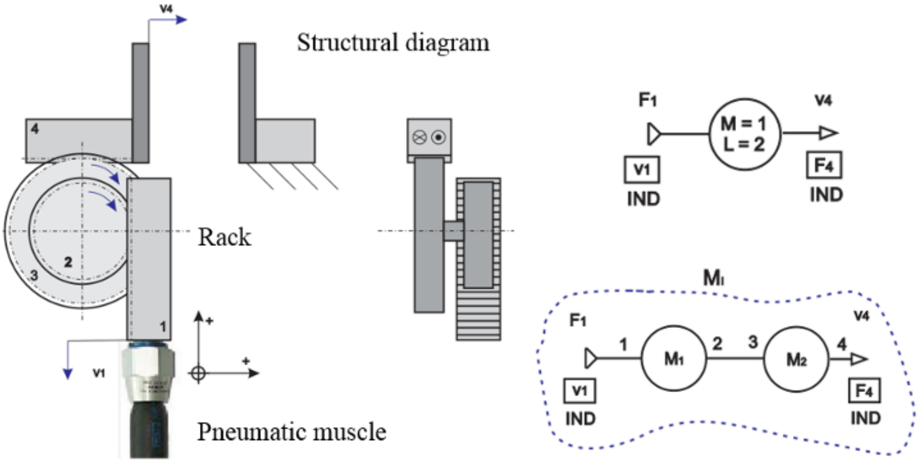

Fig. 3. Parallel asymmetrical gripper system with one mobile and one fixed jaw.

The analysed mechanism consists of a single linkage with series connected components, the number of external links of the system being L = 2. The system input is its connection to the motor (pneumatic muscle), and its output is the connection to the jaw support.

The system consisting of the two gear mechanisms that are not interconnected has the degree of mobility determined by equation (1):

$$\sum M_j = M_1 + M_2 = 1 + 1 = 2 \tag{1}$$

where j denotes the number of component gears.

Upon coupling the gears, the system's degree of mobility results as:

$$M = \sum M_j - L_c = 2 - 1 = 1 \tag{2}$$

The degree of mobility indicates that the studied fixed axes mechanism is characterised by an independent exterior motion (velocity v_1) and a dependent input force (F_1). Consequently the remaining exterior motion (v_4) is dependent, and the remaining exterior force is independent (F_4).

From the qualitative viewpoint a motion transmission function $v_4 = f(v_1)$ and a transmission function of the forces $F_1 = f(F_4)$ will be determined for the analysed gripper.

Determining the transmission forces for the velocities entails establishing the transmission ratio i_{14}:

$$i_{14} = i_{12} \cdot i_{34} = \frac{v_1}{\omega_2} \cdot \frac{\omega_3}{v_4} = \frac{\omega_2 \cdot R_2}{\omega_2} \cdot \frac{\omega_3}{\omega_3 \cdot R_3} = \frac{R_2}{R_3} = -\frac{z_2}{z_3} = -\frac{2}{3} \tag{3}$$

where z_2 and cu z_3 are the number of teeth of gears 2 and 3 ($z_2 = 20$; $z_3 = 30$).

The transmission function of the velocity will be:

$$v_4 = \frac{v_1}{i_{14}} = -\frac{3}{2} \cdot v_1 \tag{4}$$

If the friction forces in the system are not neglected and the inertial effects of the masses in motion are not considered, the transmission function of the forces is determined starting from equation (5):

$$F_1 \cdot v_1 \cdot \eta + F_4 \cdot v_4 = 0 \tag{5}$$

where η denotes the efficiency of the system and is calculated with equation (6):

$$\eta = \frac{1}{(\beta \cdot \eta_{14})^{-1}} \tag{6}$$

where η_{14} is the global efficiency, computed as: $\eta_{14} = \eta_{12} \cdot \eta_{34} = 0.97^2 = 0.941$. As this is a series aggregate with a single power branch, the output distribution coefficient is $\beta = 1$.

