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The EPSRC Centre for Innovative Manufacturing in Intelligent Automation is now well established as a national hub for intelligent automation in the UK. Since our last report we’ve seen projects reach maturity with results being transferred for further development and exploitation.

As one of UK’s leading research and education groups we are cited frequently as an international role model for how academia and industry can work together successfully. Close collaboration between Loughborough University and Cranfield University with industrial partners, including Rolls-Royce, Airbus, Controls and Data Services and the HVM Catapult via the MTC, ensures that research is industry focused with clearly defined future applications. Strong links have also been forged with key institutions across the UK, through collaborative bids, joint projects and outreach funded feasibility studies. This growing network will be a driving force for robotics and autonomous systems within manufacturing.

In the summer of 2014 we completed our Mid Term Review. This reinforced the importance of the EPSRC Centre, its unique pipeline to industrial reality and the great potential for the future of this model. There was significant focus on sustainability, and the need to build strong foundations for long term continuation of Centre research.

To date the EPSRC Centre has attracted over £14.5M in funding including over £2M of European projects.

We feel passionately that UK organisations should exploit exciting new technologies and produce high-quality innovative products and processes in order to succeed on a global stage. There is a clear role for universities in applying their knowledge and skills to business and technology. Building relationships across Europe is key to developing wider impact and the EPSRC Centre, in collaboration with the MTC and The University of Birmingham, has also been competing successfully in the FP7 European Robotics Challenges (EuRoC).

Collaborations are also being built within the UK. The EPSRC Centre has funded four feasibility studies at other universities and is now working with these research groups to look at collaborative bidding opportunities. Joint funding bids and research projects are also underway with groups from academia and industry, not involved in the Feasibility Study Programme. These range from large scale research council bids to support core fundamental research, through to small targeted projects to enable SME development. A further Feasibility Study Call was launched in June 2015 to fund another three projects.

Outreach has also focused on encouraging young people into STEM, with a particular focus on automation. The EPSRC Centre has provided substantial support through the FIRST LEGO League (FLL) programme, hosting local and national events, mentoring schools, providing equipment and demonstrating links between the automation challenges and real world manufacturing applications. With a skills shortage in intelligent automation, this national work is vital to encouraging potential future engineers. Through this work the EPSRC Centre has engaged strongly with the Rt Hon Nicky Morgan MP, Secretary of State for Education, who presented her own award at the FLL National Final.
Visitors are regularly hosted (>100 external visits to date) with an established programme of technical demonstrations and presentations to promote intelligent automation and to highlight key research streams to varied audiences from industry, academia and public office. Political engagement and strategy setting are vital aspects of the EPSRC Centre role. Of particular note, the EPSRC Centre senior management team have been active in the Robotics and Autonomous Systems (RAS) roadmapping; the Director and Deputy Director have contributed in person to the Go-Science RAS strategy workshops with Sir Mark Walport and the Director to the Dowling Review to highlight the benefits and challenges of working with the Catapult network.

From a portfolio of over 45 research projects some of our greatest achievements so far include:

- Demonstration of 3D vision guided assembly of mechanical components
- Creation of an active 3D vision system for automated measurement of surface defects
- Development of a new human skill capture methodology for automation design
- Implementation of a ubiquitous safety environment for collaborative working
- Gesture and hand following implemented on a Universal Robot arm and a 45Kg capacity industrial robot
- Development of a psychometric scale for measuring human trust in industrial robots for collaborative working

With growth and a view to long term sustainability and succession planning, we have recently appointed 3 Associate Directors:

- Niels Lohse – leading research on Manufacturing Informatics and European Projects within the EPSRC Centre
- Peter Kinnell – EPSRC Fellow, leading research on Robust Intelligent Metrology
- Sarah Fletcher – EPSRC HVM Catapult Fellow, leading research on Human Factors for Intelligent Automation

They will help us to meet the challenges ahead, building a future for UK intelligent automation research. We would like to thank them and all staff and students who have made this EPSRC Centre a success. We are proud to be highly regarded for excellence, responsiveness, adaptability and industry focus. We produce academic research that will make a positive difference to the UK economy and we will do all that we can to ensure this vital work continues beyond 2016.
VISION STATEMENT

To be the UK hub for intelligent automation that brings people and technology together to research, develop and implement advanced industrial manufacturing solutions.

