New Approach to Design of MEMS-Microfluidic Systems

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Abstract

The sufficient market need of reliable miniaturized products for industry, transport, etc. requires creation of new types of mini executive drives, which must feature with reduced vulnerability of their control parts to environmental or man-made stimuli, and with keeping the high value of transmission capacity **Nr** (kw./lb) of their executive parts. Therefore the said control part should be of hydraulic and/or pneumatic nature with no moving mechanical parts, restricted use of elastic mechanical elements, and with a few, if any, electric links. It is evident that the high value of transmission capacity should be kept in the embodiments of the new generation of mini scaled executive pneumatic or, rather hydraulic drives, equipped with static or flow-through hydraulic control circuitries. This approach is fruitful due to the following:
* Development of MEMS-Microfluidics will obviously result in creation of an integrated or modular Microfluidic Platform (**MFP**) where the input signal of any physical, chemical, or biological origin is being converted into an electric, hydraulic or pneumatic output signal.
* There has been discovered the possibility for creation of an Interface Transducer (**IT**) that would be able to convert (in the pure fluidic mode) a weak output electric, hydraulic or pneumatic signal from **MFP** into a relatively powerful hydraulic signal, capable of activating a valve-type hydraulically operated control unit (**CU**) of a mini (even of a macro) hydraulic or pneumatic drive (**H/P-D**). Consequently, for the first time there appears the opportunity for creation of such an innovative microfluidic modular assembly (**MiFluMA**) that would necessarily include all the said components (**MFP, IT, CU**) to operate mini and/or macro **H/P-D** by nano/micro or micro/meso scaled signal of various origins. This technology will be of researching interest and marketing need to industrial, energetic, medical, transports, utility, aerospace, defense, and security arenas.

Keywords: *Microfluidic Modular Assembly; pure fluidic interface transducer; mini drive.*

Introduction

The miniaturization of all the components of executive drives (valves, pumps, leverage, gear pairs, motors, etc.) is an imperative of the industrial development from at least cost-benefit, security and military points of view. Therefore, techniques and designs for miniaturization will be in progressive development under growing requirements of the market. Present-day's continuing process in the development of miniaturization of executive drives under simple scaling down the electro-mechanical, electro-hydraulic and electro-pneumatic components passes with keeping reasonable balance between the design and performance contradictions, and customized specification figures of the end products, see attached ***Flow Chart***. But the sufficient market growth thereof requires the creation of new types of mini executive drives, which must feature the reduced vulnerability of their control parts to harmful environmental or man-made stimuli, and the high value of unit transmission capacity $\mathbf{N}_r$ (kw./ lb) of their executive parts. Obviously, such an invulnerable control part should be of hydraulic and/or pneumatic nature with a few, if any, electric elements. And it is evident that the high value of transmission capacity shall be kept in the embodiments of a new generation of mini scaled executive pneumatic or rather hydraulic drives. This approach is true and beneficial for the following reasons:

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a) Development of MEMS-Microfluidics will result, at last, in the creation of alternate versions of Microfluidic Platforms (**MFP**) where the input signals of any physical, chemical, or biological origin (light, heat, smell, sound, etc.) are converted into hydraulic or pneumatic output signals.
b) There has been proved the real possibility for the creation of micro/meso scaled Interface Transducer (**IT**) that would be capable of only one-stage conversion of the said weak output hydraulic or pneumatic signal from **MFP** into a relatively powerful hydraulic signal, in turn capable of activating a valve-type hydraulically operated control unit (**CU**) of miniaturized hydraulic or pneumatic drive (mini **H/P-D)**.
c) CTRL Systems, Inc. has developed the novel design techniques (patent pending) as to creation of basic Microfluidic Component Kit (**MCK**), including static and flow-thru pure fluidic amplifiers (**IT**), pumps, valves, etc., that feature with use of either external power sources or internal energy of materials (e.g. shape memory alloys), energy of chemical reactions, and static energy of solid-liquid systems. The said micro scaled components must feature with absence of moving mechanical parts, restricted use of mechanical elastic elements and electric links. Evidently, the non-contact actuation must be utilized thereof, e.g. actuation by applying any techniques of heat transfer and exposure to electro-magnetic fields of various origins.

