Actuators and Sensors for Smart Systems

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Abstract

Smartness of technical systems relies also on appropriate actuators and sensors. Different to the prevalent definition of smartness to be embedded machine intelligence, in this paper elegance and simplicity of solutions is postulated be a more uniform and useful characterization. This is discussed in view of the current trends towards cyber physical systems and the role of components and subsystems, as well as of models for their effective realization. Current research on actuators and sensing in the fluid power area has some emphasis on simplicity and elegance of solution concepts and sophisticated modeling. This is demonstrated by examples from sensorless positioning, valve actuation, and compact hydraulic power supply.

KEYWORDS: Actuators, Sensors, Smartness, Cyber Physical Systems

1. Introduction

The term "smart" has gained high popularity in characterizing the expectations on modern technical systems. The author sees the reasons for this in a certain change of expectations on a good product. The classical approach to derive the product concept by clear requirements which assure the functionality wanted by the customer seems to be not sufficient anymore. More is wanted, namely, a certain elegance of the solution in addition to the fulfilment of the requirements. It seems to be this additional quality which can differentiate a certain product from others and give him a competitive leading edge.

In the context of Smart Production Systems or "Industrie 4.0" smartness has a different, much more specific meaning, namely machine intelligence. This lets many concluding that also components and/or subsystems - which sensors and actuators are - should be equipped with more intelligence to become smart. In a short workshop on "Smartness and Fluid Power" at the last Digital Fluid Power Workshop in Linz in February 2015 (DFP15), a different meaning of smartness at least of fluid systems prevailed under the potential users, which are machine, plant, or vehicle builders:

Easiness of handling in all phases, from design, over control and assembly to maintenance.

A too modernistic and too simple view on future product development, which only focuses on “Industrie4.0” system aspects and disregards the role of components and subsystems, is rebuffed by many engineers who hold a responsible position in industry. Unfortunately, there is not yet a clearly documented and broadly accepted understanding, which general directions of product and technology development are most important to meet the requirements of near future. This paper is an attempt of an answer for fluid power actuators and for sensors closely interacting with them.

2. Smartness of technical systems

2.1. Attempt of a useful general definition

So far, smartness has been associated with three meanings; elegance, intelligence, and easiness. The following questions arise:

1. Is smartness a useful term at all?
2. Which one of the three potential meanings is the most relevant definition for systems and subsystems?
3. What are the differences and similarities?
4. Elegance is not an obvious, easy to measure property of technical systems, although it is often used by engineers for the characterization of a good technical solution. Is there a valid and universal definition which is useful for the technical purposes addressed in this paper, i.e. to evaluate components and subsystems for their use in a certain “smart” technical system?

Unfortunately, there is a widespread meaning of the word “smart” in everyday language. The authors prefers one definition by the German dictionary Duden which reads: *Of fashionable, exquisite and remarkable elegance*.

Georg Franck, a German architect, writes in an essay /1/: “*Elegance is pure luxury. Its interesting feature, however, is that the accent lies on purity rather than on luxury. Elegance is limited to appearance. It makes the difficult obvious, something laborious very easy, something expensive modest, something complex easy, something artificial quite natural.*”

These statements express a kind of apparent contradiction, luxury and purity. But elegance is never ordinary but always outstanding. It remains in memory.

And here we find similarity with the expectations of the DFP15 workshop outcome concerning smart fluid power solutions. They must have an impressing appearance and same time a convincing simplicity.

If this definition is taken, smartness is a useful term. Simplicity is a widely accepted characteristic of good technical solutions. In Nam P. Suh's books on Design /2/, /3/ simplicity in various respects is the key general design guideline.

The second characteristic, the impressing appearance is not primarily related to the outer appearance. In the context of a technical system it means appearance of all its features to people who deal with it in some way. These are its designers (mechanical, electrical, control, programming), those who integrate it into a larger system – and these again may be people from different engineering disciplines – operators of the final system, maintenance personnel, but many more, for instance, sales people or those doing quality control.

In this sense, easiness is a feature of elegance, but elegance is more. Machine intelligence contributes to smartness if it makes the system more attractive and easier to deal with for all people coming into contact. Of course, there will be trade-offs, particularly concerning simplicity for different categories of people.