With these notations the transmission function of the forces will be:

$$F_1 = \frac{1}{\eta} \cdot \left(-F_4 \cdot \frac{v_4}{v_1}\right) = \frac{1}{\eta} \cdot \left(-F_4 \cdot \frac{1}{i_{14}}\right) = \frac{1}{\eta} \cdot \left(\frac{3}{2} \cdot F_4\right) \tag{7}$$

or

$$F_1 = 1{,}4115 \cdot F_4$$

Figure 4 shows the geometrical model of the gripper system. In the case of this constructive solution gripping is achieved by form and friction.

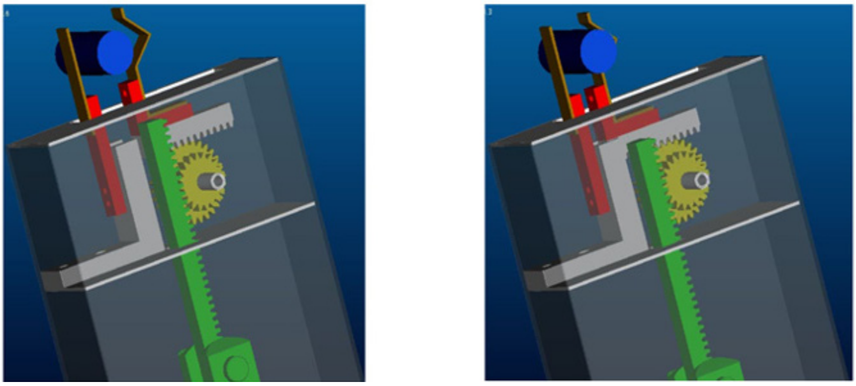

Fig. 4. The geometrical model of the gripper system.

The utilised pneumatic muscle is the smallest of the current product range of Festo AG & Co (MAS-10-45N-AA-MC-O-ER-EG). Its diameter is of 10 mm, and the length of the active part is of 45 mm. Upon being fed air at a pressure of 6 bar, the muscle shortens by 9 mm, representing 20% of its initial length.

The characteristic diagrams of the pneumatic muscles, as well as the MuscleSim application developed by Festo indicate that for a 4 mm axial contraction the muscle develops a force of 207 N [6, 7]. Under these circumstances the maximum mass of the object that can be seized by this gripper system is determined by equation (8):

$$m = \frac{\mu \cdot F_4}{(g+a_S)\cdot S} = \frac{\mu \cdot \frac{F_1}{1.4115}}{(g+a_S)\cdot S}\frac{0,2\cdot \frac{207}{1.4115}}{(9,81+10)\cdot 2,5} = 0,592\ kg \tag{8}$$

where: g = 9.81 m/s^2 is the gravity acceleration; a_S = 10 m/s^2 is the emergency stop deceleration; μ = 0.2 is a friction coefficient and S = 2.5 is a safety coefficient.

Figure 5 presents the functional model of the gripper system obtained by means of the MatLab SimMechanics module.

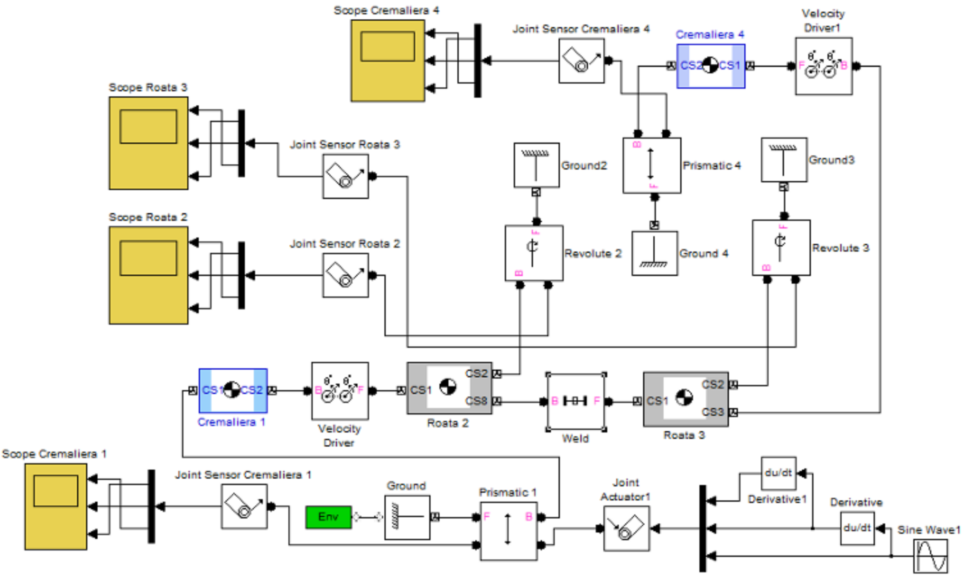

Fig. 5. The functional model of the gripper system.

