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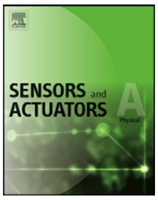

High performance integrated electro-hydraulic actuator for robotics – Part I: Principle, prototype design and first experiments�

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abstract

We design a new high performance integrated electro-hydraulic actuator (IEHA). We propose a new solution to a still open question in robotics, to provide an efficient and compliant actuation. The proposed actuator, which is dedicated to motorize independently each joint of a robotic system is designed to be fixed as near as possible to the joint itself, enhancing the performances while reducing the usual drawbacks of classical hydraulic actuation. The novel IEHA contains an integrated micro-pump with a floating barrel allowing the inversion of the flow direction without inverting the rotation of the input electric motor. The integration of a micro-valve and a rotary hydraulic distributor ensure the compactness of the proposed solution. In this paper, first, the proposed hydraulic actuation principle is given in detail. Then the designed prototype and the first experiments are presented demonstrating the novelty and the efficiency of our solution.

Nomenclature

E	eccentricity, m
R_b	radius of the interior ring, m
L_p	piston length, m
S_p	piston surface, m^2
V_p	volume of oil aspired by one piston, m^3
Q	micro-pump average flow, m^3/min
N_p	global pistons number, –
	rotation speed, rpm
n_c	number of pistons layers, –
n_p	number of pistons by layers, –
D_p	pistons diameter, m
R_a	input shaft radius, m

1. Introduction

Nowadays, actuating robotic systems is still one of the biggest challenges. High performances in actuation are needed to enhance behaviors of these systems, while more and more requirements are needed for safety, compliant and human-friendly. Especially, since new generation of robotic systems have to interact with humans and with the environment. This interaction is essential not only in the field of humanoid robotics, it is also applicable to rehabilitation devices, such as prothesis and orthesis. For instance, within the field of humanoid robotics, essential and desirable properties for actuators have to include: (1) high power to mass ratio; (2) ability to produce high torque at low speed; (3) highly integratable (reduction of occupied volume); (4) able to generate smooth human-like movements. It is clear that for safety reasons, the actuator must also ensure active compliancy of the robotic system.

Actuation of robotic system such as humanoid robots is basically based on two major solutions: (1) Electric; and (2) Hydraulic. Electric actuation is typically used for humanoid robots, like HRP series (2, 3 and 4) [1]; HONDA ASIMO [2]; TOYOTA humanoids [3]; H7 [4]; Johnnie and LOLA [5]; HUBO series [6]; NAO [7]; iCub [8]; WABIAN-2 [9] and ROBIAN biped [10]. It is worthy to note that electric actuators have the advantages of reduced cost and their easiness of usage and control. However, a number of disadvantages appear when using electric motors with mechanical reduction device. First of all, due to the quasi-rigid connection between the motor and its payload, without developing a specific control algorithm or adding supplementary mechanical components, it is difficult to produce the stiffness changes needed for safety. This issue was investigated by numerous researchers from both sides of control and mechanical design. Hogan et al. developed an impedance control method to ensure compliant interaction with the environment be possible

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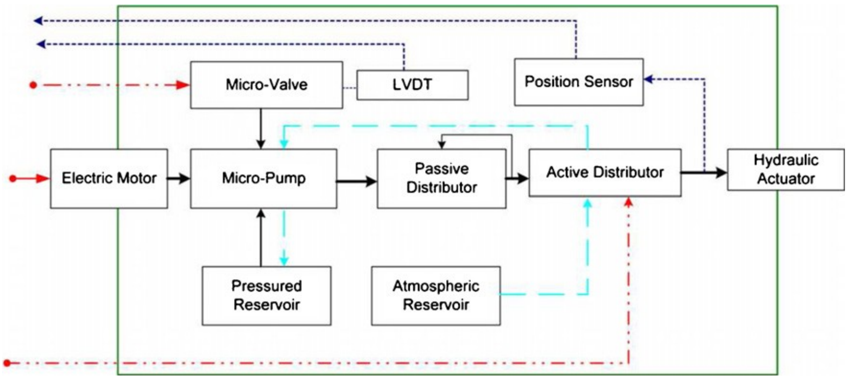
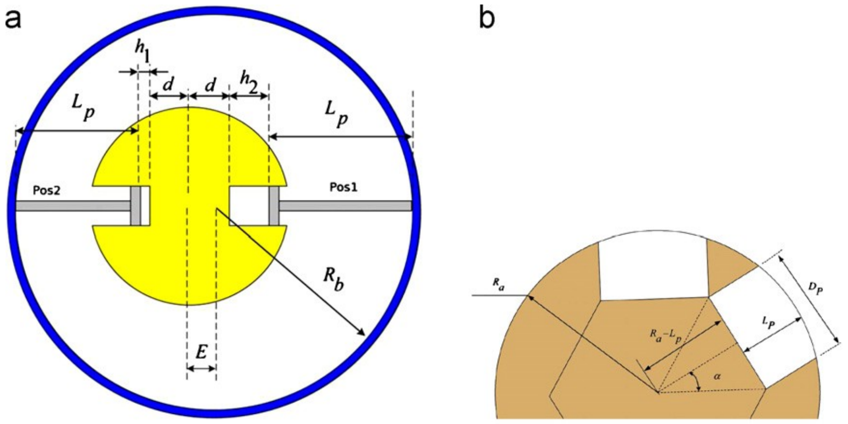


Fig. 1. IEHA functioning principle: the red arrows represent the control signals of the input electric motor and the micro-valve displacement. The black arrows give the directions of the power transmission from the input to the output. The sensor measurements of the linear variable differential transformer (LVDT) sensor [23] giving the micro-valve position and the pressure in the two lines of the hydraulic actuator are depicted with blue arrows. (For interpretation of references to color in this figure legend, the reader is referred to the web version of this article.)