The definition of smartness of technical systems by elegance is universal. It is valid for components, subsystems, and systems. Of course, such smartness is not a property of the technical unit per se but depends on its domain of use. For instance, a valve equipped with some intelligence may be an elegant solution for a machine operating in a Smart Factory environment, but might be inappropriate for a simple machine running somewhere afield.

This view on smartness does not establish a new design paradigm; in fact, elegant solutions have always been the aim of inspirational engineers engaged in product development. Only the circumstances have changed. Many new, powerful technologies exist and have to be combined with traditional technologies in a clever way. Mechatronics is the mission to accomplish this for mechanical, electrical and electronic components in combination with control and embedded software. In view of upcoming "Industrie4.0", Smart Factory, or - generally, Cyber Physical Systems environments - a diversification of mechatronics will become necessary by a proper integration of the cyber aspects in the product development work.

2.2. Smart actuators and sensors

In the scientific community „smart actuators“ has a certain meaning. In /6/ the following wording is used:

“*A smart actuator is defined as the integrated actuator of all components such as motor, controller, sensors, and communication unit*.”

It directs in the local “intelligence” direction, but only concerning the required hardware configuration, and differs from the “elegance of solution” smartness concept of subsection 2.1. We will discuss this question of actuator smartness in view of upcoming CPS requirements by means of an example later in this paper.

Reference /7/ refers to IEEE standard 1451 which defines actually smart transducer interfaces,

“*Smart sensors are defined as sensors with small memory and standardized physical connection to enable the communication with processor and data network,”*

and adds a clear functional component by addressing signal conditioning:

“Beyond this definition, smart sensors are defined as the combination of a sensor with signal conditioning, embedded algorithms and digital interface.”

There is some similarity with that of smart actuators given above, but the functional part is an addition.

2.3. Smartness in Cyber-Physical Systems

In the Cyber-Physical System (CPS) setting, which is the system-theoretical base of Smart Factories or “Industrie4.0” production systems, new information and communication technologies are added. Like in mechatronics some decades ago, the question arises if these new technologies are just added or if the existing parts, i.e., the machines and their subsystems and components, have to adapt in order to achieve smartness of the CPS. In /4, 5/ the author of the present paper together with several co-authors discuss the role of digital hydraulics for machines systems operating in an “Industrie4.0” environment. They deal also with requirements on components and subsystems in general for a successful realization of such sophisticated production systems and conclude there is a need for adaptation.

Figure 1 shows a simple architecture of a CPS. In most publications, the subsystem level is not addressed at all. But they are essential parts for the functioning of a CPS, since they collect information (sensors) and enforce the realization of the commands at the front, where the system interacts with the production process. All levels might exhibit some “intelligence”, but not all parts need to have.

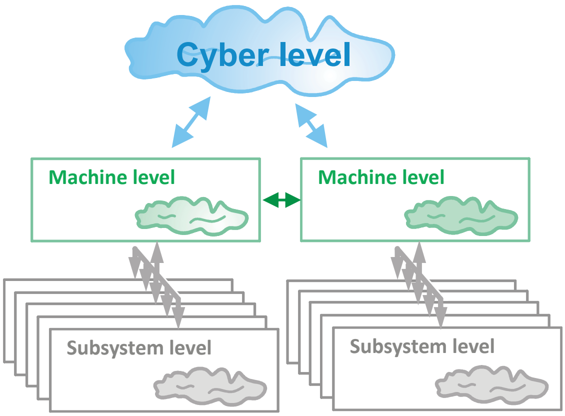

Figure 1: Cyber physical systems structure with a cyber-, machine-, and subsystem-level; machines communicate with each other and some higher level systems (Cyber level); subsystems may communicate with the machine and among each other.

An important aspect of CPS and all related initiatives (Smart Factory, “Industrie4.0”) is that software is at least partly shifted into the cloud and that models of the system are available for use by others. Of course, such models will also be stored to some extent in a cloud. These models might refer to quite different things: hardware, functionality, processes; to the system, subsystems, and components. Models can be of different granularity, simpler ones and more complex ones. They might be structured in hierarchies to document a certain relation, e.g. between models which answer the same basic question but with different resolution and accuracy. Today, this is still very much seen from a software viewpoint and concepts like “AppStore” which are so successful in the administration of smart phone software are more and more used in discussions about the future handling of such models.

