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DESIGN IN THE MICROFLUIDIC DOMAIN AS COMPARED TO OTHER DOMAINS

Katarzyna Panikowska[1], Ashutosh Tiwari[1] and Jeffrey R. Alcock[1]
(1) Cranfield University, UK

ABSTRACT
When describing microfluidics authors frequently point out its unique characteristics in terms of both the physical forces and technology drivers operating in this domain. However, this uniqueness is not translated into the area of design. Design methodologies for microfluidic devices have usually originated from micro-electromechanical systems (MEMS) design models. However, due to a number of issues, such direct transfer of these models to microfluidics is considered as insufficient, as is the adaptation of macro-domain's design flows. This paper attempts to provide an insight into design methodologies for microfluidic design. Firstly, the comparison of micro-scale device design and macro scale device design is undertaken. This is followed by a comparison of the microfluidic domain with other micro-scale domains. The paper summarises these issues and highlights a set of concerns which should be taken into account during development of microfluidic design methodologies.

Keywords: microfluidics, design of microfluidic devices, micro design, macro design

1 INTRODUCTION
Although the initial development of microfluidic devices can be dated to late 1980s [1], work on design methodologies for this area is still relatively immature.
As a starting point for the design of micro-scale devices, designers have undertaken the approach of the adaptation of existing models. They have tried to apply macro-scale device design approaches to the micro-domain. However, this adoption has showed differences between domains which make this direct transfer impossible [2].
The issue of scale, which appeared to be the main barrier for adaptation, in practice influenced other factors. The failure to successfully adapt methodologies from one domain to another has, however, allowed the differences between the micro and macro-scale domains to be more comprehensively defined, e.g. in operating forces and requirements. These differences require incorporation into design processes to make them suitable for micro-domain.
Therefore, development of microfluidics design methodologies has started, learning from models in MEMS and microelectronics. However, this has also fallen short of expectations and a generic design concept in this area had not been developed [3].
This paper discusses differences between domains that are of particular importance for the design process and in particular considers factors distinguishing microfluidics from other areas.
First a comparison of micro-scale device design and macro scale device design is undertaken. This comparison is focused on differences between domains and highlights why methods used for macro-scale where not suitable in micro domains. It is followed by a comparison of the microfluidic domain with other micro-scale domains to provide an insight into specifics of this area.
By this, the paper is intended to provide requirements to be considered in the development of future design methodologies for microfluidics in particular. Such methodologies should not only consider factors that currently characterize microfluidic domain but also future requirements and their fulfilment.

2 MICRO-SCALE DEVICE DESIGN VS. MACRO-SCALE DEVICE DESIGN
To understand the factors specific to the design of micro-scale products design, a comparison with macro-world products has been undertaken. This comparison is based on detailed differences in factors which are common to both processes.

The main difference between macro- and micro-scale designs is the factor driving these processes. Macroscopic design is strongly driven by market requirements; microscopic design is currently confined behind the barriers of what is producible, and is mainly driven by technology [4].

Albers et al. [4] have identified three main 'players' in macro-world design: customer, competitor and the producer. They also pointed out that in micro-world a fourth player exists – technology, i.e. all the scientific contributions to the development process, including production technology and material sciences.

Other important aspects which differ according to the scale of the domain include the physical forces in which play a role in the devices. Issues which can be omitted in macro-scale have significant influence in micro-scale. By decreasing the size, mechanical properties of devices such as mass, strength, stiffness, [5] can decrease significantly, while other factors such as resonant frequency are multiplied.

It can be observed that surface related forces, such as van der Waals, surface tension forces and electrostatic forces become dominant over gravitational force, the latter being the main influencing factor in macro-scale. This, for example, creates a barrier in terms of part release in assembly process in the micro-scale [6]. Because of this behaviour manipulation of parts in the micro-scale significantly differs from that which takes place in the macro-domain. Several literature sources discuss forces operating in microfluidic field in comprehensive manner [7]-[9].