The EPSRC Centre aims to undertake research at TRL 1-3 to create powerful generic technologies for application on difficult to automate manufacturing tasks and processes.

- It is a fundamental role of the EPSRC Centre to ensure that intelligent automation research conducted by partner universities makes it through to industrial deployment, via the Catapult network or other established routes
- The impact of this EPSRC Centre is expected to be core to the UK, re-establishing manufacturing on-shore and creating high skill jobs that have a strong technology content (e.g. systems integration), making companies more competitive and more able to export and grow, becoming stronger and more stable than the current industrial landscape allows
- The technologies developed will enhance and maximise the use of the existing skill sets within the workforce rather than replacing them, thereby significantly increasing their cost effectiveness and competitiveness
Figure 1
An industrial collaborative robot system which consists of an intelligent gripper, a vision system and a safety laser scanner.
The purpose of incorporating automation into an environment is to deliver efficiencies—whether related to people, workload, time, consistency or output. Before commencing with a new implementation, organisations must understand the benefits that they can expect, not only to accurately assess potential ROI, but also to set an expectation against which they can later measure the benefits realised.

For simpler automations, benefits typically come in the form of time and cost savings as well as more consistent outputs. However, it is equally important to evaluate processes that consume a great deal of time, even if they are more complex, multi-step activities.

The most effective approach is to evaluate, as far as possible, the time taken by manual activities and the frequency with which those activities are undertaken. This will allow companies to estimate the potential benefit of automation and measure its realisation post-implementation. In addition to effort reduction, it’s also vital to measure and evaluate a number of other factors that can be improved with automation such as human error rate, process compliance and system or service uptime.

The EPSRC Centre has worked with a few local companies including Percussion Plus and Quality Furniture Company (QFC) to understand the need and potential for automation. The EPSRC Centre’s research projects have focused on observing people at work in a manufacturing environment to understand whether their tasks can be enhanced by automation solutions to improve both operator well-being as well as production performance. This section highlights a set of individual studies that demonstrate the EPSRC Centre’s objective of capturing and transferring key human activity data and adapting it to intelligent automation design.
“The Centre is a great example of how academia and the MTC combine their knowledge and expertise to put together a project that would be a real game changer for us and one that we could never have begun to contemplate on our own. We very much look forward to working together in the future. I remain a firm believer that universities and businesses can work together to the mutual benefit of both parties.”

David Bramwell – Managing Director
Human Skill Capture for Automation Feasibility

Jamie Evertt, Sarah Fletcher

Although advances in technology mean it is getting increasingly likely that we can improve manufacturing efficiency by replacing or augmenting human work with automated solutions, most manufacturing systems still rely heavily on human skill for the completion of production tasks. This is because we still lack the capability for identifying what human skills and activities the automation needs to replace or augment, and those which cannot or should not be transferred.

In particular, whilst we can quite easily observe overt physical actions we do not yet have an adequate way of examining the unobservable and hidden intelligence that is applied in the performance of production tasks. Thus, there is a growing requirement within the field of intelligent automation for a formal methodology to capture both the explicit and ‘tacit’ skills deployed by operators, particularly during complex task performance, and to classify these skills for automation design.

This PhD project has developed a reliable, accurate methodology for capturing physical, perceptual, and cognitive skills so that automation designers can classify human operators’ actions and decisions to evaluate the capabilities required for any new automated system.

Although an extension of traditional task analysis (TA) methods this is a novel new dual methodology approach because it surpasses TA limitations to analyse both discrete tasks (tasks with a finite and systematic order of steps) and continuous tasks (tasks which are more reactionary in response to incoming stimuli and have less / no systematic order of steps).

Industrial case studies employing combined ethnographic observation and talk-through methods were conducted to explore operators’ demonstrations and descriptions of their task activities. A study of aircraft flap installation fitting first enabled the development of a system for discrete task analysis (DTA).

A following study of TIG welders then led to the continuous task analysis method (ConTA) which incorporates novel capture of the information flow between environment and operator based on four key categories: the physical Parameter being monitored, the operator’s Perception of the parameter, the Decisions made about the state of the parameter, and the Action taken in response, which subsequently loops back to influence the Parameter. A third study of manual metal polishing enabled the dual methodology approach to be refined.