In view of these future CPS requirements and circumstance, respectively, the view on smart actuators sensors, sketched in subsection 2.2, are probably too narrow. Software will become more separated from that hardware, where it finally will be executed for a certain purpose. This will probably also be true for actuators and sensors. CPS visions outline a world which is more differentiated than today. Hard- and software will become more independent. Reasons for not installing a controller into an actuator or sensor are manifold; examples are:

- Cost savings, if a product is under a very high cost pressure and the required functionality can be achieved by using central controllers.
- Environmental conditions, which make a local use of electronic components impossible; for instance, extreme temperatures, shock, nuclear radiation.
- Software maintenance: it might be easier to maintain software which is executed on a central system instead on a distributed controller.

In future formal, executable models will probably be more important than software. The effective cooperation between experts of the different disciplines must be based on common languages. A mechanical engineer developing an actuator, a systems engineer taking responsibility for a machine system and its proper functioning in a CPS environment, engineers writing machine control software, and those dealing with software aspects of CPS integration, need an efficient communication language which helps to clearly define the interfaces and required functionalities. More and more this will be models which can also be simulated. Thus, subsystem/component developers and providers will have to deliver not only hardware, communication and controls but also models as a kind of powerful description and specification which allows to virtually test the subsystem's/component's role in a superior system.

3. Examples of smart fluid systems

Since this paper is presented and published in the context of a fluid power conference, the general considerations of Section 2 are discussed by examples from the fluid systems domain. Sensor aspects are treated from a system's viewpoint rather than from a technological viewpoint. As far as known at the time of writing this paper, reference is also given to the other papers of the sessions “Actuator and Sensors” 10. IFK.

3.1. Sensorless position control

It seems to be a paradox that position sensing of linear motion is still a problem which asks for new solutions. Paradox, because position measurement is a very basic function in many modern technical systems for which numerous concepts and marketed solutions do exist. Position sensing of linear hydraulic actuators, for instance, was repeatedly discussed in expert forums; corresponding reports can be found in several issues of o+p journal. The 10. IFK paper

The Liebherr Intelligent Hydraulic Cylinder as building block for innovative hydraulic concepts, by Leutenegger et al.

is another attempt to find a good position sensor solution which requires minimal cylinder modifications.

From a fluid power standpoint also the knowledge of position and/or speed of solenoid actuated components, e.g. spools or poppets of magnetically actuated valves or pumps, is important and mainly for cost reasons these states should be derived by some observers from other states of the system, e.g. from voltage and/or current signals.

The following paper of the 10. IFK sessions on “Actuators and Sensors” addresses sensorless position measurement:

Smart control of electromagnetically driven dosing pumps: by Thomas Kramer et al.: A sensorless detection of the end positions of the armature – piston element by a proper observer is derived to avoid noise from end stop impact.

Similar work also for magnets is done for more general purposes by Johannes Reuter and his workgroup, see e.g. /8-10/.

Sensorless position control of hydraulic cylinders is studied in the 10. IFK - “Actuators and Sensors” session paper:

The Hydraulic Infinite Linear Actuator -- properties relevant for control: by Martin Hochwallner et al. These authors have presented the concept of a kind of stepper drive based on two short stroke cylinders which push a common rod in alternate motions already in /11/.

Sensorless position control by a hydraulic stepper drive - employing a quite different concept - is also studied in /12, 13/. Two versions, with and without energy saving, are sketched in **Figure 2**.

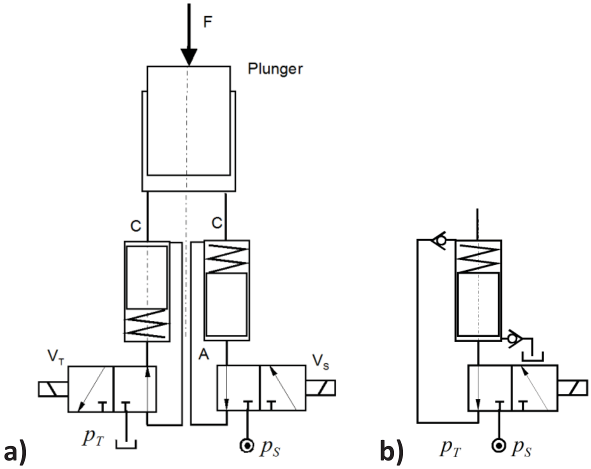

Figure 2: Hydraulic stepper drive: a) non energy saving; two stepper units to accomplish stepwise motion of the plunger in both directions; b) energy saving stepper unit (unidirectional)

Both exploit a displacement piston which performs always a full stroke from one end stop to the other in order to discharge a precise fluid quantity to the output, e.g. to a plunger cylinder. Many more than the two schematics of **Figure 2** exist to realize this principle.

