PROJECT FINAL REPORT

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1 Final publishable summary report

1.1 Executive Summary

The use of micro devices has been shown to provide huge advantages in different technological fields, ranging from electronics, mechanics, biology to medical applications. However, current manufacturing methods are often limited in their flexibility and require expensive tooling, making them unsuitable for smaller to medium scale production runs of complex microdevices with higher functionalities.

In order to bridge the gap between higher volume production and current inefficient production of medium series it is necessary to find new, more advanced and flexible approaches. SMARTLAM (Smart production of Microsystems based in laminated polymer films) is a research project, which was carried out under the FP7 Factories of the Future programme. The main aim was to create a new concept for the manufacturing of functional microdevices based on a modular, flexible and scalable 3D integration (3D-I) scenario. Combining state-of-the-art 3D-compatible technologies such as aerosol-jet printing or laser technologies, which are capable of manufacturing three-dimensional structures and parts, with modules for handling and inspection together with a recipe-based control software allowed for the successful development of a modular machine concept.

During the past three and half years, the SMARTLAM partners, a consortium of universities, research institutions and small and medium enterprises (SME), have successfully shown their outstanding expertise and capabilities in creating a fully functional manufacturing cell, showing the potential of the 3D-I approach whilst creating a unique know-how in the production of lamination based functional microdevices. The implementation of a customised database containing data on material properties, production parameters and product design in combination with a sophisticated central control system enables the fully automated fabrication of small to medium series and thus gives a tool that allows SMEs to produce more cost- and time- effective.

In order to address a wider spectrum of companies the SMARTLAM approach was promoted in a number of press releases, articles and public appearances. Additionally, a business interest group was established that allowed having direct feedback from the industry on the developments within the project and thus providing valuable input for adjustments during the project phase.

SMARTLAM has shown that the 3D-I approach proposed at the beginning of the project is capable of creating the flexibility and scalability that is necessary to take the manufacturing of microdevices to another level by making it profitable outside of the area of mass production. The developed machinery and methodology will be used all partners to further improve the overall concept and applying it to an even wider range of products.

1.2 A summary description of project context and objectives.

Current fabrication methods for microdevices are known to offer low flexibility whilst requiring high cost tooling and having long turn-around times. The limited flexibilty especially affects complex devices, which incorporate on-board valves, membranes, discrete parts, or electrodes, as they can't be developed or adapted without considerable investments in molds and assembly fixtures. These boundary conditions create a barrier for the development of small to medium series of complex and higher functionality devices, where the cost-benefit ratio of incorporating functionality is too risky for the typical laboratory, diagnostic or medical device developer. The solution proposed by the EC-funded project SMARTLAM addresses these issues by integrating modular "digital" manufacturing technologies as well as a broad range of materials into one flexible scalable machine environment.

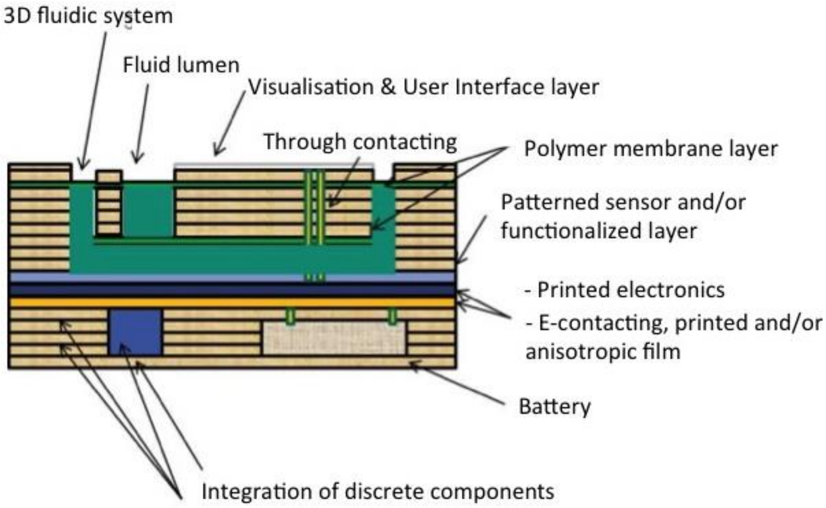


Figure 1: SMARTLAM approach building on concepts for stacking of functionalized polymer films

The SMARTLAM activities were concentrating on rapid prototyping technologies in a wider sense with a particular focus on the manufacturing of laminated objects, an established rapid prototyping technology based on layer-by-layer lamination of functionalised film sheets with different material properties (Figure 1).

With aerosol-jet printing as the selected printing technology of choice in the SMARTLAM project it was be possible to efficiently and precisely manufacture conductive tracks, electrodes and many other features.

Novel polymer film materials with advanced material properties, such as anisotropic conductive films or effects arising from combinations of composite sheets, were being combined with state-of-the-art technologies for scalable 3D-printing, structuring and welding with additional usage of micro-positioning and alignment systems.

Robot / Assembly technologies for the integration of discrete parts as well as for the handling of the films completed the list of “ingredients” applied in his novel manufacturing concept.

All the technologies mentioned above were being integrated in a modular, scalable and easy-to-synchronise manufacturing environment allowing for the production of complete 3D-Microsystems.

Figure 2: SMARTLAM success factors

The approach proposed by SMARTLAM was designed to address the manufacturing of small to medium series of micro-enabled components. This was based on a flexible and scalable concept which could be translated and applied not only for the production of single parts but also up to the provision of medium series of a few thousand parts per year, as well as for the testing of pre-series and the support of high value components applicable in niche markets.

The SMARTLAM work plan consisted of a set of development streams, each of them addressing a specific phase or topic of the product development process:

- **SMARTLAM 3D-I design approach** providing methods and tools for the specific product development process.
- **SMARTLAM 3D-I manufacturing approach** developing a production concept integrating all mentioned individual technologies in a flexible and scalable manner via standardised module-interfaces, common corporate design, standardised workpiece-carrier for transportation of intermediate goods (single and multiple layers of polymer films),

together with a set of concerted support technologies for the handling of films, discrete parts and inspection of generated results

- Derivation and development of a SMARTLAM equipment demonstrator for the validation of the main concepts and obtained partial results
- Development of the two SMARTLAM compatible demonstrators by transferring the results derived from traditional technologies to the new, SMARTLAM compatible concept.
- Economic assessment of the SMARTLAM concept with respect to the two demonstrators.

Major binding elements between the individual streams were the SMARTLAM building blocks “functional elements” (e.g. LEDs) and “feature” (e.g. conducting paths, microstructures), forming the basis for module oriented work conducted in the other work packages.

A fully functioning manufacturing cell was set up and evaluated by two SME companies from the fields of bioanalytics and lighting applications. The companies were acting as potential customers providing the respective application requirements and thus the necessary input to the 3D-I approach from a technical and economical perspective throughout the project.

1.3 A description of the main S&T results/foregrounds

1.3.1 S&T results/fore grounds

<u>Preparation of production: software solutions for design, pre-processing and configuration</u>

Besides the actual fabrication modules, a major building block of the overall SMARTLAM approach was the implementation of a knowledge-based framework supporting the product designer along the planning of a 3D-I compatible product. In addition to the actual design work, this framework also includes an extensive database on material properties, cost assessment and production parameters allowing for highly specific production planning with the selection of an optimal process chain right from the start of the design process.

The basis for this configuration tool is a web-based database following the MinaBase methodology, which was developed within the EU project EUMINAfab (FP7-226460). This basic model was expanded to incorporate all necessary process parameters, like process capabilities, processing costs and metadata, which are required for the configuration of the manufacturing process. In addition, the database was constantly updated with the latest process and material data generated within the experimental work throughout the whole project duration to ensure the advanced level of progressiveness of this software tool. Figure 3 shows a screenshot of the graphical user interface of the database, illustrating some results from the SMARTLAM experiments.

Making use of the SMARTLAM-database, the product designer is now able to create and modify layer-based micro- and nano-products whilst selecting different manufacturing approaches at the same time. During this whole process, the system is offering continuous support for the designer to select the optimal methodology for the final product. These software tools for designing products and selecting the most suitable process chain in one system were also completely developed within SMARTLAM.

