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A DESCRIPTIVE MODEL OF THE CURRENT MICROELECTROMECHANICAL SYSTEMS (MEMS) DEVELOPMENT PROCESS

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ABSTRACT

This paper uses the IDEFØ process modelling technique to present an 'As-Is' model for the current process of developing generic MEMS devices, this new model is based on information from current practitioners. The model shows a seven-stage process, from customer requirement specification to testing and verification, with multiple iterative loops between several stages of the model. Process-constraints on current MEMS development are also reported in the paper. A comparison was attempted between this As-Is model and the candidate models for future MEMS development available in literature. Differences include the number and placement of process iteration stages and the quantity and type of the development activities. Further comparison is difficult, partly because of the different approaches, taken to represent MEMS development stages and development flows, used by different authors.

Keywords: MEMS, development process, product development model, design methodology, As-Is

1 INTRODUCTION

There has been some recent interest in standardising the design practices in the MEMS domain [1]. In particular, it is considered that in the future a structured product-development model is required for MEMS due to the interaction and integration of the multi-physics involved, novelty of approaches taken and more importantly, the lack of standard design methodologies for the MEMS design process [2].

There has also been some interest in describing the current MEMS design practice, with several authors presenting descriptions of certain design process features and elements. MEMS devices have been described as being designed by practitioners and engineers with an intuitive based approach that often results in frequent design iterations [3]. The general approach to designing a MEMS process flow and device layout has been described as relying purely on the MEMS practitioners' experience and prior knowledge of similar devices [4]. It has been stated that, typically, MEMS practitioners and engineers begin the design of a new component with 'a rough sketch and very basic equations' to ensure feasibility [5].

The aim of this paper is to present a process model illustrating the design practices currently employed by practitioners when developing MEMS devices.

The paper first presents the sequence of steps used to develop the process model, and then the process model itself. Both the steps and the actual model are illustrated using the IDEFØ process modelling tool. The descriptive model represents the current MEMS development process as generic activities performed by the practitioners. Finally, this model is discussed and firstly compared with literature statements regarding current practice, then secondly with several literature models proposed for use in the development of MEMS devices.

2 METHODOLOGY

2.1 Selection of Process Modelling Tool

Several modelling tools were considered (IDEFØ, IDEF1, IDEFIX, IDEF3 and data flow diagram) for the task of illustrating the current MEMS design practices. IDEFØ was chosen, as it possesses a clear definition (containing the concepts, motivation and theory) and graphical representation, and has been successfully used as both and analysis tool and as a communication tool in a number of application areas [6]. The software used to create the models (methodology for modelling the As-Is process and MEMS As-Is process model) was the ‘BPwin Business Process Design Tool version 4.0’. The IDEFØ modelling technique consists of five constituents to model the process; activity name (clarifies activity objective), input (represents information to be converted by a particular activity into an output), control (applies rules to regulate imposing constraints of an activity), output (direct result of the information produced by activity), and mechanism (physical resources required to perform the activity which can include equipment and software tools). The graphical syntax of these constituents is illustrated in Figure 1. Creating an As-Is model usually begins with data obtained from interviews with practitioners in a particular domain. The top level or context is defined followed by identification of the proceeding functions or activities (decomposition). These are then grouped depending on their relationship or similarity. This process constructs the hierarchy of the model to be analysed.

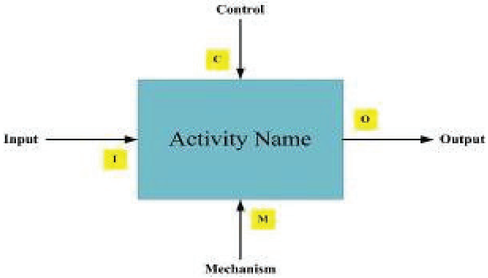

Figure 1. IDEFØ constituents

2.2 Steps in Modelling the As-Is Process

Existing design practice was captured by interviewing four MEMS practitioners who are researching into different MEMS devices domains. These include; microfluidic devices for blood monitoring and analysis for the medical profession, microsensors and microactuators for the automotive industry, resonators and comb drive microactuators for an artificial nose, and research into the use of the Casimir effect (also known as the Casimir force) for non contact transmission, application and actuation by use of repulsive force. This diversity has assisted in capturing a generic overview of how the practitioners from different MEMS domains develop diverse MEMS devices. This approach has also assisted in identifying the commonalities with the different development processes.