The methodology is now being validated and linked to automation requirements in a final industrial case study, and in consultations with automation experts, before the PhD is completed in October 2015.
Yuchen Zhao, Yee Mey Goh, Laura Justham, Niels Lohse

As industrial robots are being required to handle more complex tasks than ever before, robots increasingly need to be more adaptable to variability to make real time decisions in complex environments. Conventional programming takes too long to adjust to new contexts to meet the increasing needs for reusable or easy to generate codes. The aim of this work is to use a combination of human-centered measurements and machine learning strategies to deal with uncertainties when automating a manual manufacturing process.

A human demonstrator will be the main resource of learning for the robot to gather two main types of information: first, a contact state which can separate a task into sub-tasks so that the robot can recognise the current sub-task and recall corresponding executable control strategies and, second, a model generalising human-like actions for the robot to apply directly.

A peg-in-hole assembly task is currently under investigation. The human operator is equipped with an electromyography (EMG) sensor for direct measurement of muscular activity with minimal interference to the operators. A statically installed force and torque (FT) sensor is used to capture the reaction force generated and mappings from EMG to FT signal and task related trajectories will be modelled for robot training.
Integration and Validation of Motion Capture and Computer Aided Design Technologies

Teegan Johnson, Sarah Fletcher

In manufacturing work environments, musculoskeletal injuries caused by poor working postures remain a common source of injuries and absenteeism. This is often a direct consequence of inadequate predictions made at the design or redesign stage. Manufacturing engineers are increasingly reliant on software programmes like computer aided design (CAD) to design rigs. However, these programmes are dependent on input data accuracy. As a result, human modelling is currently limited by the partial analysis offered by in-built assessment tools. Human data is difficult to obtain because pre-operational systems provide very little opportunity to trial a design with human participants and in operational systems data collection is hampered by unavoidable obstructions in dynamic operational shop floor environments.

As we develop new intelligent systems in human working environments, it is vital that we optimise designs to enhance efficiency and reduce musculoskeletal risk.

In this project, researchers are developing a reliable method of gaining accurate human activity data for CAD modelling predictions by exploiting the integration of motion capture data. Non-optical motion capture will be particularly advantageous for capturing real human activity data from occluded situations in manufacturing environments because it uses inertial measurement units (incorporating gyros, accelerometers and compasses) to provide instantaneous data and does not require direct visibility. We have started this project with an in-depth assessment of the accuracy and validity of human data captured by an exemplar inertial motion capture suit. Future work will involve laboratory and industrial case studies to further explore how this sort of data can be gathered and processed within CAD programmes to optimise predictive human modelling and system design.
A Framework to Support Automation through Understanding Process Variability

Angel Sanchez, Yee Mey Goh, Keith Case

The inherent variability of parts and processes in many manufacturing operations make it extremely challenging to achieve cost effective automation. As a result, highly-skilled and certified human operators are employed for certain tasks, e.g. hand finishing and visual inspection, assembly of high value and/or delicate components, loading and unloading of complex shapes to jigs and fixtures. One of the key reasons is due to the fact that humans have proven capability to adapt and accommodate to this variability in an interactive and dynamic manner. An example is their ability to overcome the differences in the parts and tools to achieve the specified outcomes.

Where human beings perform processes in order to transform inputs to outputs, it is often supposed that advantages can be gained by the introduction of an automated solution that replaces the operator. Such introductions are often sub-optimal, as the tacit knowledge the human has to compensate for the process variability is not clearly understood when the automation solution is specified. This research aims at developing a framework to support automation through understanding the process variability that is critical in manual manufacturing processes.

Two industry processes have been studied in this research: (i) grinding-polishing and (ii) deburring of geometrically complex components. The research methods include analysis of documentation, observation and interviews. The Key Characteristics (KCs) methodology has been used to identify critical process parameters in these manual processes (Figure 8). Examples of the identified KCs in the grinding/polishing process are time of grinding/polishing, pressure applied and tool condition. In both cases studied, the operators are dealing with different sources of variability which are interdependent and the relationships between them change over time.