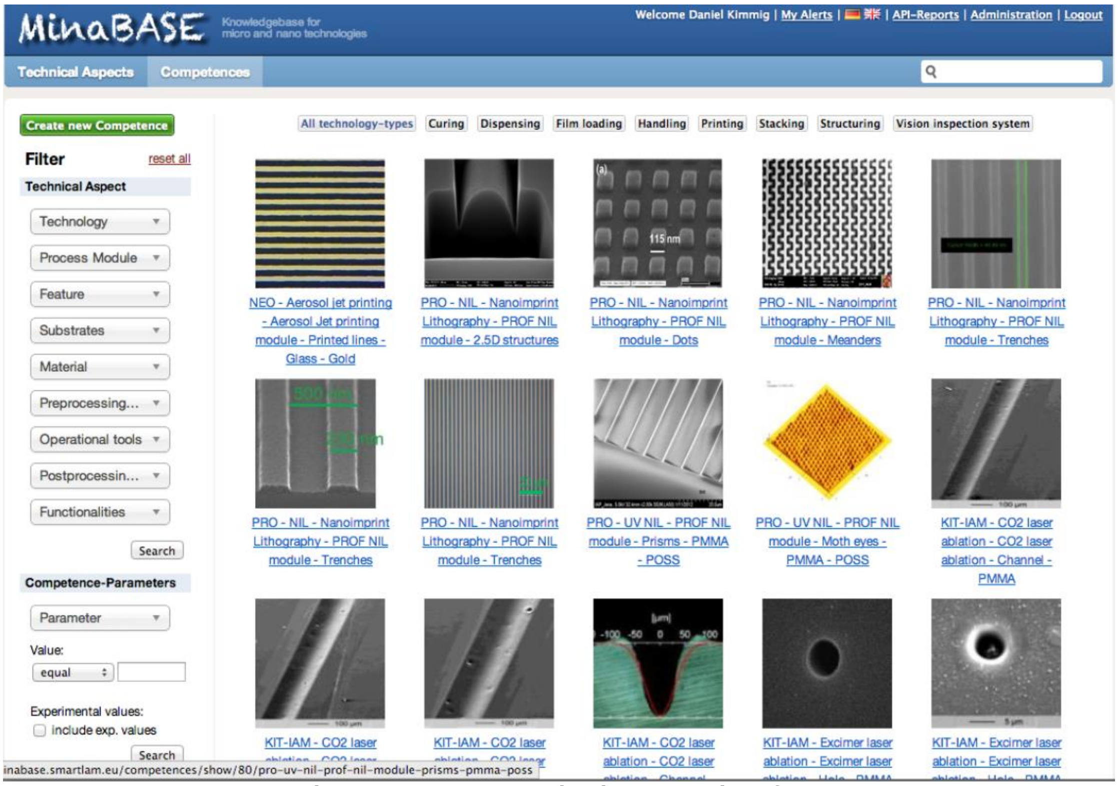


Figure 3: SMARTLAM database user interface

The design tool offers the opportunities to extract 2D engineering drawings from a CAD model as well as to use this CAD model as a template for the evaluation of different manufacturing techniques which is subsequently be modified and the geometry rebuild in accordance with the optimised production strategy. Additionally, the CAD macros included in the SolidWorks software facilitate further guidance of the designer during the design process of the different layers. Afterwards, the finalised 3D-data are exported and then fed into process selection and configuration tool for further processing. In a first step, this software solution searches the SMARTLAM database for different manufacturing alternatives capable of generating the final product. Next, a compatibility check is being performed to avoid conflicts, which is followed by the opportunity to assess the possible process chains based on special user-defined criteria such as machining time or costs. The combination of these three software solutions (design, database, process selection & configuration) provides not only an all-in-one solution for layer-based, functional micro- and nano-products but also significantly increases the flexibility as well as the predictability of the manufacturing process which was stated as one of the major goals in the project plan.

The final step of the preparation is done via a configuration, planning and code generation software, which was also developed within SMARTLAM. With the input from all previous steps, this software tool is able to compile and execute complete manufacturing recipes with the provided equipment and it is directly linked to the SMARTLAM database. In addition, the supervising engineer also has the opportunity to modify the processes in real time if the need arises.

The main result of the overall software development is a fully functional and commercially applicable solution for the design, planning, configuration and coordination of an autonomous manufacturing cell for nano- and microdevices.

The demonstration parts: flexible lighting device & microfluidic chip

Following the successful pre-processing of the data, the actual manufacturing steps can be carried out. Two demonstrators provided by the industrial partners were selected for the evaluation of the SMARTLAM approach, which should be produced by a fully autonomous, modular manufacturing cell at the end of the project. The initial design sketches for these demonstration parts are shown in Figure 4.

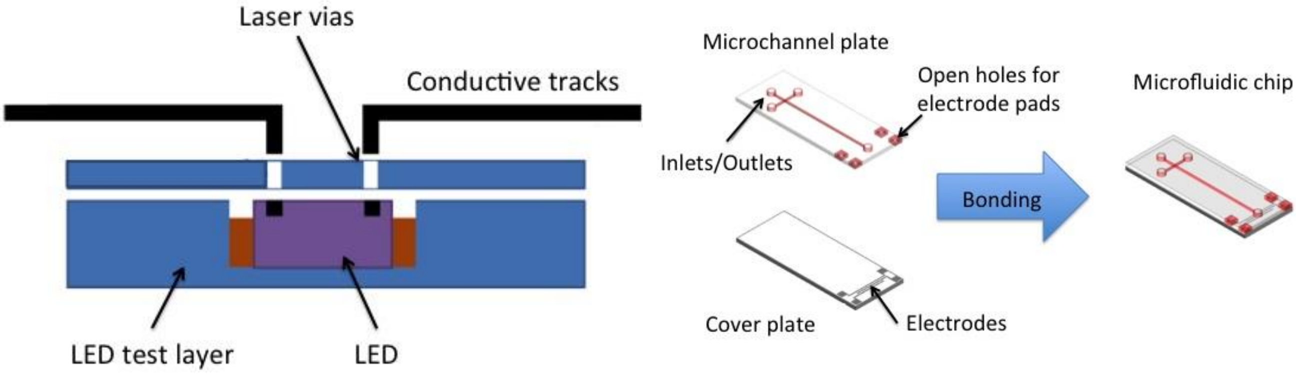


Figure 4: Demonstrators for SMARTLAM concept: Flexible lighting device (left) and microfluidic chip (right)

The first selected demonstrator is a flexible lighting device (design provided by Design LED Product Ltd, DLED) made out of two polymer foil layers. Structuring of the bottom layer facilitates the assembly of a pre-manufactured LED chip, which in turn is covered by the second laminated layer. This cover layer has equally been structured to connect a conductive path to the LED. The second demonstration part is a microfluidic chip (MicruX Fluidic SL) that also consists of two polymer layers, which contain microchannels and electrodes for analysing liquids. Both basic demonstrator designs formed the basis for all further steps starting with the generation and selection of optimal the process chains using the developed SMARTLAM software.

Development of production modules

In accordance with the specified process/product parameters, namely very tight tolerances and structural features, a manufacturing cell using six different modules was designed, generated and set up:

- **(1) Laser structuring** : State-of-the-art laser structuring module was set up for generation of pockets, channels und holes
- **(2) Assembly**: complete module for positioning and assembly of microparts was developed as the exact placement of the LED chip is a crucial step in the preparation of the lighting demonstrator
- **(3) Lamination**: Placing the top layer on the lighting device was carried out using a roll-to-roll-based laminating machine, which was also built within SMARTLAM
- **(4) Laser welding**: For the precise assembly of the microfluidic device a welding technique using laser light was successfully established
- **(5) Printing**: The electrodes and conductive paths required for the respective demonstrators were generated using the aerosol-jet printing technique, which allows for very precise deposition of metal inks

- **(6) Inspection**: The examination of the produced demonstrators together with quality control of the production processes was realised with a high-resolution inspection system designed and build within the SMARTLAM project

The following paragraphs give a short overview of the research on the individual modules, focussing on the main technological advances realised within the SMARTLAM project.

A crucial aspect for both demonstrators is the necessity of very small and precise structural features, e.g. microchannels or pockets for LEDs. Method of choice for generating such structural features was Laser structuring as this method offers the desired options and capabilities in terms of processable feature sizes and flexibility of usable materials. During the initial testing phases, the Institute of Applied Materials (IAM) in Karlsruhe (Germany) tested different polymer sheet materials for their applicability and analysed a wide variation of processing parameters. Next steps were to ensure the processing accuracy for the created microchannels needed for the microfluidic device as well as for the pockets required for the LED chips. Successful implementation of these steps made it possible to produce high quality structures whilst cutting down the time for the laser machining process at the same time. Ultimately the partners were able to manufacture microchannels with a minimum width of 200 µm, pockets with a total volume of 515x580x90 μm^3 µm and vias with a diameter of approximately 75 µm with constant quality, showing the versatile applicability of the laser structuring process (see Figure 5).