Currently, the author’s research group is developing a non energy saving stepper drive for a sensorless position control for special machine tool applications with a position accuracy of ± 5 µm. In this application, several of such drives should be installed. The schematic is shown in **Figure 3**. from which also the operating principle can be reproduced. It should facilitate a first time right production even with some varying product properties, like dimensional and material strength date variations – a clear improvement helping to realize “Industrie4.0” type production.

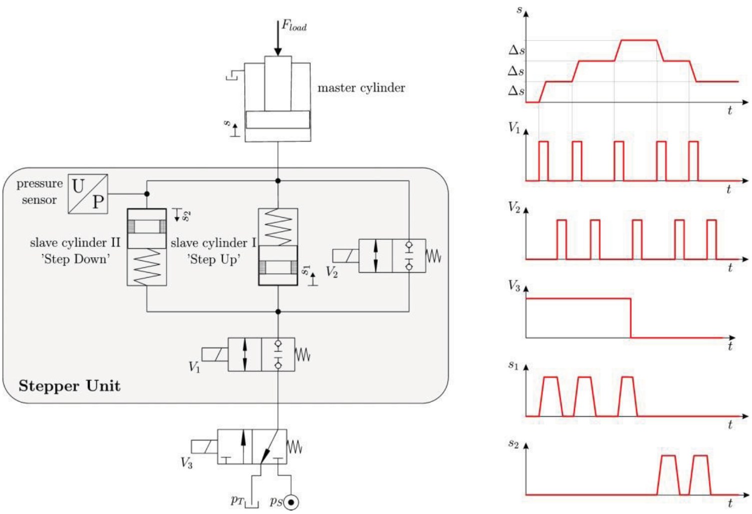

Figure 3: Hydraulic stepper drive schematic - non energy saving version - for a specific machine tool application and main signals for step up and step down motions.

Smartness in this envisaged application not only means position control without a position sensor (a pressure sensor is used to compensate the errors due to fluid compressibility) but also a very compact design and low costs. These two results of a smart solution can be guessed from the CAD drawing and photo of a test rig shown in **Figure 4**.

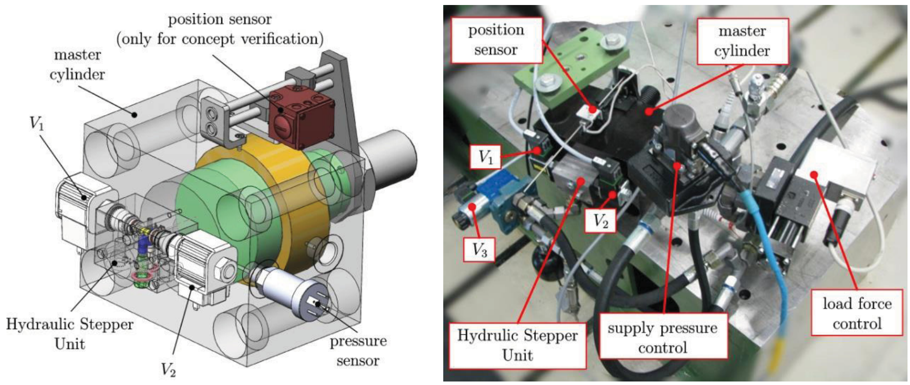

Figure 4: Hydraulic stepper drive test rig; valves $V_{1'}$, V_2 are low cost switching valves (Parker DS02).

Very much like in the sensor position estimation of solenoids, reported above, the important and difficult part is a good model of the drive behaviour. In this case oil compressibility and thermal expansion need to be compensated by a model based control to achieve the accuracy stated above. Details on this modelling and experimentally verified results are given in /13/.

An open question is, if each of these stepper drives should have its own controller (local “intelligence”, embedded control) and power electronics to drive the valve solenoids, or if these functions for all actuators are realized by a central machine control unit. Both solutions have pros and cons. Which one of both is the best, might strongly depend on the circumstances of a specific application.