Figure 2 illustrates the context activity for the steps used for modelling the MEMS As-Is process. The input into the context activity was the MEMS practitioners’ description of the existing design practices employed for MEMS. This was converted into the output – a MEMS ‘As-Is’ process model. To convert the input into the required output, physical resources, for example, data capture and a process modelling tool were required. Controlling the overall methodology were; MEMS practitioners from different domains, the number of MEMS practitioners required for ensuring that the design practices were captured and that validation of the MEMS ‘As-Is’ model could be undertaken, and modelling tool selection criteria for selecting the appropriate process modelling tool.

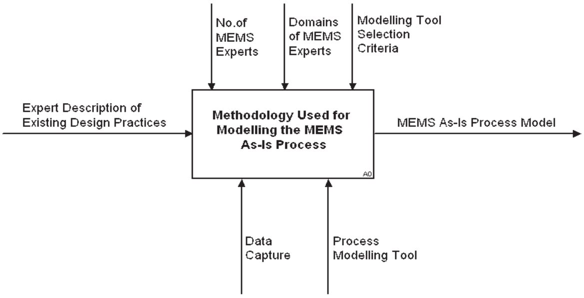

Figure 2. Context activity – steps for modelling the As-Is process

The decomposition of the methodology (Figure 3) details the lower level activities that were undertaken in creating the 'As-Is' model. Each of the individual activities from A1 to A6 had separate outputs indicating the results from each of the activities performed. These were direct inputs into the subsequent activities. Activity A7 converted this sequence of outputs into the final specified output, the process model.

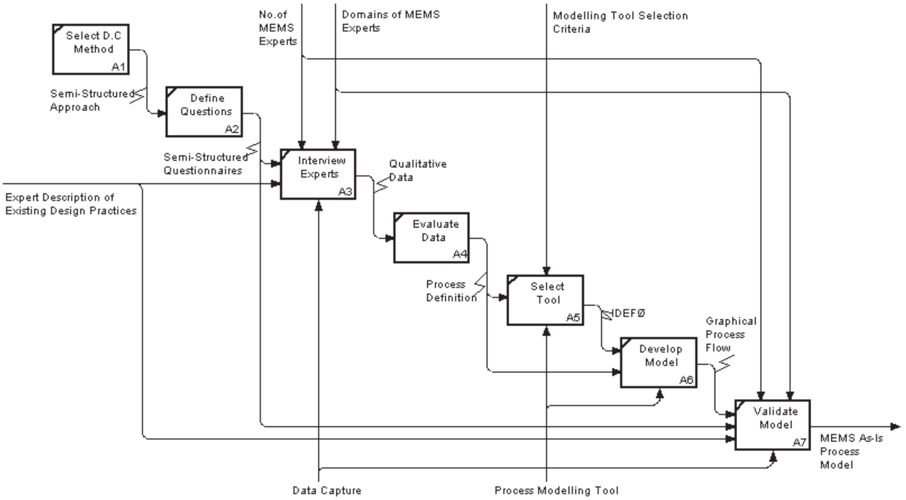

Figure 3. Decomposed activities – steps for modelling the 'As-Is' process

The initial step of modelling the MEMS process (activity - A1) began by selecting the data collection method in order to capture the existing MEMS design practices from the practitioners. The output of the activity as illustrated in Figure 3 was to take a semi-structured approach. Two sets of semi-structured questionnaires were devised (A2) for interviewing the practitioners (A3) to capture the existing design practices, and for validating the As-Is model (A7). As illustrated in Figure 3, there are two outputs from activity A2 which were direct inputs into activities A3 and A7 – 'Validate Model'. Face-to-face interviews were conducted with the MEMS practitioners (A3) using a semi-structured questionnaire consisting of fifteen open questions. These addressed; MEMS devices and their applications, design and fabrication processes, existing tools and techniques, development constraints and limitations, and future development improvements. The responses from the practitioners during the interviews were documented, evaluated (A4) and used to define the MEMS development activities. The output from activity A4 - 'Process Definition' was a direct input into activity A6 – 'Develop Model'.