The motion of the gripper system is generated by a Sine Wave block, which was selected for the discussed system because of the similarity of the pneumatic muscle's motion behaviour to a sine curve. The output quantity of this block is a linear displacement applied to rack 1 and is given by equation (9):

$$s(t) = A \cdot \sin(\omega t + \varphi) = 9 \cdot \sin\frac{\pi}{2}t \quad [mm] \tag{9}$$

where A is the amplitude of the motion, ω – its pulse, and φ is the initial phase.

Figure 6 shows the motion parameters of gears 2 and 3 upon applying the above described sine signal for 2 seconds.

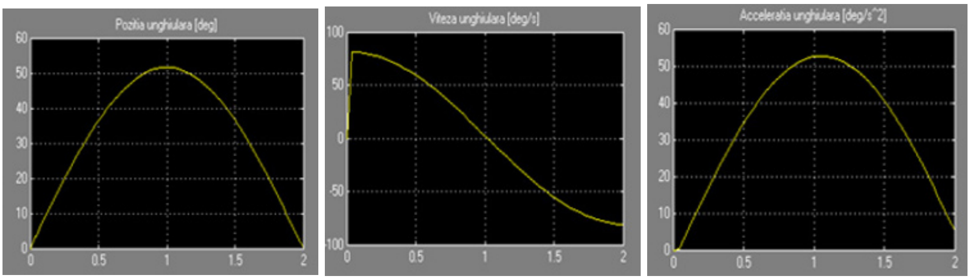

Fig. 6. Variation of the rotation angle, angular velocities and angular accelerations of gears 2 and 3 versus time.

It can be noted that for a 9 mm displacement of Rack 1, gears 2 and 3 turn synchronously by 51.56º.

Figure 7 shows the evolution of displacements [mm], velocities [mm/s] and acceleration [mm/s^2] of Rack 4 versus time.

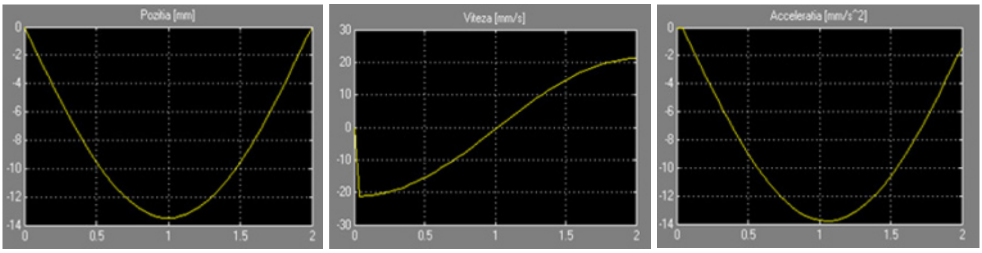

Fig. 7. Evolution of the position, velocity and acceleration of Rack 4 versus time.

The first graph reveals that a 9 mm displacement of the pneumatic muscle causes Rack 4 to move by 13.5 mm. Further it can be noticed that the beginning of the motion features a sudden leap of the velocity up to 21.2 m/s, after which the motion continues in a smooth manner, following the sine motion imposed by the pneumatic muscle. This sudden leap occurs at the beginning of the motion, before contact with the object is achieved, and does not influence the gripping process.

3 Conclusion

Within the context of a global increase in demand for industrial robots, their gripper systems need to undergo significant development such as to meet the requirements of the Industry 4.0 concept. In this respect the paper presents and discusses an innovative variant of a pneumatic muscle actuated gripper system. Characteristics of this gripper are constructive simplicity, low weight, and more importantly, the compliant behaviour specific to pneumatic drives. The latter characteristic of pneumatic muscles led to the concept of deploying this gripper system in applications requiring adaptability to concrete circumstances of object manipulation.

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