An embedded control relieves the machine controller and those who program it from extra work. The experts who design the drive can conceive also the controller and can bring in all their sound understanding of the drive to optimize the controller settings or to effectively realize diagnosis and automatic failure detection functions. Embedded control requires a minimum of cables and connectors and can help to avoid electromagnetic compatibility (EMC) problems.

Central control allows a simpler maintenance of the control algorithms. One and the same programming language can be used for machine and subsystem control, no need to do modifications in a drive firmware language. Furthermore, the tuning of the drive for an optimized system performance, in which sense ever, is eased. That might require to consider the drive’s interaction with the machine, which it is part of. Furthermore, it could be a cost saving factor and it could also ease the organization of the supply chain. For a machine builder it could be easier to order the complete mechanical hardware (blocks, valves, local pressure sensor) as an assembled unit but to do control by himself, since sub-suppliers of that unit could miss competency to develop embedded controllers. Furthermore, from the pressure sensor signal the load can be easily derived. This information may be useful to observe the process or to improve process control. Of course, this could be accomplished with embedded control as well but requires that the pressure or load force information is available in a proper way via the used communication channels.

The basis for both approaches, embedded and central control, are adequate models of the drive. As stated above, this stepper drive requires a quite elaborate model of fluid compressibility and thermal expansion to achieve a good accuracy. In its current version, heat exchange with the surrounding is disregarded. It is assumed that the surrounding - this is mainly the machine structure - has either constant temperature or the heat exchange processes are much slower than a typical actuation cycle which brings the drive back into a known reference position. If none of these assumptions holds, heat exchange needs to be know, either by sensing the surrounding temperature and combining it with a theoretical heat transfer model or from some other models which allow to observe this effect. The latter model is not limited to the drive but is related to the machine. The combination with the thermal expansion model is a system model.

Smartness was defined as featuring elegance and simplicity. It is not a property of the technical system per se, but of its combination with the use case(s). Control - if required - should have this property too, in all its manifestations. In best case, the implementation is done directly with the modelling language that was used for simulation in the development of the subsystem, provided this language facilitates an elegant formulation of the model. On the system level, models are combined, may be are also manipulated, e.g., to make models simpler. Thus, in a CPS setting working with models will gain importance. Simple models as good representatives of a system (complete or subsystem) ease the work considerably and contribute to reliability.

3.2. Valves

The following papers presented in the 10. IFK sessions on “Actuators and Sensors”

- *Energy-efficient multistable valve driven by magnetic shape memory alloys*, by Thomas Schiepp et al.
- *Design of a High Performance Energy Coupling Actuated Valve*, by Jordan Garrity et al.
- *Electromechanical actuator concept for the controlled and direct actuation of a hydraulic main stage*, by Markus Ermert,

are a strong hints that valve actuation is still deserving improvements. Quite novel approaches are taken to achieve some improvement, e.g. a performance gain. But what characterizes a smart solution and which valve actuator properties support system smartness? That depends, as stated above for sensorless positioning, on the use case too.

An important property is energy or power consumption. Depending on the circumstances, certain characteristics of those consumptions are often more important than average values: In a passenger car, peak currents are limited by the used controllers. A realization of digital hydraulics would be strongly facilitated by switching valves which could be driven by standard controller outputs without an extra power electronics. If the main part of the actuation power is taken from the hydraulic supply and this requires no extra measure for the hydraulic system and takes only negligible amounts of the hydraulic energy consumed, it is in many cases a better solution than using power demanding electric actuators. This must be accomplished in a compact, reliable, and low cost way.

Cost and size of valves are critical issues in the general perception of fluid power systems. Valve parallelization, for instance to realize digital flow control units /14/, redundant systems, or multiple buck converter concepts /15/, relies heavily on these two criteria. But even beyond these digital fluid power applications, compact and cheap valves stimulate the application of hydraulic concepts. The hydraulic stepper drive, described in section 3.1, is a good example. Its attractiveness increases with low total costs, which depend strongly on valve costs.