Modelling tools were then considered and assessed for modelling the process flow (A5) to graphically represent how the MEMS design practices are currently performed. The output from activity A5 was the selection of the IDEFØ technique as described above. This was then used to create the 'As-Is' model (A6). The context activity was initially created followed by the decomposed activities. The final activity A7 – 'Validate Model', was then performed to ensure the feasibility of the graphical process flow in reflecting the existing generic MEMS development activities. Validation of the As-Is model comprised of practitioner verification of the development activities, inputs, outputs, controls and mechanisms as depicted by the model. A semi-structured questionnaire consisting of the following questions was also used for validating the 'As-Is' model: (1) Does the IDEFØ technique reflect the existing generic MEMS development process illustrated by the 'As-Is' model? (2) Is the model feasible for the development of generic MEMS devices? (3) Are there any activities or elements in the model that are not feasible? (4) Can the 'As-Is' model be further enhanced?

3 RESULTS

The higher level context activity, represented by IDEFØ, of a model for the MEMS development process is shown in Figure 4.

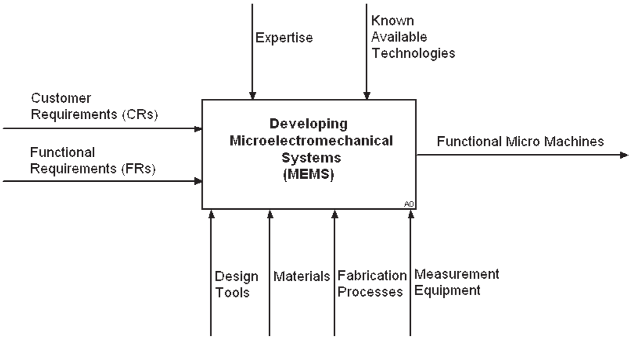

Figure 4. Context activity of the As-Is model of the MEMS development process

The direct inputs into the context activity (A0) were found to be the customer requirements (CRs – requirements specified by the customer providing detailed needs of the MEMS device) and functional requirements (FRs – functions required to perform the necessary operations). These were converted into the output – ‘Functional Micro Machines’. These are defined as: practical microdevices that fulfil the intended application, satisfy the functional requirements, and encompass a variety of functions at the micro scale by the use of multidisciplinary science and engineering principles. The mechanisms or physical resources required to produce the functional micro machines were: design tools (CAD, multi-physics solvers and functional properties analysis tools), materials, fabrication processes, and measurement equipment. Constraining (controlling) the activity were the MEMS expertise and available technologies known by the practitioners. The context activity is shown decomposed in Figure 5.

3.1 Decomposition of the MEMS As-Is Process

The As-Is process (Figure 5) was found to commence with the specification of the customer requirements (A1). The activities following this were: initial design considerations (A2), conceptual design (A3), design analysis (A4), detailed design (A5), MEMS fabrication (A6), and testing and verification (A7). Activity A1 was only applicable, and integrated in the process, when customers requested the development of specific MEMS devices. It was noted from the responses given by the practitioners during the interviews that, the MEMS practitioners and researchers usually began at the initial design considerations activity (A2). At this stage, the functional requirements were a direct input into the initial design considerations rather than the customer requirements. This was due to the focus on research and development as stated by the practitioners.