A framework to categorise the variability present in the process to better fulfil the requirements of automation solutions is currently under development. Through further experimentation in the laboratory, technical measurements are being collected in order to characterise the process variability quantitatively. A mapping of automation levels to address the process KCs and their relationships will be developed. This framework will be validated through two further case studies in assembly and welding.

If successful, this research provides a framework and principles towards the philosophy of ‘right-first-time’ for intelligent automation systems.

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Figure 8

[Key characteristic diagram for the grinding process studied]
Often in manufacturing the output from the task is clearly identifiable, and the top level procedural steps may be documented, but the cognitive aspects of the method to achieve that output are left principally within the tacit knowledge of the skilled operator. The Centre is working with Percussion Plus, a business located in the Midlands that specialises in the production of percussion musical instruments. One of their key current manufacturing processes is to produce drum beaters by manually winding yarn around the head of the beater to form an approximately spherical shape; the yarn is then tied and stitched into the head of the beater to secure it. The operator uses various cues including visual and tactile feedback but, critically, the tactile sensing of tension is monitored by the operator via their fingers only. The problem is, task proficiency is limited to one expert in the company for whom it has become almost autonomous due to decades of practice. Therefore, there is a need to analyse the skills involved in this particular manual task and explore the feasibility of developing an automated solution so that the manual procedure can be disseminated to other employees. Percussion Plus has a desire to maintain its manufacturing in the UK as they believe this helps them sell to key markets; they also require an increased output to fulfil projected future orders. In order to achieve these goals, the Centre has worked to assist Percussion Plus to develop a human factors driven mechatronic solution for the described drum beater production problem.

A human factors investigation and task analysis was first carried out to capture the manual and cognitive aspects of the task and generate a detailed understanding of the manual process. This involved a multi-stage interview and novice training observation process which was video recorded.

This information has been a key input into the mechatronic design of an automated winding machine. The machine aims to deliver the same critical shape and durability of the beater, which is the unique IP for Percussion Plus, potentially with a higher production output rate. A prototype is currently being produced and the human factors work has provided a comprehensive breakdown of the task’s work content which was previously not available and Percussion Plus can now use this to train other operators.

Percussion Plus Students’ Engagement

Through the Centre’s engagement with Percussion Plus, Loughborough University’s Mechanical and Manufacturing undergraduate students have been working on industry-based projects. Edd Macey, who was on a 10 week summer placement in 2014 worked on this project with researchers in Holywell lab. The placement was funded through the ENSURE programme and supervised by Dr Mey Goh. Edd has developed the first concept solution for drum beater winding, and had the opportunity to present his solution to Percussion Plus at the end of his placement.

Throughout the 2014-15 academic year, Percussion Plus has been the industrial sponsor for two MEng Total Product Design group projects, both supervised by Dr Mey Goh and Dr Matt Chamberlain. One group was challenged to produce a working solution with a realistic business case for automating the tambourine shell manufacturing process. Percussion Plus is currently seeking funding from InnovateUK to implement the proposed solution. The students have really appreciated the importance of an industry focused project and the support they have received from Percussion Plus and the EPSRC Centre throughout the year.
ROBUST INTELLIGENT METROLOGY

Metrology plays a critical role in all high value manufacturing applications; it also represents a significant automation challenge. Many metrology systems are designed to be heavily reliant on human intervention, to setup and optimise the measurement, filter out bad data, and interpret the results. In addition, the aim is generally to perform the measurements in stable, well defined conditions, such as a metrology or inspection lab. For many applications this is inconvenient, increasing time and cost of the manufacturing process. Therefore, new ways of collecting metrology data from non-ideal environments must be developed. The Robust Intelligent Metrology theme aims to address this by developing robot mounted metrology systems which are sufficiently robust to cope with non-perfect measurement conditions; but also poses the intelligence to filter, process, and implement actions based on the measurements.

Centre-Developed Three Wavelength Laser Scanner

Mitul Tailor, Taufiq Widjanarko, John Hodgson, Peter Kinnell

Laser scanners are commonly used to measure shape and profile in a wide range of industrial applications; they benefit from being non-contact sensors, with high accuracy and compact in size. The maturity of the device technology allows rapid and easy deployment within industrial environments.

