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MEMS DESIGN SIMPLIFICATION WITH VIRTUAL PROTOTYPING

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Abstract. *MEMS design requires a good understanding of interactions in complex processes and highly specialized interdisciplinary skills. Traditional prototyping is not easy or cheap due to typically needing very expensive manufacturing facilities for its implementation. Progress towards faster, cheaper prototyping has been achieved but, it cannot be applied to MEMS fabrication in general. This paper analyzes the benefits of Virtual Prototyping for a simplification and aid in MEMS design and proposes the continuation of MEMS Animated Graphic Design Aid (MAGDA) project. Its purpose is to simplify preliminary design stages and make MEMS design more accessible to a wider audience.*

Key words: *MEMS, Scientific Visualization, VR-CAD tools*

1. INTRODUCTION AND MOTIVATION

The purpose of this paper is to motivate making the design of MEMS more broadly accessible and to give a glimpse and overview on where to start for those who wish to endeavour into this area. Since its early days, the MEMS industry is now established and many of the papers presented here are pioneering work that have subsequently been adopted and laid the foundations of this industry. Nevertheless, the production technology options for MEMS remains vast; there is not a "one size fits all". Manufacturing challenges are more the result of a particular innovation of a specific MEMS than of the production process itself. This is also reflected in the research publications.

One of the difficulties in MEMS design and innovation is that it requires highly specialized skills and a wide interdisciplinary background with experience in, physics, advanced mathematical modelling (e.g. for microfluidics), chemistry, materials engineering and manufacturing technology to name a few. It requires such skills for both, the technology and design of the MEMS itself, and the science and engineering understanding at the MEMS' application niche. These required specializations and skills limit the potential for a broader industrial development. This is because development requires adequate tools with powerful modelling and simulation software to reduce the prototyping and

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optimization period. The introduction of CAD packages was a critical step in the widespread development of VLSI devices and reduction of the design and prototyping phase [1]. Despite the demand, there is a lack of CAD tools to aid in the development of MEMS devices. There are several packages available and their benefit is supporting the mathematical modelling part, but for a realistic and useful application, they still require a strong interdisciplinary background.

In computing for example, the introduction of icons and mouse in the early eighties made a huge impact and breakthrough for shortcuts of recurring tasks like file handling, starting programs drawing and visual output. This allowed focusing more on *using* the computer than typing commands for menial tasks. Suddenly, it allowed a broader audience to use a computer. We need to be able to bring MEMS design to a less specialized audience.

Other engineering disciplines, such as mechanics or robotics have found their way into early education and entertainment (edutainment). Despite their ballooning ubiquitosity and breakthrough as, for example, in biomedical applications, MEMS are not yet ready for edutainment, which has undoubtedly a favourable effect for a richer understanding of physical cause-and-effect and shaping of the mind in younger years. It will be many years before MEMS design can be simplified to the point of pick and place on a virtual prototyping (VP) computer screen, and see it functioning in 3D and 4D VP.

MEMS can nowadays be made of a range of materials, not just silicon. Those materials have different physical properties and behave differently in manufacture and use. Therefore a virtual reality (VR) computer aided design (CAD) software that can mimic functioning with physically correct results can be the Meccano or Lego toy for edutainment and discovery (acquiring an intuition) at earlier ages than postgraduates. Our aim should be making the whole MEMS domain more popular. This could be by bringing it to undergraduate or even final years of high school level with introductory courses and gradually adding more ambitious courses in a similar way, as introductory mathematics courses are taught early on, shaping the mind. To achieve that, we need simulation tools that are easy to use and to understand. Just the lengthy training time to handle the software tools and time their calculations take is a discouragement. Novices do not have the patience or the maturity to wait for something they have neither background nor meaning. The bottleneck is no longer the computing power but having usable and curiosity stimulating simulation tools for the uninitiated. Our research has developed techniques suitable for Virtual Prototyping that reduce the calculation time without sacrificing physical correctness. Our methods are suitable for initial design that can then be refined with conventional methods. It serves for advanced researchers and novices alike.

The paper is organized in the following way: Overall, we progress throughout the following sections towards MEMS Virtual Prototyping. Section 2 brings some background and context about the wide range of applications, product ramifications and variety of problems as MEMS have evolved in just two decades. Section three discusses existing tools for MEMS modelling and simulation and moves into existing CAD systems. It explains some of the difficulties and complexities affecting reliability in MEMS modelling. Chapter four looks at the importance of Prototyping and its strong potential for innovation. Chapter five discusses Virtual Prototyping as an important and flexible design tool that has not yet really found its way into MEMS design. In Chapter six gives a snapshot of our contribution MAGDA. It briefly explains our fast algorithms that make the difference for speedier Virtual Prototyping. The last section concludes the discussions with suggestions for future work.

2. BACKGROUND AND CONTEXT

This section looks into the multidisciplinary aspect of MEMS. Its main purpose is to motivate and provide context towards an easier design phase and Virtual Prototyping (VP) and this is reflected in its literature review. Due to the diversity and amount of MEMS material published, this paper does not and cannot replace review papers. Both MEMS and VP are extensive disciplines with their own specialization branches. The project of VP for MEMS is huge and ambitious, and requires specialization topics such as for example "physically based rendering" or "turbulent flow" and many more. Such topics require in-depth study on their own. The project also requires to overcome the old dilemma that engineers are weak programmers, and software developers are weak in science and engineering.

MEMS are minute devices that are in widespread use, for example in airbag triggers and inkjet print heads, optical, medical, and many other applications. With ever increasing new applications in the R&D phase, the MEMS industry is strong and growing, in particular in the medical and optical applications. By their very nature, MEMS devices are microscopic and therefore difficult to observe in action. In the macroscopic world of our daily experience, inertia and gravity dominate the motion of objects. In contrast, in the microscopic domain of MEMS adhesion and friction are the dominant forces. Therefore, MEMS designers cannot use their intuition on how things behave. Because of the different dominant forces, MEMS cannot simply be downscaled counterparts of larger mechanical machines, requiring innovative designs and arrangements of their components, whose effects are often not fully understood. For example, a fluid pump with macroscopic dimensions would not function if it were downscaled to a miniature version with microscopic dimensions.

2.1. Evolution and rise of MEMS

MEMS emerged in the late eighties and nineties with the downscaling of transistors' structures into the submicron scale and by perfectioning microlithography patterning. Since these early days, MEMS sizes are not only in the micron range but can be several millimetres big. The intention is to keep them as small as possible. Small means less materials and therefore less cost and more flexibility in their placing. MEMS materials are no longer limited to silicon but also other materials e.g. polymers or metal are used.