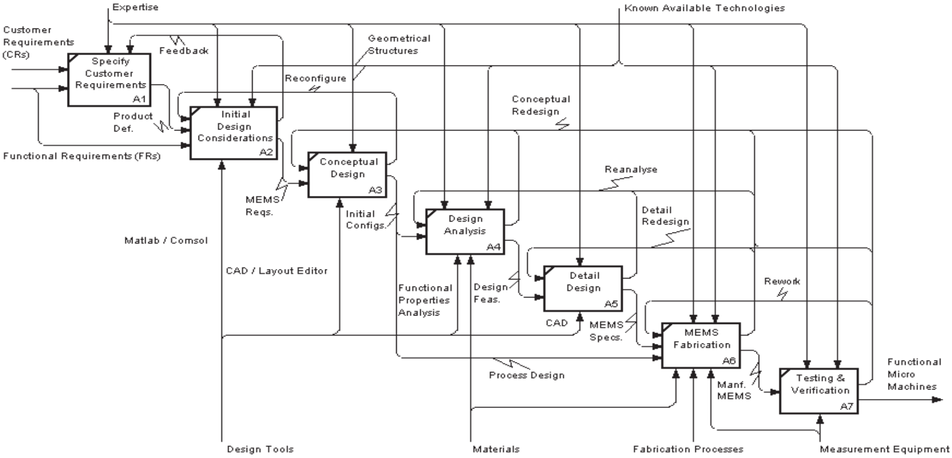

Figure 5. Decomposition of the As-Is model of the MEMS development process

Activity A2 (Figure 5) translated the functional requirements into an initial set of requirements for the MEMS device. Depending on the type of MEMS, initial design parameters were considered at this stage, which included: the design constraints, material selection, selecting the appropriate fabrication processes based on the available technologies known by the practitioners, electro-mechanical systems, and packaging and assembly requirements. The design tools specified by the practitioners that were used during this activity were: equation based modelling tools and multi-physics solvers such as Matlab and COMSOL. The outputs from activity A2 were the initial specifications of the MEMS device and a feedback loop to activity A1. The feedback loop from activity A2 acted as a control on activity A1, if the requirements specified by the customer could not be achieved or required re-specifying based on the practitioners feedback.

At the conceptual design activity (A3), conceptual designs of the intended MEMS devices were created using design tools such as CAD tools and layout editing tools for schematic capture and simulation. Initial configurations for the MEMS device were the direct output from this activity (A3), i.e. MEMS geometry, dimensions, materials and processes. A reconfigure loop was also an output from this activity which was an input back into the initial design considerations, if the created concepts did not comply with the initial design considerations.

The next stage in the development process was to perform a design analysis (A4) on the conceptualised designs using properties analysis methods such as: FEA (finite element analysis) for stress analysis and CFD (computational fluid dynamics) for fluid flow analysis. As mentioned above, other multi physics solvers, such as COMSOL, were also used to analyse the electromagnetic-structural, thermal-structural, fluid-structure and electromagnetic-fluid interactions. The output from activity A4 was the design feasibility of the MEMS device. A second output from A4 linked to the 'conceptual redesign' loop whereby; the practitioners returned back to the previous activity to either, create new concepts or modify the design of the MEMS device based on the results obtained from the analyses.

The detail design activity (A5) generated the final detailed engineering drawings and schematic diagrams for the dedicated MEMS devices. This included the final specification (output – MEMS specifications) of the MEMS device detailing the materials, fabrication processes, and packaging and assembly requirements. The tools commonly used at this stage were CAD based (AutoCAD) which were also used to design any required masks (photolithography) and moulds (microinjection moulding) for the fabrication equipment and processes. Activity A5 was controlled by the practitioners' knowledge of their chosen design tool.

Activity A6, (MEMS fabrication) represented the physical processes, materials and techniques required to manufacture the generic MEMS devices and components. Responses from the practitioners stated that the physical resources required to perform this activity (A6) were: materials (plastics or silicon), fabrication processes (microinjection moulding, photolithography, wet and dry etching and micromachining processes such as FIB – focussed ion beam milling), and measurement equipment to monitor and measure the fabrication processes and device parameters. The two outputs from activity A6 were; the manufactured MEMS devices which was an input into the final activity (A7), and iteration loops returning to the previous activities (A3 – A5). The iteration output is linked to the following three loops: detail redesign, reanalyse and conceptual redesign.

The final activity (A7) of the MEMS development process was the testing and verification of the manufactured MEMS devices. Measurement equipment was used at this stage to test functionalities, performance, quality and reliability in application of the fabricated MEMS devices. Physical devices that failed in functionality or did not conform to the specifications could be reworked. This required them to return back to the previous development stage (A6 – MEMS fabrication) for rework or follow the existing iteration loops. This depended on the results obtained from the testing and device verification activity. Once the MEMS devices were fabricated to the specifications (revisions maybe necessary), and the testing and verification was complete, the final output from the MEMS As-Is process model (A7) was 'functional micro machines'.