A problem with the existing technology is that most sensors are preconfigured to allow only basic changes to the sensor setup; for example, the type and colour of the laser used, the triangulation angle and the camera angle are all properties that have a strong impact of sensor performance, but are currently fixed on most commercial sensors. In response to this limitation we have built a set of laser scanners that allow high levels of reconfiguration.

These have been used to investigate a number of parameters that affect the scanner performance, including: laser colour, camera exposure settings, and triangulation angle. With this knowledge we are able to build highly optimised custom laser scanners to suit the particular metrology or vision task.

For example, comparison of laser colour shows that for fine surface features, or shiny surfaces, blue lasers offer superior performance. For general shape measurement however, red and green lasers perform equally well or even better in certain circumstances. Green lasers also offer improved sensitivity due to the spectral response of typical machine vision cameras.
Investigation into the Use of 3D Vision Technologies and their Application to the Industrial Manufacturing Environment

John Hodgson, Peter Kinnell, Laura Justham

The use of 3D image acquisition devices is becoming increasingly common in industrial applications. They can be used for a wide variety of tasks including bin-picking, reverse engineering, quality control, robot navigation and automated assembly. The initial aim of the project was to investigate the use of 3D vision technologies and their amalgamation with other sensing technologies such as 2D machine vision and force/torque sensing, primarily for application to assembly operations such as object recognition and inspection. However, an initial literature review revealed current 3D vision technologies struggle to measure shiny, metallic objects typically found in industry. In addition, there is no widely accepted method of characterising sensor performance on such surfaces. It is therefore difficult for a practitioner to suit a scanner to a particular task.

Whilst the development of 3D vision sensors capable of measuring both shiny and matt surfaces has been identified as a high priority, it is first necessary to define performance metrics to quantify any improvements. Work has progressed to this effect.

A set of novel experimental procedures are being developed to map the performance of a sensor as a function of properties of the surface being measured, in particular orientation and roughness. Performance parameters are based on the quantity and accuracy of data points collected on a particular surface configuration.

This approach provides predictive power not previously available to the 3D vision practitioner. At a basic level, performance maps can be used to assess a scanner’s suitability for measuring a particular component based on geometry and surface texture. For advanced optimisation of a process, the maps can be used to predict optimum scanning orientations.

Experimental work is ongoing to finalise sensor performance metrics. Once complete, they will be used to measure the performance of a selection of commercially available 3D scanners. This will benefit the practitioner by providing more relevant performance metrics to inform scanner selection and will allow future improvement of sensor technologies to be quantified.

Figure 11
Performance map of a 3D laser scanner. Colour represents point reliability (standard deviation) when a sample is inclined in the (a) X and (b) Y directions.
Automated Visual Inspection Using Plenoptic Cameras

Shreedhar Rangappa, Peter Kinnell, Jon Petzing

The number of new vision sensors for 2D and 3D vision and inspection is continually growing. One example is the Plenoptic camera, which is gaining attention for its unique light gathering and post-capture processing capability. A micro-lens array is placed between the main lens and the image sensor to capture both spatial and angular information of a scene. This approach transforms a normal camera into a single lens 3D sensor. (See Figure 12).

By converting the depth data to a 3D format such as a mesh or point cloud, we gain access to additional techniques and opportunities for data analysis. A key concern is how to assess issues such as calibration, traceability, coordinate geometry correlation and performance inter-comparisons with other 3D camera systems.

Another benefit of plenoptic camera technology is that the additional angular information, although at the expense of spatial resolution, allows the post-acquisition change of aperture, focus and viewpoint through computational techniques.

The light striking a given sub-region of the aperture is structured somewhat differently than the light striking an adjacent sub-region. By analysing this optical structure, we can infer the depth of objects in the scene and hence can achieve “single lens stereo”.

Current uses are generally focused on general purpose consumer level photography, with limited work looking into how this interesting low cost technology may be applied to industrial applications. We are investigating application areas related to 3D visual inspection, with the ability to capture a single image and then refocus using software, as illustrated in Figure 13.