MEMS appeared as a new opportunity in microelectronic manufacturing, in which many of the fabrication steps and factory facilities of semiconductor industry could also be used for MEMS fabrication. LIGA technology, developed at the FZK, Germany [2] for micropatterning precise aspect ratio microstructures with steep trenches or walls, played an important role in patterning microstructures [3]. Examples of achievements and benefits in aspect ratio precision with LIGA are micro optical devices using filters with submicron sized structures, wave guides and photonic crystals, or gears of gold (luxury watch components), that are so perfectly fitting that they do not need lubrication [4]. The use of polymers opened a new opportunity for MEMS. One often speaks of MEMS as complex devices. However, the structural complexity and the functional complexity of MEMS [5] can be very different. They can be made of a few simple components that produce sophisticated function (example: a movable mirror in an optical switch), or several components in a complex arrangement that do simple function (example: a microfuidic pump). By their small size and electronic controllability, MEMS can be built into larger devices, often replacing hitherto large, heavy equipment (e.g. gyroscopes) or saving time and laboratory space in chemical analysis (e.g. lab on a chip).

2.2. Impact in medicine

An increasingly important impact of MEMS is in the medical industry where it has changed medical diagnostics and surgery in an evolution from microgrippers to endoscopy and robotic surgery. This in turn has transformed and brought in new capabilities e.g. ultrasonic surgery, microsurgery e.g. in eyes, on embryos, tactile feedback and with it keyhole surgery with all its associated benefits [6]. MEMS' share in the medical industry alone has grown into a multi billion dollar industry in less than twenty years.

Another successful niche for MEMS with remarkable advances are in biophysical applications. For example, Margesin et al. designed a MEMS for measuring the electrical activity and metabolic activity (ion concentration) in a network of neurons using ion-sensitive field-effect transistor (ISFET) arrays [7].

A word of caution, Microsystems and Nanotechnology are often erroneously thought as being the same. They are not; they operate at different scales of resolution. Nanotechnology deals at molecular and particle level and therefore uses different models; it has different challenges and different industrial potential. However, in Microtechnology it is possible to produce nano-sized structures whenever necessary. Rieth has written a good introduction in a nutshell about Nanotechnology (suitable for advanced readers) [8].

2.3. Training and specialization

When it comes to education, VR is nowadays a well established option in undergraduate multimedia curricula in many tertiary institutions, with some institutes more specialized in VR than others. In contrast, the teaching of Microsystems is usually deferred to at least Masters level. This is due to the multidisciplinarity required in understanding MEMS. Institutes that are known by their excellence in the field also offer regularly specific specialization short courses. Such short courses and summer schools provide an introduction to a specific topic; they are a valuable step towards postgraduate research. Programs for short courses can be easily found through international professional organizations. Examples are FSRM Fondation Suisse pour la Recherche en Microtechnique (Swiss Foundation for Research in Microtechnology), Neuchatel [9], IMEC - Interuniversity Microelectronics Centre, Leuven [10] or the IEEE [11] and Eurotraining [12]. While a researcher or student should stick to reputable and peer reviewed literature, one must never forget that in Industry is where results of research come to fruition. There is a wealth of real life information in industry reports that they should take advantage of, albeit, with some caution. They complement research findings by providing eye opening context.

2.4. MEMS design

Here we present a selection of issues arising in MEMS design, with the intention of preparing the scene towards Virtual Prototyping. MEMS design can be overwhelming by the wide, almost infinite range of possible structures and how these structures work together to provide a useful function. Mastromatteo and Murari have designed and proposed an architecture to address the diversity of MEMS by grouping them into the traditional categories MOEMS, MEMS, Lab on Chip, RF MEMS, Data Storage MEMS.

However, it is not always possible to allocate a MEMS into just one of any these categories in a very strict sense due to their cross category functionality [13]. Grouping them helps to conceptualize, but it is not a strict definition or standard.

Spearing analyzes scaling the size of MEMS in the context of macro versus micro scaling. In his work the relation between mass – volume scaling and volumetric to area scaling are explained. This is summarized in a table for guidance for possible scaling in MEMS design. The work shows how some of the most important effects of scale on MEMS design or performance cannot be attributed to a single physical factor. It also shows the need for fabrication processes that allow for dimensional tolerance but that this can be limiting to the shapes achieved. As a consequence in MEMS distinct, more expensive materials may be used, whose cost would be prohibitive for larger sized devices [14].

Materials play an important role, in for example flexing membranes in micropumps, or cantilever switches. Senturia offers an introductory overview into this area structures, processes and modelling [15]. Another good source is by Pelesko and Bernstein explaining structures and device behaviours by motivating and developing understanding and intuition and then moving into the modelling and optimization [16].

2.5. MEMS evolving manufacturing alternatives

MEMS are 3D devices. The traditional functional distinction is into sensors and actuators [17]. They can be one single structure, or the result of many components but they all need some circuitry or interaction to control them. In silicon manufacturing, it would save huge fabrication costs if MEMS and the circuitry to control them could be manufactured together on the same wafer. Unfortunately, this is rarely possible because processing steps that involve heat can damage previously accomplished structures. Depending on the materials used, the structures of MEMS components are either removed from a solid material, or built up in a deposition process. This is the area of microlithography and micromachining [18] and [19]. There is a good range of introductory and advanced literature available, but publications hardly keep up with MEMS' fast technology advances. One reason for publication delay is industrial non-disclosure. An overview about the fabrication process, materials, processes and micromachining are presented by G. Fedder [20] and Subramanian et al. [21] about design. Despite mature fabrication processes, new MEMS applications and innovations in their fabrication present constantly new hurdles that must be overcome. This is illustrated by the design and realization difficulties of a micromachined silicon nanopositioner with electrothermal positioning by Zhu et al. [22]. Another example is nanochannel fabrication using bond micromachining by J. Haneveld [23].

Normally, the fabrication of MEMS is not a simple process. If it is in traditional silicon technology, it requires a semiconductor foundry, capable of handling around 200 processing steps and very expensive equipment. Some processing steps that require very specialized equipment or processing facilities may be outsourced to other foundries. Experimental implementations are fundamental for frontier research. Due to the high costs, research centres are often equipped with whatever funding allows and sometimes fabrication steps have to be carried out at industrial facilities. The collaboration between research institutes and fabricants providing service for prototyping and fabrication is a convenient way to overcome shortages for mutual benefit, sometimes even sponsoring research [24].

A vast range of technologies have been developed and there is more to come. Nowadays MEMS are not only made of silicon but other materials are used, for example, glass, photoresists or other polymers that can be patterned by laser, Rapid Ion Etching (RIE) or other technologies. For example, Desbiens et al. found that for prototyping, an Excimer Laser (UV laser) can be used for the removal of materials (ablation) for MEMS micromachining of 3D structures in approximately 1-5 μm range. Their research studied the interactions of repetition rate and mask dragging speed as parameters in a systematic study and measured the etch rate of material on samples of different materials, Si, PZT and Pyrex [25]. Delille et al. have shown how photopatternable UV sensitive adhesives can be used for patterning up to 1cm thickness. The benefit is that the process is low cost and requires no baking and does not even require a cleanroom. Some of these polymers bond irreversibly to glass and they can be compatible with living cells [26]. Due to the ability to work in any room and under any light condition, makes their findings suitable for education purposes of MEMS fabrication. Material deposition by 3D printing is becoming popular, but all depends on the purpose of the MEMS. More about 3D printing further down.

