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3D-MINTEGRATION
THE DESIGN AND SERIAL MANUFACTURE OF 3D MINIATURISED PRODUCTS

Narrative Final Report

October 2005 – March 2010

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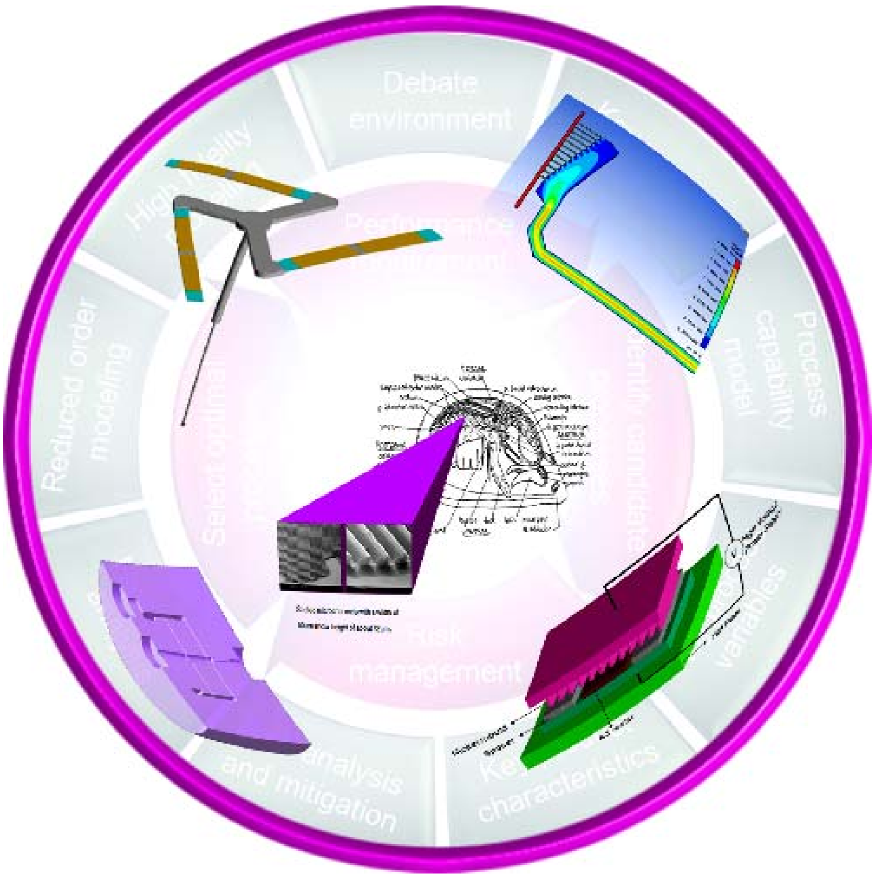


Summary

3D-MINTEGRATION was one of the four Innovative Manufacturing Grand Challenge projects awarded by the EPSRC. The original academic partners of the Consortium were Heriot-Watt University, Cambridge University, Loughborough University, the University of Greenwich, Nottingham University and Cranfield University. Later in the project, Brunel University joined the Consortium.

Its vision was to develop the technologies and strategic approaches, in all aspects of the manufacturing cycle (from design, processing, assembly, integration, test and metrology), required for the design and manufacture of tightly integrated 3D miniaturised products. The approach, directly integrating micro- features into multi-material 3D macro- products, presented a momentous departure from the customary planar integration of semiconductors and the use of 2D printed circuit boards. As such, further to the technical advances resulting from the project, 3D-MINTEGRATION has created a community of researchers capable of conceptualising products in three dimensions whilst concurrently choosing the processing technologies that best allow their manufacture.

3D-MINTEGRATION has produced the following outcomes:

- A thorough literature review at all branches of the manufacturing cycle: design, manufacturing, assembly, integration and test, applicable to three dimensional miniaturised products.
- The creation of a software framework, *3D-MINTEVISION*, that knits together conceptual design and its manufacturing embodiment to facilitate the manufacture of wholly new products using newly-created manufacturing technologies
- A breakthrough product and process introduction methodology, embedded in 3D-*MINTEVISION* framework, that mitigates risk through comparing the similarities between new manufacturing techniques and a cohort of previously used techniques.
- A design methodology to evaluate how a product or a process can be broken down into simple factors and on how variations in design, process or product dimensions can be related and quantified to improve process yield and product performance.
- A design methodology to transform physical principles in 2D diagrammatic form directly into beneficial 3D structures
- The identification of a special application of “Similitude” to help designers visualise and debate micro-behaviour at everyday macro- scale
- A portfolio of 32 manufacturing processes susceptible to be used for 3D miniaturised integrated products.
- The creation of 4 new processes, some of them patented, which include the use of microwave energy to cure interconnections, megasonic agitation for advanced electroplating of materials, electrostatic pressure to free-form polymer material in 3D, laser energy to create features at the nanoscale or write metal tracks onto 3D non conductive surfaces.
- The development of Focused Ion Beam technology as a manufacturing tool rather than its conventional use in measurement and analysis, with particular applicability to the creation of low-cost precision tooling for high volume manufacturing.
- New assembly methods were devised which make use of van der Wall forces or fluidic forces to assemble miniaturised parts.
- The better understanding and development of micro-injection moulding, overmolding,induction heating and ultrasonic bonding as means of creating, sealing and packaging 3D components.
- The development of a novel phase shifting interferometric method for examining high aspect ratio microstructures and undercuts.
- The demonstration of the validity of the academic research through the production of three test prototypes: a flexible microprobe, a foldable multisensory system and a 2D, then 3D blood-plasma separator unit.
- The generation of extensive academic dissemination with 71 journal articles, 163 conference proceeding articles, 23 MSc or Ph.D. theses as well as book chapters created, 4 patents filed, 1 software created and around 118 separate dissemination activities.

Introduction and background

Even though advances in semiconductors, interconnects and microsystems (MEMS) are driving extraordinary advances in products, they will only at best provide component-level parts, not fully-assembled and packaged products. Moreover, the design philosophies behind products made from these parts are also essentially two-dimensional, bound to planar processes, and reduced to the “cut & paste” combining of standardised elements using regularised processes rather than a true fusion of integration using manufacturing optimised specifically for a target product.

The capital costs for the components that currently underpin portable electronic products are formidable, with a semiconductor manufacturing plant requiring an investment of some $3Bn, and mask sets ranging from $250k to $3m.

The 3D-MINTEGRATION (3D-Minaturised/INTEGRATION) project was therefore conceived to provide a fresh, highly speculative and blue-sky research approach for the manufacture of “smart” complex systems with less dependence upon conventionally-produced components, whilst encouraging also a holistic product-level design approach based directly upon 3D thinking. The change in manufacturing practice that this project aimed to foster is provided in the table below.

	Today	Tomorrow
Design & Simulation	19th Century Approach 20th Century Tools	Inclusive Design Risk Mitigation
3D Processing	2D Technologies 20th Century Si fabrication	3D Technologies Multi Materials
Microassembly	Product Specific	Package-device interaction Generic packaging platforms ‘The disappearing package’
Packaging & Integration	Discrete Costly Approach	
Test & Measurement	Thought of last, done last. Lab-based practices	Multi-probe metrology In-process testing methods. Traceability and calibration
Manufacturing strategy	Economy of Scale Artificial Constraints	Volume independent Highly responsive Low cost entry

Table 1: Forecast paradigm shifts in manufacturing

3D-MINTEGRATION was one of four Grand Challenge awards made by the EPSRC in 2005. The overall aim of the Grand Challenge award programme was to address research activities that had the potential of major impact on national manufacturing progress through the creation of a multi-disciplinary team across several universities and with significant funding to achieve world-leading breakthroughs.

The original academic partners were Heriot-Watt University, the University of Cambridge, Cranfield University, the University of Greenwich, Loughborough University and the University of Nottingham. Following the identification of a gap in this group’s research expertise, Brunel University was invited to join the academic Consortium to contribute skills in conceptual design.

The EPSRC support ran from October 2005 until March 2010, including a six month extension brought about by maternity leave for one of the researchers. Additional financial contributions came from IMRCs at Heriot-Watt University, the University of Cambridge, Cranfield University, Loughborough University and the University of Nottingham.

The research was organised in five themes, with developments tested within three prototype demonstrators. The five interrelated themes were:

- *Design & Simulation* (Leader: Greenwich University, Partners: Brunel University, Nottingham University, Heriot-Watt University)
- *3D Processing* (Leader: Cranfield University, Partners: Cambridge University, Heriot-Watt University)
- *Microassembly (*Leader: Nottingham University, Partners: Cranfield University, Cambridge University, Greenwich University, Heriot-Watt University, NPL)
- *Packaging & Integration* (Leader: Loughborough University, Partners: Greenwich University, Heriot-Watt University)
- *Test & Measurement* (Leader: NPL, Partners: Cambridge University, Heriot-Watt University, Loughborough University, Greenwich University, Nottingham University)

The themes, divided into corresponding work packages with multiple tasks, were complemented by three demonstrators which provided tangible test beds to focus the research, to validate developments, and to promote discussion with the industrial collaborators. These demonstrators were:

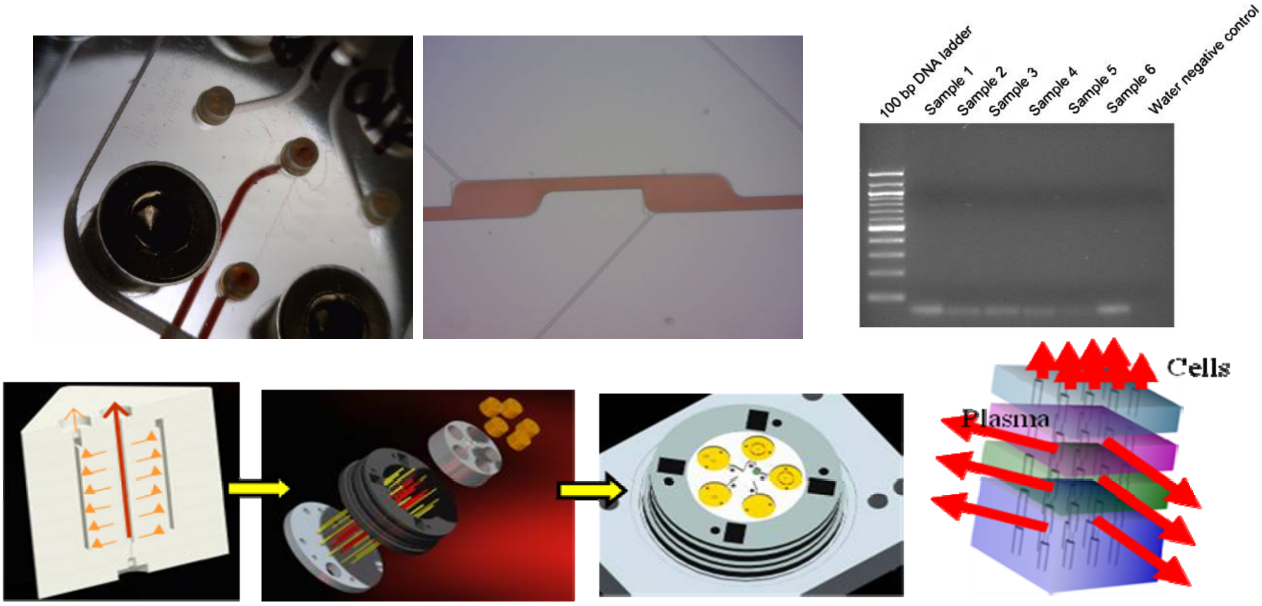
- ***Health and Usage Monitoring System (HUMS)*.** A new generation of products will allow the health and usage of large or complex systems to be monitored by sensing critical product, system and environmental parameters. Whereas the manufacture of individual sensors (electrical, temperature, pressure, humidity, chemical, acceleration etc) is now in the commercial realm, the 3D integration and packaging of collections of sensors, and their remote interrogation systems, still remains to be tackled in terms of system design and integration, packaging and test techniques. Understanding and classifying the potential failure mechanisms of new complex HUMS assemblies is especially important as HUMS will need to be more robust than the systems they monitor.

Rogowski coil used as a HUMMS for the monitoring of cable ageing and the foldable packaging housing the sensor and electronics

- ***Miniaturised flexible microprobe****.* Metrology equipment with the capability to to measure the profile of high aspect ratio microstructures is still in its infancy. The microprobe demonstrator tested a combination of in-depth simulation and modelling, laser based machining processes, , and research into the manufacture and assembly of the microsphere needed to provide minimum contact with the surface of the object to measure. The demonstrator also provided a platform for product development routines that capture the key product and process characteristics and assist with determining risk mitigation strategies.