Figure 12
Plenoptic camera model

Figure 13
Images at different depths (top four figures focusing at front, middle, rear and all in focus respectively) and raw sensor image of small region ‘microlens image’ (bottom).
Automated Visual Inspection of Sculptured and Reflective Components

Zahid Usman, Mike Jackson

Large, glossy, free form, or sculptured surfaces often represent a significant inspection challenge. This is particularly true in automotive applications where inspection is required for the bodywork, but also for many under-the-bonnet components. Defects on the painted surfaces of such parts are difficult to detect because of the size of parts, complex features and reflections. Despite the need to automate, such parts are inspected manually at present which is not consistent and disrupts the flow of production. Automated inspection faces the challenges of elimination of reflections, covering the large surface area and complex orientations, and distinguishing defects from designed features.

To tackle this type of problem we have investigated robust robot deployed inspection systems, using novel lighting systems that can be used as part of a fully automated visual inspection system. The developed system involves the use of an industrial robot to provide the manipulation required to cover the size and complex faces of a typical part. A dome light is used to eliminate the reflections as part of the vision system.

In addition to hardware implementation, software algorithms and image filters have been developed and employed in image processing to eliminate defects, and distinguish defects from the designed features. The integration of the image processing, vision system and the industrial robot provides an automated visual inspection system that is consistent in defect recognition and also facilitates the flow of production.
HUMAN-ROBOT COLLABORATION

The way humans and robots work together in manufacturing environments is continuing to evolve: from robots delivering parts to production lines for humans to assemble, to high volume manufacturing automation where the human takes a supervisory role, to human robot collaborative systems where the human and the robot work collaboratively to complete a complex multi stage task. All of these applications involve an interface between a human and a robot, but all raise different questions in terms of design, safety considerations and interaction level.

For human-robot collaboration to be feasible and cost effective we must first understand how tasks can be divided between industrial robots and human operators to maximise the capabilities of both. In collaborative mode, when both are working on the same process, the human can augment the capabilities of the robot or vice versa. However this should not simply be the allocation of the hard and complex tasks to the humans and the simple repetitive ones to the robots. To optimise this process a comprehensive methodology for task analysis and decomposition is being developed by researchers at Cranfield University.

Working with robots in a safe and collaborative way raises questions not only concerning the design of the robot and the interface, but also how humans react and adapt to such a shift in working practices. Research is being carried out within the Centre to establish ways of interacting with robots safely and effectively. One current barrier to the use of robots is the cost and complexity of the different programming interfaces, making any interventions in the operation of the system the domain of the skilled robot operator.

Researchers Gilbert and Seemal have been investigating the potential for using gestures to control robotic systems. As well as functionality, factors such as usability, feedback and workload should all be considered when assessing these systems as well as the safety implications of utilising them.
Figure 16
Eye-tracking glasses
Shifts in ISO standards have made collaborative systems inherently more attractive to manufacturers due to the ability through technology to use non-physical guarding, leading to the concept of ubiquitous safety where all physical guarding is replaced by electronic systems such as laser scanners and 3D vision. Other changes to the standard have provided the opportunity to use soft limits to dynamically change the area needing to be guarded according to the task being undertaken. This has led to the development of projection-based indication of safe and hazardous zones, allowing dynamic sharing of working areas between the human and the robot.

From a human factors perspective, the use of collaborative systems raises questions at an individual and an organisational level. A recent PhD graduate from the Centre, George Charalambous, identified these two main themes when considering the use of collaborative systems in manufacturing environments. Trust was seen to be a key factor in the uptake of collaborative systems at an individual level, and one he explored extensively. Following on from this, an initial exploratory study was carried out using the collaborative cell in the lab at Cranfield University. This used eye tracking software and focused on individual factors regarding human-robot collaboration, including trust, acceptance and awareness. This highlighted that there are no existing models or tools suitable for measuring or predicting levels of awareness or acceptance specifically designed for human-robot collaboration environments. Current awareness tools focus on ‘situation awareness’ and are typically used in complex environments with a large amount of information being communicated to the user from different sources, such as nuclear power plants or cockpits. Automation changes the task demands significantly, shifting the operator in many cases from controlling the task and machinery to monitoring it. There has been considerable research in the domain of situation awareness and automation. However, in human-robot collaboration applications, specifically in high-value manufacturing, the operator will remain a key part of the process, actively carrying out tasks, while jointly co-operating with automation. This creates additional challenges for the operator and a need to understand what affects the operator’s awareness, and the levels of awareness required to carry out tasks effectively and safety; specifically how to communicate information from the robot to the human and vice versa.