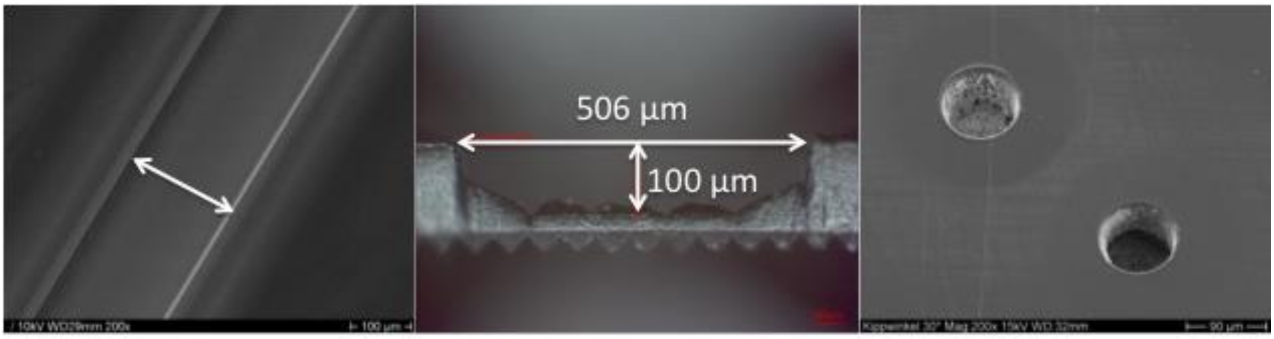


Figure 5: Different geometries generated with the laser structuring method (from left to right): microchannel, pocket for LED chips, vias for contacting LEDs

Subsequent step in the production of the lighting demonstrator was the placement /positioning of the LED chips in the bottom layer. As the precise placement of the LED chip is a crucial step in the assembly process, a module was developed and built exclusively for this task.

The assembly module itself contains three major process steps. First, the LED-chips are picked up from the storage tray and visually inspected for their orientation in order to avoid misplacing. Next, a dispensing unit for the adhesive had to be developed, which is capable of precise dosing of the adhesive into the pockets as the LED chips need to be firmly held in place in the pockets. This proved to be challenging, since a large number of adhesives had to be tested for their suitability and the narrow tolerance for the dispensing volume was crucial for a correct placement of the LED chips without creating any gaps or overflow. The final action carried out by the assembly module was the correct placement of the LED chip into the laser-milled pockets without damaging either the substrate material or the chip. The module developed by the Fraunhofer IPA in Stuttgart (Germany) proved to fulfil all required criteria with robust and precise positioning processes during the final demonstration setup as shown in the following pictures in Figure 6.

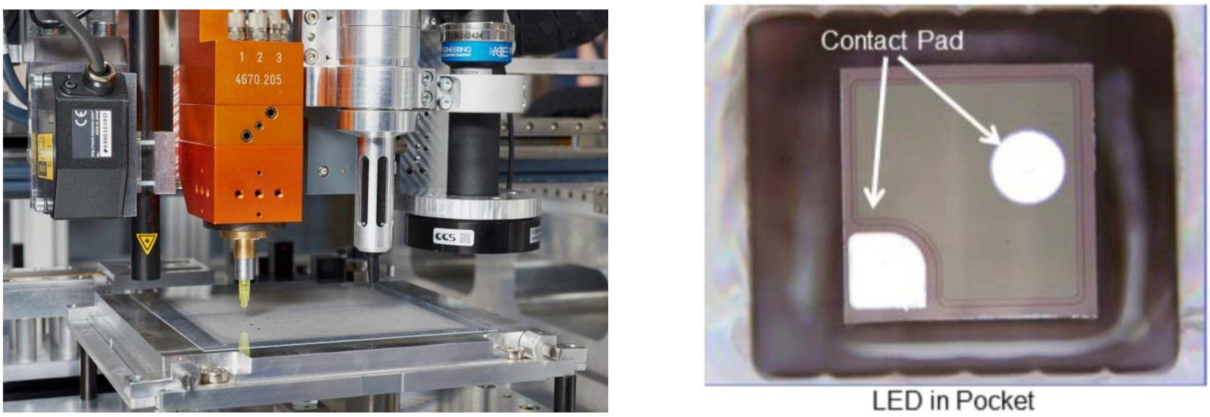


Figure 6: Assembly module in final setup (left) and LED chip placed in adhesive-filled pocket (right)

After positioning of the LED chips during assembly, the lighting device is sealed with a top layer (lid) also made out of polymer material. For the secure and exact positioning of the lid, a lamination module was developed by nsm Norbert Schläfli AG (Zofingen, Switzerland) that is able to pick up single polymer films from a storage rack using a vacuum gripper, which are then transferred to a carrier roll. This top layer is then coated with an UV-curable adhesive and precisely positioned and laminated to the bottom layer that contains the embedded LED chips. Having completed the stacking of the layers as well as the hardening of the adhesives, the lighting demonstrator is ready for the subsequent process steps. In addition to developing the overall lamination process, a number of different sheet and adhesives materials were investigated for their suitability. During the final project meeting the lamination module was successfully integrated into the SMARTLAM manufacturing cell where a significant number of laminated stacks were produced. A schematic drawing of the module and the real-life lamination module is shown in Figure 7.

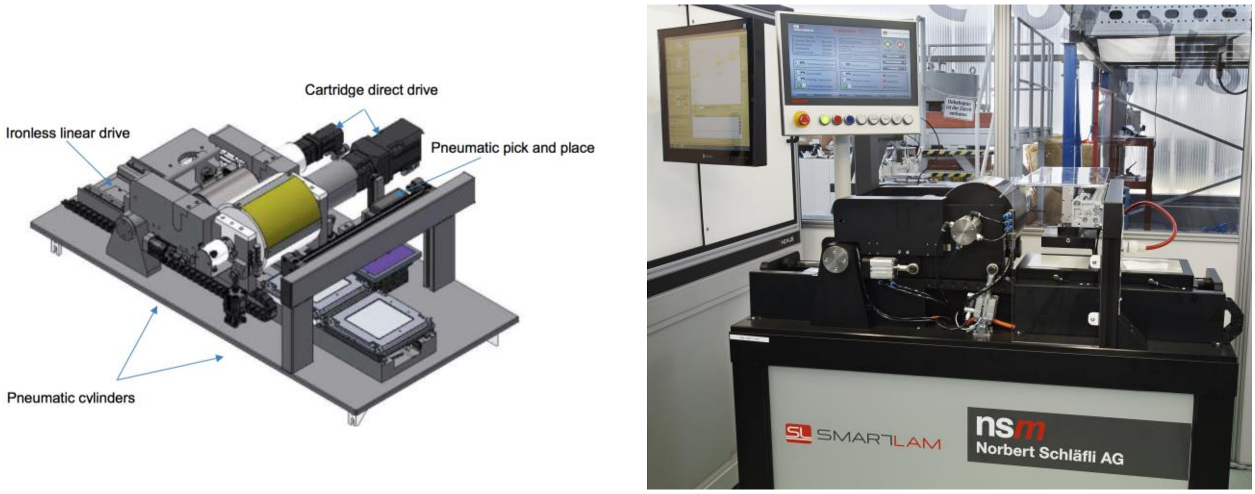


Figure 7: Lamination module: Schematic drawing (left) and finalised module at the final demonstration (right)

In case of the microfluidic demonstrator, a second method was established for joining different polymer layers that uses a diode laser for transmission welding of the pre-structured foils. Central factor for a robust welding process was a guaranteed secure bond between the different films of the microfluidic demonstrator. Therefore, an extensive study of different material combinations was carried out, investigating the welding area for defects (bubbles, cracks) and analysing the process parameters and potential damage of structured areas of the foils.

In addition to the laser welding, the module also contains an alignment system, which was fully designed and built within SMARTLAM at the Karlsruhe Institute of Technology. The system allows for a precise stacking of foils using cross-shaped markers as guidance featuring a vacuum gripping plate and a camera inspection system to detect and align the markers on both layers of the product. Like the lamination module, the laser welding and alignment system was successfully integrated into the SMARTLAM manufacturing cell and presented at the final demonstration site. The following figures show a representation of the alignment step and the finalised module.