From design, manufacturing and assembly of the 3D microprobe

- ***Microfluidic delivery system*** The high throughput manufacturing of 3D components promises to be particularly advantageous for microfluidic devices, as used for example in biomedical, agrochemical and food applications. Particular emphasis was put in the manufacturing of a medical sample preparation unit capable of separating plasma from blood. Modelling and simulation addressed the complex physical interactions in the above processes and the interaction of red blood cells with the flow and geometric features of the channels, and indicated 3D topologies that should provide performance benefits in the use of a range of devices. The new manufacturing techniques tested included CNC micro-milling; wide area injection moulding and embossing techniques. Physical prototypes compared the performance of a 3D device in comparison with a more conventional planar device.



From 2D validated microfluidic separator of plasma from blood to 3D manufacturing

Aims, vision and outcomes

The vision of 3D-MINTEGRATION was to develop the technologies and strategic approaches, in all aspects of the manufacturing cycle (from design, processing, assembly, integration, test and metrology), required for the design and manufacture of tightly integrated 3D miniaturised products. The approach, directly integrating micro- features into multi-material 3D macro- products, presented a momentous departure from the customary planar integration of semiconductors and the use of 2D printed circuit boards. As such, further to the technical advances resulting from the project, 3D-MINTEGRATION has created a community of researchers capable of conceptualising products in three dimensions whilst concurrently choosing the processing technologies that best allow their manufacture.

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Industrial collaboration

The project originally had 7 large companies and 16 SMEs covering a wide range of industrial sectors as well as the whole value chain in manufacturing. The SMEs were as follows: SLI Ltd, MicroStencil Ltd, BCF Designs Ltd, Multi-Physics Software Limited, Flomerics Ltd, TQC Ltd, VideoJet Limited, Carl Zeiss Ltd, SPI Photonics, Unipath, Tecan Ltd, Epigem Ltd, Accuromm UK Ltd, Battenfeld UK Ltd, Omniscan, Laser Optical Engineering Ltd. The large companies included NPL, Syngenta, Sun Microsystems, Unilever, MBDA, BAe Systems, Astra Zeneca, Glaxo SmithKline. The total industrial support from these companies amounted to £2.8M.

During the lifetime of the project, 3D-Mintegration witnessed many changes within their industrial collaborators which resulted in a change in their level of participation.

- SLI Ltd moved to the Research Park of Heriot-Watt University which enabled a strengthening of their collaborative research activities with this University. This resulted in the creation of two additional research projects targeted at the design and manufacturing of Microsystems. MicroStencil Ltd moved to Singapore to establish a joint venture with DEK, one of the major stencil printing equipment manufacturers in the world. This move decreased the direct contribution in kind from that company. BCF designs Ltd was taken over by the group Ultra, becoming thereby Ultra Electrics. The newly branded company increased threefold their contribution to the Consortium as original work with BCF Designs Ltd had resulted in the company gaining a £1.2M contract with SEEDA. Flomerics Ltd was bought by Mentor Graphics and their contribution to the project decreased. Tecan Ltd was bought over by the Dutch company Stork Veeco, Prior to this acquisition, Tecan contributed to a significant market survey on the current state of the art in stencil printing. Accuromm UK Ltd moved their activity to Eastern Europe shortly after the start of the project and did not contribute to it. Epigem Ltd increased their contribution to the project and has entered license negotiations with Heriot-Watt University for the commercialisation of the microfluidic demonstrator. The company benefited from this work through the ward of two additional research projects under TSB funding.

- Amongst the large companies Syngenta, MBDA and Unilever changed their research strategy and decreased their level of participation. The fact that key people at Syngenta and Unilever left the companies also made it difficult to sustain the same level of enthusiasm with such companies. NPL contributed so much to the project in the extent that they become, alongside BCF Designs Ltd, the industrial leaders for the microprobe demonstrators. Negotiations have started with NPL to commercialise the microprobe with the company Carl Zeiss.

- Additional companies have joined either formally or informally the project. Renishaw plc is very interested in some of the work, especially in the processing work package as the company is always interested in novel technologies that can help manufacturing their encoders in a cheaper way. Two other UK companies, EM Systems Support Ltd and EDAX UK contributed to the work effort from the University of Cambridge. The project was identified by the international Fiat Group as being of seminal importance, and consequently FIAT contributed to the content of 3D-MINTEGRATION Annual Conferences.

Heriot-Watt University is also in negotiations with four Fraunhofer Institutes for the set up of an antenna on the Research Park of the University of a Centre for low cost micro-manufacturing. The Centre will be financed by the German Government and University and RDA in the first instance and aims to translate into industry technical outputs obtained from the University activities.

Management

Management structure

The Grand Challenge faced by the 3D-MINTEGRATION project was a complete revision of "traditional" manufacturing practice at the micro- scale, moving away from the no-expense -spared mindset of high-tech planar fabrication which had become universally accepted, stemming from advances in semiconductors over a 50-year period.

Wiping the slate clean required visionary research based upon fundamentally new ideas and consequently taking unexpected paths into totally uncharted territory. Reconciling this with a strict need to remain on budget, within timescale and providing useful deliverables required management that was at the same time both firm yet flexible.

To achieve this, administrative management including finances, contractual matters and the collation of outputs such as publications and reporting was undertaken solely by the lead participant, Heriot-Watt, whilst matters of research direction were the responsibility of an Executive Group with representatives primarily from each of the project partners and an independent Coordinator – the whole supported by a process of consultation and inspiration from a lively Industrial Steering Group.

Function:	**MANAGEMENT**	**CONSULTATION**
Responsible Body:	**Executive Group**	**Industrial Steering Group**
Membership:	Principal Investigator (Chair) Co-Investigators Project Coordinator Industrial Advisors Invited Academics	Project Coordinator (Chair) Representatives from collaborators Invited industrialists and trade and public sector bodies as nominated by the collaborators
Ex-officio Members:	EPSRC Secretariat	Principal & Co- Investigators Secretariat
Role:	• Execution of the research programme • Responsibility for monitoring of academic quality and research deliverables • Develop strategy for knowledge transfer and dissemination activities • Meets twice per year	• Represents the industrial collaborators and wider industry • Advises on direction and themes of research • Resources dissemination activities • Meets 3 times per annum

Coordination

In addition to the management groups, the management hub appointed Mr. David Topham as project co-ordinator. With a vast industrial experience drawn from small and large companies, Mr. Topham was technically literate with good communication skills, and with a very strong understanding of the agendas of the academic and industrial communities. He chaired the Industrial Steering Group; attended the Executive Group; provided sector expertise; developed links to the broader industrial and academic communities; drove dissemination activities, ran workshops and seminars where appropriate; developed links with other initiatives such as the European manufacturing platform EPoSS and the Network of Excellence MiocroSapient; and contributed to the annual strategic overview of the project.

Beyond the contract, the Coordinator paired with and mentored each of the academic partners, individually and jointly, to encourage and open approach to innovation – as early in the project it was recognised that the partners needed to be reassured that the Grand Challenge was indeed "a licence to dream" and not a framework of incremental developmental research as had become the researchers' normal experience.

Community building

As an extension of the recognition that "a new way of thinking" would be seminal to the success of the project, a new management feature in the form of an annual "Community Event" – involving all researchers and industry partners – was put in place. It was revealing to observe the caution, especially of the less-experienced researchers, blossom through the four events to create a cadre of free-thinking innovators who are now carrying this torch to other projects and a multiplying community. As a consequence 3D-Mintegration has created a body of people more familiar with the challenges and opportunities presented by 3D manufacturing.

The community events also drew magnificent support from several of the industrial collaborators. It should be mentioned here that successful industrial support does not come from companies; it comes from star individuals within these companies. This "extra-mile" support saw spin-out projects develop within companies, and one industrialist himself joining a research group as an industrial adviser, transferring deep experience to a new generation.

Design becomes a driver

The flexibility to pursue emerging themes was tempered with a need to focus upon application. In this respect there was an ever-present danger that the three "Demonstrator" devices would become primary objectives as "product development" in their own right, dangerously laying down "specifications" to be met, which in themselves would tempt the use of "tried and tested" solutions.

To emphasise creativity through design, the School of Engineering Design at Brunel University was invited to join the project through a DTA disbursement, which immediately provided an expected impetus of conceptual design, plus an unexpected discipline in terms of a formal design framework from concept to embodiment.

This matter revolutionised the direction of the project. The Design & Simulation work package, conceived originally as support services for the other work packages, came into its own as a driver of the project, just as design pushes both process and product development in leading companies.

Dissemination and the broader community

Of particular importance was the organisation of 3D-MINTEGRATION annual conferences which were well attended by the industrial community. Whenever possible, the Conference was attached to an existing conference such as the IeMRC annual conference drawing thereby more attendees. Annual report and/or news letters were produced to highlight advances made by the Consortium. In addition, a website www.3D-MINTEGRATION.com was created right at the writing of the proposal and constantly populated by news items.

Annual conferences and in-company teach-ins provided an extensive audience for the deliverables of the project, plus contributions to leading world-wide symposia attracted by the fresh approach broadcast by the 3D-MINTEGRATION web site and the fervour of the individual research teams.

It is difficult to convey the almost "evangelic" drive of the project members, challenging the status quo at academic and industry events, pushing the need for disruptive innovation to fuel economic breakthrough. Individually, project members gained a will to challenge as a result of the developing strength of the 3D-MINTEGRATION partnership.

The phenomenon resounded beyond the UK to strike resonances with the Fraunhofer network – attracted by a fountain of ideas – and global corporations such as Fiat, who insisted that 3D-MINTEGRATION should join the European Technology Platform EPoSS to invigorate the EU Framework community engaged in Smart System Integration.

Future development and funding

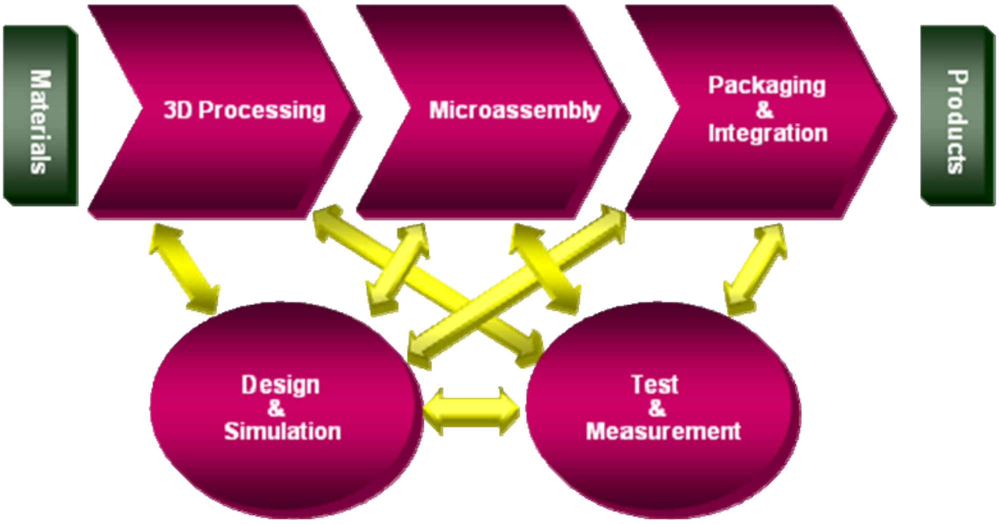
3D-MINTEGRATION enabled additional funding for its academic and industrial members of over £9.1M as broken down in the table below.

FUNDING SOURCE	DETAILS	SUPPORT (£)
EPSRC	1) SMI-JWI IMRC grant follow up new process created under 3D-Mintegration. ASPECT: Electrodeposition using megasonic agitation. 2) Cambridge IMRC. Project contribution RG45382 3) Link with the University of Milan in commercial exploitation of bioscience 4) Microelectrode arrays (IMCRC) 5) Prognostics (IeMRC)	520,000 400,000 151,116 247,884 250,000
Other UK Research Council	1) KTP with Ultra-BCF Designs Ltd, industrial partner in this project. Contribution from UK Research Council towards KTP. 2) DTA: nanostructured magnet manufacture	191,113 75,000
Other UK Government	1) TSB SMART Laser: micro laser machining studies using ps pulse outputs 2) TSB ENDVIEW 3) TSB MEMSpatch	166,000 88,000 1,300,000
UK Industrial	1) KTP with Ultra-BCF Designs Ltd. Industrial contribution towards KTP. 2) EngD sponsorship on HUMS (Ultra-BCF designs Ltd) 3) Industrial PhD funded studentship 4) Stryker Howmedica: microfabrication of Ti surfaces 5) Feasiblity study Renishaw LTCC	94,130 40,000 50,000 10,000 28,000
UK Other	1) MEMSiDesign Phase 1: The Design of integrated Microsystems. In collaboration with Strathclyde university and SLI Ltd, one of our industrial partners. Funding by the Regional Development Agency, Scottish Enterprise. 2) MEMSiDesign Phase 2 3) SEEDA – RDA grant to BCF designs Ltd as a consequence of work achieved on HUMS, one of the prototype demonstrator. 4) NMS 2005-2008 Microprobe project 5) NMS 2008-2011 Microprobe project	263,398 47,613 1,200,000 450,000 780,000
European Commission	1) Frequency Agile Microwave Oven Bonding System (FAMOBS) – FP7-SME-2007 -1 (# 218350 -2) - 2,347,654 Euros total costs - 1,760,220 Euros funded. Collaboration with the University of Greenwich, co-investigator in this project. 2) FP7 project: nanostructured magnet manufacture – 2,500,000 Euros total costs 3) FP7 Integ-micro “New production technologies of complex 3D micro-devices through multi-process integration of ultra precision engineering techniques”. Euros 547,952 to Cranfield University from total of €7.4m for the 20 partners.	1,517,310 750,000 500,000
TOTAL		£9,119,564

Although the project lasted 4.5 years, the Consortium has barely scratched the surface of revealing the benefits and opportunities that 3D-manufacturing can offer. Most of the projects cited above have targeted specific technical problems revealed during the course of the project. No funding was specifically targeted towards taking forward 3D-MINTEGRATION in a holistic manner.