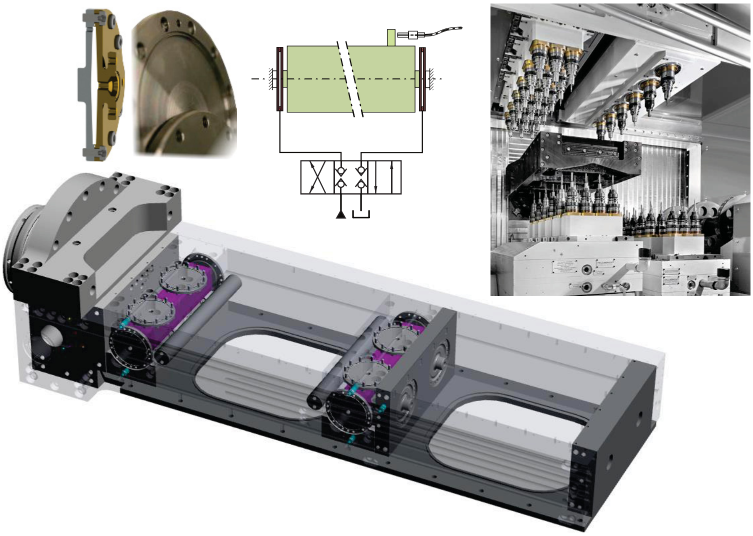

Figure 5: Hydraulic micro-positioning units for a milling machine; the relative position of two work-pieces in the work-piece holder of a multi-spindle milling machine can be changed in all three space directions by $\pm$ 50 μm with a precision of 5 μm.

Another example is the hydraulic micro-positioning actuator /16/. The latest version can position two separate work-pieces relative to the work-piece holder in order to compensate for tolerances of the individual milling or drilling tools and spindles, respectively, or of the work-piece clamping system. The basic mechanism of this precise system are two membrane actuators (see sketch in Figure 5) which are hydraulically actuated by switching valves. This drive has to be overall very compact and the valves should be tightly integrated. The lower valve cost and size, the higher the chance to employ this actuator in other applications with low available free space.

A further general valve property which promotes its smartness perception is very low or no leakage. Leak proof valves are a must for the stepper drive of Section 3.1 to achieve high accuracy. Leakage might cause by far the highest share of all losses, if actuators have to position a device and hold it there for a long time without a motion. It is not so much the energy cost, what is crucial, but, perhaps, a larger supply system or its permanent running with the corresponding noise or heat generation, even in phases with no output motion.

Of course, in many cases valves equipped with some local "intelligence" can be smart components contributing to an overall smart system. Many manufacturers offer such valves, particularly proportional valves. Also a fast switching valve /17/ is equipped with on-board electronics. It handles current control, coil temperature monitoring, communication with central control, and can be programmed to perform certain modes of operation automatically.

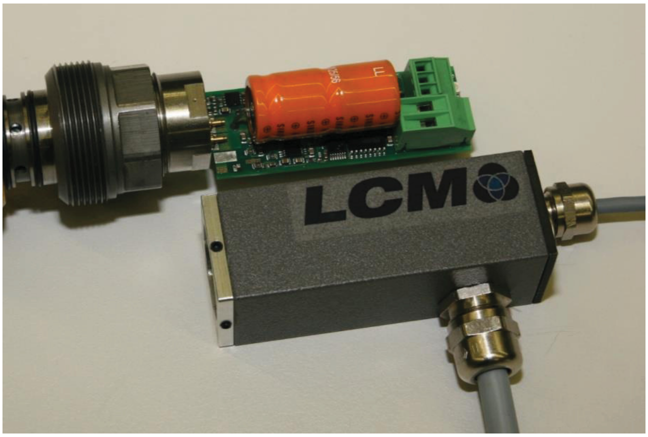

Figure 6: Fast switching valve with onboard electronics; valve type FSVi by LCM, Linz; valve is shown in a disassembled state.

The picture of this valve in **Figure 6** shows that the by far largest space of the electronic board is consumed by a capacitor, which provides the electric power for the peak current at the initial switching on phases and by the terminal blocks. This is definitely a non-smart feature of the valve and asks for a modification. If the rather big electrolytic capacitor can be skipped or replaced by a compact capacitor of different type, also the robustness of the system would be highly increased.