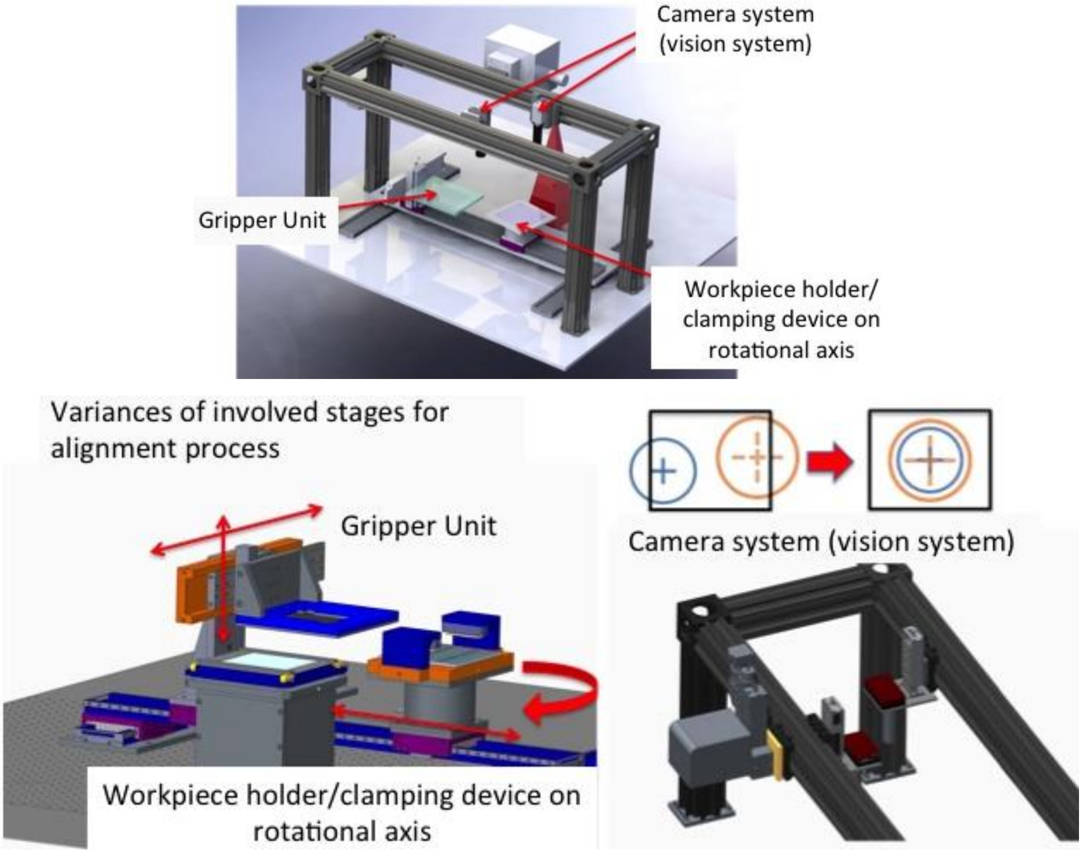


Figure 8: Setup and working principle of the alignment module

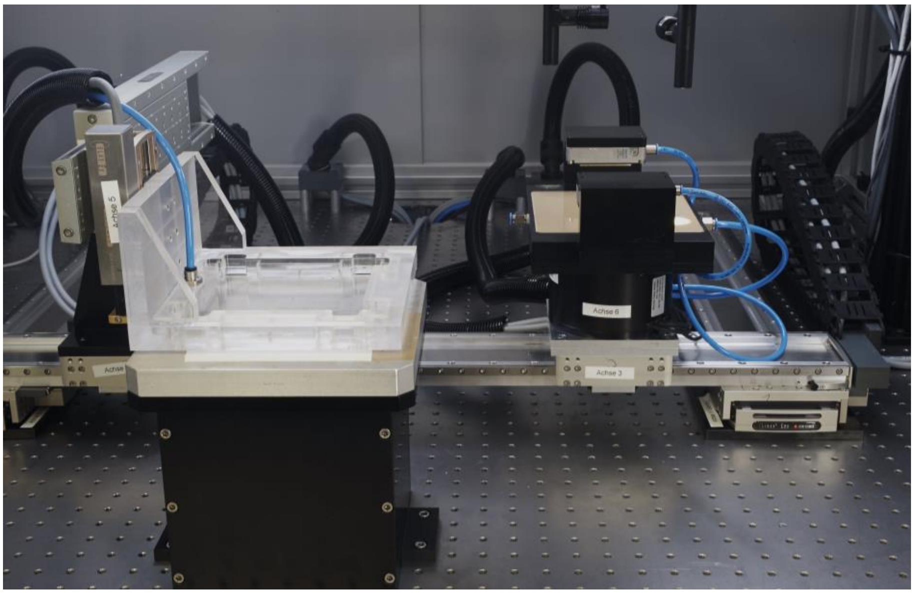


Figure 9: Final setup of alignment & laser welding module; vacuum gripper (left) and welding stage (right)

Since both demonstration products contain functional elements in the form of electrical elements, namely conducting paths for the lighting device and electrodes for the microfluidic application, a technique for deposition of these structures had to be implemented. Aerosol-jet printing was selected as the method of choice due to the needed accuracy and precise assembly requirements (Figure 10). The steps of development and set-up of the aerosol-jet printing module were carried out by NeoTech AMT (Nürnberg, Germany).

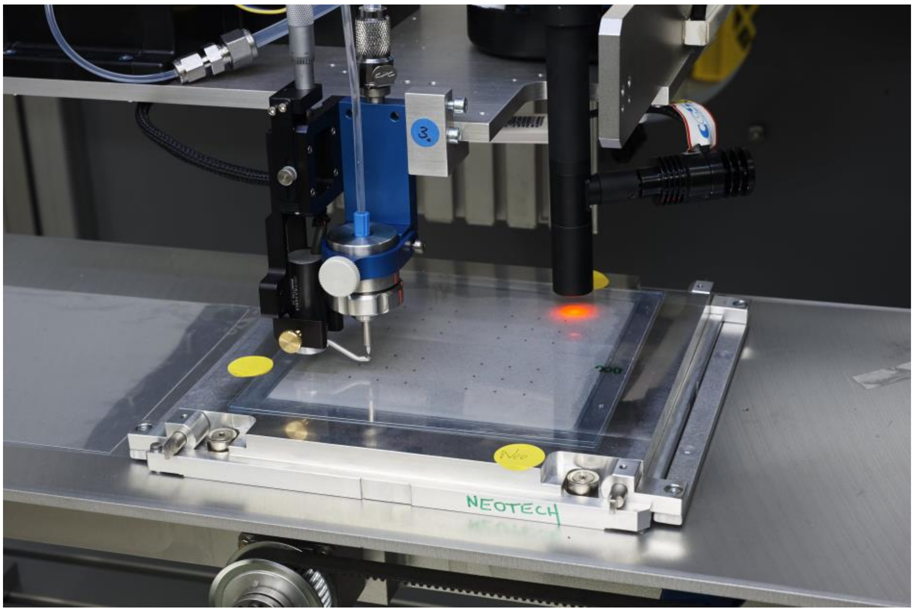


Figure 10: Aerosol-jet-printing module with vision system

The printing module is equipped with a vision system that is able to detect fiducial marks and perform the application of the conductive layer based on a pre-programmed working path. The main scientific challenge was to develop a suitable process routine that is able to print on different polymer materials, achieve a good adhesion of the deposited ink on the substrate and create a high quality print with sufficient conductivity and without interruptions at the same time. Special attention was paid to the different types of available metal inks since they are an important factor to take into account in terms of long-time costs for the overall printing process. Within SMARTLAM, the aerosol-jet-printing technology was enhanced to a state where the automatic deposition of conductive layers was possible and the structures of both demonstrators could be manufactured (see Figure 11).