Nevertheless a restricted group of Universities (Greenwich, Heriot-Watt and Brunel) and Companies (Selex, Arts & Science) have chosen to exploit the new freedom in thinking boldly and in an innovative way through the creation of a proposal for a new Innovative Centre for Manufacturing for Naturally Inspired Manufacturing. Decision about this outline proposal is imminent.

The individual workpackages



Work Package 1: Design & Simulation (Greenwich)

The Design & Simulation work package was originally conceived to underpin the three manufacturing-orientated work packages, by providing analysis, simulation and modelling of the processes and the demonstrator products to be developed during the project, and to extract data and characteristics from those processes and products to generate risk mitigation strategies for their adoption by industry.

Early during the course of the project it was realised that (i) the simulation and modelling would need a consistent discipline-linking framework to be best effective across processes and products that themselves would become closely linked, (ii) the generation of risk mitigation strategies, aimed at managing the introduction of new products and processes bereft of field experience, would form a vital module within this framework, and (iii) in order for the demonstrators to be created an element of conceptual design would be needed, which in itself would have to embrace knowledge of how to share and debate concepts remote from everyday experience between design/manufacturing teams.

By adopting these enhancements, the Design & Simulation work package transformed from its original role as an underpinning activity, to become a primary driver for the project as a whole, intimately connected with every element. As a result, the work package bound together project-wide activities to create an unforeseen deliverable in the form of a draft "design front end" for advanced manufacturing – "3D-MINTEVISION".

Maintaining a balance between "serving" the manufacturing work packages by performing modelling and analysis, yet "leading" the project as a whole by injecting design concepts and providing a knowledge framework proved demanding, and undoubtedly the Greenwich team went "the extra mile" on behalf of all the project partners.

The primary activities within the Design & Simulation work package evolved to be as follows:

1.1 Specification of Design & Simulation Toolset (Greenwich)

The focus of this work was a review of the applications of computer-based numerical techniques in manufacturing and design processes and relevant potential prospect for extension into 3D-MINTEGRATION applications. The conclusions and discussions were presented in ae report suggesting enhancements in the application of numerical analysis in manufacturing and design processes with relevance to 3D-MINTEGRATION development.

A selection of publications:

1.1.1 Project Report: Advantages and Disadvantages of Current D&S Technologies used by Industrial Communities, Greenwich University, August 2006

1.1.2 Project Report: Matrix of processes used in 3D-Processing, Assembly, Packaging, Test and measurement and data analysis requirements, Greenwich University, Nottingham University, Heriot-Watt University, September 2006

1.1.3 C. Bailey, H. Lu, S. Stoyanov, M. Hughes, C. Yin, D. Gwyer, Multi-Physics Modelling For Microelectronics And Microsystems - Current Capabilities And Future Challenges, EuroSIME 2007, London, 2007

1.2 Simulation Tools (Greenwich)

Based on functionality and characteristics, analytical tools were divided into four groups namely high-fidelity analytical tools, i.e. finite element analysis (FEA); fast analytical tools referring to reduced order modelling (ROM); optimal synthesis, including optimisation design and sensitivity analysis; and probability based analytical tools, e.g. reliability and uncertainty. The characteristics of these four groups were researched, including strengths, weaknesses, application areas and development trends. One developing area of analytical tools rvery relevant to 3D-MINTEGRATION was the supplementation of multiphysics analysis functions and the integration between different software tools.

A selection of publications:

1.2.1 Project Report: Scoping Document on High Fidelity Models and Reduced Order Methodologies to be used within the Project. Greenwich University, August 2006

1.2.2 S. Stoyanov, X. Xue, C. Bailey, 3D-Mintegration: Optimisation Modelling Framework for 3D-Mintegration Design, entation at 3D-MINTEGRATION Conference, September 2006

1.2.3 C Bailey, H Lu, S Stoyanov, X Xue, Book chapters: Nanopackaging: Nanotechnologies and Electronics Packaging ISBN: 978-0-387-47325-3, 2008

1.2.4 C Bailey, S Stoyanov, Y Tang, X Xue, and T Tilford, Multi-Physics Modelling for the Fabrication, Packaging and Reliability of Micro-Systems Components, 8th World Congress on Computational Mechanics (WCCM8/ ECCOMAS 2008), Venice, Italy, 2008

1.3 Risk Mitigation Engine (Nottingham)

The work commenced with a review concerning Key Characteristics (KCs) applications and methods. Several references indicated the importance of using the KCs method to provide a focus for different engineering activities, but not many resources have handled the KCs identification process in detail; that is, apart from some related MIT research work and some industrial applications motivated by the necessity to manage complex products and systems, and in both of them mostly the KCs application was related to variation reduction activities.

The activity progressed to investigate process capabilities, notably of the micro-injection moulding, Focused Ion Beam (FIB), Laser Machining and Electro Hydro Dynamic Instability Patterning (EHDIP) processes being investigated at Cranfield, Cambridge and Heriot-Watt.

As a result of the work, innovative methodologies were developed to (i) assess numerically the risk of introducing new process technologies and (ii) predict to capabilities of entirely new processes by examining their similarity to aspects of known techniques.

A selection of publications:

1.3.1 Project Report: Scoping Product Key Characteristics - Applications and Methods. Nottingham University, July 2006

1.3.2 Sailesh Narania, Tarek Eshahawii, Nabil Gindy, Ying Kit Tang, Stoyan Stoyanov, Stephen Ridout, Chris Bailey, Risk mitigation framework for a robust design process, Proc. of the 2nd ESTC conference, Greenwich, 2008

1.3.3 Katy Voisey, Nabil Gindy, Salesh Narania, Study of the effects of laser and process parameters in Nd:YAG based laser ablative mllling on roughness value and depth of material removed using DOE, International WLT conference on Lasers in Manufacturing, 2009

1.3.4 Clifford R Fowkes, Yunfei Sun, Nabil Gindy, A Novel methodology for analyzing variation risk introduced by the manufacturing process in Microsystems, EMPC Rimini, Italy, 2009

1.3.5 Sailesh Narania, Clifford R Fowkes, Nabil Gindy, Risk quantification for emerging technologies, IERMC Loughborough, 2009

1.4 Conceptual Design (Brunel, Heriot-Watt)

This activity was introduced into the project when it was realised that in order for the demonstrators to be created designs would have to be generated from first principles, as the benefits of the developing 3D-MINTEGRATION manufacturing processes could not be reflected in existing product topologies.

Embarking upon the design of the demonstrators revealed that the activity of conceptual design itself would have to be extended to cope with the transformation of underlying product principles, typically in 2D diagrammatic form, into 3D topologies. Moreover, this experience demonstrated problems of how to share and debate concepts remote from everyday experience between design/manufacturing teams.

As a result, a unique transformation routine was developed for the generation of 3D topologies from 2D examples, which was tested through the design of the Minifluidic demonstrator. The share and debate of concepts was investigated through the application of (i) similitude and (ii) haptic sensing

A selection of publications:

1.4.1 D. Topham, D. Harrison, The conceptual design of products benefiting from integrated micro-features, Electronics System-Integration Conference 2008. ESTC 2008, DOI:10.1109/ESTC.2008.4684544, 2008

1.4.2 D. Topham, D. Harrison, The Design of smart systems with embedded micro features, Smart Systems Integration. ISBN 978-3-8007-32008-1, 2010

1.4.3 M. Calis, O. Laghrouche, M.P.Y. Desmulliez, Implementation of Cosserat theory into haptic sensing technology for miniaturised systems, International Journal of Industrial Systems Engineering, Vol.5, N.3, 2010

1.5 Applied simulation (Greenwich)

To underpin the process development activities of 3D-MINTEGRATION as a whole, the Design & Simulation work package provided analysis, simulation and modelling of the processes and the demonstrator products to be developed during the project.

This work not only underpinned the three manufacturing-orientated work packages and the demonstrators, it also extracted data and characteristics from the processes and demonstrator products as input to the risk mitigation activity of 1.3 above and provided design guidelines for the conceptual design activity of 1.4 above.

A selection of publications:

1.5.1 Xiangdong Xue, Michael Hughes, Chris Bailey, Michele Turitto and Svetan Ratchev, Modelling and structural concept design of micro pneumatic feeder system, Journal of Sensors and Actuators, 2008

1.5.2 M.Hughes, C.Bailey, K.McManus, Multi-Physics Modelling of the Electrodeposition Process, Proc of Eurosime, ISBN: 1-4244-1106-8, 2007

1.5.3 T. Tilford, K.I. Sinclair, C. Bailey, M.P.Y. Desmulliez, A.K. Parrott and A.J. Sangster, Coupled FDTD-FVM Simulation of Microwave Heating of Polymer Materials for Micro-Systems Packaging Applications, IMPI 41st International Microwave Power Institute Symposium, Vancouver, Canada, 2007

1.5.4 J. Kaufmann, M.P.Y. Desmulliez, D. Price, M. Hughes, N, Strussevich, C. Bailey, Influence of megasonic agitation on the electrodeposition of high aspect ratio blind vias, IEEE/CPMT 2nd International Conference on Electronic Systems Technology Integration (ESTC), Greenwich, 2008

1.5.5 Stoyanov S, Bailey C, Leach R K, Hughes B, Wilson A, O'Neill W, Dorey R A, Shaw C, Underhill D, Almond H J, Modeling and prototyping the conceptual design of 3D CMM micro-probe, Proc. 2nd ESTC, Greenwich, 2008

1.5.6 X. Xue, M. Patel, M.K. Kerhoas, C. Bailey, M.P.Y. Desmulliez, D. Topham, Effect of Fluid Dynamics and Device Mechanism on Biofluid Behaviour in Microchannel Systems: Modelling Biofluids in a Microchannel Biochip Separator, ICEPT-HDP International Conference, Beijing, China, 2009

1.6 Development of Front End Environment (Greenwich, Brunel, Nottingham, Heriot-Watt)

The Design & Simulation work package transformed from its original role as an underpinning activity, to become a primary driver for the project as a whole, intimately connected with every element. As a result, the work package bound together project-wide activities to create an unforeseen deliverable in the form of a draft "design front end" for advanced manufacturing – "3D-MINTEVISION".

This work pulled together, for the first time, all the elements of design, from conception through modelling, risk mitigation and process selection and embodiment. The scheme adopted allows for real-life design iterations and will form a comprehensive reference for designers embarking upon the creation of new products using innovative manufacturing processes.

A selection of publications:

1.6.1 Ying Kit Tang, 3D Mintevision – bringing it all together, Presentation at 3D Mintegration Annual Conference and Exhibition, September 2008
1.6.2 S. Stoyanov, X. Xue, M. Patel, Y. K. Tang, P. Rajaguru, C. Bailey, 3DM design methodologies and 3D-Mintevision, Presentation at 3D Mintegration Annual Conference and Exhibition, September 2009

Work Package 2: 3D Processing (Cranfield)

Current micro fabrication techniques have evolved from the growth of the microelectronics sector and utilise production methods that have been designed for semiconductor materials. These systems are capable of writing features with sub 100nm resolution and step and repeat capabilities that deliver staggering complexity.

There is a need however to extend the range of micro fabrication capabilities to encompass a wider range of materials and geometric forms since current techniques are essentially two dimensional in nature, and that was the challenge taken up by the 3D Processing work package.