[11]. In the other side, Pratt and Williamson. developed at MIT the elastic actuator to enable joint compliance [12]. At Stanford university, Khatib et al. proposed a hybrid device by associating two actuators (an electric and a pneumatic) to increase the ability of their D2M to handle safe interaction [13]. Recently, at IIT (Genova), Tsagarakis et al. added four linear springs around the reducer output shaft to vary the stiffness of a motor-reduction device aimed to equip it to the second version of their iCub humanoid robots [14]. In the same way, Choi et al. from KIST developed an interesting solution based on including leaf springs with changing fixed points [15]. For all the above mentioned solutions, adding mechanical components (passive or active) leads irremediably to a substantial increase on the size and the complexity of the mechanical hardware. Although, a high gear box reduction ratio has to be chosen, it is always limited and cannot be increased indefinitely, which is clearly a limitation if the optimisation of the energy consumption is needed. Finally, electric actuation systems have to be sized for the worst case, defined by satisfying the instantaneously highest torque required (”peak” torque for a long period). This leads also to a non-optimal selection: a large electric motor, which will not be used all the time at its full capacity.

Another interesting technology to actuate robotics systems such as humanoids is the use of hydraulic energy. This technology, based on a hydraulic central group, showed exceptional performances in these last years. The DB and CB humanoid robots series built in close cooperation between ATR, Kyoto and the SARCOS company are based on such solution with the uses of hydraulic central group and servo valves [16]. One huge motor-pump is usually used to produce the pressure and the flow necessary to actuate several joints. This solution was able to demonstrate high performances, for large output forces as well as for generation of smooth movements. However, the hydraulic central group solution suffers from several drawbacks. First, and in our opinion the major one, is related to the whole system dimensioning leading to the necessity to satisfy the worst case requirements in terms of flow and pressure needed by all the joints. Another disadvantage, is linked to the the increase of the whole size and the weight of the system, due to, one servo-valve has to be included for each hydraulic actuator. Carrying on the hydraulic central group limits drastically the use of this technology in the case of the development of autonomous systems. The used servo valves to control hydraulic actuators leads also to severe decrease in back-drivability. Further drawback concerns the hydraulic tubes passing through the joints needed to connect the hydraulic motors to the central group. This induces an increase of potential leakage in the connections and pressure drop.

Based on the analysis of above mentioned solutions, several researches investigate how to merge them in order to take benefit of their advantages. This leads to a technology named Hydrostatic Transmission, first proposed for robotic application by Bobrow and Desai at the beginning of the 1990s [17]. Almost ten years later, Habibi et al. introduced the concept of ElectroHydraulic Actuator (EHA) based on a fixed displacement pump with speed variation with a controlled motor. They also designed a symmetrical linear actuator to show high performance in moving a 20 kg load,



Total distance achieved by the pistons

Pistons distribution

Fig. 2. Stroke calculation: geometrical description.

through a high pressure and specific high gain control laws [18]. The same EHA was used to carry out high precision micro and nano-manipulation tasks [19]. Kargov et al. have developed a miniaturised hydraulic actuation system for artificial hands [20]. Recently, Nakamura et al. carried out hydrostatic transmission research to activate an anthropomorphic robot hand [21] and a new joint for a humanoid robot [22]. The objective of our approach is the development of new highly Integrated ElectroHydraulic Actuator (IEHA), which uses a uni-directional built-in volumetric radial pistons micro-pump to control linear or rotary hydraulic motors.

The developed solution satisfies all the performances needed for actuating a robotic system, since that each joint will have its own IEHA dimensioned to fulfill the force and the velocity requirements. In order to reduce the leakages and the pressure drops, the IEHA is designed to be placed as near as possible to the joints. This paper is organised as follow: in the second section, the proposed IEHA principles are explained. Hydraulic scheme is presented to show the proposed solution. In the third section, the design and the manufacturing stages of a prototype are presented and its characteristics are listed. Finally, experimental results are presented.

2. IEHA functioning principle

As introduced in the previous section, it is clear that our aim is to take advantage of the high power to mass ratio present by hydrostatic transmission systems. As mentioned by Habibi [18], the main components of an EHA are: an electric motor, a pump (may be bidirectional or not), pressure and positions sensors and its reservoir(s). The last component is the hydraulic actuator itself, which can be either linear or rotary. Our basic idea and novel challenges in developing our IEHA, concern in one hand the integration of all these components in the smallest space possible while simplifying its control. Our solution fulfils these requirements using an unidirectional integrated micro-pump actuated with an electric motor, which rotate at constant speed. The micro-pump is connected through built-in reservoirs to a standard linear (non-symmetric) or rotary actuator. We have no need to design neither a specific actuator nor use of sophisticated control strategies, which leads to reduction of its total cost, and hence making it attractive for robotic applications. In this section, the IEHA components functioning principle is presented, then the hydraulic schemes of the several components are detailed.