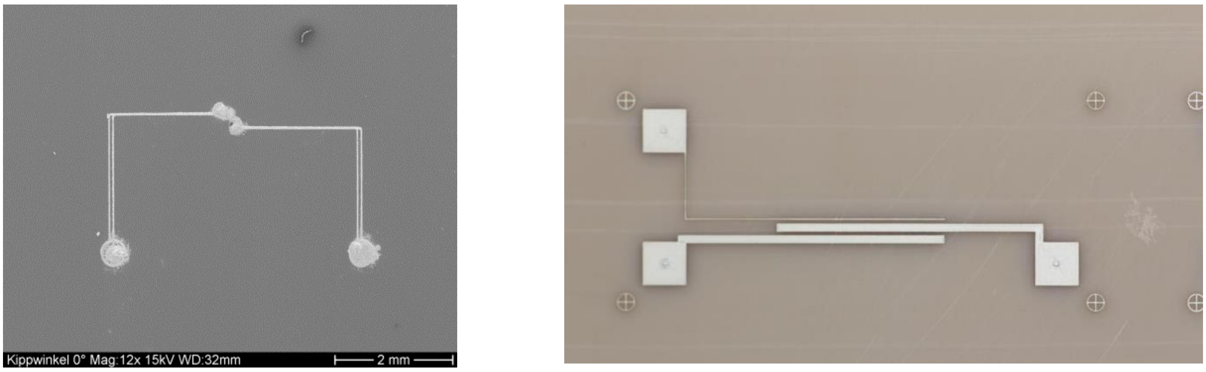


Figure 11: Examples for printed structures: Conducting paths of lighting device (left) and electrodes for microfluidic chip (right)

The final module of the SMARTLAM manufacturing cell used in the demonstration setup is the visual inspection module for quality assurance, which was developed by PROFACTOR (Steyr, Austria). The system consists of a high-resolution, monochrome line-scanning camera with a magnification lens, a positioning table for planar product movements and a LED lighting setup to allow for an illumination from different directions. The inspection module is used to precisely scan the top layer of the product and detect irregularities and faults thus assessing the products' quality after predefined steps of the manufacturing process. The necessary software to use and operate the inspection module was also developed within SMARTLAM. The software system was designed and build in a modular way making sure that the individual components were capable of mostly operating independent from each other. This concept enables the inspection system to exchange data between the different modules without too many dependencies making the overall system more flexible and maintainable.

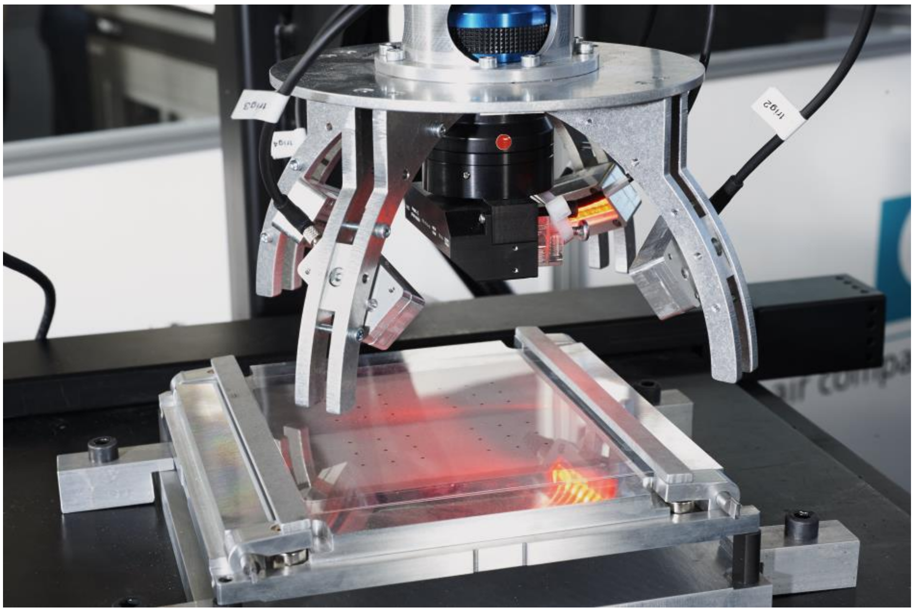
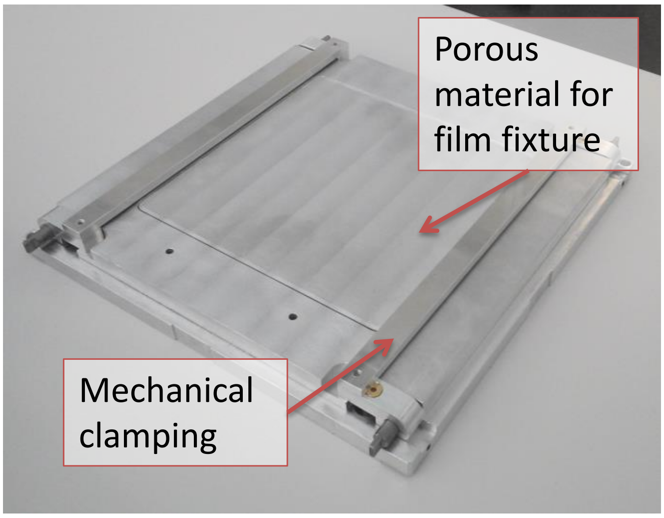


Figure 12: Close-up of inspection module

Bringing all individual process modules together in the aspired all-in-one SMARTLAM manufacturing call requires the linking of these modules to the software tools described above as well as to a central control unit. This was realised via an uniform interface design also implemented during the project phase. Besides connecting all modules, the central control module with an integrated sophisticated safety system ensured handling of errors potentially occurring during the manufacturing process. In addition, each module was equipped with safety switches to immediately stop the whole manufacturing cell in case of an emergency.

The second and even more important purpose of the main controller system was the execution of the current production recipe. First, a number of tasks from a given manufacturing recipe are identified and then send to the respective module for execution of the designated processes. The feedback loop back to the control unit upon completion of these tasks ensures the overall progress and further processing of the product. This procedure is repeated until no pending tasks are left in the recipe and the product is finished.

Initially, a transportation system was planned for the transfer of the demonstrator parts to and between the modules. Due to time and cost limitations, an alternative approach was generated with a workpiece holder compatible to the different modules (assembly, aerosol-jet printing, inspection). It provides two types of fixation for the polymer sheets: a mechanical and a vacuum clamping mechanism. The built-in valve is responsible for maintaining the vacuum during transfer and the vacuum inserts can be removed if necessary, e.g. for inspection or alignment purposes. The fixture is depicted in in Figure 13.



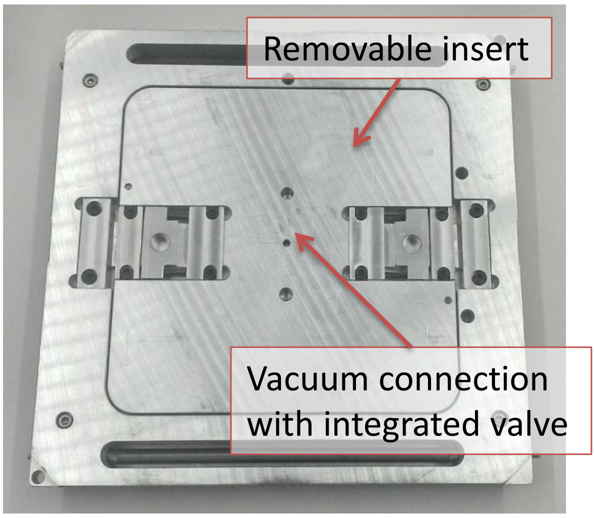


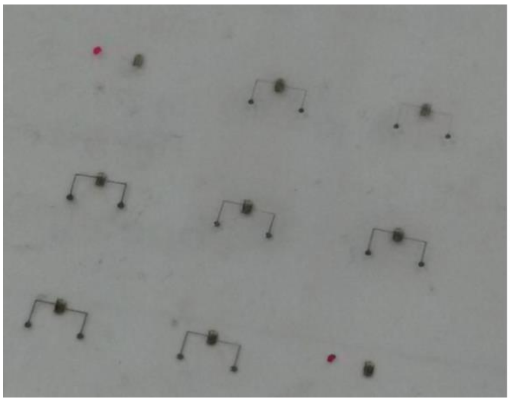
Figure 13: Workpiece pallet

Final setup of SMARTLAM manufacturing cell

After all modules and sub-systems achieved their final stage of completion (development and build-up), a stand-alone demonstration manufacturing cell was set up at the Institute of Applied Computer Science in Karlsruhe (Germany). The SMARTLAM manufacturing cell consisted of all six modules for the demonstrator production together with the main control system and a clean room housing for appropriate manufacturing conditions. An overview of the full setup is shown in Figure 14.

Figure 14: Final demonstration setup of the SMARTLAM manufacturing concept

Due to the preceding extensive spadework during the course of the project, the SMARTLAM consortium was able to set up the complex manufacturing structure within a short time frame (of approximately 4 weeks) and the flexible lighting device demonstrator (DLED) could be successfully produced during the final project meeting. Figure 15 shows an overview picture of the lighting device demonstrator produced by the SMARTLAM process consisting of nine individual LED chips (see Figure 15, left) with fully functioning contacting (see Figure 15, right).