The aim of the 3D Processing workpackage was to develop low cost manufacturing approaches capable of producing complex three dimensional single material and composite microparts. This saw the development of advanced fabrication techniques capable of producing 3D microfluidic chips and other intricate products from polymers and metals and ceramics. CNC precision micromachining, focused ion beam (FIB) and laser machining were employed to fabricate master moulds for micro injection moulding, large area embossing and Laser Print Forming technology.

The primary activities within the 3D Processing work package were as follows:

2.1 Critical review of current processes (Cranfield, Cambridge, Loughborough)

The focus of this work was a review of the state of the art in 3D microfabrication, the technical capabilities and aspects of economics.

A selection of publications:

2.1.1 Project Report: 3D Micro-fabrication Processes, Cranfield University, Loughborough University, 2006
2.1.2 S. Marson, R. Evans and D.M. Allen, Replication of polymer microcomponents: the economics of hot embossing versus injection moulding, Proceedings of the 20th International Conference on Computer-Aided Production Engineering (CAPE 2007), Glasgow, 2007.

2.2 Focused Ion Beam Processing (Cranfield, Cambridge, Greenwich)

Focused Ion Beam (FIB) technology originated as a measurement and analysis technique. The 3D Processing work package extended the application of FIB to become a manufacturing resource, especially suited to the manufacture and finishing of hard tooling in diamond, sapphire and metals..

A selection of publications:

2.2.1 R.W. Evans, S. Marson and D.M. Allen, A review of focused ion beam technology for the fabrication of ultra precision diamond cutting tools, Proceedings of the 6th International Conference on Materials for Microelectronics and Nanoengineering, Cranfield, 2006.
2.2.2 Q. Hu, W. O'Neill, Focused Ion Beam induced clustering on glassy carbon and associated cleaning for toolsets application, NanoFIB 2009, Wadham College, Oxford, 2009
2.2.3 R.W. Evans, I.S. Durazo-Cardenas, D.M. Allen, PCD tooling made by combined laser beam machining and focused ion beam machining, Proceedings of the 9th Euspen International conference, San Sebastian, Spain, 2009
2.2.4 Q. Hu, W. O'Neill, Occurrence of particle debris field during focused Ga ion beam milling of glassy carbon, Journal of Applied Surface Science, 2010
2.2.5 S. Stoyanov, Y.K. Tang, C. Bailey, R. Evans, S. Marson, D.M. Allen, Modelling and process capability of focused ion beam, Proceedings of the 32nd International Spring Seminar on Electronics Packaging, 2009

2.3 Laser Machining (Cambridge)

Work with very low capital cost fibre-optic lasers was directed towards (i) finishing mould tools, (ii) fabricating tooling for the laser-induced deposition of 2.4 below, and (iii) the machining of 20 micron diameter bars, 2mm long, as the shaft component of the microprobe demonstrator.

A selection of publications:

2.3.1 W. O'Neill, MOPA-based fibre lasers offer processing options, Optics and Laser Europe, 2008
2.3.2 W. O'Neill, K. Li, Q. Hu, P. Chopra, J. Kanghee, A. Buntardjo, Microfabrication using a single mode Yb fiber laser, Fourth International Conference on Multi-Material Micro Manufacture (4M2008), Cardiff, 2008
2.3.3 W. O'Neill, Laser based micro manufacturing developments, Fraunhofer-Institut fur Lasertechnik, Aachen, Germany, 2009.
2.3.4 Q. Hu and Chopra, P. Hu, W. O'Neill, 3D microprobe manufacturing techniques, 3D-Mintegration Annual Conference, Greenwich, 2008

2.4 Laser Print Forming (Cambridge)

Laser Print Forming was developed as a novel fabrication process for the production of 3D micro parts using the physical characteristics of nano particles, i.e. low melting and sintering temperatures. The technique allows for the creation of micro or nano components on planar or contoured surfaces through the deposition of nano inks using high resolution stamps created by Focused Ion Beam and/or ultrafast laser machining. The technology, developed in a number of variants for different applications, opens up the possibility of providing low cost manufacturing solutions for micro-, nano- and 3D-MINTEGRATED products.

A selection of publications:

2.4.1 Q. Hu, P. Hu, W. O'Neill, Laser-assisted micro structure fabrication using nano-particles, The Laser User, 2008
2.4.2 Q. Hu, W. O'Neill, Laser assisted micro and nano replications, 3rd Pacific International conference on applications of lasers and optics (PICALO), Beijing 2008
2.4.3 P. Hu W. O'Neill, Q. Hu, Synthesis of 10 nm Ag nanoparticle polymer composite pastes for low temperature production of high conductivity films, Journal of Applied Surface Science, 2010

2.4.4 P Hu, K Li, W O'Neill, W Chen, P Lib, D Chu, Fabrication of Organic Field Effect Transistor Using Nano Imprinting of Ag Inks and semiconducting Polymers, Journal of Micromechanical Microengineering, 2010

2.5 Electro Hydro Dynamic Instability Patterning (EHDIP) (Heriot-Watt)

A novel process, EHDIP, was developed, using electrostatic pressure to free-form polymer material in 3D. The process proved capable of fabricating high aspect-ratio 3D patterns including also microlenses, and hollow-section patterns in the form of tubes and capsules.

A selection of publications:

2.5.1 M.P.Y. Desmulliez, W.Yu, Techniques for producing 3D-patterns and hollow structures in surfaces using applied electrostatic forces, Patent GB0823090.6, 2008
2.5.2 W.Yu, S. Cargill, M. Leonard, M.P.Y. Desmulliez, Micro-fabrication on 3D-surface by electrostatic induced lithography, IEEE/CPMT 2nd International Conference on Electronic Systems Technology Integration (ESTC), Greenwich, 2008

2.6 Microinjection Moulding (Cranfield)

Injection Moulding is an established technology for the production of macroscopic components from thermoplastic material. In practice, the thermoplastic is fed in the form of granulates into the plasticating unit and then injected at high pressure into a mould, which is the inverse of the desired shape. The molten polymer freezes into the mould becoming a solid part and is then released from the mould by opening the mould end and ejecting the plastic part with a set of ejection pins. The whole process is normally very fast with production cycles of a few seconds.

In microinjection moulding, the mould cavities contain features in the micrometre range which need to be completely filled by the polymer melt. In many cases this requires the process to be adapted to take into account the air entrapped in the small features and for the very fast cooling of the injected melt into small, cold mould features. The fast cooling of the polymer melt in the mould causes the polymer to freeze within the very small cavities which typically results in the cavity being only partially filled.

The work of 2.6 addressed these challenges by (i) the fabrication of master moulds with very well defined features, (ii) a study of fluid flow during the moulding process, supported by modelling and the subsequent optimisation of parameters, and (iii) The measurement and characterisation of microinjection moulded test pieces and demonstrator parts.

In the course of the work, the fabrication of master moulds interfaced with activity 2.1, the fluid flow study interfaced with activities 1.3 and 1.5 of the Design & Simulation work package, and the measurement and characterisation engaged with the Test & Measurement work package. Validation of the work concentrated upon the fabrication of a prototype blood plasma separator with demanding dimensional constraints.

A selection of publications:

2.6.1 S. Marson, U.M. Attia, J.R. Alcock, D.M. Allen and A. Wilson, Flatness measurement of micro-injection moulded discs for the manufacture of a 3D microfluidic device, Commercial Micro Manufacturing, 2009
2.6.2 S. Marson, U. Attia, D.M. Allen, P. Tipler, T. Jin, J. Hedge and J.R. Alcock, Reconfigurable micro-mould for the manufacture of truly 3D polymer microfluidic devices, Proceedings of the 19th CIRP Design Conference 2009
2.6.3 U.M. Attia, S. Marson and J. Alcock, Micro-injection moulding of polymer microfluidic devices, International Journal in Microfluidics and Nanofluidics, DOI: 10.1007/s10404-009-0421-x., 2009

Work Package 3: Microassembly (Nottingham)

Microassembly techniques are constrained by interactions between the handling device/tool and the small scale parts that they manipulate. For instance, adhesive forces can become more dominant than gravitational forces, causing failure of the process.

The key emphasis of this Microassembly work package was on developing new solutions for the automatic handling of large volumes of very small parts, and the development of multi-process microassembly incorporating a wide variety of specialised product specific processes. The critical enabling technologies developed included: high precision positioning devices; the precision tracking and control of applied forces; process monitoring and feedback; and miniaturised "super-clean" environments, with a target methodology being the use of standardized "Plug & Produce" modules.

In addition to the microassembly-related research, this work package also provided services to the 3D Processing work package concerning ultrasonic bonding, and to the Test & Measurement work package concerning the assembly of the microprobe demonstrator.

The primary activities within the Microassembly work package were as follows:

3.1 Critical review of current techniques (Nottingham)

The first activity concerned state of the art reviews covering micro-manipulation, robotics, gripping, feeding, joining and design for micro assembly. This refined the initial assumptions in our original proposal, allowing industrially-relevant cases to be developed to assess the influence of different design features and materials as well as other constraints such as regulatory requirements.

A selection of publications:

3.1.1 Project Report: State of the Art Review, Nottingham University, 2006
3.1.2 S. Ratchev, Microassembly – Introduction and State of the Art and ongoing work in 3DM, 3D-MINTEGRATION Conference 2006

3.2 Design For Microassembly (Nottingham)

Although Design For Assembly is a widespread and important tool for industry operating in the macro- domain, creating a similar set of resources for the micro- domain meant bringing together different techniques and a different emphasis upon physical laws.

This needs of Design For MicroAssembly could not be fulfilled by simply transferring know-how from the macrodomain. A scaling down approach would present a number of flaws as it does not take into account the specific physical phenomena that emerge with the interaction between the microparts. In fact, in the microdomain, mass-related forces such as gravity and inertia are often less relevant than surface related forces such as surface tension, electrostatic or Van Der Waal's forces. Moreover, constraints like the fragility and the contamination of the microcomponents have a bigger relevance than in macroassembly. Furthermore, disturbing influences, generally negligible at macroscale such as fabrication defects, wear and environmental conditions become significant.

A selection of publications:

3.2.1 Project Report: Design for μ-assembly – identification of key process characteristics, Nottingham University, 2007

3.2.2 C. Tietje, R. Leach, M. Turitto, Application of a DFμA Methodology to facilitate the Assembly of a micro/nano Measurement Device, Fourth International Precision Assembly Seminar, Chamonix, France, 2008
3.2.3 C. Tietje, S. Ratchev, Design for Microassembly – A Methodology for Product Design and Process Selection, IEEE International Symposium on Assembly and Manufacturing (ISAM). ISAM 2007, University of Michigan, Ann Arbor, USA, 2007

3.3 Pneumatic Microfeeder System (Nottingham, Greenwich)

Particular emphasis was placed in the work package upon the development of new ultra-precision techniques for microgripping and micro-manipulation. The work focused around the development of contactless and smart micro-grippers using linear electrostrictive and piezoelectric actuators and air flotation.

The microfeeder as developed consists of an array of micronozzles. Air is used for keeping the parts suspended and moving them through the control of the micronozzles. A single microactuator pixel is made up of four nozzles formed by a central electrode and four walls around it. Airflows can be arranged in such a way that microparts can be moved to any specific position. It is also possible to maintain the position and just change the orientation.

The device also provided an exercise in 3D-MINTEGRATION design and manufacture, and benefitted from the modelling resource in activity 1.5 of the Design & Simulation work package.

A selection of publications:

3.3.1 Project Report: Contactless Microfeeding Methodology, Nottingham University, 2006
3.3.2 M. Turitto, S. Ratchev, Xiangdong Xue, M. Hughes, C. Bailey, Pneumatic contactless microfeeder design refinement through CFD simulation, 4M2007 Conference on Multi-Material Micro Manufacture, Borovets, Bulgaria, 2007
3.3.3 X. Xue, C. Bailey, M. Turitto and S. Ratchev, Modelling and optimization of a pneumatic microfeeder system, International Journal of Simulation and. Multidisciplinary Design Optimisation, 2009

3.4 Applied Microassembly (Nottingham, Cranfield, Cambridge, Heriot-Watt, NPL)

Practical support was given to co-workers in the other work packages in the form of (i) the development of ultrasonic welding for the Minifluidic demonstrator, (ii) an investigation of folding techniques for the HUMS demonstrator, and (iii) work directed towards spider/shaft/ball microjoining in the Microprobe demonstrator.

A selection of publications:

3.4.1 D. Smale, S. Haley, J. Segal, S. Ratchev, Application of the Ultrasonic Welding Process to the Manufacture of a Micro Fluidics Device, 10th International Conference of the European Society for Precision Engineering and Nanotechnology, EUSPEN, 2010
3.4.2 Project Report: State of the Art review on Origami Folding Techniques for Polymers, Nottingham, 2007
3.4.3 D. Smale, S. Ratchev, J. Segal, R. K. Leach, J. Claverley, Assembly of an innovative probe tip for micro-CMMs, 9th International Conference and Exhibition on Laser metrology, machine tool, CMM and robotic performance, London, UK, 2009

<u>Work Package 4: Packaging & Integration (Loughborough)</u>

Packaging, conventionally seen as providing the protective outer skin of a product, and also the interconnects between its parts, can be developed to be a smart boundary layer between a product's internal components and also a gateway to the outside world with which the complete product must interact.