2.1. Hydraulic components description

The proposed solution of the hydrostatic transmission is based on the power transmission from an electric motor to a hydraulic actuator. The basic idea consists of converting an electric power to a mechanical one using a highly integrated micro-pump producing a hydraulic pressure and a flow. Fig. (1) provides a functioning principle description of our scheme. Between the input (i.e. electric motor) and the output (i.e. hydraulic actuator) are the three main components that constitute the IEHA, these can be distinguished: (1) the micro-pump; (2) the micro-valve; and (3) the passive distributor. In the heart of the IEHA, a volumetric micro-pump produces hydraulic energy by an electric motor without any speed reduction. This hydraulic energy is converted to a mechanical one in order to drive a linear or rotary hydraulic actuator. In order to vary the power produced by the micro-pump, a micro-valve is integrated inside the IEHA in order to vary the micro-pump stroke through a displacement control inducing a variation of the produced flow and pressure. The micro-valve integration will bring a tremendous advantage in terms of efficiency in comparison to classical centralised hydraulic systems. Since the IEHA is equip, in standalone mode, each robotic device joint, theoretically (almost) no power will be consumed when insuring a desired position of that joint. The two hydraulic actuator chambers will be locked while the micro-valve will ensure almost zero stroke. In the following subsections, the functionalities of three main components are detailed.

2.1.1. Micro-pump stage

To produce hydraulic energy, the stroke has to be changed. One can chose either speed controlled pumps with fixed stroke or volumetric pumps. The later kind requires a displacement (position or orientation) control of the pump components in order to vary the stroke. The displacement to be controlled is either angular whenever axial pumps are used or linear in the case of radial pumps. Due to geometrical constraints in designing robotic systems, especially anthropomorphic humanoid robots, we select to based our design on radial pumps. It is worthy to note that using almost constant speed pumps will bring several advantages. As we can avoid the use of mechanical gear boxes while will deeply simplify the motor control. Hence, either DC or brushless motors can be indistinctly used to actuate the micro-pump. The stroke of a classical radial pistons pump can be changed by controlling the eccentricity between the main shaft linked to the input electric motor and the pump-barrel. The pistons, which are in contact with the hydraulic pump-barrel, are driven radially, changing from aspiration to repression states. For a given direction of rotation, the pistons approach the centre when the angle belongs to $[0, n]$ and move away with interval $[n, 2n]$. While moving away from the centre, a piston aspires oil, and drives it back when it approaches. Thus, it is enough to keep the same direction of rotation of the input axis, and to change the eccentricity to exchange the roles of aspiration and repression. The eccentricity change is allowed thanks to the radially movable pump-barrel. The proposed solution for our IEHA is based on these considerations and constitutes a real innovation compared to the traditional ones [24]. Hence, the IEHA micro-pump stage will be able to invert the flow direction without inverting the direction of rotation of the input motor. Once again, this will simplify the motor control while increases the dynamics properties of the IEHA since the input electric motor is one direction constant speed device. Another consideration which has to be taken into account is related to the optimal number of pistons (n_p) that the micro-pump stage has to have. This pistons number is related to the flow needed (i.e. the joint speed) and the available space, the technological considerations shall directly influences the over-all performances of the proposed IEHA in terms of producing hydraulic energy. In order to identify the optimal distribution of pistons for a given IEHA size, the theoretical average flow produced by the micro-pump is first established. Then, a geometrical study helps to identify the optimal pistons number. Fig. 2(a) presents a simplified IEHA with two pistons.[1] In this example, the two pistons are located respectively in the two dead points, named high and low and defined as following. The high dead point corresponds to the position where the piston leaves the maximum of its housing (Pos 1) and the dead bottom centre is where the piston returns to the maximum position in its housing (Pos 2).

In order to calculate the variation of the micro-pump stroke, defined by the volume of oil produced during a rotation for a given eccentricity (E), the distance which the piston achieved during half-rotation related either to the aspiration or to repression has to be established. First of all, two obvious geometrical relations using the radius of the interior ring R_b, and the piston length L_p are defined

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[1] In the general case depicted in Fig. (3), these two positions are those occupied by the same piston when switching from aspiration to repression states.

(see also Fig. 2(a)).

$$E + d + h_1 + L_p = R_b \quad (1)$$

$$d + h_2 + L_p = E + R_b \quad (2)$$

where h_1 is the distance between the piston at the dead bottom position and the bottom of its chamber. In the same way, h_2 is the distance between the piston at the high dead point and the bottom of its chamber. The other geometrical quantities are directly defined as shown in Fig. 2. Subtracting Eq. (1) from (2), we can express the eccentricity (E) by:

$$h_2 - h_1 = 2E \quad (3)$$

By taking into account the surface of piston S_p, the volume of oil aspired and driven back during a rotation is thus:

$$V_p = 2ES_p \quad (4)$$

if the micro-pump has a total number of N_p pistons and its rotation speed is . The micro-pump average flow is then Q given by the following relation:

$$Q = N_p V_p \quad = 2N_p ES_p \quad (5)$$

As shown by Eq. (5), the flow produced by the micro-pump is a linear relationship with the number of pistons and is proportional to the surface of each piston. Once the product ($N_p \times S_p$) is chosen, the question concerning the distribution of these pistons has to be solved. From a kinematic point of view, as the total flow is equal to the sum of the flows produced by all the pistons, it is preferable, for a given space, to decrease the surface of each piston and to increase the total number of pistons. This will drastically reduce the ripple created by the alternating aspiration and repression phases. This aspect can be shown by analysing the individual flow produced by each piston. The choice is consolidated by a dynamic analysis of the efforts produced by the pistons on the pump-barrel. That is, a great number of pistons with small surfaces will generate distributed efforts on the ring, improving dynamic balancing of the total system. This will facilitate moving the pump-barrel in order to change the eccentricity and will also reduce the noise. It is clear that for reasons of constraints in manufacturing, it is necessary to leave sufficient matter between the pistons making it possible to balance the pressure created in the individual chambers. To identify the optimal number of pistons (N_p), a geometrical analysis based on the available space of the input shaft leads to identifying the maximum number of pistons (n_p^{max}), which can be housed on a given input shaft diameter. Fig. 2(b) gives a simplified sketch of the shaft where the pistons chambers are housed; D_p is the piston diameter and R_a is the input shaft radius. The angular position of each piston is defined by an angle equal to 2ˎ. Hence, n_p^{max} for a given D_p and R_a can be expressed by the floor function ∗:

$$n_p^{max} = \mathbf{I}\left(\frac{n}{ˎ} = \frac{n}{\arctan \; D_p/2(R_a - L_t)} \right) \quad (6)$$

To optimise the available space and reduce the overall IEHA dimensions, several layers of pistons can be housed in the longitudinal direction of the input shaft. Hence, the total number of pistons N_p can be established by:

$$N_p = n_c \times n_p^{max} \quad (7)$$

where n_c is the number of layers. Theoretically, the maximum number of layers can be equal to n_p^{max}, since an angular offset of ˎ has to be introduced between layers. Increasing the number of layers will also reduce the ripple of the produced flow. Practically the number of layers has to be limited due to manufacturing constraints induced by housing oil paths inside the input shaft. Fig. (3) shows the proposed staggered arrangement of $n_c = 3$ layers of pistons chosen for our first micro-pump prototype. The middle layer is shifted by an angle ˎ relative to the two extremes. As the layers are parallel, their respective pistons play the same role of suction and discharge at the same time, and hence, their oil paths are connected.

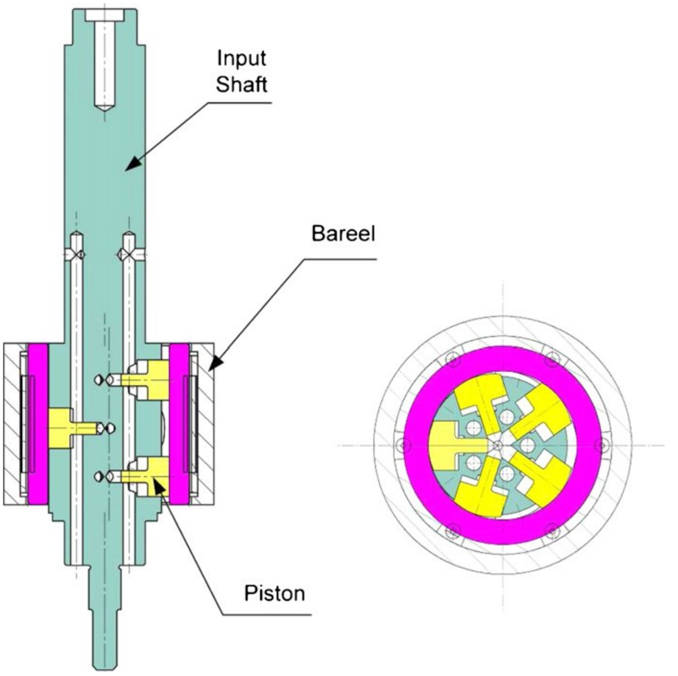


Fig. 3. First prototype micro-pump stage.

2.1.2. Micro-valve stage

The next stage is related to the micro-valve, which has the role of adjusting the eccentricity value. Moving the pump-barrel between the two extremal positions gives by a positive value to a negative one to change the pump stroke, and hence the produced flow. Actuating this degree of freedom may be accomplished either electrically or hydraulically. However, the necessary force which has to be applied to the pump-barrel in order to change the eccentricity can be large. For instance, if the following values are considered: the maximal pressure of P = 100 bars, pistons diameter D_p = 5 mm, and number of layers n_c = 3, the maximum value of this necessary force can be almost equal to 600N. This force can estimated by applying equilibrium principle to the pump-barrel as follow:

$$F_{max} = P n_c n \left(\frac{D_p}{2} \right)^2 \quad (8)$$

As it is clear the adopted solution for the IEHA is an electro-hydraulic system, it is natural to use the hydro-electric power to vary the eccentricity. So, a linear jack must be integrated in the direction of the eccentricity (perpendicularly to the input shaft). For reasons of symmetry, two simple effect jacks CH_{e1} and CH_{e2} are integrated on both sides of the pump-barrel in order to move it with regard to the fixed frame, as depicted in Fig. (4). Fig. 4(b) corresponds to the a null value of the eccentricity (E = 0). To control the eccentricity, an integrated micro-valve with two lines and three positions is used, as shown in Fig. (4). Once the linear voice-coil of this micro-valve is activated in a positive direction, the micro-valve body takes position (I) (see Fig. 4(b)) allowing high-pressure fluid P be sent to the left jack CH_{e2} and, at the same time, be driven back T by the right jack CH_{e1}. When the linear voice-coil is activated in the negative direction, the micro-valve body takes the position (III) and the connections P and T are automatically reversed.