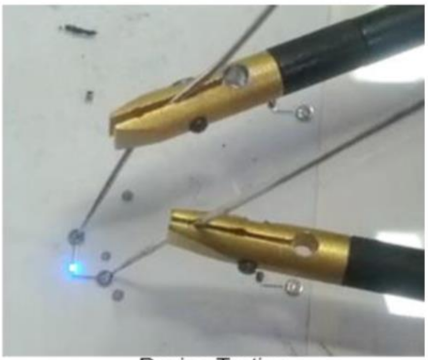


Figure 15: Array of LEDs produced by the SMARTLAM manufacturing cell (left) and testing of produced device (right)

The microfluidic device of MicruX could not be manufactured in the final demonstration cell due to the restricted timeframe that was available. However, the results prior to the final stage clearly proved that the SMARTLAM concept is suitable for manufacturing of the MicruX product, too. The required individual features were successfully generated, namely milling of microchannels using the available laser techniques, printing of the electrodes using aerosol-jet printing as well as the final bonding step (Figure 16).

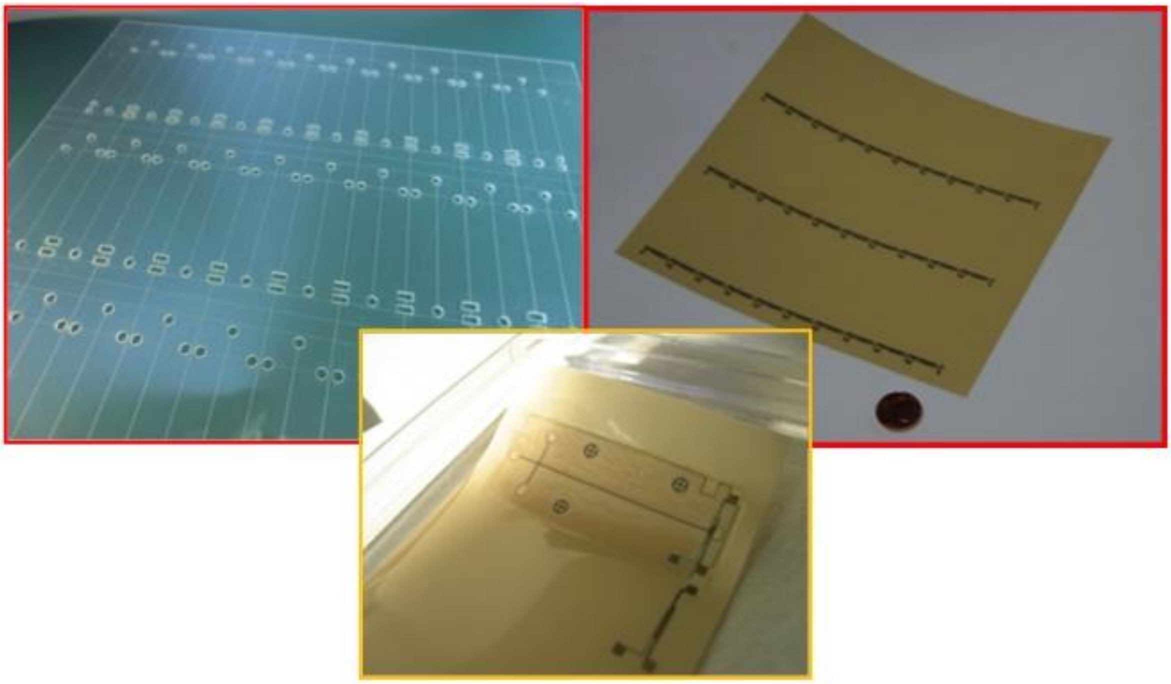


Figure 16: Demonstrator fabrication for microfluidic chip demonstrator (MicruX): laser machined microchannels (top left), printed electrodes (top right) and bonded demonstrator (bottom)

Given the enormous workload for establishing the overall concept, building of some modules from scratch (from a first blueprint to the actual machine), setting up the whole manufacturing cell and actually producing functional parts, the only hindrance to completing both demonstrators was the limited time frame at the final project stage. Nevertheless, SMARTLAM provides a proven concept for the manufacturing of small to medium series of microsystems by offering a complete all-in-one solution from supporting the designer and the supplying engineers with a database for processing parameters up to the establishing of an automated manufacturing cell concept completed by a whole controlling setup.

1.3.2 Lessons learned

Due to the complexity of the overall work program and the difficulties that occurred during the project runtime, all partners provided a short view on their experiences.

Karlsruhe Institute of Technology – Institute of Applied Materials (KIT-IAM)

In the complete range of tasks in work package 3 a lot of aspects about the process optimization could be learned. This affected all the processes that were included. Furthermore, a lot of experience was gained concerning limits of technology, but especially in the development of systems. Effective and very good cooperation and communication between the partners provided a valuable basis. In consequence, learning from each other was possible very good. It was also important to recognize that the development of such high complex systems need more time than expected. In development of special components more time is needed to mature the technology. A larger amount of personnel is advantageous as well.

University of Nottingham (UoN)

Technical teleconferences (with an interactive whiteboard and video chat) were extremely useful to go through technical details of the work package. Due to the international nature of the project and budgeting, it was not possible to have physical meetings too frequently but these technical teleconferences with a very good alternative. The monthly teleconferences for WP1 enabled us to keep track of actions and progress of reports/deliverables.
The project SharePoint was very useful to enable presentations from previous meetings to be found easily and to keep track of deliverables, meeting attendance, etc.
Live demonstrations during project meetings were useful to demonstrate the full extent of completed work.
Assigning specific deliverable as the primary responsibility of a single research fellow ensured that each deliverable always had a high priority and was achieved on time.

Fraunhofer Institute for Manufacturing Engineering and Automation (IPA)

A stronger parallelization of development and implementation in projects is required for better handling of tight schedules. For example, an enhanced V-Model with earlier implementation of prototypes could be used to shift the equipment implementation to earlier project phases.
The financial calculation for a project with such a large part of demonstration in equipment hardware was too optimistic. Beside the personnel expenditure for the realization of the equipment demonstrator, in particular the hardware costs were much higher than initially planned.
The “distributed” process development with autonomous process modules has shown itself to be beneficial. As the manufacturing processes were mostly in a progressed development stage and sensitive to several ambient conditions they could be developed and optimized until later project phases.

MicruX Technologies

Smartlam technologies might be a good alternative to fabricate true lab-on-a-chip by integrating in the same process microfluidics and electrochemical sensors. It would bring advantages such as high flexibility for custom-made designs at an affordable cost per unit in medium-scale production series. However, it seems, aerosol jet printing (AJP), laser milling and welding are not still the most promising technologies for this purpose. Many drawbacks still remain to accomplish the final goal in the current lab-on-a-chip market. Alternative technologies such as screen-printing, hot-embossing, injection-molding look currently more suitable for this purpose.

More data about the initial expenses, minimum quantity order in real market sceneries should be collected and compared with current technologies. All these issues are critical points to take advantages of SL technologies by SME´s.

Summarizing the main value lessons learned from Micrux´s perspective are:

- Technologies should be adapted to the real market needs. It may be very hard to adapt the market to the technology.
- Product specifications might be adapted to the technologies, as long as the new product still covers a market need.
- Real sample testing is the best way to demonstrate a new technology.
- The combination of very different technologies is not easy without a worthy initial planning. It is a very important point in order to get asap testing samples.
- Real end-user costs should be included as a primary goal in order to know the exploitability of the technologies by SME´s

Neotech AMT GmbH

The project has come farther than planned. Was a little bit challenging to manage for an SME - the costs incurred for investments needed were very difficult with only a small part covered in the write off period of the project. For future projects a better funding method/model is needed for SMEs that have to make investments.

1.4 The potential impact and the main dissemination activities and exploitation of results.

1.4.1 Impact

Based on the developments that have been achieved within SMARTLAM a number of economic and societal impacts can be expected.

- ***Contribution to a faster product development and upscaling to pre-series for testing or specialized small series for mass customized products***

The modular approach in combination with the design tools enables engineers and designers to quickly try different approaches to manufacturing their products. The database and configuration tool helps to assess different routes and their suitability for a cost-effective and profitable production. Therefore, the SMARTLAM approach will contribute to a easier and faster commercialization of new ideas, especially for multi-material micro components. SMEs can rely on a solution for overcoming the “valley of death” by the capability to avoid intensive developments for ineffective processing routes or design flaws.