To power a MEMS requires some source of energy. For medical MEMS implant applications or situations where MEMS application requires independence from a clumsy battery this means an additional difficulty. This leads to a niche for technologies and materials to harvest energy and supply to power a MEMS. Iniewski et al. present a good introduction to this area about such materials and technologies [27] Bermejo and Castañer have studied to drive MEMS electrostatic actuators with a direct photovoltaic (PV) source. The benefits are that the number of solar cells can be customized for specific MEMS switches and better performance with increased reliability [28].

3. TOOLS FOR MODELLING AND SIMULATION

This section explains the evolution and need of CAD systems for MEMS. It also shows with examples the vast diversity of problems that appear and need to be addressed. MEMS design and fabrication requires a range of modelling techniques at different stages. On one hand, we have the mechanical and circuit modelling for the functioning of the MEMS. On the other hand, we have the fabrication design and experimentation with physical modelling to find out desired properties of our object MEMS. For CAD tools, we have to distinguish the mathematical modelling and the visual images providing information about what we are modelling. Mathematical modelling (MM) is essential in device design. MMs are also the underlying simulation tool for MEMS CAD software. Without it, there can be no serious outcome in MEMS design. MM occurs at different levels. Napieralski et al. have elaborated an interesting work on the evolution of MEMS and modelling. They demonstrate how the advances in MEMS technology and modelling methodologies not only depend on each other but even drag each other forward [29]. Lyshevski provides a good introduction to the fundamentals of Mathematical and Physical modelling in context with MEMS and NEMS structures [30]. These models are necessary to calculate the dynamic behaviour of those structures working together in a purpose or function. In this endeavour, further calculations are needed to solve the resulting differential equations. This is done with numerical calculations, using solvers such as Matlab^{TM} and for MEMS in particular Finite Element Analysis (FEA) calculations. Comsol Multiphysics^{TM} is a popular and steadily growing environment for calculations using finite elements [31]. Another one is ANSYS^{TM}. These are not the only ones; there are other multiphysics solvers.

One important step in modelling MEMS is the order reduction of differential equation systems (in particular non-linear) and differential algebraic equation systems. Greiner et al. have developed a method to reduce the order (dimension) for finite element models of second order systems, which appears to work well for linear conditions [32]. Additional practice about numerical and experimental evaluation of the mechanical properties of MEMS and NEMS are collated by Frangi et al. in [33]. It also contains an investigation by Ananthasuresh about continuous parameterization and the problems that arise and ways for optimization. Bechthold et al. have developed a methodology for model order reduction for a range of MEMS [34]. Their method has the potential for an automated implementation.

MEMS involving fluids have a substantial impact in medical applications. Fluids play a special role in many microsystems because fluids behave differently in a microchannel than in a macroscopic space. Design considerations and microfluidic behaviour requires special mathematical and modelling skills in a different physical domain. Nguyen and Wereley provide a good introduction into this domain and microfluidics in MEMS [35].

3.1. Reliability

Reliability is defined as the time before failure. This quantity has been used for decades, but on closer observation, it does not give any indication why the device fails. This is aggravated in MEMS; they are not just the microelectrical circuitry but also the mechanical part that goes with it. Microscopic structures will function in different physical domains than macroscopic devices. It may not be easy to pinpoint the source of functional failures because the dominant physical forces change gradually as their geometric dimensions increase or decrease. Because it is a gradual change, it may not be evident how much is due to - say - adhesion, capillarity, or any other force, it is appropriate to consider a more structured approach. To address this issue, we have developed a hierarchically structured reliability model that allows giving different failure weights to different components. Some components are more robust (or vulnerable) in their design than others. Likewise, some materials are more robust (or vulnerable) than others; and again, some assembly or manufacturing processes are more difficult (vulnerable) than others. Our model allows assessing and pondering a priori different combinations of options for design, materials and manufacture or assembly [36].

In a somewhat similar way, Muratet et al. have focused on failure analysis given that the vast variety of structures in MEMS represent different points of material weakness and/or design failure. To demonstrate this, they have developed a time before failure prediction model and illustrated the procedure by implementing a wobble electrostatic micromotor as an example. They use testing failure (including failure criteria and conditions) and combine these observations with FEA simulations (by including failures into the simulations) from which they can identify risk conditions (deformation, stress) from which they derive the time before failure model [37].

3.2. CAD systems

In the early days, a relatively small number of MEMS design software environments were available on the market. Their application potential was rather restricted to modifications of existing library designs. Dewey et al. used analog hardware description languages (VHDL-AMS) for their project Visual Integrated-Microelectromechanical VHDL-AMS Interactive Design (VIVID) [38]. Often the tools were by-products from code written for the design of another specific project [39,40] and often difficult to use [41]. They appear as a collection of tools [42], sometimes limited to specific applications [43]. One of the first CAD systems for MEMS was MEMCAD built at MIT in the late nineties [44]. Since then many more systems have been brought to the market, some of them disappeared, while other evolved with state of the art facilities. Few have calculating MEMS manufacturing parameters as their primary purpose, and if so, more often than not, they are beyond reach researchers due to their high cost [45, 46].

Due to the amount of calculations involved, the development of a CAD tool is not an easy task, in particular for MEMS. This is caused by their multifaceted, multivariate aspect. We are dealing with 3D mechanical devices, with critical timings (4D) and acting forces, sensing, or performing chemical, spectral analysis or pattern recognition adding to the complexity and at the time of design most of it squeezed into a multiple representation on a 2D screen display. To aid imagination and interpretation, schematic drawings have progressively grown into CAD tools. These in turn have diversified for specific application niches and with the purpose to be fed as a run specification program into a microlithography or micromachining tool, e.g. a laser. The reality is that design is usually a mix of back and forth between simulations and the development of prototypes. It appears that a one-only streamlined workflow that goes from the CAD drawing board to the fabrication of a prototype does not exist yet. In an early endeavour for optimum design, Gaddi et al. have developed a framework for a top down design approach based on IC design and electrical and mechanical parameters. Their aim was for a hierarchically mixed design environment, using FEA for validation [47]. This is unusual, because FEA are normally used for calculating optimal parameter combinations in a systematic set of simulations, not the other way round. This model appears to be limited to silicon technology. One very early CAD tool was developed by Dasigenis et al. Their CAD tool recycles a previous MEMS converter design and allows its updating to a new design and producing its new processing parameters [48]. This approach is devoid of any modern user/menu driven software or architecture facilities. It equates to building up a library from scratch each time when it comes to designing another device, using a new technology or materials. A classic computing simplification approach was chosen by Bardohl et al., who have used graph (that is the graph description of images) and transforming it into sets of reduced graphs [49]. It is questionable, whether these transformations for reducing information handling are efficient or even practical in a MEMS–CAD application.