Tietje and Ratchev [10] listed issues which in their opinion have high importance in the micro-domain. These included:

- Focus of the design on functionality
- Reduction of device complexity –sticking effects and tight tolerances increasing the complexity of simulation and manufacturing
- Close relations between design, fabrication and assembly – where the focus is on designing what is producible not on how to produce what is already designed. Such issues in the macro-world are often successively dealt with by different persons, while in micro-world the necessity of simultaneous work exists
- High importance of production and assembly – with consideration of material properties, part positioning and environmental effects
- Cleanliness – in terms of the room, controlled temperature and humidity
- Precision – necessity of exact definition of tolerances and measurement capabilities for the whole process. This factor is underlined as the main difference in terms of assembly between micro and macro scale. The existing kinematic models are poor and not sufficient in dealing with thermal effects and the need for their compensation

Although all of these issues are important also in the macro-world design, when going to micro-scale each requires increased attention. Issues such as dimensions and tolerances start to be crucial and cannot be omitted and/or disregarded when high precision is required on every step from design to manufacturing and assembly. This focus on accuracy of details makes design in micro-scale strongly linked with technology and fabrication.

2.1 Assembly issues

In both micro- and macro-scale device designs, direct fabrication of whole products is not always possible and/or profitable. For example the development of multifunctional systems requires, in some cases, usage of a variety of materials and, owing to this, manufacturing methods.

Sub-sections of products possessing various functionalities need to be connected to provide the required performance of the system – a performance which could not be obtained using monolithic design with a single material and limited manufacturing options.

Although the avoidance of serial-assembly steps by creation of monolithic structures is consider as one of the most remarkable aspects of MEMS [11], it also limits the functionality which it is possible to be achieved. Therefore, assembly methods were developed.

Table 1 presents a brief comparison of the factors influencing successful assembly in these domains. It can be observed that, once again and as would be expected, higher precision is required at the micro-scale as a result of the feature size. Moreover, the forces operating at this scale make it more difficult not only to grip elements without damaging them but also to release them.

Reviews of existing micro-assembly techniques has been provided by several researchers [12]-[14]. They point out that current techniques need to be enhanced to be cost-effective, reliable and automated.

Table 1 Comparison of micro and macro-scale assembly

	Micro-domain	**Macro-domain**
Assembly main force operating	Van der Waals, electrostatic and surface tension forces [6], [10], [12]	Gravity [10], [12]
Positioning	Submicrometer [10]	Few hundred micrometers [10]
Element stiffness and mass for assembly equipment	Low [15]	Vary [15]
Assembly methods	Mainly manual, time consuming, tiresome [6], lack of automation, not reliable and not cost-effective [13]	Standardised and automated [13]

Again, as highlighted above, a major difference between microfluidic assembly and assembly in the macro-domain is dominance of particular physical forces in the micro-domain.

2.2 Influence of technology on the micro-scale devices' design

Albers, Marz and Burkardt [2] have stated that product design of micro-scale devices is driven by technology, a view confirmed by their work [4], [16]-[18] and that of others [19].

The strong influence of technological conditions and restrictions, e.g. maximum flow length, in terms of microfluidic devices, operating stresses, the manufacturing processes and the fabrication equipment available, means that technology-specific knowledge needs to be incorporated in the early stage of design [4]. In many cases knowledge demanded from designer is not only multidisciplinary, since many devices combine electrical, chemical, mechanical and electronic elements, but also creative in that new production processes need to be developed in order to manufacture the device [19].

Design of these devices is viewed as a slow process because of the need for simultaneous design iterations in process, devices, and system, large and also hence the requirement for multidisciplinary teams with the associated overheads in costs [20]. A clear focus on what it is possible to achieve, e.g. minimum diameters, and minimum wall thickness, again disconnect micro-devices from other customer demands.

Designers in micro-areas are concentrating on creation of the design rules [18], which have to be followed as an aid to speed up the design process. They have also concentrated on simulation and modelling tools which can be beneficial not only in terms of time saving but also as commercial products in their own right [21].

Researchers also state that although design of micro-scale devices is technology driven, some basic technological issues have yet to be solved. For example, new strategies need to be built-up into micro systems to address issues of dimensioning of these devices [17]. Some researchers have identified the need for the market-orientation of these devices especially in terms of tool-based micro-technology[1] [18].

The orientation of the micro-scale device design towards technology can be viewed from two perspectives. First is the technology driven approach presented above, which influences decisions about the device. Second is the high dependence of the design flow on the technical tools, e.g. on CAD tools, used to automate this process.