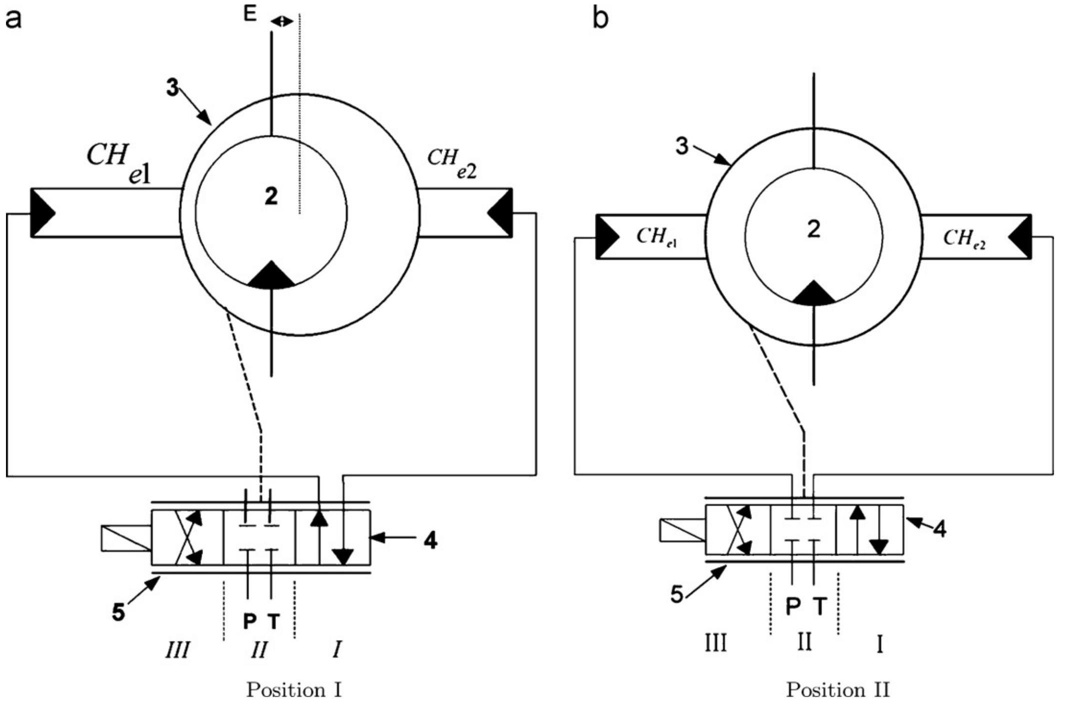


Fig. 4. Micro-valve hydraulic scheme presented in positions I and II.

Once the eccentricity reaches the desired value, the micro-valve body is moved to the closing position that corresponds to middle (II). Thus, the eccentricity value remains constant as long as the micro-valve body is kept in this rest position. It is thus necessary to have a control loop linking both the micro-valve body (4) and the pump-barrel (3). This control loop is carried out mechanically in the IEHA proposed solution by physically connecting the micro-valve external fixed part (5) to the pump-barrel (3) (dashed line in Fig. 4).

2.1.3. Passive distributor

The above stages including the micro-pump, the micro-valve and a voice-coil actuator to control the micro-valve position can be seen as an integrated volumetric (stroke variable) pump. In general, there is no reason to use a symmetric hydraulic actuator since the range of motion in both direction is different. In the case of non-symmetric hydraulic actuator, the quantity of oil which leaves one chamber is not equal to that which returns back, but the pump, always drives back almost what it aspires. To solve this problem Habibi et al. [18] propose the construction of a special actuator, in which the two chambers are equal. This solution limits the use of this special kind of actuators. Moreover, even if one uses a symmetrical jack, the phenomenon of the leakage (internal and external) always persists, requiring re-injection fluid to the circuit, to guarantee normal operation. To solve these technical difficulties and to allow the use of non-symmetric actuators, it is necessary to include in the IEHA a reservoir, which must always be connected with the driven back line. Hence, three lines, three positions valve called a “passive distributor” is included in the proposed IEHA. The position of this distributor is determined by the differences in pressure at the output of the micro-pump stage. Its main role is to connect the output of the micro-pump with the first chamber of the actuator. At same time, the input of the micro-pump is connected with the reservoir which itself is linked with the second chamber. The two chambers reverse their roles once the direction of fluid circulation is reversed in the circuit in order to move the joint in the opposite direction. Fig. (5) provides a hydraulic diagram which includes a passive distributor. This distributor may be either linear or rotary.

2.2. Hydraulic scheme

In order to explain how the IEHA is able to actuate a system such as a robotic limb, the hydraulic scheme is detailed in Fig. 6(a). Depending upon the pressure difference between the two lines A and B, the passive distributor introduced above takes one of three positions namely, S_1, S_2 and S_3. If the pressure, in the line A, noted by P_A, is smaller than that in the line B, named P_B, the distributor takes the position S_1, in which the right chamber of the linear (or rotary) actuator linked to the segment of the robot is connected to the atmospheric reservoir R. Line A is connected with a reservoir R while the line B is connected with the left chamber of the actuator through the P line. This activates the piston of the actuator to move it towards the right. In position S_3, the role of lines A and B is reversed leading to motion generation of the actuator towards the left. In the position S_2, both pressures P_A and P_B are equal and the payload represented by the actuator is completely disconnected from the micro-pump stage. Hence, the actuator keeps the same position without theoretically consuming any energy. In fact, it will only be necessary to compensate for the possible leaks, which would exist between both chambers of the actuator. The passive distributor is non-symmetric rotary, thus allowing us to have different durations whenever switching from the position S_1 to the position S_3, and reversely. Going from S_1 to S_3 will take slightly more time than from S_3 to S_1. This allows during, in one direction, to draw out the internal leakages present in the internal space where a pressure P_E occurs and to bring them to the reservoir R. On the other hand, as the passive distributor changes its position according to the difference between the pressures P_A and P_B, two lines, P and T can be added to the distributor outputs such as the line P is always connected to the high pressure while line T is linked to the reservoir R. Both lines P and T will be used to feed the micro-valve, as detailed in Fig. (4), making the proposed IEHA completely autonomous and enhance its high level of integration. Finally, a