The Packaging & Integration work package developed a broad suite of processes categorised as (i) Polymer Integration, embedding and surface engineering, addressing materials interaction and surface engineering issues to create multi-functional integrated systems, (ii) 3D multifunctional interconnection, concerned with interconnecting multifunctional devices within systems, and (iii) selective polymer microwave and RF processing to create new bonding or sealing technologies that are localized, material selective and therefore not detrimental to the operating lifetime of the whole 3D system.

The primary activities within the Packaging & Integration work package were therefore as follows:

4.1 Polymer Integration (Loughborough, Heriot-Watt)

Much of this work was concerned with overmoulding and adhesion. Although these matters are widely practised in industry, the underlying mechanisms were found to be poorly understood, and worthy of study and development, particularly in respect of microfluidic systems.

A selection of publications:

4.1.1 Webb, D.P., Conway, P.P., Hutt, D.A., Knauf, B.J. and Liu (Changqing), C., Processes for Integration of Microfluidic Based Devices, 17th European Microelectronics and Packaging Conference (EMPC), Rimini, Italy, 2009
4.1.2 Webb, D.P., Hutt, D.A, Hopkinson, N., Conway, P.P. and Palmer, P.J, Packaging of Microfluidic Devices for Fluid Interconnection Using Thermoplastics, IEEE/ASME Journal of Microelectromechanical Systems, 2009
4.1.3 Patrick Webb, Overmoulding for integration of components with MIDs, Molded Interconnect Devices (MID) 2008 meeting, Fuerth, Germany, 2008
4.1.4 Hrushikesh Abhyankar, D. Patrick Webb, David A. Hutt and G. West., Adhesion of Thermoplastics to Materials used in Electronics (Tin), 10th Electronics Packaging Technology Conference (EPTC), Singapore, 2008
4.1.5 S. Millar, M.P.Y. Desmulliez, W. Yu, A review of hermeticity test methods for packages with ultra-small cavities, 33rd IEEE/CPMT International Conference IMAPS-Poland, 2009

4.2 3D Multifunctional Interconnection (Loughborough,Heriot-Watt)

The emphasis here was on the creation of reliable interconnects - electronic, optical and fluidic – upon contoured surfaces and notably surfaces capable of flexure.

A selection of publications:

4.2.1 Tze Yang Hin, Changqing Liu, Paul P. Conway, Controlling Interfacial Interpenetration of Polymer Waveguide Deposited on Plasma Treated Flexible Substrate, 10th Electronics Packaging Technology Conference (EPTC), Singapore, 2008
4.2.2 Tze Yang Hin, Changqing Liu, Paul P. Conway, Weixing Yu, Scott Cargill and Marc P.Y. Desmulliez, A polymeric optical waveguide-on-flex fabrication using electrostatic induced lithography, IEEE Photonics Technology Letters, 2009
4.2.3 J. Kaufmann, M.P.Y. Desmulliez, D. Price, M. Hughes, N, Strussevich, C. Bailey, Influence of megasonic agitation on the electrodeposition of high aspect ratio blind vias, IEEE/CPMT 2nd International Conference on Electronic Systems Technology Integration (ESTC), Greenwich 2008
4.2.4 Y. Tian, J. Kaufmann, C. Liu, D.A. Hutt, B. Stevens, M.P.Y. Desmulliez, Megasonic enhanced wafer bumping process to enable high density electronics interconnection, IEEE/CPMT 2nd International Conference on Electronic Systems Technology Integration (ESTC), Greenwich 2008
4.2.5 J.H.-G. Ng, M.P.Y. Desmulliez, M. Lamponi, B.G. Moffat, A.C. Walker, A. McCarthy, H. Suyal, K.A. Prior, D.P. Hand, UV direct-writing of metals on polyimide substrates, IEEE/CPMT 2nd International Conference on Electronic Systems Technology Integration (ESTC), Greenwich, 2008

4.3 Selective polymer microwave and RF processing (Loughborough, Heriot-Watt, Greenwich)

Creating new bonding or sealing technologies that are localized, material selective and therefore not detrimental to the remainder of the whole 3D system vital. The Packaging & Integration work package developed innovative approaches as (i) the development of evanescent microwave fringing fields for heating, and (ii) low frequency induction methods whereby a deposited reluctance absorbed energy which then transferred to adjacent features. This latter shows promise as a permanent method for joining fluidic interconnects. These developments were supported by modelling within the Design & Simulation work package, activity 1.5.

A selection of publications:

4.3.1 T. Tilford, K.I. Sinclair, G.Goussetis, C. Bailey, M.P. Y Desmulliez, Numerical simulation of encapsulant curing with a variable frequency microwave processing system, International conference on thermal, mechanical and multi-physics simulations and experiments in microelectronics and microsystems (EuroSim), 2008
4.3.2 K. Sinclair, A. Sangster, M. Desmulliez, H.Goussetis, T. Tilford, C. Bailey, K. Parrott, Open ended microwave oven for packaging, Symposium on Design Test Integration and Packaging of MEMS/MOEMS (DTIP), Nice, 2008
4.3.3 Knauf, Benedikt J.; Webb, D. Patrick; Changqing Liu,; Conway, Paul P., Packaging of polymer based microfluidic systems using low frequency induction heating (LFIH), International Conference on Electronic Packaging Technology & High Density Packaging (ICEPT-HDP 2008)

<u>Work Package 5: Test & Measurement (NPL)</u>

The Test & Measurement work package was originally envisaged to serve the manufacturing-orientated work packages, but developed along two main threads, (i) the conception and prototyping of a novel 3D Microprobe, using 3D-MINTEGRATION design and manufacture processes and (ii) the development of a novel phase shifting interferometric method for examining high aspect ratio microstructures and undercuts.

The two primary activities within the Test & Measurement work package were as follows:

5.1 Micro CMM probe manufacture (NPL, Cranfield, Cambridge, Greenwich, Nottingham)

Early in the project, the Test & Measurement work package teamed up with the 3D Processing work package to co-develop a micro- scale Co-ordinate Measuring Machine (CMM) probe. The dual benefit of this collaboration saw the 3D Processing and Microassembly research activities benefiting from having a real, and taxing, requirement to aim their developments at, whilst the Test & Measurement activity gained insight into how micro-miniature probes might be manufactured, and what may be expected in respect of dimensional accuracies, physical properties and costs.

Moreover, the probe with its intimate electronic driver, sensors and 3D suspension provided a unique opportunity for optimisation through multi-physics modelling.

A selection of publications:

5.1.1 D. Smale, S. Haley, J. Segal, R. Ronaldo, S. Ratchev, R. K. Leach, J. Claverley, Utilisation of FIB/SEM Technology in the Assembly of an Innovative Micro CMM Probe, 5th International Precision Assembly Seminar, Chamonix, France, 2010
5.1.2 Claverley J D, A vibrating micro-scale CMM probe for measuring high aspect ratio structures, HARMST 2009, Saskatoon, Canada
5.1.3 C. Tietje, R. Leach, M. Turitto, S. Ratchev, Application of a DFμA Methodology to facilitate the Assembly of a micro/nano Measurement Device, Fourth International Precision Assembly Seminar, Chamonix, France, 2008
4.1.4 Stoyanov S, Bailey C, Leach R K, Hughes B, Wilson A, O'Neill W, Dorey R A, Shaw C, Underhill D, Almond H J, Modeling and prototyping the conceptual design of 3D CMM micro-probe, IEEE/CPMT 2nd International Conference on Electronic Systems Technology Integration (ESTC), Greenwich 2008
5.1.5 D. Smale, S. Ratchev, J. Segal, R. K. Leach, J. Claverley, Assembly of an innovative probe tip for micro-CMMs, 9th International Conference and Exhibition on Laser metrology, machine tool, CMM and robotic performance, London, UK, 2009
5.1.6 Yunfei Sun, Clifford R Fowkes, Nabil Gindy, Richard Leach, Variation risk analysis: MEMS fabrication tolerance for a micro-CMM probe, International Journal Advanced Manufacturing Technology, 2009

5.2 Advances in Interferometry (NPL, Loughborough)

Seminal work was undertaken in identifying errors of interpretation in White Light Interferometry, resulting in numerous publications and a Good Practice guide issued at national level.

Allied interferometric work showed that it is possible to extract information about undercuts and steep structures.

Scanning white light interferometry (SWLI) is an increasingly popular method to measure the surface profile of miniature components. Although it is tolerant to step changes in profile, its capability to measure the large surface gradients that are characteristic of high-aspect-ratio surfaces is limited. This is in part due to the numerical aperture of the objective lens which restricts the spatial frequency content of both the illumination and recorded fields. More fundamentally, though, SWLI instrumentation neglects the effects of multiple scattering and assumes that the field which illuminates the object is that which would be present if the object were absent. Although this is a reasonable approximation for slowly varying surfaces, it is generally not true for those with steep gradients.

Work in the Test & Measurement work package presented a 3D theory of SWLI: Using finite element methods (FEM), SWLI interferograms were demonstrated for the cases of 2D Silicon V-grooves and step artefacts, and the effects of multiple scattering were observed. Methods to improve the capability of SWLI to measure large surface gradients, first by tilting the sample and subsequently by using an iterative FEM model to provide improved estimates of the illuminating conditions were introduced.

A selection of publications:

5.1.5 J. Lobera, F. Gao, J. Petzing, J. Coupland and R. Leach, Limitations and innovations in scanning white light interferometry, EUSPEN 08 Zurich, 2008
5.2.2 Jon Petzing, Jeremy Coupland and Richard Leach, Guide for the Measurement of Rough Surface Topography using Coherence Scanning Interferometry, National Measurement Good Practice Guide (Crown copyright 2010)
5.2.3 J. M. Coupland, J. Lobera, Measurement of Steep Surfaces Using White Light Interferometry, STRAIN, 2009
5.2.4 F. Gao, J.M. Coupland and J. Petzig, V-groove measurement with a white light interferometer, Photon06 Manchester, 2006
5.2.5 J. Lobera and J. M. Coupland, On The Measurement of High Aspect Ratio Surfaces using White Light Interferometry, Photomechanics 08 Loughborough, 2008

DTA Allocation

3D-MINTEGRATION benefited from a large number of DTA funding as a result of the size of the grant. The awards were given according to the availability of students, the quality of the proposed work by the partners and the immediacy importance and relevance of the research work to be carried out. All University partners received DTA income, outlining the importance of each university in the whole research effort. The DTA students were integral part of the cohort of PhD project students and postdoctoral students and were invited to the community events and all annual conferences. All students were trained in their respective Universities to become efficient researchers.

Year	HWU	Nottingham	Brunel	Cranfield	Loughborough	Cambridge	Greenwich
2006	0.5 Jack Hoyd-Gigg Ng, 0.5 Chris Popov (WP2)	Daniel Smale (WP3)	David Topham (WP1)				
2007				Daniel Zdebzky (WP2)	Benedikt Knauf (WP4)		
2008	0.5 Elizabeth McKeever (WP4)						0.5 Nadia Strussevich (WP1) Pushparajah Rajaguru (WP1)
2009	0.5 Elizabeth McKeever (WP4)	1 DTA person selected (WP3)				David Hopkinson (WP2)	

Table: Breakdown of the DTA funding allocation.
The name of the students is given in the entry of the matrix alongside the link with the relevant work package.