Figure 6 uses the IDEFØ approach to represent the feedback loops in the MEMS development process. Several iterative process loops can be highlighted: feedback, reconfigure, conceptual redesign, reanalyse, detail redesign and rework. Responses from the practitioners indicated that these were present in the current process due to the research based development, incorrect initial specifications, unavailability of the required materials, technology based on older existing technologies, not fully developed to produce complex structures and components at the micro scale, current measurement facilities limiting the testing of MEMS parameters and lack of available software modelling tools to model the diverse MEMS properties.

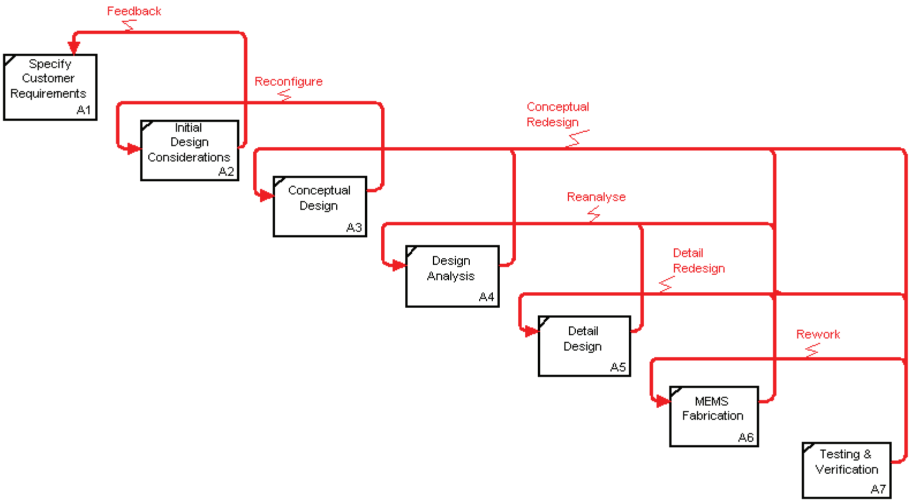

Figure 6. Iterative process loops

The decomposition of the MEMS As-Is process model (Figure 5) illustrated the absence of a ‘mechanism’ (physical resource) at activity A1 – ‘Specify Customer Requirements’. The practitioners were asked how the initial MEMS requirements from any external customers were captured and elicited, and if techniques such as QFD (quality function deployment) were used to analyse the requirements feasibility. The practitioners who did have interaction with external customers responded by stating that the initial MEMS requirements were captured but in an informal way, and these were then documented into descriptions of the device requirements (functional and non-functional requirements). Designated software was not used at this stage to capture, elicit and manage the intended MEMS device requirements.

3.2 Development Process Constraints

Practitioners stated that they used specific design tools and techniques that they were comfortable with and had knowledge of. It was considered to be a time consuming process to learn new and unfamiliar technologies. Therefore the MEMS development process is based on the process restrictions of the available technologies known to the practitioners.

As illustrated in the decomposition of the As-Is process (Figure 5), restrictions in the MEMS development process included the controlling of each activity by the practitioners. When the practitioners were asked what they thought the main limitations of the current development process were, all of the practitioners responded in a similar manner. They answered by stating that; progression in the development of MEMS devices was limited firstly by the existing technologies used and known to the practitioners, and secondly by the new technological advances which would be required to produce the devices.

New aspects or parameters in the MEMS design, such as the use of the Casimir force, required a novel approach in the development process and new technology was required to measure the effects produced. However, understanding of the new technologies and having to research and develop them for future use, was considered to be difficult and time consuming by the practitioners. Therefore, it was efficient in terms of the time and cost of the MEMS development to use the known technologies which were better understood by practitioners and researchers. This also applied to adapting the existing technologies known by the practitioners to conform to the MEMS specification which also limited the progress of development. It was also noted that, devices developed using a trial and error approach restricted the MEMS development process due to the time taken in redesign and redevelopment activities.