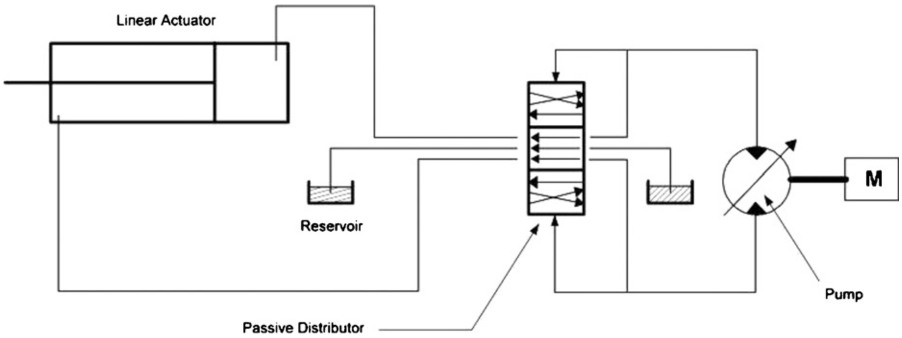


Fig. 5. Passive distributor.

Table 1
Part numbers and corresponding names

Number	Definition
1	Electric motor
2	Micro-pump stage
3	Micro-pump bareel
4	Micro-valve
5	Magnetic coil to actuate the micro-valve
6	Reference part
7	Passive distributor closure
8	Reservoirs

Table 2
IEHA main dimensions

Parameter	Value
R_a (mm)	3
L_p (mm)	3
D_p (mm)	5
P_{max} (bar)	100
Length (mm)	80
Width (mm)	40
Height (mm)	40

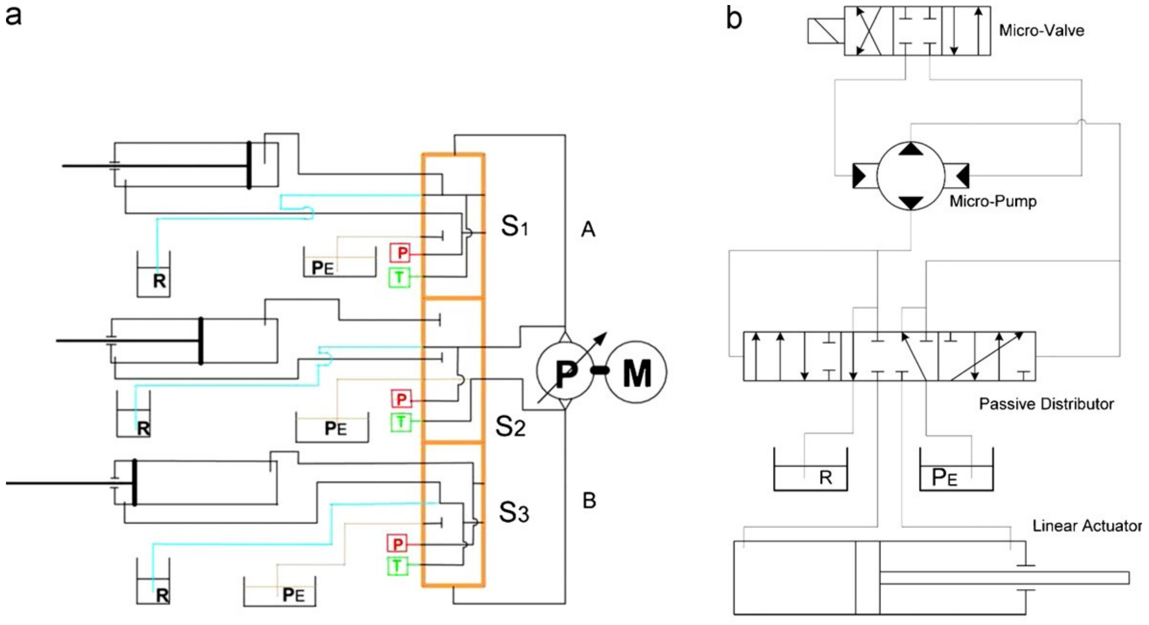
standard hydraulic description of the proposed IEHA is given in Fig. 6(b).

3. IEHA prototype design

We developed a IEHA prototype to demonstrate the real performances of the system. Fig. (7) shows the CAD scheme of the IEHA first prototype designed. Table (1) gives the part numbers and their corresponding functionalities of the main components stages described above.

3.1. Dimensions and constraints

Since, the IEHA is dedicated to actuate a robotic system by placing it near as possible to the joint, dimensional constraints was taken into account. An example of these parameters is given in Table (2) for the IEHA for the actuation of an active toes joint of a humanoid robot HYDROïD[25]. The external dimensions are fixed to meet our desire to locate the above mentioned IEHA in the calf. This first prototype is designed to reach a maximal pressure of 100 bars.