CAD tools are essential in the design of micro-scale devices mainly in later stages of the process. They help to understand and identify second-order effects that can easily be missed in the first phases of product design. Based on these aspects, Senturia [22] identified two types of CAD requirements: in the conceptual phase of a new device, to assist in finding practical configurations, and in the product-level phase, to enable careful attention to physical behaviour and parasitic phenomena. In many cases use of CAD tools is viewed as necessary in micro-scale design especially to create 3D solid models, This requirement has still not been fully achieved and needs further development in terms of both a framework and corresponding technologies [23].

[1] This group covers the entirety of all processes needed for creating microsystems, consisting of cast or injection moulded components [4].

3 MICROFLUIDICS DESIGN COMPARED TO THAT OF OTHER DESIGN DOMAINS

Literature regarding design of microfluidics is scarce. It is usually very specific and focused on the development of one particular device e.g. a biochip. The microfluidics area differs from MEMS and microelectronics by the demands which are put in front of the designers. The required knowledge varies between the macro- and micro-domains but also between micro-domains. This variation makes it difficult to adapt design models from one area to another.

Given below, a series of tables provide a comparison of design methods of the micro-domains with the macro–domain. The macro-domain itself is not discussed, as such discussions can be extensively found elsewhere. Instead, the discussion focuses on the differences between the micro- and the macro-domains and differences between micro-domains.

3.1 Comparison of micro-domain requirements and characteristics

Some general characteristics distinguish the microfluidics domain from others. These factors are listed in Table 2. Their spectrum is broad, from area maturity to the required dimensions and the operating physical forces.

Table 2 Microfluidics in comparison to other domains - general characteristics

	Microfluidics	**MEMS**	**Microelectronics**	**Macro-domain**
Area maturity	Low [8], [3]	Low [24]	High [18]	Very high [18]
Main operating force(s)	Micro-fluid dynamic[8], [25], viscous forces and Brownian random motion [26]	Multidomain – mainly mechanical and electronic forces [24]	Electric forces [27]	Gravity an inertial effects [26], friction [28]
Physical failure mechanisms	Not well understood [29]	Understood	Well understood [30]	Well understood
Size scale of structures	Tens of microns [31]	1µm to 2mm [32]	Micron scale or smaller [31]	Wide range
Number of dimensions required	3 [33]	3 [34]-[36]	2,5	3 [37]
Arbitrary shapes	Required [34]	Required [34]	Not required [34]	Required [34]
Precision required	High	High [32]	High	Low-high [32], [38]
Price per unit	Low [39]	Low [40]	Low	Low-high [41](market driven)

Microfluidics, in comparison to other domains, is being considered very immature. This is true even in comparison to MEMS, which microfluidics can, in some cases, be considered as part of (if the MEMS posses microfluidic elements).

A key example of the immaturity of the domain is that certain physical failure mechanisms are still not well-understood, e.g. the thermal effects on microfluidic assay operations. Also, the defects associated with power supply or environmental temperature variation are hard to detect. Therefore, they cannot be properly characterized and simulated [29]. Due to this error-prone approach, it is harder to achieve required functionality, and design processes for microfluidics are more complicated and time-consuming.

The higher number of controlled dimensions that are required from microfluidic devices (Table 2), complicates the manufacturing of these devices. Fabrication methods used in microelectronics to remove layers of materials from places where gaps will be required, e.g. etching, are not considered profitable to be applied to microfluidics. This low profitability is due to the larger amounts of material to be removed in microfluidic device production, for example in laying down microfluidic channels [31].

Customer demands from microfluidics and MEMS, in terms of the higher number of required dimensions and the shapes of products are similar, whereas in microelectronics 2.5 dimension structures usually satisfy present requirements. These demands have impacts on the fabrication methods that it is possible to apply in the domain. An increased number of controlled dimensions and variations in device shapes increase whole life cycle cost of devices by influencing its design and manufacturing.

The precision required from all of the devices in micro-domain is high due to the dimensions of elements. In microfluidics, wall effects can dominate fluid flow behaviour. Hence, variations from the required shape or surface quality influence the fluid flow and device performance. However, high-precision shapes and surfaces require an increased cost of manufacturing as they influencing equipments specifications and process times.

An important factor is the unit price which customer is willing to pay for device. In every micro-domain this price is low, which stand in opposition to high costs of design and of manufacturing equipment (see Table 5). To meet this demand producers struggle to minimize design costs and will use foundries in preference to in-house equipment. Low profitability on a single device in micro-domain makes it more difficult to design and manufacture it.

3.2 Microfluidic design vs. other design in other domains

Design itself varies across domains. Table 3 summarizes the current aspects of design in the different domains. Microfluidic design, similarly to MEMS, varies significantly from microelectronics.