In a biometric approach to manufacturing biomedical microdevices, Hengsbach and Díaz Lantada have produced a multiscale biomedical microsystem for addressing the effect of surface texture on the cell mobility. The purpose was to fabricate multiple length scale geometries that allow interactions of implants with living tissues. They used a laser writer for the device structure (several mm) and a direct laser writer for finer, submicron size details. One problem that arose with the fine textures and microstructures was the CAD file size of several hundred MB and some GB, which in turn affected the fabrication time excessively. The solution was to revert from a descriptive geometry as sets of layers to algorithmic geometry, by mapping a grid of channels as fractal surface functions to a matrix. This reduced the fabrication time by more than one order of magnitude [50].

Another problem that requires attention is that in the design of MEMS different physical or chemical phenomena must be simulated. That means several suites of solvers, and because they require surface or volume meshing for their calculations, they are slow and not suitable for interactive design. This is an inconvenience with all currently existing CAD products for MEMS that are on the market, for example Coventor^{TM} [51], MemsPro^{TM} [52], Tanner^{TM} MEMS Design Flow [53], IntelliSuite^{TM} [54] and others. They offer mixed capabilities, mixed interactive facilities, speed and popularity. Some of them are sophisticated but all require a good understanding of Physics, Mathematics, Engineering, knowledge in MEMS design and training time to use the CAD package efficiently. Computing power has not yet resolved the problem of speed, the very essence for rapid prototyping.

4. PROTOTYPING

For larger systems, industrial rapid prototyping played a substantial role in the development of new articles. A prototype is a model of a device with emphasis on either replicating its functioning and scale (dimensions) of the intended device, or to study its production feasibility. If the aim is to study the functioning, then neither materials nor the production process need to be the same as the intended ones for regular fabrication. However, the closer to the reality, the better is the prototype. If the aim is to study the feasibility of a certain production process, then the intended production process must be replicated. Typically this is a “no frills” approach aimed at simplification, be it reduction in fabrication time or cost of materials or need of expensive equipment. Prototyping is aimed at answering the question “can it be done” and “does it do what it is meant to do”. The answer must be fast, before large sums are invested in its production. This is why rapid prototyping has evolved over the years. Even rapid prototyping requires to some extent a worked out design. A prototype serves to eliminate design flaws or unnecessary costs early on. The “no frills” means that the focus is on the functioning of a device for its intended purpose, the famous “fit for that purpose”. As an analogy, there is no point in modelling comfortable seats for an airplane that is unable to take off and fly. It must fly! *That* is its purpose.

It was the search for faster, cheaper prototyping that enabled the evolution of MEMS from silicon manufacturing to other materials and processes. This happens when a MEMS prototype turns out to be satisfactory to the extent that the initial experiment goes almost instantly into production maturity. This is triggered by the insight that originally intended materials or the production process can be replaced with the cheaper ones used in the prototype. This has lead to an explosion of alternative MEMS materials and technologies, and with it pushing innovations and applications further from initially expensive devices to cheap single use medical MEMS products. In what follows, we will illustrate this with selected examples in a brief journey in time.

In the process of rapid prototyping sometimes specific tools are required for being able to see small structures in MEMS. One such tool is “small spot” stereolithography but it was insufficient for small structures, and being replaced by Microstereolithography, which was not yet fully developed. Bertsch et al. have [55] conducted a comparative analysis of those different types of stereolithography and their suitability in MEMS prototyping. Conventional stereolithography’s resolution was too limited for small MEMS structures. However, a later integral Microstereolithography’s resolution with at least an order of magnitude better than small spot lithography turned out particularly suitable for manufacturing complete layers with small 3D structures of 0.05 to 0.2mm but without high aspect ratio.

Lin et al. used a thin layer of baked on photoresist, instead of a conventional mask on soda-lime glass substrates to produce microfluidic channels approximately 36 μm deep. A two-step baking process ensured good adhesion of the photoresist to the glass. This was then etched off in an iterative progression of wet etching of dipping and etching with ultrasonic agitation, which led to smooth etching results. The process was aimed at fast prototyping and mass production of microfluidic systems. After successful etching, the microfluidic channels were sealed with glass chips at 580oC. The whole process was done in ten hours [56]. Another similar technique using photoresist as was developed by Sampath et al. [57] to produce free moving structures. The authors use a 20 μm layer of patterned Photoresist (SU-8) to form an insulating spacer layer on a silicon wafer. Then they used wafer bonding to apply a 50 μm layer of crystal silicon on top of the insulating spacer. This was followed by patterning the crystal silicon layer with RIE to produce the desired structures, in this case, a spring and a piston. The difficulty was to achieve a tight bond between the photoresist and the crystal silicon layer, given that the thickness of the photoresist is critical to produce precisely the desired thickness but it is thermally sensitive and can crack in the silicon patterning processing steps.

In MEMS manufacturing and prototyping we often see additive (building up in layers) and subtractive (removal of material) processing steps to achieve the desired structures. These fabrication methods allow alternative materials, often polymers and they do not need cleanrooms. They are faster, often cheaper alternatives to the traditional silicon wafer processing. Li et al. have adapted Shape Deposition Manufacturing (SDM) to microfabrication by developing an ultrasonic-based micro powder-feeding mechanism for precise microdeposition of dry powder onto a substrate. This was followed by patterning by sintering the powder patterns with a micro-sized laser beam to clad them onto a substrate [58].

Khoury et al. used liquid phase photopolymerization for ultra rapid prototyping that are suitable as masters for micromoulding microfluidic channels. The process is suitable for lab on a chip MEMS used in life science, where fluids in very small quantities are used, mixed, cultured, etc. and discarded. For the process, the authors used a multichannelled universal cartridge as master. The cartridge was filled with fluid photoresist and unwanted parts were masked off before exposing with UV to harden the desired channel geometry. The remaining structure was then rinsed, leaving the desired channels open. The process is also suitable for a fast production of microfluidic devices without micromoulding [59].

High aspect ratio (structures with deep narrow trenches with straight walls) is a specific niche in MEMS. The processes that can be used for prototyping and the production of MEMS that require high aspect ratio depends on the materials used and consequently the intended application and life span of the MEMS. Sarajlic et al. have used plasma processing with Low Pressure Chemical Vapour Deposition (LPCVD) for high aspect trenches and after a few more processing steps using the “black silicon method” (BSM) for pattering, passivating and release with isotropic plasma etching [60]. The benefit is that the processing was drastically simplified with BSM by keeping all in the same run, that is, in the same vacuum chamber. This made it suitable for rapid prototyping.

In an endeavour for finding alternative micromachining to produce polymer-based capacitive micro accelerometer Yung et al. [61] have used direct write laser ablation (removing material by laser sublimation) for its production. They have shown that this is a more convenient and suitable technology than traditional lithography methods. This is because traditional lithography as used in semiconductor manufacturing requires expensive equipment and expensive masks, which is justified for mass production, but not for smaller productions of some MEMS. The cheaper laser ablation made it ideal for non-mass produced MEMS and it is also much simpler by allowing other materials.