- ***Contribution to new business models***

During the runtime of the project the proposed 3D-I approach was developed to a stage where it could be offered to OEM service providers who will be enabled to produce even small and medium series of a microsystem in a competitive manner due to the ease of configuring and scalability of the concept. In addition, the flexibility allows using different machines for a number of different projects or several types of micro components without modification of the setup and in a manifold of combinations. This ensures a high work load of the equipment, making it more profitable for the providers of such manufacturing services.

Considering the end users of such products, the SMARTLAM concept will provide easy access to enabling smaller companies to sell their products. The approach gives the opportunity to develop different design versions, produce a limited number for testing purposes and then starting the production of the most promising design within a short timeline and in a affordable manner. Due to the software solutions that have been developed within the project and in combination with the flexibility of the manufacturing setup, the innovation process and the time-to-market can be significantly shortened. Also, expenditures for the research & development process can be minimized due to the supporting design, database & controlling systems of SMARTLAM.

Based on these two assumptions an overall high impact can be expected for the manufacturing of micro components if the intended quantities are ranging from the pilot manufacturing of small series in a range between one and a few thousand parts.

- ***Acceleration of product development and market intake processes***

As mentioned beforehand, the SMARTLAM concept involves the combination of state-of-the-art fabrication techniques for micro manufacturing and adds a overall control system, making it possible to exchange modules for different products and product requirements. By basing the approach on already available machines and techniques it is possible to quickly transfer the knowledge of the prototyping phase to the actual production of small series by using the same technology and process constraints. This allows for a faster assessment and reduced efforts for process qualification.

Also, if the production is scaled up the manufacturing parameters can be transferred to similar machines due to the extensive data management system implemented in the process of the project.

- ***Contribution to a benchmarking of new (digital) technologies such as additive manufacturing or aerosol-jet printing***

At the beginning of the project the workplan proposed to benchmark novel materials. One material property of special interest was the anisotropic conductive behaviour, their micro structural behaviour and the interaction with the production process compared to the capabilities offered by the traditional manufacturing methods. The aerosol-jet printing process played a major role in the manufacturing of both SMARTLAM demonstrators, so an extensive study of different metal ink systems was carried out by investigating their characteristics in the printing process, compatibility with different substrate materials and their final conductive properties and therefore their applicability in the production of printed electronics. Thus, the results of the developments for the printing process are transferable to a variety of different applications and products in the future.

- ***Flexible scalable manufacturing for customized parts***

Current trends in the manufacturing of micro components are pointing towards a further demand for customized parts. The concept of a flexible production cell, being able to combine multiple manufacturing techniques, materials and software solutions provides a starting point for small to medium series production. By giving the opportunity to exchange single modules and manufacturing different, similar products in close succession or even in parallel without having to adapt sub-systems or peripheral devices gives the opportunity to react on changing demands and limits the cost for tooling, that may be required for other production alternatives. The technologies that were ion focus within the project can be seen as an example structure and have been adapted to the requirements of a more generic platform. In the future, other manufacturing techniques can be implemented in a similar way and the capabilities of the concept can be extended even further.

- ***Inspection and alignment support for laminated object manufacturing (LOM) -based components***

The SMARTLAM demonstrators represent only a small example for the possibilities in manufacturing products based on the principle of laminated objects. Since the products will most likely be situated in the higher price range, an effective quality control is crucial for their impact in the market. The inspection and alignment systems developed within SMARTLAM allow for a fast and precise examination of the alignment markers, placing of e.g. LED chips and overall quality checks throughout the process, either between different process steps and/or at the end of the manufacturing process. Due to the fast processing times and the ability to handle parallel tasks a 100% inspection of the products is possible, which will lead to a high output quality. In addition, the flexibility of the system gives the opportunity to sort out flawed products between single production steps, saving time and costs for the manufacturer.

- ***Impact with respect to energy efficiency***

Since the SMARTLAM concept is based on additive manufacturing techniques the typical benefits compared with more traditional production types apply, too. The application of printing conductive paths can lead to significant energy savings in comparison to e.g. subtractive electroplating. Furthermore, the possible incorporation of other AM-technologies such as fused deposition modelling (FDM) or stereolithography (SLA) allows for a significant reduction of material requirements, which also leads to a more economic and eco-friendly process.

Due to the centralized production approach of SMARTLAM, being based on a modular manufacturing cell, significantly reduced logistics and storage needs are expected by the consortium, since it makes the transport and storage of semi-finished products superfluous.

- ***Societal Impact***

The societal impact of SMARTLAM is focused on SMEs and the creating of high skilled jobs in SMEs in the field of services using SMARTLAM technologies. As SMARTLAM will be able to create benefits in the area of small lot size production, the technology is a typical example for service providers (SMEs) using the technology. So-called print shops and business models driven by SMEs create a social impact by profiting from the developed concept.

1.4.2 Main dissemination activities

General dissemination

In order to make the project visible for the scientific and the public a number of dissemination activities have been carried out, with only some mentioned here directly. A website has been set up at the beginning of the project (see 1.1.5) to inform about the context and goals of SMARTLAM. In addition, the partners were present at different exhibitions, fairs, industrial workshops and conferences to present the achievements gained during the project runtime and promote the SMARTLAM concept. Also a total of 9 scientific papers were published, with more being currently planned to be submitted.

Newsletter

For making the project known in the micro-manufacturing community a yearly newsletter, which gave an overview over the general project outlook, recent developments and, in more detail, specific outcomes of the project. Three annual Newsletters were spread out to the community which were distributed by each partner in electronic form.

Open regional days

The presentation of the project to a wider industrial audience was done by taking part in open regional days activities like the Industrial Technologies 2014 Conference in Athens or the Add+It 2015 symposium. These meetings gave the opportunity to interact with a variety of engineers, manager and scientist working in different filed (research, industry, academia) and introduce them to the 3D-I approach and gain feedback.
In total 6 regional open days were held every 6 months:

Regional Open Days Month 6: Micronarc Event, Villars-sur-Ollon, Switzerland
Regional Open Days Month 12 Nil Industrial Day in Linz, Austria
Regional Open Days Month 18: Booth at the IndTech in Athens in April
Regional Open Days Month 24: 3rd Polymercongress Wels, Austria
Regional Open Days Month 30: Microtec SW, Fachgruppe Drucktechnologien, Stuttgart, Germany
Regional Open Days Month 36: Add-it participation in Linz, Austria

Industrial workshop Milano

A highlight of dissemination activities was the **SMARTLAM workshop** in MILANO, 30th of March 2015, which was an Event in the frame of the 4M2020 Conference. It was a WORKSHOP entitled “Higher Value production technologies and KET enabled applications”. The Workshop was organized together with 9 other EU funded projects, almost 60 participants and 30 five minutes pitches presenting the results.

Business Interest Group (BIG)

Another communication platform for the whole project consortium and the overall project was introduced with the Business Interest Group (BIG) meetings. Within this group several companies were invited to act as an advisory group to monitor the development within SMARTLAM and give advice on possible enhancements and exploitation strategies. Within the 3 ½ half years of the project two meetings of the BIG were held. The feedback provided by the associated companies was considered as input to the consortium in terms of finding the weak points of the proposed concept and identifying possible markets. In conclusion, the main findings evolving from the BIG meeting are:

- SMARTLAM approach should be a service provided by a OEM company or in-house for bigger or highly innovative companies
- Easy integrating of existing manufacturing equipment is vital
- Possible markets: Smart sensor applications, plant engineering, smart plastics
- Based on the final state of the concept: Reproducibility has to be shown

In general, the BIG meetings proved to be a very fruitful addition to the dissemination activities, making the project consortium aware of the weak spots of the SMARTLAM approach but also giving input on how to overcome the disadvantages and sharpening the profile for a possible industrialization of the concept.