Innovative technology

The now-days' micro scaled pumps and valves are being designed for handling of low-power liquid flows thru integrated and/or modular MEMS-Microfluidic platforms-**MFP**. Therefore, the pneumatic and hydraulic low-pressure and low flow-through devices of the said **MFP** fail to activate directly a miniaturized, or even meso scaled valve-type **CU** of a mini **H/P-D** [1]. The challenging task of such atypical activation should be resolved by applying new design principles, while observing strong requirements to MEMS-Microfluidic components and systems [2, 3]. There may be suggested at least two novel options for accomplishing successfully this decision:
1) The pumps and valves of **MCK** are being non-traditionally designed for enabling the powered enough hydraulic signal, which should be capable of activating directly a valve-type, operated hydraulically, **CU** of a mini **H/P-D**. CTRL Systems, Inc. may suggest to the interested partners the properly designed (for pressure and flow rate) embodiments of micro/meso scaled pumps and valves that contain only a few elastic mechanical parts and electric links, and are being actuated by thermal energy (light, heat transfer, chemical reactions, etc.) or by electro-magnetic energy. There is an evident necessity of nano-micro-meso scale signal transition therein [4].
2) There must be included in **MCK** the micro/meso scaled Interface Transducers (**IT**), embodied optionally as the innovative static or flow-thru pure fluidic amplifiers, where pneumatic, hydraulic and electric input signals shall be used [4]. Use of electro-hydraulic servo control units in design of said pure fluidic amplifiers opens way for utilizing present-day sophisticated digital electronics (e.g. IC assemblies of Moog Inc., Parker Hannifin Corp., etc.), which should speed up pushing the innovative technology of CTRL Systems, Inc. onto the market.

At present CTRL Systems, Inc. owns unique prototype of **IT** for flow-thru hydraulic circuitries in the embodiments of pure fluidic jet flow pneumatic-to-hydraulic (**JPHA**) and jet flow hydraulic-to-hydraulic (**JHHA**) amplifiers-converters of new generation, see attached **Snapshot**, which feature with improved I/O performances, namely with high efficiency (Ó 25%) and fine repeatability (å 100%), outstanding pressure recovery coefficient (å 1.0), big values of pressure gain (å 100) and flow rate gain (å 60), fast response (Ò 30 msec), small overshoot (å 30%) and transient oscillations (2 ÷ 2.5), phase delay in the range of 1/8÷1/4 ´ at å 20 mps of high-impulse liquid jet flow, see **Table 1**. Though this prototype has been made in flow consuming embodiment (Ò 1.0 gpm), the power loss in its neutral position is nearly ten times less than one at typical designs of pilot operated directional and servo valves. There is also the real possibility to develop the static **IT** in the embodiments of pneumatic-hydraulic and hydraulic-hydraulic

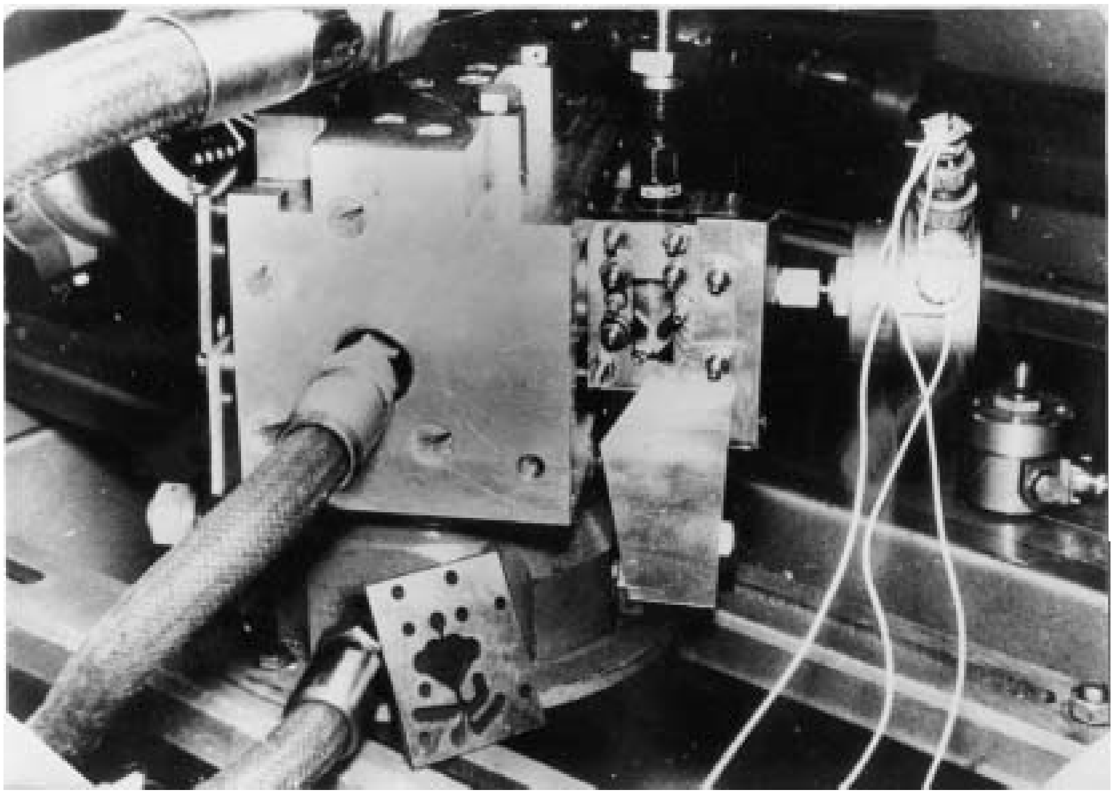
Operating indices of meso scaled JPHA (prototype). Table 1.