4 DISCUSSION

Using the IDEFØ tool to model the existing generic MEMS development process, the As-Is model has illustrated the individual design activities performed by practitioners when developing diverse MEMS devices. The decomposition of the As-Is model (Figure 5) showed that seven phases, activities A1 to A7, were present in the existing MEMS development process. Each activity had a minimum of one input ranging to a maximum of three inputs. There was a minimum of one output per activity that directly linked the activities together in a linear and sequential manner. The labelled outputs (product definition, MEMS requirements, initial configurations, design feasibility, MEMS specifications, manufactured MEMS and functional micro machines) were a direct result of the activities performed by the practitioners.

Other outputs included six iterative process loops which were individually labelled (Figure 6). The iterative process loops (feedback, reconfigure, conceptual redesign, reanalyse, detail redesign and rework) highlighted the repetitive nature of the existing MEMS development process. The MEMS practitioners have provided a ‘raison d'être’ for the presence of these iterative loops in the current process. It was stated by the practitioners that the existing MEMS development process was based on the process restrictions of the available technologies known to the practitioners.

The As-Is model confirms two prior observations of the development process as found in the literature and qualifies a third.

Firstly, the iterative nature of the current MEMS development process [3] is confirmed. Responses from the practitioners who were interviewed stated, the cause of these iterations was not only due to an intuitive approach taken in MEMS design, but also because of the research based development, technology is based on older existing technologies and is not fully developed to produce components at the micro scale.

Secondly, a common approach to designing a MEMS process flow and device layout relies on the MEMS practitioners’ expertise [4]. The As-Is model has also illustrated that the existing MEMS development process involved the interaction of the practitioners at each of the individual activities from A1 to A7 (Figure 5). The controlling of each activity by the practitioners limited the progression in MEMS development. Limitations included the existing technologies used and known to the practitioners, and the new technological advances which were required to produce the devices at the micro scale.

However, the As-Is model indicates that prior statements in the literature about the starting point for the MEMS development process [5] require qualification. The As-Is model (Figure 5) has illustrated that the initial stage of developing functional micro machines (activity A1) was to specify the customer requirements. It was noted from the responses given by the practitioners that, activity A1 was only applicable when customers requested specific MEMS devices. MEMS practitioners usually began at the initial design considerations activity (A2) which translated the functional requirements into an initial set of requirements for the MEMS device. Furthermore, some of the initial design parameters considered at this stage by the practitioners, required the use of design tools such as equation based modelling tools and multi-physics solvers. Conceptual designs of the MEMS components and corresponding device layouts, were illustrated as being created at activity A3 in the As-Is model.

It is worthwhile comparing the As-Is model with models of candidates for future MEMS development processes currently found in the literature. This may illustrate how well current practice matches literature recommendations and what step-changes away from current practice may be required in the future. Models currently available in literature for MEMS development are briefly summarised below and then compared with the As-Is model.

Whilst process models do exist in the literature for MEMS design, they lack an end-to-end framework not only for the design of new devices but also for the general product development process for MEMS [7].

Alting et al have presented an example of a design process applied to MEMS which provides a schematic overview of the approach [8]. This approach has illustrated the division of the MEMS product into four levels: system, device, physical and process level. It is stated by the authors that, this process is based on the assumption of silicon technologies. The features illustrated in the model include: the four levels which are considered for the MEMS product, three iterative loops that are linked in between the four levels and two flows, which illustrate the verification and simulation activities as bottom-up and top-down processes. It is not easily distinguishable in the model at which stage the MEMS development process commences.

MEMS design methodologies consisting of an unstructured and structured design flow have also been developed based on existing digital and analog design methodologies [9]. The unstructured design flow is commonly followed for MEMS that feature an interplay between electronics and micromechanical components. The structured design methodology combines the design of micromechanics and electronics into a single flow in which the MEMS circuit representation plays a central role [10]. The structured and unstructured design flows illustrate the development flow to commence with the specification of the system followed by the system description. The portion of the flow that is unique to micro mechanics consist of the following five stages: system specification, system description, micromechanical device, micromechanical layout and fabrication and test. Iterations in the development flows for both the structured and unstructured models are not clearly defined.

The “Y-chart” model illustrated a top-down process [11]. Features of the model include three stages (geometry, structure and behaviour) dedicated to electronic circuit design. No iterative process loops between these three stages were present and the development process was illustrated as beginning in the centre of a circle. This expanded in an anticlockwise direction linking to each of the three stages. This model did not represent a linear development process.