Abdelgawad et al. [62] have developed a cheap technology to produce actuators with 50-60μm electrode separation that allow droplets of 1-12 μL microfluid to move, merge or split. They use digital microfluidics and electrowetting and electrophoresis to measure enzymatic activity (enzymatic assays). What makes their work so different is that they did most of this with very cheap resources, i.e. recycled circuit boards and compact disks (CDs) for gold and metals. For electrode patterning they used an ink pen and ink masking made with a razor blade instead of expensive photolithography with UV exposure. For dielectric coating, they used cling wrap (plastic film used to cover food). For protective hydrophobic treatment, they used cheap car windshield protector instead of expensive and licensed use of Teflon. They have successfully realized their experimental work for prototyping. To read about this work is not just inspiring, it is also highly commendable for education.

In the strive for rapid prototyping of precise submicron and nanogaps, Villarroya et al. have experimented combining a focused ion beam (FIB) followed by reactive ion etching using aluminium masking. Their process achieved trenches of 80nm wide and 11nm deep. The goal was to produce nanodots [63].

Microfluidics present another challenge to rapid prototyping. The quantities of fluid used in the end product are minuscule and in biomedical application they are used briefly and discarded. This requires large quantities of MEMS or NEMS to be produced. This makes conventional manufacturing in silicon unattractive due to their complicated and slow production and expensive equipment in a foundry with cleanroom. Do et al. have developed a process using a cutter plotter (a “printer” that removes material) to scratch or cut through a polymer substrate, patterning the structures layer by layer with holes and trenches. The polymer sheets are then assembled one upon the other (like pancakes) and bonded. The arrays of overlapping holes make the containers for the fluids. This process achieved 20μm wide and 30μm deep channels in less than 30 minutes. This process is fast and does not need cleanroom conditions [64].

Another interesting case is printing MEMS onto paper. In a feasibility study, Meiss et al. have developed a method and special ink to print resistive sensors onto paper substrates using inkjet equipment. The technique can be used in iterative development and complex model design of sensors for low cost applications, such as medical disposal or consumer goods packaging [65].

Speed is paramount in prototyping. 3D printing had a substantial impact in rapid prototyping because it is a fast way of building up structures. By adding layer after layer, fine structures can be produced using materials like plastic and metal. Lifton et al. have researched and compared 3D printing with other technologies. They found that for some currently silicon-based MEMS, the production time can be drastically reduced by replacing long-cycle prototyping and packaging loops with 3D printing. There is the potential to use 3D printing for electronic packaging of MEMS devices at the wafer stage. 3D printing is suitable for features larger than 1μm, such as lab on a chip. However 3D printing is not suitable for structural elements such as cantilevers and springs because the polymers used incompatible with their desired functions [66].

5. VIRTUAL REALITY PROTOTYPING

Virtual prototyping has been around for over a decade. It became possible with increased computing power and faster VR algorithms. Its application in MEMS is rather limited, which is understandable, given the complexity of manufacturing.

Cecil et al. have presented a comprehensive research in virtual prototyping [67]. However their work was aimed at VP in general, not necessarily MEMS, but the explanations are equally important for MEMS VP. Jiang et al. have developed a proposal for a service driven MEMS CAD design tool. Contrary to traditional bottom up approaches, the authors argue for a top down approach. This project was aimed at designers with little knowledge in MEMS manufacturing process technologies and the requirement to detach the MEMS design from its fabrication. The authors have produced a partial software prototype; its output produced Bond Graphs. [68]. Schröpfer et al. went a step further and presented an overview of different modelling levels in MEMS and the CAD tools that are relevant to these modelling levels. It serves both MEMS and IC designers. The authors also analyze the differences and benefits between their applied Behavioural Modelling and the two popular modelling with FEA and Boundary Element method (BEM). Another important feature is the use of voxels (think of pixels in 3D) instead of pixels for their displays to facilitate 3D animations [69]. Cecil et al. have proposed a virtual reality-based environment for micro assembly (VREM) that is linked with the physical manufacturing. The software for the VR environment mimics and displays on screen the tools and movements from the point view of an operator. An automated assembly sequence generator uses genetic algorithms to optimize assembly sequences. The outcomes from the virtual environment aim to produce a validated schedule for the fabrication of a MEMS, and the assembly instructions for the physical part (tools and autonomous robots) to be assembled by the available work cell resources. Some examples of VREM are developed as prototypes [70].

Despite the potential of current computing power, the availability of virtual reality with animations is still non-existent or very limited for MEMS. In 2001 we initiated our MEMS Animated Graphic Design Aid (MAGDA) project [71]. This project is summarized below and specific example shown further down. MAGDA aims for starting design templates for structures of MEMS. These design templates give priority to those parameters that are most sensitive in the proper functioning of the MEMS. It aims to provide a library with typical designs that can be changed further in a similar way as Dewey et al. did in their project Visual Integrated-Microelectromechanical VHDL-AMS Interactive Design, VIVID [38]. The difference is that our starting point is based on theoretical MEMS whose design templates summarize the features of typical classes of MEMS. This provides a more general starting point with more freedom, while in VIVID only those designs that are available from the foundry cell libraries provided by the designers of the software can be used. Our motivation for our more generic template is to start with a “feasible” MEMS. We use Chua’s notion of “local activity” [72] to step into the design of a MEMS, whose internal complexity (hence its detailed mathematical modelling) can be deferred for a subsequent stage of fine-tuning. This is important to bring MEMS design closer to the less specialized and novices, and still offer (albeit limited) understanding and learning of cause and effect in MEMS parameters.

6. THE MAGDA PROJECT

MEMS Animated Graphic Design Aid (MAGDA) is our Virtual Prototyping project that aims at building a simulation environment to aid in the design of MEMS. The purpose of MAGDA is to overcome the weaknesses of commercially available CAD software. Specifically, it aims to overcome the weakness in interface usability, by simulating the functioning of MEMS interactively, and by producing animated VR visualizations. It aims at contributing in a similar way to the MEMS industry as the introduction of CAD packages was a critical step in the widespread development of VLSI. In its implementation, MAGDA acts as a layer between the user and existing CAD solvers currently used in MEMS design, with a capability for calculations on its own. Figure 1 shows the basic organization of MAGDA

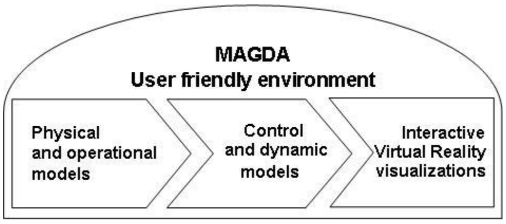


Fig. 1 MAGDA organizational diagram.