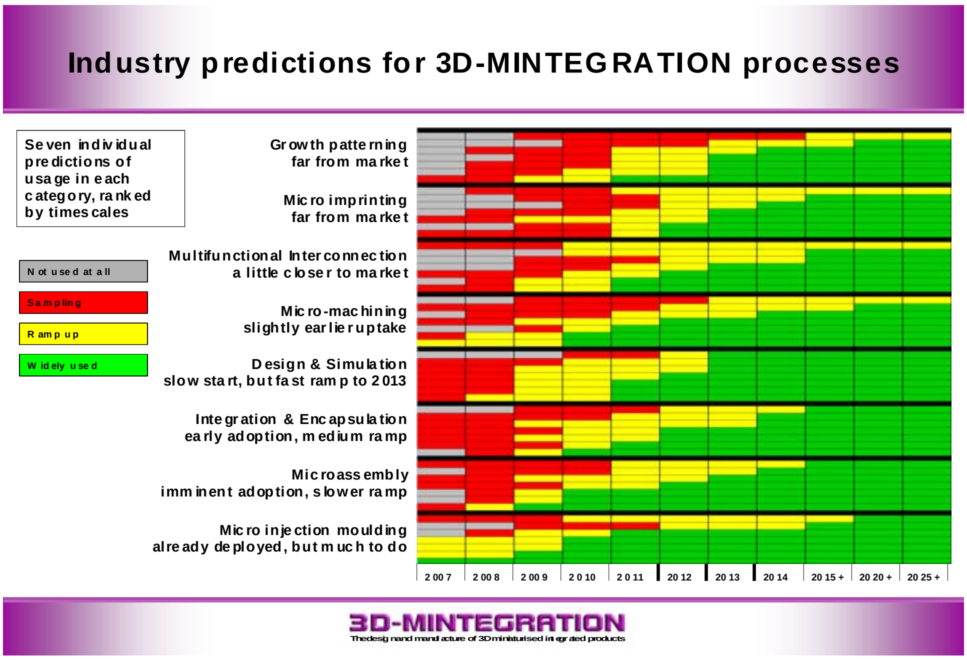
Concluding Observations

The activities of 3D-MINTEGRATION have proved unique in the research arena worldwide. There is no international institution whose activities could be benchmarked to the work achieved by the Consortium.

The novel perspective in manufacturing achieved by the Consortium has been recognized through the delivery of over 15 Keynote Presentations in international conferences, mostly sponsored by the IEEE. At least four best papers awards were given to partners in national or international conferences (London 2008, Shanghai 2008, Beijing 2009, Boston 2010). In addition Consortium partners were invited to deliver over 33 talks to present the progress made in 3D manufacturing.

Three visiting professorships were conferred to partners: Richard Leach from NPL at Loughborough University, David Allen from Cranfield University at NUAA and Marc Desmulliez from Heriot-Watt University at the Chinese Academy of Sciences Institute of Fine Optics, Mechanics and Physics at Changchun University. The last award is only conferred to twenty international scientists every year in China.

Interaction with industry was excellent; in particular seven companies were invited to benchmark some of the processes. The results of their feedback are given in the figure below.



The project was invited as part of the EPSRC Impact! Exhibition (London 2010) where it received good publicity coverage in newspapers and online publications.

Academic dissemination of the results were also excellent with today 71 journal articles, 163 conference proceeding articles, 23 MSc or Ph.D. theses as well as book chapters created, 4 patents filed, 1 software created and around 118 separate dissemination activities. Around another 20 journal publications and 30 conference proceedings are still expected this coming year in periodicals with larger impact journal than those usually encountered in manufacturing.

The exposure of 3D_MINTEGRTION in Europe has gone from strength to strength. The project has gained the interest of 4 Fraunhofer Institutes (ILT, IPA, IMS and IPKG) who have been attracted by a fountain of ideas – and global corporations such as FIAT, who insisted that 3D-MINTEGRATION should join the European Technology Platform EPoSS to invigorate the EU Framework community engaged in Smart System Integration.

Discussions to create a UK/Fraunhofer Collaboration framework in low cost micro-manufacturing are currently under way. Cambridge University has already been successful in attracting around £750K in a European proposal under EPoSS as a consequence of their work within 3D-MINTEGRATION. One member of the Consortium is also part of the CEPoSS Technology Platform on Smart System Integration, the only UK partner in the Executive Committee. This platform has 20 partners, 18 of those are industrial. Another member is part of the INTEG-MICRO FP7 programme to use precision machining technique to machine 3D components in a reduced footprint machine. The Consortium has 20 partners, of which 14 are from industry.

3D-MINTEGRATION has provided important lessons for their academic partners and researchers:

- Thinking 3D in manufacturing is hard and the project has only made forays in this promising field of research. The legacy of manufacturing in 2.5D, especially in electronics, has conditioned many generations of designers, process engineers and engineers. Our researchers have had to “de-learn” those techniques used today.
- The Grand Challenge approach to research has enabled a rapid step change in the visibility of a significant group of researchers in institutions as well as providing some influence at the international level.
- It has been hard and long to change the research perspective of some academics who have been used to implement incremental technological research.
- Individual technical problems are easy to solve and it is tempting to gravitate towards them. Gaining vision and pushing forward the big picture is tough yet overwhelmingly inspiring.
- The project has created a pool of researchers unafraid to research disruptive innovation and apply radically new approaches to manufacturing challenges - community-building is almost magical, transcending equipment and physical resources.
- Blue sky research allows the rapid creation of techniques that can find quickly applications to industry. Examples include laser print forming or electroswelling, new technologies created by 3D-MINTEGRATION.
- Large, blue sky thinking, projects are attractive to companies as they allow them to gain market intelligence and a technology brief that can disrupt their business model and permit them to leapfrog their competitors.
- Great collaborations result from inspired individuals, not universities or companies.

Acknowledgements

The considerable work achieved under 3D-MINTEGRATION would not have been possible without the effort and contribution of the academic members of staff, Ph.D. students, MSc. students and postdoctoral students appointed in this research project. In addition, the intellectual and material contributions from our industrial partners were crucial in guaranteeing a successful outcome of this project. We particularly would like to thank Epigem Ltd, BCF Designs Ltd, NPL for their outstanding and mutually beneficial contribution to the project. We hope that the technology brief and market intelligence acquired throughout the project will have benefited our SMEs and large companies alike.

All PIs of the project would also like to thank the EPSRC for having given them the “opportunity to dream” and step away from the incremental technology research that they are too commonly familiar with.

Finally, our most sincere thanks to the Project co-ordinator, Mr. David Topham, for having done a sterling job in not only co-oridnating activities across a wide range of discipline but also bringing his own contagious enthusiasm into blue-sky thinking the impossible.

Appendix

Impact Cases (using the EPSRC success story format)

Greenwich	Development, Integration and Deployment of Simulation Tools
Nottingham	Risk Mitigation Engine
Brunel	Conceptual Design
Greenwich	Development of a Front End Design and Simulation Environment
Cambridge	Laser Print Forming
Heriot-Watt	Electro Hydro Dynamic Instability Patterning
Cranfield	Microinjection Moulding of a Demonstrator Minifluidic Blood Plasma Separation Device
Nottingham	Pneumatic Microfeeder System
Loughborough	Localised Polymer RF Joining
Loughborough	Advances in Interferometry

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EPSRC Success Story Form

Have an example of how EPSRC-funded research has had a positive impact on society or the economy?

Please fill in the following form and return it to rachel.blackford@epsrc.ac.uk

1. University **Greenwich – WP1: Design & Simulation, 1.1, 1.2, 1.5, Development, Integration and Deployment of Simulation Tools**

2. Summary of Case Study/Research Project

Aims

Every new product design to some extent breaks new ground. But typically, even "high technology" products today are based on well-tried building blocks, silicon systems, interconnections to discrete sensors and transducers, and external housings to protect against the environment.

This scheme of doing things has run its course, especially when it comes to gaining the best benefits from microtechnology, which goes beyond electrical systems and promises to integrate smart electronics with mechanics, chemistry, biology, photonics and other disciplines.

Simulation methods are needed that can on the one hand provide designers with real-time guidance to resolve and optimise alternative approaches, not only in product configuration but also in the manufacturing process, coupled with higher fidelity simulation methods that in the longer term can validate products and processes where multiple disciplines have to co-exist and interact predictably.

Achievements

Based on functionality and characteristics, analytical tools were divided into four groups namely high-fidelity analytical tools, i.e. finite element analysis (FEA); fast analytical tools referring to reduced order modelling (ROM); optimal synthesis, including optimisation design and sensitivity analysis; and probability based analytical tools, e.g. reliability and uncertainty. The characteristics of these four groups were researched, including strengths, weaknesses, application areas and development trends. One developing area of analytical tools very relevant to 3D-MINTEGRATION was the supplementation of multiphysics analysis functions and the integration between different software tools.

Future directions

The work continues a progression of developments in this field, but in particular brings a new ability to assess the viability of products and processes for which there is no historical or field experience, by referring directly back to fundamental physical processes.

One avenue for further study is to determine how modellers choose their models from a vast array of possibilities, and how much this is driven by "experience" that might itself be analysed and then synthesised.

Key references

C Bailey, S Stoyanov, Y Tang, X Xue, and T Tilford, Multi-Physics Modelling for the Fabrication, Packaging and Reliability of Micro-Systems Components, 8th World Congress on Computational Mechanics (WCCM8/ ECCOMAS 2008), Venice, Italy, 2008

Stoyanov S, Bailey C, Leach R K, Hughes B, Wilson A, O'Neill W, Dorey R A, Shaw C, Underhill D, Almond H J, Modeling and prototyping the conceptual design of 3D CMM micro-probe, Proc. 2nd ESTC, Greenwich, 2008

X. Xue, M. Patel, M.K. Kerhoas, C. Bailey, M.P.Y. Desmulliez, D. Topham, Effect of Fluid Dynamics and Device Mechanism on Biofluid Behaviour in Microchannel Systems: Modelling Biofluids in a Microchannel Biochip Separator, ICEPT-HDP International Conference, Beijing, China, 2009

3. EPSRC support *(Amount, type(s) of grant or scheme, grant references (if applicable), date)*

Grand Challenge Project 3D-MINTEGRATION EP/C534212/1

4. Other sources of significant sponsorship (if applicable) *(Amount, sponsoring organisation, date)*

-

5. Names of key academics and any collaborators *(Include organisation details)*

Key academics involved at Greenwich: C Bailey, S Stoyanov, Y Tang, X Xue

Collaborating institutions: Brunel, Cambridge, Cranfield, Heriot-Watt, Loughborough, Nottingham

Primary industrial collaborators regarding this topic: Flomerics, NPL

6. Evidence of impact on the economy and/or society

The outputs have wide potential for impact:

- Products and manufacturing processes that are not incremental developments of what has gone before
- Products with tightly-integrated functions, yet highly predictable interactions between those functions
- Products with ever accelerating market introduction, and continually shrinking prices

The application of the work is now a topic for the European Technology Platform EPoSS which recognises that Smart System Integration based upon holistic design will provide competitive advantage for European industry.

7. Benefits to researchers, students, or collaborators

The Simulation developments were themselves exercised to underpin the process development activities of 3D-MINTEGRATION as a whole, providing analysis, simulation and modelling of the processes and the demonstrator products to be developed during the project.

8. Background information and relevant website(s)

http://cnmpa.gre.ac.uk/group_cmrg.html
http://www.3d-mintegration.com

9. Who should we contact for more information? *(Include email and tel. number)*

Professor Chris Bailey C.Bailey@gre.ac.uk 020 8331 8660

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Please fill in the following form and return it to rachel.blackford@epsrc.ac.uk

1. University **Nottingham – WP1: Design & Simulation, 1.3, Risk Mitigation Engine**

2. Summary of Case Study/Research Project

Aims

Ground-breaking new products and the innovative processes needed to produce them bring risks in terms of, reliability, yield and performance failures, and cost and time over-runs. Mitigating these risks rests with the identification of the key characteristics (KCs) that need to be controlled in products and processes that make them, with feedback to gain a good picture of what is known and unknown, and building upon this feedback to aid designers and management to pinpoint potential pitfalls and to assess and reduce the probability of failure.

Achievements

Several references indicated the importance of using the KCs method to provide a focus for different engineering activities, but not many resources have handled the KCs identification process in detail; that is, apart from some related MIT research work and some industrial applications motivated by the necessity to manage complex products and systems, and in both of them mostly the KCs application was related to variation reduction activities.

As a result of the work, innovative methodologies were developed to (i) assess numerically the risk of introducing new process technologies and (ii) predict to capabilities of entirely new processes by examining their similarity to aspects of known techniques.

Future directions

Although spurred by the abrupt technology impacts of 3D-MINTEGRATION, the work is applicable to any manufacturing domain where technological progress is a major factor in business risk. Future research should examine scenarios in further industrial contexts.

Key references

Sailesh Narania, Tarek Eshahawii, Nabil Gindy, Ying Kit Tang, Stoyan Stoyanov, Stephen Ridout, Chris Bailey, Risk mitigation framework for a robust design process, Proc. of the 2nd ESTC conference, Greenwich, 2008

Clifford R Fowkes, Yunfei Sun, Nabil Gindy, A Novel methodology for analyzing variation risk introduced by the manufacturing process in Microsystems, EMPC Rimini, Italy, 2009

3. EPSRC support *(Amount, type(s) of grant or scheme, grant references (if applicable), date)*

Grand Challenge Project 3D-MINTEGRATION EP/C534212/1

4. Other sources of significant sponsorship (if applicable) *(Amount, sponsoring organisation, date)*

-

5. Names of key academics and any collaborators *(Include organisation details)*

Key academics involved at Nottingham: N Gindy, S Narania, T Eshahawii, Y Sun

Collaborating institutions: Brunel, Cambridge, Cranfield, Greenwich, Heriot-Watt, Loughborough

6. Evidence of impact on the economy and/or society

Demonstrated a world first in the definition of "Manufacturing Readiness Levels" to ascertain the risk of introducing new manufacturing technologies, akin to NASA's "Technology Readiness Levels" which have become currency world-wide.