Brück et al compared microelectronics (VLSI – very large scale integration) with MEMS design to illustrate a MEMS design model [12]. The design methodology model showed the MEMS development process to consist of the following six phases: concept, behaviour, structure, geometry, process management and fabrication. The model illustrated a linear process. Iterations from each of the stages in the development process were illustrated. However, it was unclear as to the amount of iterations that would be required and when the development process comes to an end.

The “pretzel” model provided an impression of the interrelationship between top-down and bottom-up design phases [13]-[14]. The model illustrated five stages in the MEMS development process which were divided into the following two aspects: behaviour driven and process driven. Iterations between the five stages were not illustrated in this model. The model illustrated in a non-linear way, the beginning of the development process to commence with specifying the device requirements. However, it was unclear from the model, what class of requirements were needed i.e. functional or non-functional requirements.

The “circle” model was a model of physical MEMS design which looked at the bottom-up design phase [15]-[16]. The circle model presented a development flow for MEMS that was restricted to photolithographic processes. The circle model illustrated a cyclical development flow consisting of six development stages. The first stage was specification. However, it was unclear if the next stage in the process is fabrication or layout design. Flow paths are present at the specification stage pointing to the layout design stage and fabrication. This model showed that the development process has much iteration between the following process stages: layout design, process development (mask design), verification and process modification (mask refinement). It was uncertain from the model as to the amount of iterations that occur in the development process. Depicted in the inner core of the model are boxes which were labelled: tools, materials, process stages and active principles. These were illustrated to be linked together in a continuous loop. However, the circle model did not illustrate the types of tools or individual process stages required in the design process.

To summarise, it is evident that some of the available models in literature did not indicate any iterations in the process. Furthermore, it was unclear from the models that did illustrate iterative processes, the quantity, and to some extent the placement, of the iterations in the design flow. The end of the development process was difficult to discern in some models.

As can be seen from the model summaries presented above, there were variations within both the development flows and the descriptions of development activity represented by the different models. The development flows varied from linear to cyclical flows. The entities within the different models provided quite varied descriptions of the principal development activities, some of which were ‘low-level’ descriptions not applicable to all MEMS. The number of stages of development activity represented in the models also varied considerably.

The above model descriptions illustrate that inter-model comparisons are difficult, a difficulty partly based on the different visual methods used to present the models. Furthermore, none of the models summarised above used a formal modelling tool, such as IDEFØ, to represent the process, nor to represent the stages by which the model was derived. As such, a goal of identifying the stages required to move from current MEMS development practice to those practises recommended in the literature is difficult to meet.

5 CONCLUSIONS

This paper has presented a MEMS As-Is process model captured using the IDEFØ process modelling technique.

The model graphically represented the current MEMS development process as a set of linear and sequential activities showing the; inputs and outputs from each activity including the physical resources required to perform them. The individual activities of the decomposed As-Is process were illustrated and described. Data captured from the practitioners and illustrated in the As-Is model were used in recognising the elements constraining the current development process. Visualisation provided by the modelling tool also assisted in identifying physical resources that were formally absent in the development process.

The As-Is model illustrated that the current MEMS design process requires many iterations. This confirmed the iterative nature of the existing development process as stated in literature. It was also stated by the practitioners that, the cause of these iterations was not only owing to an intuitive approach taken in MEMS design, but also because of the state of development of the research base. The decomposition of the As-Is model illustrated that MEMS practitioners controlled the individual development activities. This limited the progression in MEMS development.

The MEMS As-Is process model presented in this paper was compared to some of the available models in literature for MEMS design. Differences included the number and placement of process iteration stages, with certain models exhibiting no iterative stages. In general the literature models described a smaller number of activities than that described by current practitioners for the As-Is model. Furthermore, there was considerable inter-model variation in the descriptions of the stages of the development activities and variation between these descriptions and those of the As-Is model.

The difficulty of comparing literature models both between themselves and with the As-Is model perhaps provides an argument for a more formal approach to the literature representation of MEMS development models than is currently the case. Finally, the descriptive model of the current MEMS development process presented in this paper will be used as a basis for developing and proposing a ‘To-Be’ model for future MEMS development.

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