Passive Distributor Positions S1, S2 and S3

Normalized Description

Fig. 6. IEHA hydraulic scheme.

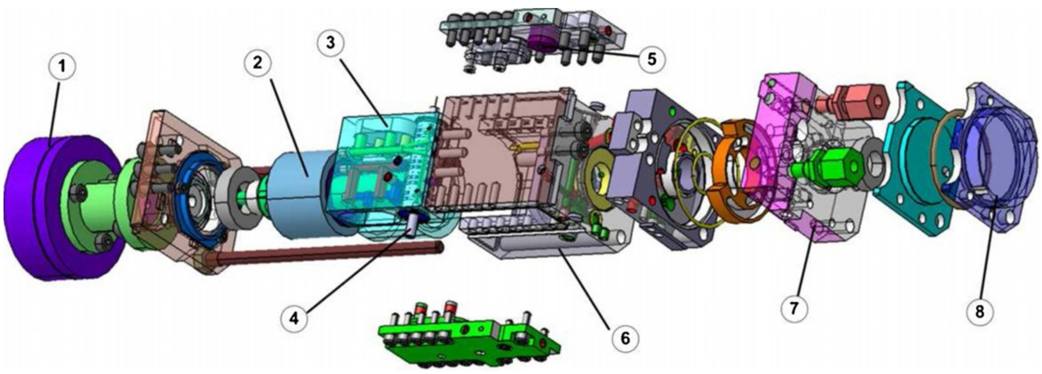


Fig. 7. IEHA split CAD scheme.

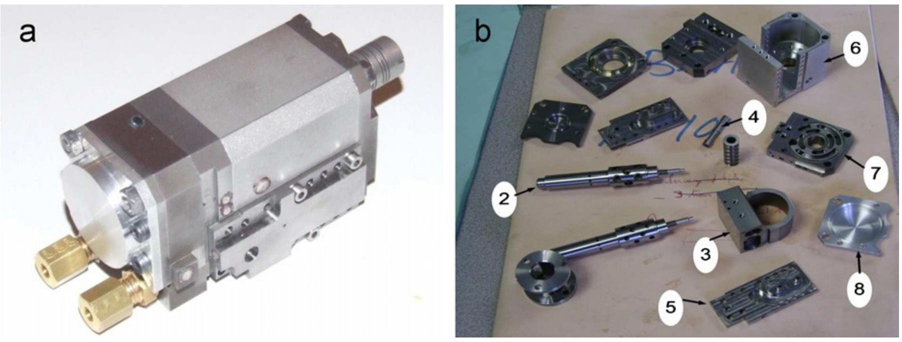


Fig. 8. IEHA real prototype and its several parts.

3.2. Realisation

Fig. (8) presents a photo of the first IEHA prototype manufactured and its several parts. The dimensional constraints lead us to ensure the waterproofness with high quality contact surfaces. This first prototype was tested to demonstrate the effectiveness of the proposed concept.

4. Experimental results

In order to carry out experimental results, a test-bed device dedicated to the IEHA is designed and developed. The main components of this test-bed are given in Fig. (9). Flow Sensors C_D are installed at the IEHA input and output levels. Two pressure sensors C_P are also used in order to measure the pressure produced at the micro-pump stage. A tachymeter generator is installed on the electric motor shaft actuating the system, to measure its rotation speed. The voltage applied to the electric motor and the absorbed current are also measured with the aim of considering the electric power consumption. A flow reducer L, playing the role of a payload is also included as part of the test-bed device. Closing this reducer increase the value of the payload at the IEHA output level. To always guarantee that the flow reducer plays its role at the output level, four by-pass vanes C_l are also used. These vanes also allow the isolation of the passive distributor, this is used to validate its function by driving tests with or without the distributor. A filter (F) and a reservoir (R_v) are also added to the test-bed setup. This allows us to carry out continuously several experiments as detailed in the following subsections:

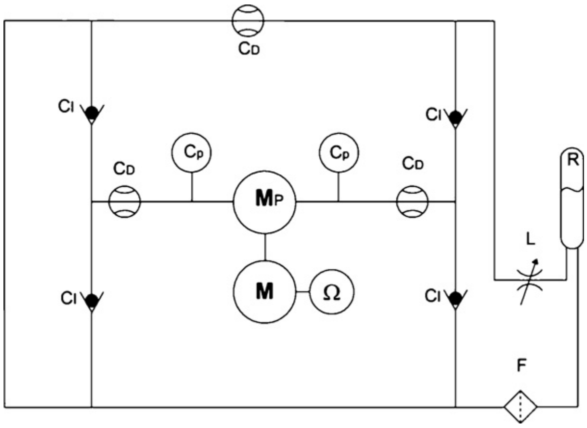


Fig. 9. Test-bed hydraulic scheme.

4.1. Experiment 1: effect of the eccentricity on the characteristic (flow, pressure)

Several trials allowed us to identify good regulations of mechanical offsets inside the the micro-pump stage. This allowed us to estimate at best the values of theoretical flow to carry out this experiment, for which three values of the eccentricity E (mm) are fixed (0.07, 0.14 and 0.34). For each value of E, the characteristic giving flow according to the pressure is recorded. Fig. (10) shows three characteristic curves showing the relation between the flow and the output pressure. A shifting of the characteristics towards the right upper corner of the graph is observed whenever the eccentricity is increasing. This corresponds logically to an increase of the IEHA converted power function to the eccentricity.