7. Benefits to researchers, students, or collaborators The activity progressed to investigate process capabilities, notably of the micro-injection moulding, Focused Ion Beam (FIB), Laser Machining and Electro Hydro Dynamic Instability Patterning (EHDIP) processes being investigated at Cranfield, Cambridge and Heriot-Watt.
8. Background information and relevant website(s) http://www.nottingham.ac.uk/nimrc/index.aspx http://www.3d-mintegration.com
9. Who should we contact for more information? *(Include email and tel. number)* Professor Nabil Gindy nabil.gindy@nottingham.ac.uk 0115 951 4069

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1. University **Brunel – WP1: Design & Simulation, 1.4, Conceptual Design**
2. Summary of Case Study/Research Project **Aims** Integrating micro-capabilities directly into macro products means leaving behind the comfort of component-level hierarchical design and manufacture, and adopting a holistic approach to both. In particular, designers need to transform physical principles, typically understood in planar diagrams, into more effective 3D structures. **Achievements** A unique transformation routine was developed for the generation of 3D topologies from 2D examples, which was tested through the design of a minifluidic demonstrator in the form of a blood plasma separation device to be integrated into point-of-care medical equipment.. **Future directions** (i) The minifluidic device is progressing towards commercialisation. (ii) The application of the transformation process to further implementations is foreseen. **Key references** D. Topham, D. Harrison, The conceptual design of products benefiting from integrated micro-features, Electronics System-Integration Conference 2008. ESTC 2008, DOI:10.1109/ESTC.2008.4684544, 2008 D. Topham, D. Harrison, The Design of smart systems with embedded micro features, Smart Systems Integration. ISBN 978-3-8007-32008-1, 2010
3. EPSRC support *(Amount, type(s) of grant or scheme, grant references (if applicable), date)* Grand Challenge Project 3D-MINTEGRATION EP/C534212/1
4. Other sources of significant sponsorship (if applicable) *(Amount, sponsoring organisation, date)* -
5. Names of key academics and any collaborators *(Include organisation details)* Key academics involved at Brunel: D Harrison, D Topham Collaborating institutions: Cambridge, Cranfield, Greenwich, Heriot-Watt, Loughborough, Nottingham Industrial collaborator: The Medical Device Company
6. Evidence of impact on the economy and/or society Non Disclosure Agreement has been signed with The Medical Device Company Ltd to pursue the commercialisation of the blood plasma separation device conceived during the work. The successful deployment of the device would enable low-cost highly effective diagnosis of disease and its treatment, away from supporting infrastructure.
7. Benefits to researchers, students, or collaborators The work demonstrated and explored problems of how to share and debate concepts remote from everyday experience between design/manufacturing teams throughout the 3D-MINTEGRATION project.

8. Background information and relevant website(s) http://www.brunel.ac.uk/about/acad/sed/sedres/dm http://www.3d-mintegration.com
9. Who should we contact for more information? *(Include email and tel. number)* Professor David Harrison David.Harrison@brunel.ac.uk 01895 266321

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Please fill in the following form and return it to rachel.blackford@epsrc.ac.uk

1. University **Greenwich – WP1: Design & Simulation, 1.6, Development of a Front End Design and Simulation Environment**
2. Summary of Case Study/Research Project **Aims** The 3D-MINTEGRATION project revealed interdependences requiring that all aspects of design and embodiment should be linked more closely than in typical commercial CAD packages. **Achievements** A draft "design front end" for advanced manufacturing – "3D-MINTEVISION" - pulled together, for the first time, all the elements of design, from conception through modelling, risk mitigation and process selection and embodiment. **Future directions** The draft framework has potential for in-depth development as a substantial research project. **Key references** Ying Kit Tang, 3D Mintevision – bringing it all together, Presentation at 3D Mintegration Annual Conference and Exhibition, September 2008 S. Stoyanov, X. Xue, M. Patel, Y. K. Tang, P. Rajaguru, C. Bailey, 3DM design methodologies and 3D-Mintevision, Presentation at 3D-Mintegration Annual Conference and Exhibition, September 2009
3. EPSRC support *(Amount, type(s) of grant or scheme, grant references (if applicable), date)* Grand Challenge Project 3D-MINTEGRATION EP/C534212/1
4. Other sources of significant sponsorship (if applicable) *(Amount, sponsoring organisation, date)* -
5. Names of key academics and any collaborators *(Include organisation details)* Key academics involved at Greenwich: C Bailey, S Stoyanov, Y Tang, X Xue Collaborating institutions: Brunel, Cambridge, Cranfield, Heriot-Watt, Loughborough, Nottingham Primary industrial collaborators regarding this topic: Flomerics, NPL
6. Evidence of impact on the economy and/or society The scheme adopted allows for real-life design iterations and will form a comprehensive reference for designers embarking upon the creation of new products using innovative manufacturing processes.
7. Benefits to researchers, students, or collaborators As a result of 3D-MINTEVISION, the Design & Simulation work package transformed from its original role as an underpinning activity, to become a primary driver for the project as a whole, intimately connected with every element. The comprehensive drawing together of Design & Simulation topics through 3D-MINTEVISION will form an effective aid for students and researchers in engineering design.

8. Background information and relevant website(s) http://cnmpa.gre.ac.uk/group_cmrg.html http://www.3d-mintegration.com
9. Who should we contact for more information? *(Include email and tel. number)* Professor Chris Bailey C.Bailey@gre.ac.uk 020 8331 8660

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Please fill in the following form and return it to rachel.blackford@epsrc.ac.uk

1. University **Cambridge – WP2: 3D Processing, 2.4, Laser Print Forming**
2. Summary of Case Study/Research Project **Aims** The high cost of silicon fabrication plants offers a considerable barrier for competing manufacturers wishing to enter the market. This can lead to reduced innovation rates and limited growth. This work set out to create a paradigm shift in manufacturing by developing the technologies and strategic approaches required for the production of highly-integrated, cost-effective and reliable multi-functional 3D miniaturised/integrated devices. **Achievements** The Cambridge team has developed a novel fabrication process for the production of 3D micro parts using the physical characteristics of nano particles, i.e. low melting and sintering temperatures. The Laser Print Forming technique allows for the creation of micro or nano components through the deposition of nano inks using high resolution stamps created by Focused Ion Beam and ultrafast laser machining. This technology opens up the possibility of providing low cost manufacturing solutions for traditional micro systems and early stage developments in nano fabrication processes. More specific outputs include: • A high resolution nano and micro toolset fabrication lab • A variety of nano-ink formulations for fabrication routes using metals and semiconductors • Production routes for additive micro fabrication using multi material systems • Production routes for the direct printing of light emitting elements utilising ZnO electro luminescence operating at low voltages • Establishment of a high precision machining processes for glassy carbon, diamond, sapphire, non-ferrous metals, and polymers. These materials have wide ranging application potential in medical devices, microsystems, micro-elecrronics, semiconductors, bio-sensors, and wear resistant and corrosion resistant interfaces. **Future directions** The new production techniques have generated interest in the precision surface community. As a result of this the Cambridge team are now part of the EPSRC IKC in precision structures in conjunction with Cranfield, UCL and a host of collaborating companies. **Key references** Q. Hu, P. Hu, W. O'Neill, Laser-assisted micro structure fabrication using nano-particles, The Laser User, 2008 Q. Hu, W. O'Neill, Laser assisted micro and nano replications, 3rd Pacific International conference on applications of lasers and optics (PICALO), Beijing 2008 P Hu, K Li, W O'Neill, W Chen, P Lib, D Chu, Fabrication of Organic Field Effect Transistor Using Nano Imprinting of Ag Inks and semiconducting Polymers, Journal of Micromechanical Microengineering, 2010
3. EPSRC support *(Amount, type(s) of grant or scheme, grant references (if applicable), date)* Grand Challenge Project 3D-MINTEGRATION EP/C534212/1
4. Other sources of significant sponsorship (if applicable) *(Amount, sponsoring organisation, date)* -
5. Names of key academics and any collaborators *(Include organisation details)*

Key academics involved at Cambridge: Bill O'Neill

Collaborating institutions: Brunel, Cranfield, Greenwich, Heriot-Watt, Loughborough, Nottingham

Primary industrial collaborators regarding this topic: SPI Lasers

6. Evidence of impact on the economy and/or society

The research outcomes have so far been directly applied in the production of a range of demonstrator products that have increased perofmance levels when designed in a 3D context. The demonstaror products include:- a 3D microprobe for a new nano coordinate measuring machine manufactured by Zeiss and designed by the National Physical Laboratory; a microfluidic cell separator for white blood cells- a preliminary stage of a genetic testing kit; and a wiring loom diagnostic system for current carry systems in aircraft. These are challenging products and form the testbed for the integrated production approach developed here.

The direct impact on the economy and society is not yet determined, however, the long term impact is significant as the research outputs will provide radically new production capabilities that will be employed to develop high value products necessary to maintain the competitiveness of the UK economy.

7. Benefits to researchers, students, or collaborators

The research outputs have also created research collaborations and opportunities in the developing field of Synthetic Biology. The IMRC and 3D-MINTEGRATION research infrastructure in nano fabrication have resulted in the creation of pilot research programmes for the development of precision structures for bio-molecular engineering. This work is in collaboration with Dr Paul Barker, a Cambridge bio-chemist and the Dr Raymond Sparrow of the CSIR in South Africa. The IMRC is funding a PhD student in bio-chemistry to help advance our knowledge of interfacial bio science, the first step of creation a synthetic biological system. This new and exciting research field promises much in the way of bio based micro and nano system technology. Initial projects will study nano surface pattering for regulated self assembly of bio cells.

8. Background information and relevant website(s)

3D-MINTEGRATION:
http://www.3d-mintegration.com/
http://newsweaver.co.uk/mntnetwork/e_article001181237.cfm?x=b11,0,w
http://gow.epsrc.ac.uk/ViewGrant.aspx?GrantRef=EP/C534212/1

IKC Grant:
http://gow.epsrc.ac.uk/ViewGrant.aspx?GrantRef=EP/E023711/1
http://www.phoebusassociates.co.uk/assets/546/ikc_win.pdf
http://new.wales.gov.uk/news/archivepress/enterprisepress/einpress2006/1090740/?lang=en

9. Who should we contact for more information? *(Include email and tel. number)*

Dr Bill O'Neill, wo207@eng.cam.ac.uk. 07525 826223

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1. University **Heriot-Watt – WP2: 3D Processing, 2.5, Electro Hydro Dynamic Instability Patterning (EHDIP)**
2. Summary of Case Study/Research Project **Aims** Low cost processes for the manufacture of macro- scale products with micro- scale features need to be developed to break free from the standard practice of engineering high-tech microcomponents in high cost fabrication facilities then trying to integrate these components into macro- scale products which are typically made using very different techniques, hence introducing detrimental compromises in both cost and performance. This work sought to directly pattern contoured surfaces with micro- scale features over essentially unlimited areas and unlimited orientations in a normal atmospheric environment. **Achievements** A novel process, EHDIP, was developed, which uses electrostatic pressure to free-form polymer material in 3D. The process proved capable of fabricating high aspect-ratio 3D patterns including also microlenses. An unexpected development of the process provided the ability to fabricate hollow-section patterns in the form of tubes and capsules. **Future directions** The non-contact tooling – essentially a source of formed electrostatic fields – lends itself to further development in the form of a programmable stylus or set of probes, allowing "batch of one" production. This, and the combination of the process with other techniques viable in standard atmosphere shows promise to build into a complete suite of processes, desk-top factory production line. **Key references** W.Yu, S. Cargill, M. Leonard, M.P.Y. Desmulliez, Micro-fabrication on 3D-surface by electrostatic induced lithography, IEEE/CPMT 2nd International Conference on Electronic Systems Technology Integration (ESTC), Greenwich, 2008
3. EPSRC support *(Amount, type(s) of grant or scheme, grant references (if applicable), date)* Grand Challenge Project 3D-MINTEGRATION EP/C534212/1
4. Other sources of significant sponsorship (if applicable) *(Amount, sponsoring organisation, date)* -
5. Names of key academics and any collaborators *(Include organisation details)* Key academics involved at Heriot-Watt: Marc Desmulliez, W Yu Collaborating institutions: Brunel, Cambridge, Cranfield, Greenwich, Loughborough, Nottingham
6. Evidence of impact on the economy and/or society Patent GB0823090.6, 2008
7. Benefits to researchers, students, or collaborators The activity encouraged the 3D-MINTEGRATION research community to consider a breadth of blue-sky products which have captured the imagination of industrial collaborators.