Table 3 Microfluidics in comparison to other domains – design characteristics

	Microfluidics	MEMS	Microelectronics	Macro-domain
Factor(s) driving the design	Technology [4]	Technology [16], [22], [24], [33], [36]	Market + fabrication	Market [4], [18], [33]
Customer input	Specifications [29]	Specifications	Specifications	Throughout the process [41]
Specifications	Performance, size and in some cases cost	Performance, size and in some cases cost [40]	Detailed in terms of performance, size and cost	Relatively detailed from products and service point of view [38], [42], [43]
Design processes	Not suitable for domain [29], [44]	Cover majority of issues [44]	Well established, structured [45], highly formalised ad automated [46]	Highly developed, broad selection [41]
Standard element of design	-	No generic elements [47]	Circuit [34]	N/A
Design rules	Requirement for design rules [29], not well defined	Difficult to define, however exist [32]	Clearly defined [33], conservative [48]	Clearly defined
Link between fabrication and design	Fabrication driven design	Fabrication driven [16], lack of separation [48]	Clearly separated [48]	Mainly separated [41]

Factors which drive design on micro scale were discussed in section 2.2. They are often technological, with less consideration of market requirements necessary to sell the product on market.

These requirements taken from the market are limited to the customer input in form of specifications, which for microfluidics and MEMS are constrained to performance, size and in some cases cost of the devices [40].

This limited customer input can constrain future customisation of microfluidics by mismatching the manufactured device with customer needs. The requirements for complex and customized shapes demanded for these devices indicate the necessity of customisation. Hence, to increase the potential value of these devices customer input in the process should be revised.

Hardt [3] has pointed out that microfluidics do not have one generic design concept, analogous, for example, to that of circuit design in microelectronics. To bridge this gap, recently, researchers are trying to select and/or develop the standard element for microfluidics [3]. However, the trend towards a generic design concept is still in its infancy.

In the micro-fluidic domain makes the establishment of design rules is difficult as some physical microfluidic effects are still not well understood. These rules are required to allow for processes automation and simplification of designers tasks [29].

In other domains, where operating forces and fault mechanisms are understood, development of rules supported by establishment of standard elements has led to development of design support tools (Table 4) and, in terms of microelectronics, for clear separation between fabrication and design stages in product life cycle process (Table 3). In microfluidics and MEMS, the current separation of fabrication from design is considered as harmful; the strong influence of technology, the restricted resources available and the limited physical knowledge leads to multiple iterations along the whole design process [23].

Flexibility of design is useful across all domains, but is currently difficult to achieve in the microfluidics domain. Particular factors which have to be considered during development of an individual microfluidic device often do not allow the application of the method used for that device to another, for example when moving from a continuous flow to a “digital” microfluidic device. This issue still needs to be overcome in the development of generic methodology model.

The lack of suitable design methodologies for microfluidics is also based on the requirement, created by the technology driven design approach, for advanced design support tools. Such tools are not yet commercially available (Table 4) and no design support developed particularly for microfluidic has been identified. Again, their development is limited due to the lack of physical understanding of the area. However, design automation for microfluidics via associated support tools has shown improvements [49]. Table 4 compare design supports across the domains.

Table 4 Microfluidics in comparison to other domains - design support

	Microfluidics	**MEMS**	**Microelectronics**	**Macro-domain**
Design style in design support	-	Problem oriented [50]	Technology oriented [50]	Broad range
Tools available	Suitable tools not commercially available [8], [19], [51], [48], [52]	Poor selection [36], lack of suitable cross-domains tools [16], [34], [50], [53], lack of consideration of product development tools [18]	Commercially available [33], [35], highly developed [20]	Broad selection of multifunctional tools [42], [54]
Component libraries	Lack of standard elements [34]	Exist [55], contains many elements inside [28]	Commonly used [17], [34], [56]	Commonly used [37]
Model reusability	No	No [57]	Yes [20]	Yes
Dimensioning	Lack of empirical basis – need for new strategies for building up working systems [17]			Broad empirical basis [17]

In microelectronics due to establishment of the circuit – which is core element in the area – development of libraries took place and allowed for design automation. However, because of the lack of standard elements microfluidics, this is considered to render the development of components libraries very difficult or impossible [34].