No.	Specification Figures	Meso scaled prototype of JPHA	Notes
1	**2**	**3**	**4**
1	Width of liquid supply channel, $\mathbf{b_1}$, mm	1.25	
2	Length of liquid jet flow, **l**, mm	27.0	
3	Aspect ratio (as ratio of liquid supply channel height **h** to its width $\mathbf{b_1}$), **q**, dimensionless	2.0	The aspect ratio **q** is recommended not to exceed the value of 5.0 to avoid events of undulation, sequent interface inversion along length **l**, and droplet break of a planar, restricted liquid jet flow, going up to 25 mps.
4	Liquid supply pressure, $\mathbf{p_1}$, kPa	Max.370.0	
5	Speed of liquid jet flow, **U**, mps	Ò25.0	
6	Flow rate of liquid supply, $\mathbf{Q_1}$, Gal/min	Ò1.0	
7	Pressure recovery coefficient, **kpr**, dimensionless	Ò1.0	
8	Pressure gain, $\mathbf{k_p}$, dimensionless.	Ò100	
9	Flow rate gain (at open hydraulic outputs), **kq**, dimensionless.	Ò0.61 (at liquid supply pressure 370.0 kPa)	
10	Response time, **Ű** msec.	å 30.0	
11	Band width (as a response to the harmonic input pneumatic signal), **Hz**	Ò30.0	At 70% of max. amplitude of full static hydraulic output signal.
12	Phase delay, **Ҁ**, in fractions of ´	Ò´/8	At $\mathbf{p_1}$ = 370.0 kPa
13	Efficiency, *Ǽ*%%	å25.0	
14	***Physical model*** of each of the two inverse-and -adjacent pneumatic control chambers inside an entire pneumatic interacting area.	***Pneumonic two-port*** with flow-through entrained control gas and elastic wall, i.e. planar restricted liquid jet flow.	The model features with hydraulic ***fast response*** to the rapid change in pneumatic control action.

Note: At the elaboration of **IT** in the experimental same-scaled embodiment of **JHHA** there were achieved the liquid supply parameters and hydraulic output static parameters having been similar to ones for the embodiment of **JPHA**, and besides it has been revealed, that:

* input hydraulic control signals were available as in pulse (digital) as in analog modes;
* the value of input hydraulic control signal didn't exceed the value of 10% of hydraulic supply data, as in pressure as in flow rate.

amplifiers for the static or for the flow-thru, but resource-limited circuitries. Attached hereafter **Snapshot** shows the experimental embodiment of two-stage Jet-and-valve amplifier (**JVA**).



Snapshot

The purposefully shaped prototype of **JPHA** (shown at the bottom of the picture) is used in the first stage of **JVA**. It has been design to operate in digital and analog modes, i.e. for acting as a multi-input trigger (R-S flip-flop), an analog amplifier, a pulse-width modulator, and, at least, as a multi-functional logic gate.

The availability of such Microfluidic Component Kit opens the way to creation of reliable and efficient Microfluidic Modular Assemblies (**MiFluMA**) in comprise of the above-mentioned **MFP**, pumps and valves, different types of **IT**, **CU** and mini **H/P-D**, where an executive drive may be activated by a signal of light, sound, heat, smell, magnetic field, inertial force, etc. [4,5].

Benefits of Application

Today, compact and uniquely powerful actuating hydraulic and pneumatic drive units are traditionally used in main and redundant trains of critical objects where hazardous environmental or man-made stimuli are of concern for operational reliability and safety of embedded electronic circuitries, i.e. humidity, heat fluxes, vibrations, electro-magnetic and radiation fields, liquid and gaseous corrosive chemicals. The harmful influence of these factors becomes much more dangerous upon downscaled **MCK** embodiments, unless they are designed according innovative technology of CTRL Systems, Inc., mentioned here before. Thus, the anticipated beneficial applications of suggested **MCK**, and **MiFluMA** as a whole, should be at least as follows:
* Industrial robots. Fire robots. Mine clearing and reconnaissance robots.