Video

A video was produced of the SMARTLAM platform and is available online.
https://www.youtube.com/watch?v=6NEd_pIbr2IVideo

Published papers in the SMARTLAM project

Steffen Scholz, Tobias Mueller, Matthias Plasch, Hannes Limbeck, Tobias Iseringhausen, Markus Dickerhof, Andreas Schmidt and Christian Woegerer: SMARTLAM - **A Modular Flexible Scalable and Reconfigurable System for Manufacturing of Microsystems**, International Symposium on Intelligent Manufacturing Environments InManEnt 2015, October 11 - 16, 2015 - St. Julians, Malta

A modular flexible scalable and reconfigurable system for manufacturing of Microsystems based on additive manufacturing and e-printing *Steffen Scholz, Tobias Mueller, Matthias Plasch,Hannes Limbeck, Raphael Adamietz, Tobias Iseringhausen, Daniel Kimmig, Markus Dickerhof, Christian Woegerer*

Special issue of Robotics and CIM Journal DOI: 10.1016/j.rcim.2015.12.006
Projects to advance micro manufacturing technology and applications. *Pestarino, A.; Kueck, H.; Qin, Y.; Matteazzi, P.; Azcarate, S.; Dickerhof, M.; Romero, P.; Qjan,* J. EU FP7 'Factories of the Future'. Commercial Micro Manufacturing International, 8(2015) pp.19-25

*M. Plasch, *M. Hofmann, *G. Ebenhofer, *M. Rooker. Reduction of Development Time by Using Scriptable IEC 61499 Function Blocks in a Dynamically Loadable Type Library; Präsentation bei der ETFA’2014 – 19th IEEE Intl. Conf. on Emerging Technologies and Factory Automation, 17.-18. September 2014, Technische Universität von Katalonien, Spanien, Paper ID: 978-1-4799-4845-1/14/.

A generative manufacturing-based concept for flexible, scalable manufacturing of microsystems. *Dickerhof, M.; Kimmig, D.; Adamietz, R.; Iseringhausen, T.; Segal, J.; Vladov,N.; Pfleging, W.; Torge, M.* 7th Internat.Precision Assembly Seminar (IPAS 2014), Chamonix, F, February 15-18, 2014

A design framework for micro devices manufactured by a modular multi-process platform. *Gleadall, A.; Vladov, N.; Kimmig, D.; Plasch, M.; Dickerhof, M.; Segal, J.; Ratchev, S.* 9th International Workshop on Microfactories (IWMF 2014), Honolulu, Hawaii, October 5-8, 2014

A modular flexible scalable and reconfigurable system for manufacturing of microsystems based on additive manufacturing and E-printing. *Woegerer, C.; Plasch, M.; Heidl, W.; Dickerhof, M.; Kimmig, D.; Scholz, S.; Adamietz, R.; Iseringhausen, T.* 24th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM 2014), San Antonio, Tex., May 20-23, 2014

M. Dickerhof, D. Kimmig, S. Scholz, Ch. Woegerer, R. Adamietz W. Pfleging: **„An Additive Manufacturing and E-Printing Based Approach for Flexible Scalable Manufacturing of Microsystems"**: 10th International Conference on Multi-Material Micro Manufacture, 8 – 10 October 2013, San Sebastián, Spain, ISBN 978-981-07-7247-5

An additive manufacturing and e-printing based approach for flexible, scalable rapid manufacturing of microsystems. *Dickerhof, M*. Commercialization of Micro- and Nanosystems (COMS 2013), Enschede, NL, August 25-28, 2013

1.4.3 Exploitation of results

The exploitable results are summarized in the Exploitation plan and are the outcome of two different services supported by the EU: The ESS (Exploitation Strategy Seminar) and the BPD (Business Plan Development) Seminar. A short overview is also given in the so called exploitation booklet, were all identified exploitable results are described. It is a short analysis about existing products and markets as well as the possible way to the market after the project.

In this booklet hardware, software and applications results described. For the single modules as well in the hard- and also in the software there are adequate TRL levels reached so that the proposed exploitation strategy could be further elaborated by the companies. The only deviation from the exploitation planning as proposed in the description of work is the lack of an ambitious OEM provider.

<u>Overview of Exploitable results and owners</u>

Hardware: SMARTLAM modular equipment system:

- Equipment system – (IPA)
- LAMINATOR (NSM)
- Aerosol-Jet Printing (Neotech)
- Inspection System (PROFACTOR)
- Surface Modification Module (KIT)
- Improved process for Lamination (KIT)

Software: SMARTLAM Integrated Software System

- Integrated Software System (UoN)
- Process/System Design Modelling (UoN)
- MINABase (KIT)
- Technology selection Tool (UoN)
- System Control Code Generator (PRO)

Application demonstrator:

- OEM Service Provider for manufacturing of micro components
- Micrux Microfluidic Applications
- Lightning for DesignLED
- Future Application in ENERGY (KIT)

SMARTLAM Exploitable Results - Business Casas

No.:	Titel	Business Model(s)
	Hardware: SMARTLAM modular equipment system:	
1	Equipment system – (IPA)	Open-source platform, which is continuously improved and where different process providers can supply their process cells, Realisation of projects by general contractor, Consulting by institutes
2	LAMINATOR (NSM)	Portfolio extension, Integration of laminator in **nsm Challenger C650** (see **Figure 17)**
3	Aerosol-Jet Printing (Neotech)	Increase of application range, Integration of new capabilities in Neotech's 3D Printed Electronics systems.
4	Inspection System (PROFACTOR)	Selling the system as a single Component and as a module in SMARTLAM Technology, Using the Know How for further Research projects
5	Surface Modification Module (KIT)	Industrial projects
6	Improved process for Lamination KIT)	Industrial projects
	Software: SMARTLAM Integrated Software System	
7	Integrated Software System (UoN)	Contributes to 11
8	Process/System Design Modelling (UoN)	Contributes to 11
9	MINABase (KIT)	Contributes to 11
10	Technology selection Tool (UoN)	Contributes to 11
11	System Control Code Generator (PRO	Selling the system as a single Component and as a module in SMARTLAM Technology Using the Know How for further Research projects
	Application demonstrator:	
12	OEM Service Provider for manufacturing of micro components	Some Companies are basically interested in pre-series manufacturing services but wouldn´t buy the system – OEM Service Provider required
13	Micrux Microfluidic Applications (Micrux)	Offer services that base on a continuous technological platform – important for bio analytics disruptive change of the technology along the product development process should be avoided because of the changing surface properties, influencing dramatically the fluidic and biological behaviour of the system. Lab-on-a-chip technology will soon become an important part of global health improvements through the development of point of care (POC) testing devices. Thus, this project is the gate for MicruX to be present in this emerging POC market with a competitive product satisfying the current demand of European society.

		Diversification -Microchips electrophoresis with electrochemical detection integrated have multiple applications.
14	Lightning for DesignLED (DesignLed)	Use SMARTLAM factory to provide high level of customisation, Address a large number of personalised surgical requirements (different operations, different animals), Improves safety of the surgical operation (measurable), and Reduces cost of surgical operation (50%)
15	Future Application in ENERGY (KIT)	Future Application in ENERGY (KIT)

As mentioned above, Norbert Schläfli AG has developed a machine (Challenger C650, shown in **Figure 17**) that is inspired by the SMARTLAM concept. It consists of different modules, including the SMARTLAM laminator and a highly precise printing and coating system (for functional printing, printed electronics and security printing), forming a real-life process chain for the manufacturing of OLEDs, solar cells, displays, lighting, sensors, batteries, etc.. The Challenger 650 is designed to explore various possibilities and combinations of coating and printing with a precision of 10 µm in one machine. Available units for Challenger 650: Gravure, Flexo, Screen, Slot die, Indirect gravure, Inkjet, Pick & Place and Laminator.

Technical data and performance:

- Printing and coating on flexible and rigid substrates
- Integrated air bearing guide allows vibration-free movement of the substrate carriage
- Individually programmable printing and coating speed at each station
- Programmable drying process (UV / Air / Photonic Curing, etc.)
- Optical alignment system
- Measuring software -
- Accuracy and reproducibility <10 µm
- Substrate size: Max. 297 x 216 x 4 mm
- Printing size: Max. 240 x 170 mm
- Printing speed: Up to 90 m/min.

Figure 17: Challenger 650 manufacturing cell from Norbert Schläfli AG

1.5 Project public website and relevant contact details

The project website www.smartlam.eu was established and will be maintained after project end.

Contacts: Scientific Coordinator: Steffen Scholz (steffen.scholz@kit.edu) +49 721 608 25734 Administrative and financial Project Manager: Cornelia Reimann (cornelia.reimann@kit.edu) +49 721 608 48237	Figure 18: SMARTLAM Logo

Consortium Members:

	KIT	Karlsruhe Institute of Technology
	PRO	Profactor
	IPA	Fraunhofer Institute for Manufacturing Engineering and Automation
	NEO	Neotech AMT GmbH
	UoN	University of Nottingham
	NSM	Norbert Schläfli AG
	MIC	MicruX technologies
	DLED	DesignLED