Dimensioning of created models, where developed, for microfluidics and MEMS is an issue. In the micro-domain some dimensions are impossible to be measure. Measurement devices have to be smaller than features of elements and have to obtain access to these elements in complex and re-entrant shapes.

3.3 Factors characterizing manufacturing of micro-scale devices

The separation of the design and fabrication processes, which exists in microelectronics, is an achievement of the maturity of the domain which has allowed the standardisation of elements. However, as indicated in Table 5, this separation is not yet possible for highly customised microfluidic devices. Manufacturing technologies for this area are relatively new and still under development.
Three factors contribute to this immaturity: lack of knowledge about the area – which makes designs error prone, lack of available technologies and poor understanding of the profitability of the process.

Table 5 Microfluidics in comparison to other domains – factors characterizing manufacturing

	Microfluidics	**MEMS**	**Microelectronics**	**Macro-domain**
Manufacturing technologies	Relatively new [31]	Broad [58], not fixed [34], novel and in a wide range[24], diversified [35]	Fixed [34], [35], standardized [21]	Standardized, broad range [42]
Cost of manufacturing equipment	High [59]	High [60], [61]	Average-high [59]	Low-high [62]
Required accuracy of manufacturing methods	High accuracy required to be provided in a reproducible and economical way, which is not provided [17]			Required accuracy possible to obtain [62]
Production scale	High [39], [63]	High	High [64]	Low-high

Cost of manufacturing equipment for microfluidics and MEMS is also high, because of the high precision required from surfaces and the limited materials which can be used. Usage of foundries limits these costs. However outsourcing a part of the process, in case of technology driven designs, can decrease the amount of feedback from production and hence the amount of knowledge which could be captured to improve designs.
Manufacturing methods have to be reproducible and economical, both of which are difficult to achieve in the micro-domains [17]. This is owing to the lack of elements and device standardisation and also owing to the necessity of changing production lines to adapt them for new models. Low cost micro-devices produced by high cost of the manufacturing technologies is economically justified only fore large volumes of production.

4 CONCLUSIONS

This paper identifies microfluidics device design as a unique domain, based on tangible issues, such as dimensions, sizes, and cost, and intangibles, such as domain knowledge and area maturity
The lack of suitable design methodologies identified for the microfluidics domain is an effect of the area's infancy and the current unavailability of design support tools.
General design methodologies neglect several issues which need to be taken into account in successful microfluidic design. The two key issues identified are: the incorporation of fabrication and assembly considerations into an early stage of the design process and the establishment of design rules and standardised elements of design - which will allow for automation of the design by development of component libraries.
Further issues in this domain are: a lack of standardised and precise measurement tools and techniques, insufficient understanding of physical failure mechanisms - and hence accurate modelling and simulation tools - and a lack of multidisciplinary support-tools - which would enhance design as well as allowing simultaneous iteration of the changes in manufacturing processes and system and device design.
In addition, a lack of service-orientation in the design of devices has been identified. Service-orientation should be incorporated, in order to address not only present requirements, but those of this domain in the future. The potentially high level of customisation of microfluidics has also been identified as important. An approach to this issue may be a modular-build philosophy based on the development of micro-assembly methods.

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Contact: Katarzyna Panikowska
Cranfield University
Department of Manufacturing
Cranfield, MK43 0AL
UK

Tel: Int +44 1234 75 5656
Fax: Int +44 1234 75 4605
Email: k.e.panikowska@cranfield.ac.uk
URL: http://www.cranfield.ac.uk/sas/decisionengineering/research/projects/pss-micro/peoplebasedactivities/page39579.jsp

Katarzyna is a PhD Student in the Manufacturing Department at Cranfield University, UK. She is interested in many aspects of service-oriented design, design of microfluidic devices and methods to deal with sub-section interactions. In particular she is investigating how service thinking can help in dealing with sub-section interactions in design of microfluidic devices.

Dr Ashutosh Tiwari leads a research group in engineering optimisation within the Decision Engineering Centre of Cranfield University. His research focuses on the application of computing techniques to process and product design optimisation. He has developed a strong research track record by leading a number of research projects and publishing over 100 research papers.

Dr Alcock's areas of interest are micro-device design and fabrication, micro-injection moulding, powder processing science, materials tribology, and magnetic materials. His current research is concentrated in the medical devices sector, particularly on the prototyping and manufacture of micro-fluidic devices for point of care testing, and the design of those devices for services.