* Robots for handling the poisoning and radioactive materials.
* Rock-cutting equipment, operating in a dust-laden and explosion hazard ambient.
* Coal-plough machines, utilized in an enclosed, explosion hazard ambient, e.g. at gas inrush.
* Casting, milling, rolling, forging and pressing equipment, operating in specific industrial conditions of high temperature, contaminated air, and vibrations under loading.
* Gearboxes of large dimension metalworking tools, where it seems to be economically reasonable to feed the power input of **JPHA** and **JHHA** from the oil lubricating net.
* Automated hydraulic drives for the wheel or track trailers and other ground vehicles.
* Hydraulic steering or other control drives of the live or unmanned air, ground and marine vehicles, where it is economically advantageous to feed the power input of **JPHA** and **JHHA** from the vehicular flow-thru fuel system.
* Automated distributing/dispensing unites for liquid products in petrochemical and food plants.
* Flammable liquid loading level regulators for gas and oil, pharmaceutical and chemical plants.
* Programmed loading test benches for fatigue trials onto the carrying structures of any critical airspace, marine or ground objects.
* Theoretical courses on Microfluidics for lecture-room studies, and experimental techniques for prototyping in research laboratories.

References

[1] Weigl, Bernhard H., “Microfluidics-based lab-on-a-chip systems”, IVD Technology; November 2000, p. 47.
[2] Stone H.A. and Kim S. “Microfluidics: Basic Issues, Applications, and Challenges”, AIChE Journal, Vol.47, No.6, 2001.
[3] Jiantao Pan “MEMS and Reliability”, Carnegie Mellon University; 18-849b Dependable Embedded Systems. Spring 1999.
[4] Buyalsky, Vadym, “Microfluidics for Miniature Hydraulic & Pneumatic Drives”: “ Flow Control”, October 2004. Vol. X, No.10.
[5] Yoshimitsu, Toshihiro; Oyama, Osamu and Yamamoto, Keijiro; “Characteristics of Opto-fluidic Control System”: Proceedings of 7-th FLUCOME Symposium, August 13-17, 2000.

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Flow Chart

M I N I A T U R I Z A T I O N of P O W E R D R I V E S

Goals: I. Diminishing of products' dimensions and mass. **II**. Decreasing of power consumption. **III.** Improving in accuracy of space positioning. **IV.** Shortening response time. **V.** Enhancing unit power. **VI.** Increasing output of manufacture. **VII.** Saving of production space and maintenance costs.

Requirements to keeping up high performances	Alternative approaches to appropriate technical solutions
Functional Reliability	Reduce (or rather withdraw at all) a number of the moving mechanical parts and vulnerable pieces of electronic control circuits. Arrange redundant trains with unlike, independently acting equipment therein.
Operational Quality	Keep up the stable and rated values of performances likewise in the similar macro scaled products.
Power Transfer Efficiency at maximum Unit Power	Preferable use of miniaturized Hydraulic or Pneumatic Drives (mini **H/P-D**) with: Either electronic control units for ordinary and nonhazardous conditions; or Non-electric, i.e. pure fluidic control units for hazardous ambient, special conditions, and for use in redundant trains of critical objects; or Novel combined intrinsically safe and explosion proof electric/fluidic micro scaled control units.

Traditional Approaches

Design principles: Scaling down the traditional products that contain moving mechanical parts and electronic circuitries, which are sensitive to environmental or man-made internal and external stimuli: heat fluxes, humidity, vibrations, electro-magnetic and radiation fields, corrosives.

Necessary Present-day Approaches

Design principles: Assembling the products with disproportionately scaled down electric actuators vs. their mechanic-hydraulic or mechanic-pneumatic executive units, as e.g. for the present-day simply miniaturized valves and pumps. It results in loss of power transfer efficiency, unit power and quality. Use of such micro scaled valves and pumps needs special amplifiers to interface them with mini **H/P-D**.

Innovative Approaches

Design principles: Applying innovative techniques and devices for creation of typical micro scaled microfluidic component kit (pumps, amplifiers, valves, etc.) that features the absence of moving mechanical parts, restricted use of mechanical elastic parts and electric links, and applying mostly any of known techniques of non-contact actuation.