MAGDA is an ambitious project that was initiated in 2001. It has attracted postgraduate students and international exchange students for research and implementation. To illustrate why it is an ambitious project, we look at collision detection that is suitable amongst the many collision detection algorithms. What adds appeal to it is the VR placing of different shapes in different conditions and arrangements, for example modelling a gear or a spring into a device being assembled. MAGDA is about the manufacturability, which impacts on the suitability of models that can be used; it does neither use nor replace existing commercial products or finite element calculations. The objective of MAGDA is to calculate faster for interactive early design and narrowing to a desired range of parameters and functionality towards a prototype. The result of MAGDA can then be used for further fine tuning with finite elements or other mathematical models. This system must have several major components that are interrelated with each other. For the Virtual Prototyping project, this is a huge task that must be broken down into smaller, more manageable parts. We do this by following the naturally given classification of actuators and sensors according to their operational principles. However, we cannot isolate the design of each class of sensor, because it would defy the overall purpose of providing a design tool that offers flexibility and allows for innovation perhaps across different technologies. This has been exemplified in the previous sections of this paper. It is therefore that the Virtual prototyping facility must be able to combine different technologies and at the same time work in concert with the different components of the MEMS to be designed. MAGDA is not intended for virtual manufacturing; this is a different niche altogether. An exception to this is virtual etching because the different types of etching affect the shape of material removal and consequently the shape of the object (straight or curved corners, edges and shapes).

For the software, development Matlab^{TM} and C wereu sed for the physical shape design drawing board and VRML for the visualizations. The benefit of Matlab is that it can be used on Windows and UNIX OS. It is widely available, affordable, and it has good graphics facilities. For the Control and interaction of the MEMS (systems modelling) Simulink is suitable. An additional advantage for using Matlab is that MEMS design engineers can link the Virtual Prototyping with their earlier calculations and results if they were done in Matlab. However, one severe problem with Matlab is that it is not a stable software. As we have regrettably experienced, it suffers from version changes and upgrades that are not backward compatible, sometimes rendering existing software useless.

6.1. Visualizations and animations

In our MAGDA VR Visualizations, we use physically based rendering. Most of the code is written in VRML. We also use transparency for flexibility and easier understanding the devices in 3D visualizations. Visualizations can be rotated for easier inspection from different aspects. Images on screens are two-dimensional arrays of pixels, sometimes representing 3D and moving structures. Representing specific movements by showing series of lights (pixels) some flashing alternating with each other to make the whole series appear moving in a specific direction and changing, is not trivial, because its outcome depend a range of "by-effects" that affect the visual perception in either good or bad ways. A well known example is wheels (or gears) rotating "backwards" while the object where they are attached moves forwards. One of the main purposes of MAGDA is to show animations of a functioning MEMS in scaled observable "real time". This can include components simultaneously moving at cycle times that can differ in orders of magnitude, for example, a gear rotating, a cantilever flipping and a membrane bending. Therefore, animations cannot be a simple a zoom in time, because it would cause too much distortion between moving parts with different motion rhythms. While observing the movement of one component in slow motion, another one could come to a stand still. We have to be aware that we are performing animated visualizations of simulations that must strictly map to their object's physical behaviour without ever degrading to a cartoon.

We have addressed this problem by simulated stroboscopic illumination with flexible fine tuning its two virtual stroboscopic flash parameters: duration and interval. This is necessary for overcoming results of specific undesirable visual side effects (jumpy or flickering images) and hardware influences such as pixel size and computing latency effects [73, 74] and to provide a smooth observable animation. If, for example, in a visual experiment the thickness of a micropump membrane as shown below in Figure 2 is changed, the two stroboscopic parameters can be reset by moving a virtual slider on the screen, to bring the new conditions again into a smooth, non flickering animation. This makes MAGDA different from other simulators.

Fig. 2 InteractiveVR environment showing a micropump with flexing membrane, flow and user controls [73].

In what follows, some of MAGDA's research results are briefly presented and what difficulties they are overcoming. For an interactive system, fast response is paramount [71]. Much of MEMS physical modelling is done with finite elements. Despite substantially increasing computing power, they are still too slow for interactive modelling. There is another issue: the physical domain. MEMS can be microscopic or macroscopic. The boundary for the separation of the dominant physical forces (e.g. inertia and gravity vs. adhesion, capillarity etc) is hazy to say the least. This is crucial for the distinction of fluidic and microfluidic modelling, because the viscosity and channel materials affect the slip length which in turn affects the Reynolds number and depends on the pumping speed or flow rate and the physical characteristics like size, hydrophyllia or hydrophobia of the channel [75]. In addition, a novice MEMS designer would rarely be familiar with the rather specialised topic of Navier Stokes equation systems for fluid modelling.

In a systematic FEA analysis, we have simulated microfluidic flow by varying stepwise a set of parameters to find the distinction between laminar and turbulent flow [76]. Such subtle details affect the mathematical modelling, hence the outcome, but this is important in the vast area of chemical and medical analysis. The interactive VP environment must be equipped with recommended model guidance in (e.g. like a pop up alerting to turn on a menu for specific parameter setting combinations).

6.2. Fluid flow

In a microchannel, the fluid is flowing at very high velocity. This velocity is different throughout the channel: it flows at different rates in different regions. For example in the centre of a square section microchannel with 152 µm sides, the flow has a velocity of 8.3e10 µm/s, while towards the channel walls the velocity drops to 2/3 of the maximal velocity, and touching the walls it flows only at ¼ of that velocity. This velocity reduction is due to an electric friction with the walls of the microchannel, pulling into the opposite direction as the flow and it is induced by the high velocity of the fluid flow in the channel.

In our research, we have been looking for valid replacements for finite element calculations because they are too slow. We have investigated new models for laminar and turbulent flow of microfluidics in a channel, for example how to model an inversion layer in a channel. We use a layer model for the different velocities as if they were distinct strata. This is shown in Figure 3. Those layers next to the channel walls rub against it producing friction and to lesser extent, they slow down the adjacent layer, which in turn also exerts friction on the next layer and so on. In the centre,

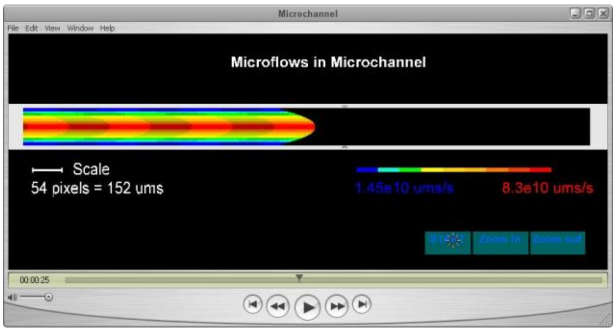


Fig. 3 VR simulation of fluid entering the channel and formation of the bullet nose as it moves at different velocities (coloured layers). The vertical stripes of the flow are to distinguish the movement. To the lower right are user visualization controls (blue/green) [73].

the particles move at high speed because there is little or no friction anymore. In the outer layers, the particles move much slower due to the friction with the channel wall.

Our aim was to model the different layers of fluids as an electrical network. To do this we have modelled the flow segmented into layers to the pertinent models. We used first a continuum model (Euler and Navier-Stokes) for incompressible flow (liquids). This was done by solving the Navier-Stokes equation, obtaining an analytical model for the circular and a numerical model for the rectangular channels. These were then used to model the layers as an electrical network model in Matlab Simulink. The resistances of the layers are obtained from the velocity profile of the flow. Compared with ANSYS, our electric network model for the circular microchannel gives percentage errors up to 6.6% and compared with Hagen-Poiseuille equation, the error is below 5.22%. One must bear in mind that ANSIS' error can reach up to 10%. This is a satisfactory result for a faster model that does not require meshing nor lengthy iterative calculations [77, 78].