8. Background information and relevant website(s) http://www.3d-mintegration.com http://misec.eps.hw.ac.uk/welcome.htm
9. Who should we contact for more information? *(Include email and tel. number)* Professor Marc Desmulliez, m.desmulliez@hw.ac.uk, 131 451 3340

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Please fill in the following form and return it to rachel.blackford@epsrc.ac.uk

1. University **Cranfield – WP2: 3D Processing, 2.6, Microinjection Moulding of a Demonstrator Minifluidic Blood Plasma Separation Device**

2. Summary of Case Study/Research Project

Aims

Injection Moulding is an established technology for the production of macroscopic components from thermoplastic material. In practice, the thermoplastic is fed in the form of granulates into the plasticating unit and then injected at high pressure into a mould, which is the inverse of the desired shape.

In microinjection moulding, the mould cavities contain features in the micrometre range which need to be completely filled by the polymer melt. In many cases this requires the process to be adapted to take into account the air entrapped in the small features and for the very fast cooling of the injected melt into small, cold mould features. The fast cooling of the polymer melt in the mould causes the polymer to freeze within the very small cavities which typically results in the cavity being only partially filled.

The work of 2.6 addressed these challenges by (i) the fabrication of master moulds with very well defined features, (ii) a study of fluid flow during the moulding process, supported by modelling and the subsequent optimisation of parameters, and (iii) The measurement and characterisation of microinjection moulded test pieces and demonstrator parts.

Achievements

Validation of the work concentrated upon the fabrication of a prototype blood plasma separator with demanding dimensional constraints.

Future directions

The demonstrator indicated ways forward for the practical implementation of the separator, including pitfalls regarding the sealing of a multi-part construction, requiring integrity whilst maintaining precise dimensions at the micro- scale. Micro-scale bonding of such structures is an opportunity for further work of significant industrial relevance.

Key references

S. Marson, U.M. Attia, J.R. Alcock, D.M. Allen and A. Wilson, Flatness measurement of micro-injection moulded discs for the manufacture of a 3D microfluidic device, Commercial Micro Manufacturing, 2009

S. Marson, U. Attia, D.M. Allen, P. Tipler, T. Jin, J. Hedge and J.R. Alcock, Reconfigurable micro-mould for the manufacture of truly 3D polymer microfluidic devices, Proceedings of the 19th CIRP Design Conference 2009

3. EPSRC support *(Amount, type(s) of grant or scheme, grant references (if applicable), date)*

Grand Challenge Project 3D-MINTEGRATION EP/C534212/1

4. Other sources of significant sponsorship (if applicable) *(Amount, sponsoring organisation, date)*

-

5. Names of key academics and any collaborators *(Include organisation details)*

Key academics involved at Cranfield: D M Allen, S Marson, U M Attia, J R Alcock

Collaborating institutions: Brunel, Cambridge, Greenwich, Heriot-Watt, Loughborough, Nottingham

Industrial collaborator: Battenfeld

6. Evidence of impact on the economy and/or society

In order to avoid invasive techniques of extracting cells from pregnant women to detect genetic abnormalities such as Down's Syndrome, an attempt is being made to detect an abnormality by analysis of foetal cells contained within maternal blood. The small number of foetal cells requires concentration of the mixed maternal/foetal red blood cells prior to analysis.
The demonstrator indicated ways forward for the practical implementation of such a separator.

7. Benefits to researchers, students, or collaborators

In addition to the primary work, real-life data were provided in terms of product and process characteristics of immense value to research partners working upon Design & Simulation.

8. Background information and relevant website(s)

http://www.3d-mintegration.com

9. Who should we contact for more information? *(Include email and tel. number)*

Professor David Allen, d.allen@cranfield.ac.uk, . 01234 754058
Dr Jeff Alcock, j.r.alcock@cranfield.ac.uk, 01234 754185

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1. University **Nottingham – WP3: Microassembly, 3.3, Pneumatic Microfeeder System**

2. Summary of Case Study/Research Project

Aims

Microassembly techniques are constrained by interactions between the handling device/tool and the small scale parts that they manipulate. For instance, adhesive forces can become more dominant than gravitational forces, causing failure of the process.

One of the key topics of the Microassembly work package was the developing of new solutions for the automatic handling of large volumes of very small parts.

Particular emphasis was placed upon the development of new ultra-precision techniques for micro-manipulation.

Achievements

The microfeeder as developed consists of an array of micronozzles. Air is used for keeping the parts suspended and moving them through the control of the micronozzles. A single microactuator "pixel" is made up of four nozzles formed by a central electrode and four walls around it. Airflows can be arranged in such a way that microparts can be moved to any specific position. It is also possible to maintain the position and just change the orientation.

Future directions

The demonstrator was fabricated using Rapid Prototyping techniques. The next stage will see the productionising of the manufacturing technique..

Key references

M. Turitto, S. Ratchev, Xiangdong Xue, M. Hughes, C. Bailey, Pneumatic contactless microfeeder design refinement through CFD simulation, 4M2007 Conference on Multi-Material Micro Manufacture, Borovets, Bulgaria, 2007

X. Xue, C. Bailey, M. Turitto and S. Ratchev, Modelling and optimization of a pneumatic microfeeder system, International Journal of Simulation and. Multidisciplinary Design Optimisation, 2009

3. EPSRC support *(Amount, type(s) of grant or scheme, grant references (if applicable), date)*

Grand Challenge Project 3D-MINTEGRATION EP/C534212/1

4. Other sources of significant sponsorship (if applicable) *(Amount, sponsoring organisation, date)*

-

5. Names of key academics and any collaborators *(Include organisation details)*

Key academics involved at Nottingham: S Ratchev, M Turrito, C Tietje

Collaborating institutions: Brunel, Cambridge Cranfield, Greenwich, Heriot-Watt, Loughborough

6. Evidence of impact on the economy and/or society

The needs of Microassembly cannot be fulfilled by simply transferring know-how from the macro-domain. A scaling down approach would present a number of flaws as it does not take into account the specific physical phenomena that emerge with the interaction between the microparts. In fact, in the micro- domain, mass-related forces such as gravity and inertia are often less relevant than surface related forces such as surface tension, electrostatic or Van Der Waal's forces. Moreover, constraints like the fragility and the contamination of the microcomponents have a bigger relevance than in macroassembly. Furthermore, disturbing influences, generally negligible at macroscale such

as fabrication defects, wear and environmental conditions become significant. The direct impact of microfeeding on the economy and society is not yet determined, however, the long term impact is significant as the research output will provide radically new production capabilities that will be employed to develop high value products necessary to maintain the competitiveness of the UK economy.
7. Benefits to researchers, students, or collaborators The microfeeder also provided an exercise in 3D-MINTEGRATION design and manufacture, and benefitted from the modelling resource in the Design & Simulation work package.
8. Background information and relevant website(s) http://www.precisionmanufacturing.co.uk/ http://www.3d-mintegration.com
9. Who should we contact for more information? *(Include email and tel. number)* Professor Svetan Ratchev, Svetan.Ratchev@nottingham.ac.uk, 0115 9514018

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Please fill in the following form and return it to rachel.blackford@epsrc.ac.uk

1. University **Loughborough – WP4: Packaging & Integration, 4.3, Localised Polymer RF Joining**

2. Summary of Case Study/Research Project

Aims

The Packaging & Integration work package developed a broad suite of processes categorised as (i) Polymer Integration, embedding and surface engineering, addressing materials interaction and surface engineering issues to create multi-functional integrated systems, (ii) 3D multifunctional interconnection, concerned with interconnecting multifunctional devices within systems, and (iii) selective polymer microwave and RF processing to create new bonding or sealing technologies that are localized, material selective and therefore not detrimental to the operating lifetime of the whole 3D system.

Much of this work was concerned with overmoulding and adhesion. Although these matters are widely practised in industry, the underlying mechanisms were found to be poorly understood, and worthy of study and development, particularly in respect of microfluidic systems.

One key problem concerning microfluidic “lab-on-a-chip” devices is the creation of reliable connections between the device and any tubing conveying fluids to and from the device.

Achievements

One particular innovation entailed sandwiching an electrically conducting layer, in the form of a closed circuit loop, between two polymer parts to be joined. Inserting the whole assembly within a radio frequency field induces a current in the loop, which then heats by resistive and eddy current effects. The energy so focused heats the adjoining polymers which then fuse together.

Future directions

The technique has promise not only in fluid interconnects, but also in the sealing of closed packages.

Key references

Knauf, Benedikt J.; Webb, D. Patrick; Changqing Liu,; Conway, Paul P., Packaging of polymer based microfluidic systems using low frequency induction heating (LFIH), International Conference on Electronic Packaging Technology & High Density Packaging (ICEPT-HDP 2008)

3. EPSRC support *(Amount, type(s) of grant or scheme, grant references (if applicable), date)*

Grand Challenge Project 3D-MINTEGRATION EP/C534212/1

4. Other sources of significant sponsorship (if applicable) *(Amount, sponsoring organisation, date)*

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5. Names of key academics and any collaborators *(Include organisation details)*

Key academics involved at Loughborough: P Conway, D P Webb, C Liu, B Knauf

Collaborating institutions: Brunel, Cambridge Cranfield, Greenwich, Heriot-Watt, Nottingham

6. Evidence of impact on the economy and/or society

Making reliable contamination-free seals in fluid interconnects and hermetic device packaging, at low cost, is an essential enabler for the adoption of advanced Microsystems.

7. Benefits to researchers, students, or collaborators The development provided a real-life exercise in modelling and simulation for the Design & Simulation work package.
8. Background information and relevant website(s) http://www.lboro.ac.uk/eng/research/mam/Man.html http://www.3d-mintegration.com
9. Who should we contact for more information? *(Include email and tel. number)* Professor Paul Conway, p.p.conway@lboro.ac.uk, 01509 227670

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EPSRC Success Story Form

Have an example of how EPSRC-funded research has had a positive impact on society or the economy?

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1. University **Loughborough – WP5: Test & Measurement, 5.2, Advances in Interferometry**
2. Summary of Case Study/Research Project **Aims** Scanning white light interferometry (SWLI) is an increasingly popular method to measure the surface profile of miniature components. Although it is tolerant to step changes in profile, its capability to measure the large surface gradients that are characteristic of high-aspect-ratio surfaces is limited. **Achievements** Work in the Test & Measurement work package presented a 3D theory of SWLI: Using finite element methods (FEM), SWLI interferograms were demonstrated for the cases of 2D Silicon V-grooves and step artefacts, and the effects of multiple scattering were observed. Methods to improve the capability of SWLI to measure large surface gradients, first by tilting the sample and subsequently by using an iterative FEM model to provide improved estimates of the illuminating conditions were introduced. Allied interferometric work showed that it is possible to extract information about undercuts and steep structures. **Future directions** The work, undertaken in close collaboration with NPL is part of an ongoing refinement in metrology of national importance.. **Key references** J. M. Coupland, J. Lobera, Measurement of Steep Surfaces Using White Light Interferometry, STRAIN, 2009 F. Gao, J.M. Coupland and J. Petzig, V-groove measurement with a white light interferometer, Photon06 Manchester, 2006 J. Lobera and J. M. Coupland, On The Measurement of High Aspect Ratio Surfaces using White Light Interferometry, Photomechanics 08 Loughborough, 2008
3. EPSRC support *(Amount, type(s) of grant or scheme, grant references (if applicable), date)* Grand Challenge Project 3D-MINTEGRATION EP/C534212/1
4. Other sources of significant sponsorship (if applicable) *(Amount, sponsoring organisation, date)* -
5. Names of key academics and any collaborators *(Include organisation details)* Key academics involved at Loughborough: J M Coupland, J Petzig, J Lobera, F Gao Collaborating institutions: Brunel, Cambridge Cranfield, Greenwich, Heriot-Watt, Nottingham Industry collaborator: NPL
6. Evidence of impact on the economy and/or society Industry will immediately benefit from the publication "Guide for the Measurement of Rough Surface Topography using Coherence Scanning Interferometry, National Measurement Good Practice Guide" (Crown copyright 2010)

7. Benefits to researchers, students, or collaborators Scanning white light interferometry (SWLI), can be considered to be a tomographic process. Although some caution should be exercised (for example, it is not usually possible to decide whether a given solution is unique), it is interesting to note that despite the disparity in resolution, digital holography and computer technology might yet create 3D images of greater clarity than the best optical holograms.
8. Background information and relevant website(s) http://www.lboro.ac.uk/eng/research/mam/Optical.html http://www.3d-mintegration.com
9. Who should we contact for more information? *(Include email and tel. number)* Professor Jeremy Coupland, j.m.coupland@lboro.ac.uk, 01509 227506