4.2. Experiment 2: Lifting a mass of 38 kg at a speed of 2 cm/s

The second experiment concerns a test of real actuation without using the test-bed device in order to quantify the IEHA capacities to move a given payload. Fig. (11) gives several snapshots illustrating

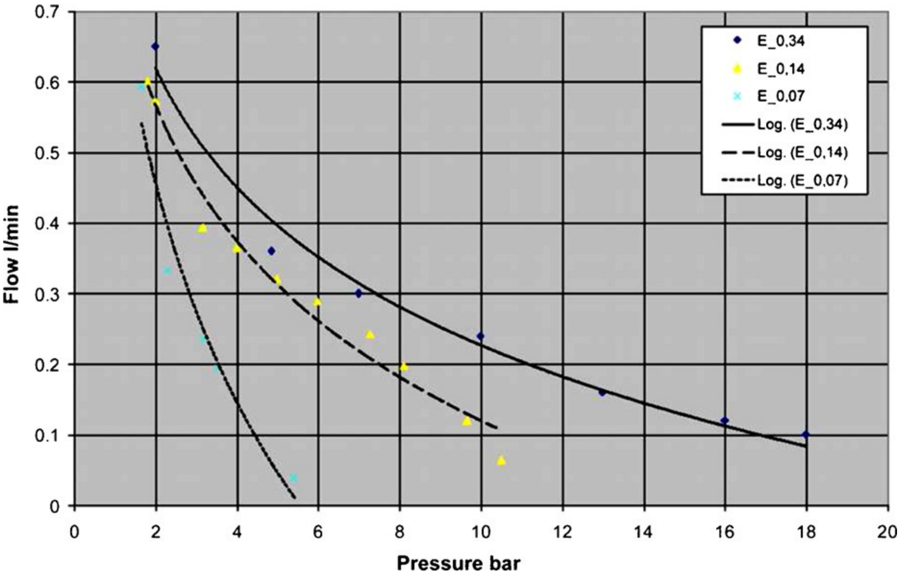


Fig. 10. Flow versus pressure function of the eccentricity.

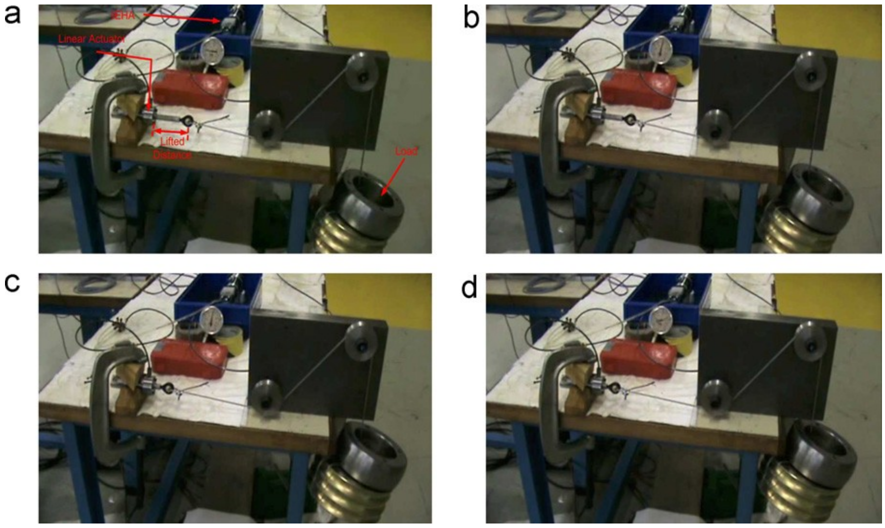


Fig. 11. Lifting of 38 kg Load at a speed of 2 cm/s.

the experiment lifting. In this experiment, the IEHA is connected to a linear actuator which its piston has a radius of 1 cm and a length of 12 cm. The linear actuator output is connected by means of a cable and a pulley to a mass that is able to move vertically. Several tests, with an increasing mass, were carried out. The objective of these tests were to evaluate the maximum payload and the corresponding lifting speed. A first successful test with a 25 kg load allows us to measure a lifting speed of 2 cm/s. The same speed was obtained with a payload of 38 kg. These results show, clearly, the IHEA potential capabilities not only in terms of high power to mass ratio since it uses the hydraulics but also a nice power to volume ratio due to a high level of integration developed in the proposed work.

5. Conclusion

In this paper, we presented a new integrated hydrostatic actuator for humanoid applications. First, analysis of existing solutions were carried out in order to focus on a solution that is able to produce smooth, natural and strong movement. The challenge was to develop a solution able to produce both isotonic (low force at high speed) and isometric (large force at low speed) modes. The basic idea developed in this paper focused on an IEHA converter with a continuously reducing the speed at the output level (i.e. joint) while the input speed is almost constant. The reduction is carried out through a variation of a displacement (an eccentricity) between two extremal values (one positive and one negative) while keeping the same input rotation direction. The proposed IEHA was presented, the several subsystems (micro-pump, micro-valve and passive distributor) were detailed. The functioning principle of each subsystem were given. In order to validate our concept, a highly integrated prototype with drastic geometrical constraints ($40 \times 40 \times 80$ mm^3) was designed and manufactured. A hydraulic test-bed was developed and used to quantify the real performances of the proposed IEHA. This allowed us to carry out several experiments giving the variation of the flow and the pressure function of the eccentricity.

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