6.3. Turbulences

Turbulences are an important phenomenon in fluidic MEMS design; they may be desired (e.g. for mixing fluids in or undesired (for medical implant medication dispensers). Turbulences have several phases in their existence: a beginning, a movement, and an end phase. The can move in rotational or undulated movements. Initially the velocities of the fluid can be rendered with larger patches of colour, while as the turbulence sets in, the patches become increasingly smaller. This is because a turbulent diffusion process is ongoing, but the diffusion is slow, following the swirls and eddies that characterize turbulent flow [79]. The strict layered flow as it occurs in non-turbulent fluid starts mixing and some parts will move faster, some move slower across the channel.

We have developed the cluster splitting method for displaying turbulences in a microchannel. Our method is suitable for fast calculations virtual reality visualizations in an interactive CAD tool with a 2D display. Instead of calculating and recalculating all the nodes in a mesh as in finite elements, our method takes advantage of redundancies.

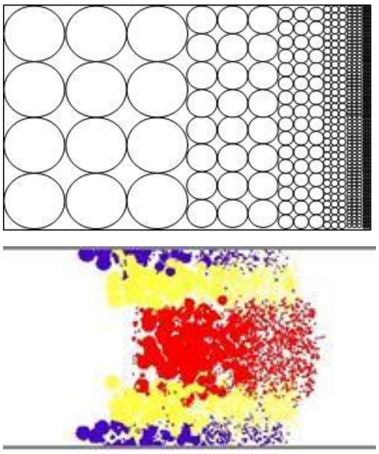


Fig. 4 Cluster Splitting [81] Upper: model diagram (1:2 split) Lower: simulation (1:4 split).

For graphic visualizations, we do not necessarily have to go down to the level of atoms or molecules. Our objects of interest can be composed of macroscopic particles or clusters, but interacting in similar ways like smaller particles. However, by staying in the potential domain instead of the force domain, physical approximations can be made, simplifying complex and lengthy calculations. We use the Lennart-Jones potential model, but instead of individual particles, we use clusters of particles [80]. We start when the fluid is pumped with a given force into a nozzle and the microchannel at (t_0) with larger clusters of particles (think of circular droplets) that are moving with equal speed and direction in the stream pumped through the channel. After a time (t_1) we divide each cluster in half (t_2), calculate, divide again (t_3) and so on [81]. The total time is the sum of a well-known geometric progression. Ideally, by just dividing each cluster into two we save 50% of calculations. In reality it takes slightly more because the calculation times have to be added in both cases, cluster splitting and FEA [82] for comparison. In this method, calibration is required for different materials; this becomes part of the data library. For the example shown in Figure 4, we used three layers and progressively reached finer cluster granularities that are well suited to show the bullet nosed fluid flow in the channel. Our calculation of the channel used 6000 clusters in our worst-case dynamic simulation examples. The corresponding FEA calculations used 90000 nodes for a static image.

6.4. Flexing movements.

Another research aimed at developing faster models for MAGDA were flexing membranes and cantilevers. Normally these components are also calculated with finite elements. We derived faster models using splines. Our parameters were material, thickness of membrane and size (diameter or length of cantilever). These were fed into ANSYS and the values obtained were then imported into MATLAB where splines and quadratic polynomials are fitted to them. Then the equations describing the curves are obtained as well as the coefficients and errors of the structures. The process involves dividing the surface into three regions or segments of curvature. Figure 5 shows the difference between the real flexed membrane and the calculated values at maximum deformation. The obtained errors are still within the errors of ANSYS. For the purpose of MAGDA our models can be repeated by systematical stepped analysis and then bundled and simplified into a more generic model with simple parameter input [83].

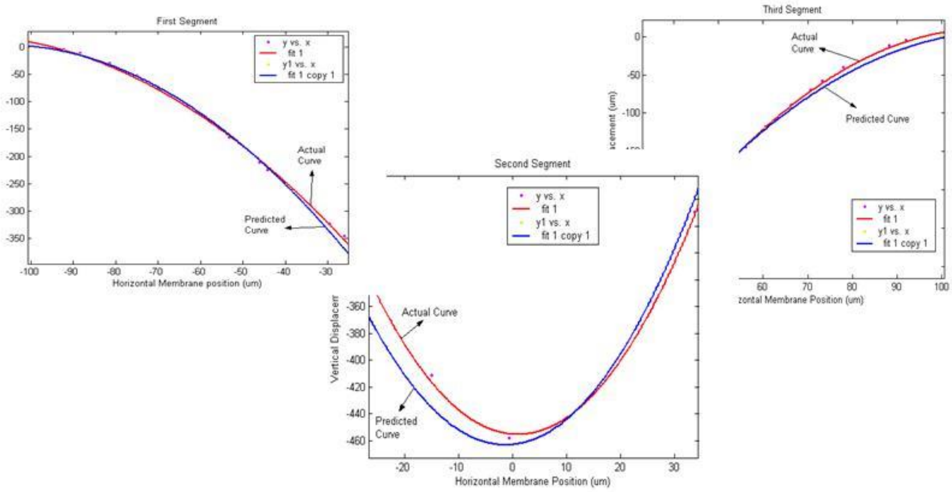


Fig. 5 Membrane flexing modelled as three different segments and using spline approximations (red: actual, blue simulated).

6.5. Virtual etching

Again, after an in-depth comparison of available software techniques, we found that the main problem is that they use finite elements to calculate material removal. Again, this is not suitable for interactive VP because at current HW status this is still too slow. Etching performance is well known from the Integrated Circuit processing, but it is not so predictable in MEMS because the shapes are more complex. Underetching is not desired in IC technology, but it is crucial in shaping and releasing MEMS structures for free movement. The preparations for animated anisotropic etching, both for wet and dry etching are relatively straight forward, but isotropic etching requires a more sophisticated approach.

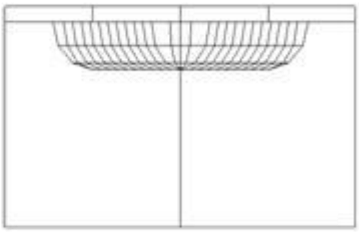


Fig. 6a Etching square mask wiremesh obtained with Marker String method, 2D view [84].

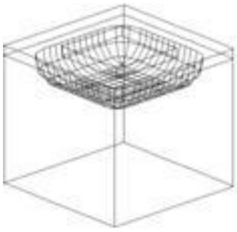


Fig. 6b Etching square mask wiremesh obtained with Marker String method, 3D view [84].

Fig. 6c Etching square mask (Marker String method) rendered , 2D view [84].