In hydraulics a superior valve concept is still missing, bringing a progress comparable to what the transistor – or, more right, semiconductor technology – did in electronics. This statement refers to the basic principle which transfers an electric input signal into a changing hydraulic resistance. Such a superior metering element should render all the mentioned properties, low cost and size, high robustness, and – additionally – fast response possible. According to Altshuller's theory of inventive problem solving /18/ very new principles require a huge number of different inventive ideas to finally find the wanted solution. The manifold current attempts to discover new valve principles, which are strongly motivated by the requirements of digital fluid power, hopefully will generate such a superior solution being this desired breakthrough.

3.3. Compact power supply

For an overall smart solution the micro-positioning system of subsection 3.2 not only requires a compact valve but also a very compact power supply unit which can be placed close to the actuators and saves the machine tool builders from complex hosing work. In the current solution, hydraulic power is coming from a central unit and is transferred to the micro-positioning system by pipes and hoses. The hoses are heavily bent and twisted because the work-piece holder is moving and rotating relative to the machine frame and limited space is available. Such flexible hose connections are also used in other milling machines for the hydraulically actuated clamping units, where also the valves are located centrally and each clamping actuator is supplied by an extra line.

The author's workgroup develops a high frequency oscillation pump as a promising concept for a compact, fractional horsepower motor-pump unit. A first prototype operates at 300 Hz and has a rated power of 600 W; the best measured energy efficiency (electric input to hydraulic output power) is 86%. Currently, a prototype for a second, modified concept is developed heading for a higher power density, both in terms of weight and volume. Such a pump could serve as a power supply module and those modules can be combined in various ways to adapt pressure or flow rate.

Hydraulic power supply is not just motor and pump but also reservoir and several accessory devices for oil treatment and handling. In best case, such devices can be skipped and the reservoir can be shrank to a minimum size or can even be fully omitted. Closed hydraulic circuits, for instance those employing a speed variable drive in combination with a constant displacement pump for motion control /19/, are definitely a direction of development with a high potential particularly for many industrial applications.

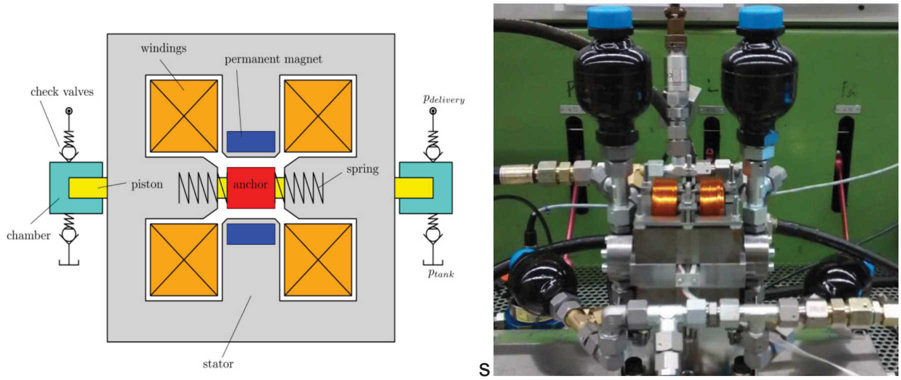

Figure 7: Concept and prototypal realization of a high frequency oscillation pump; max. operating frequency 300Hz; rated power 600 W; optimal measured efficiency 86% (Electric input power to hydraulic output power).

4. Summary

In this paper, smart systems have been characterized by elegance and simplicity of solution. It is postulated that this is a universal property valid for components, subsystems, and systems and is particularly useful for fluid power technology, which always works as a subsystem of a machine or plant. Machine intelligence integrated into components or subsystems, which today is the usual perception of smartness of a technical system, is not always an appropriate characterization of smartness. In view of upcoming Cyber Physical System structures, where physical objects tend to be represented by models in the cyber domain, modelling in general will gain even higher importance than today. The question where models are implemented or corresponding simulations are performed at some embedded or a central hardware or in cyber space, will be secondary compared to technical systems and model development.

Current fluid power related actuator research activities, also several of those being presented in the “Actuators and Sensors“ sessions of the 10. IFK, show this clearly. Sensorless methods, which rely on adequate models to estimate position or speed form other measurable system states, are smart solutions at least in the sense of simplicity and, partly, also elegance of solutions. Valve actuation and compact hydraulic power supply units are also attempts to obtain more elegant solutions for basic functions.

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