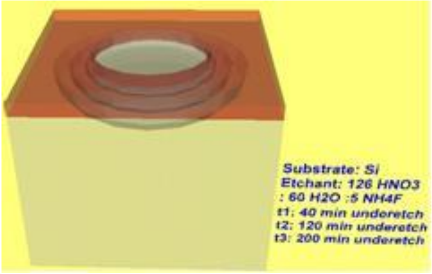


Fig. 6d Etching round mask (Marker String method) rendered, 3D view [84].

For visual simulations of isotropic etching we use a Marker/String method for the progressive mesh as a faster method suitable for interactive design [84]. The method is not known much for etching but has been proposed for modelling other IC processing [85]. The model never took off due to a problem with swallowtail conditions that appear on corners. We have found a way for overcoming swallowtail conditions and we are also able to simulate underetching. Fig. 6a and 6b show the wire meshes obtained in the progress of etching using a square lithography mask calculated in 2D then rotated, and a square mask calculated in 3D respectively. The method can be extended into larger material removal CAD visualizations. This is a crucial step towards filling a long existing need in virtual prototyping. Figures 6c and 6d show rendered images (using the wire meshes calculated earlier) for etching with a square and a round mask respectively. Transparency is part of MAGDA visualizations, to allow better perception of ongoing processes. Our Marker String method can be adapted for Direct Laser Writing (DLW).

For the simpler anisotropic visual simulation, we use the etch rate together with data picked from a small database of materials, crystalline orientation, and etchant. This is the input for the visualization, which is displayed progressively at simulated times (typically 2 min) intervals. Image transparency is used to be able to observe the progress of the concave well formed by etching using basic geometric shape masks (square, round, rectangular). This process could be used for a round shaped mask only but other mask geometries will not produce a truthful visualization [86].

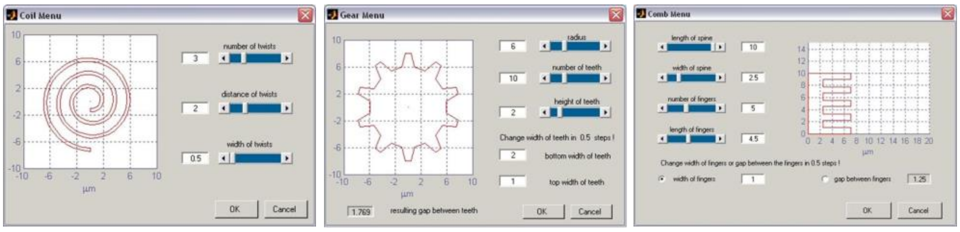
6.6. Microassembly

In small MEMS microassembly is integrated with their production by etching out structures and then underetching them for mobility. In MEMS sufficiently large to be handled under a magnifying device, microassembly is done with microgrippers, but there are other means e.g. air, magnets, liquids, etc. In MAGDA we do simulate microassembly disregarding the nature of helping devices (i.e. microgrippers) or autonomous visual servoing. We do not simulate microgrippers or aiding devices. We mimic assembly simply by mouse movements and clicks to test the feasibility of assembly in our virtual environment. Simulating assembly is important. It allows testing for conflicts or impediments in the assembly of a device before prototyping or production. For interactive VRP these algorithms have to be fast and smooth.

Precision in collision detection is paramount for virtual microassembly. To this end, a comparison of efficiency and suitability of collision detections algorithms was performed and a new, more suitable and more efficient algorithm was derived [87]. This algorithm exploits the essentially 2D nature (flat shapes) of typical MEMS components (which are often etched into a silicon wafer and then underetched and released). In order to take advantage of a new point-based collision detection method, a convex hull is computed around the object, and using this convex hull, a series of concavities is derived. The shape itself and the derived concavities are then divided into a minimum number of convex shapes. A point-based collision detection to check for convex shapes can then be applied in one of two ways: (a) by checking all the convex bodies that make up the solid portion of the object, or (b) by checking the convex hull and the concavities to rule out a possible collision. By using the method that requires the least number of checks, we can arrive at a result in the quickest manner possible. This modification produces a computational advantage of this method over other popular existing methods for 2D (and 3D) collision detection.

6.7. Design desk

A design drawing board was implemented in MAGDA. A range of shapes and typical MEMS components can be picked and placed on the drawing board. This is includes free hand drawing a component. All components can be edited, e.g. the number and sizes of cogs in a gear or comb. Fig. 7 shows some examples of the interface. This work was done by final year students from Germany [88].



number of twists 3
distance of twists 2
width of twists 0.5

radius 6
number of teeth 10
height of teeth 2
Change width of teeth in 0.5 steps !
2 bottom width of teeth
1 top width of teeth
1.769 resulting gap between teeth

length of spine 10
width of spine 2.5
number of fingers 5
length of fingers 4.5
Change width of fingers or gap between the fingers in 0.5 steps !
● width of fingers 1
○ gap between fingers 1.25

Fig. 7 Examples of the shapes available from MAGDA drawing desk menu. All shapes can be extruded into 3D shapes that can be placed individually or merged (intersected) to other shapes. The shapes can be associated with materials from a small database [88].

In its current state, the user interface and drawing board of MAGDA are implemented with a good range of MEMS components, facilities and 3D including rotation and assembly. The moving parts (membranes, cantilevers, fluids) and consequently the functioning of MEMS as described earlier are researched and published but not implemented in code. This is the sad consequence of disrupted research continuity as it happens when postgraduate students graduate and other key players retire altogether. MAGDA should be continued, but it needs a new owner, new postgraduate students and programmers. Our team has done the groundwork and set the foundation but this is just the tip of the iceberg. One option is to continue it as a Wiki with global contribution, but this is dangerous and difficult to track for scientific correctness. Interactive VR can do many miracles, not necessarily real, but a VP MEMS design simulator must stick to the reality and manufacturability. The results must not become cartoons, but they must neither inhibit what could be done in the future, for example more research on a cheap MEMS technology with carbon nanotubes. A fast and easy Virtual Prototyping environment could help finding manufacturable designs and cheaper technology. One must never discard a Jules Verne's like vision. To climb a mountain one has to take a first step. We have done that first step. Now it needs a next generation and the vision to keep on climbing further.

7. CONCLUSIONS

MEMS design and fabrication are currently in the hands of a highly skilled, highly multidisciplinary privileged minority. To continue filling the trend of this fast expanding industry, we need to find ways to ensure understanding and development of intuition for MEMS to younger generations and enable the way to satisfy the increasing need for innovation and new MEMS technologies in the following decades. The aim of this paper is to motivate scholars to engage in this endeavour and contribute to researching fast algorithms suitable for interactive Virtual Reality design to ease MEMS understanding. This paper has also presented a progression from earlier research on MEMS towards alternative technologies, prototyping and MEMS Animated Virtual Prototyping Design Aid (MAGDA). The contribution of our research is that we demonstrated that there are ways for alternative methods and faster calculations for the visualizations, without compromising physical validity. MAGDA is far from complete. We have barely scratched the surface. It needs to be developed further by dedicated programmers to complement the research that we have initiated. This requires financing, implementation with extended user facilities, populating databases and beta testing by a commercial body in continuous cooperation with a dedicated research group.

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