The above research strands have been combined in a series of collaborative cells with different scales and capabilities, allowing them to be realistically demonstrated and evaluated. By considering the system holistically, rather than viewing the technical and human factors in isolation, we are able to test state of the art technology and consider the application in real world environments.

George Charalambous, the Centre’s first PhD researcher to complete the programme, graduated in March 2015. His thesis titled, ‘Development of a human factors framework for implementing industrial human-robot collaboration’ explored the various characteristics of manufacturing organisations and individual operators that impact on the adoption of advanced automation in manufacturing systems and identified the key factors that need to be considered in design and implementation. His work details the development of practical tools for measuring organisational factors and human trust in industrial robot systems, and provides a decision guidance model which links these key factors to developmental stages of technology readiness.
The Development of an Industrial Human and Robot Collaborative System

Gilbert Tang, Seemal Asif, Phil Webb

In a human-robot collaborative working environment robots and humans share the same working area and interact with each other. Many functions and capabilities are shared by the humans and robots in the system so it is important to consider the synergies and conflicts that can arise. For example, research on human-automation interaction has shown that automation can change the cognitive process of a human user in a way that is unanticipated by the system designers and which may result in dangerous and unexpected responses. A technology-centred system approach has been the cause of many human performance issues and accidents when using automated systems such as in the Three Mile Island accident and the Kegworth air disaster.

This research aims to create a collaborative human-robot system through the integration of state-of-the-art robotic and sensing technologies that will be able to work collaboratively with humans in close proximity, and with a high level of safety and user-friendliness. To realise this, a human-centred design approach has been adopted so human factor issues can be understood and used to optimise human-automation performance as well as the technology requirements. For example, a user’s ability to anticipate and respond to robot motions is important for optimum collaborative working and can increase the fluency of a process whilst also preventing the occurrence of potentially hazardous situations.

One of the major activities of the project has been to develop a robust and intuitive gesture control system. A range of different control techniques have been investigated as part of a comprehensive comparison study to determine the most suitable method to provide robust and reliable robot control. Based on this research, an optimal approach has been selected using a Leap Motion hand tracking device which has been implemented to
control of a medium size industrial robot using mid-air gestures. The resulting system allows the robot manipulator positions to be altered using natural hand movements. In addition further hand movements can also be used to control the robot gripper. A project demonstrator has been built and tested in the Cranfield Aero-Structure Assembly and Systems Installation Laboratory.

As well as allowing effective human to robot communication, another major project objective is to develop a robot indication system to communicate between robot and user; this will improve the user experience and effectiveness of a human-robot collaborative system. Various robot indication systems are currently being tested at Cranfield including overhead floor signs projection and an integrated robot LED indication light system for interaction in proximity.

Further work will be completed using the demonstrator in realistic industrial scenarios and in particular investigating how to avoid unwanted conflicts and errors between operator and robot.
Many aerospace manufacturing businesses are seeking to automate processes in order to improve efficiency, by driving down costs and increasing production rates, whilst maintaining or improving quality. However, some of these processes are not always possible to completely automate, especially when they involve a complex mixture of skilled and non-skilled tasks. Non-skilled parts of a process are defined as those that do not require mental workload by the operator, e.g. manual handling of assembly items.

One solution is to automate the non-skilled parts of the manufacturing process with the use of industrial robotics, whilst retaining the manual skilled tasks for the human to carry out. In some instances therefore the human would need to interact directly with the industrial robot. This mode of working is known as ‘collaborative automation’.

The traditional safety measure used to safeguard the human from the potentially hazardous industrial robot is the installation of a physical guard along the boundary of the robot cell. Given that this measure separates the human from the moving robot, its deployment on certain manufacturing flow lines is limited when the human tasks cannot be completely separated from those of the robot. Furthermore, the physical guard does not completely mitigate against the risk of injury due to a human trespassing the guarded area.

Other factors that preclude the use of physical guards include the requirement for a flexible solution for certain applications. For example, there are some aerospace manufacturing flow lines that involve transferring an assembly item manually from one part of the plant to another, rather than mechanically with the use of moving tracks that can be more readily caged off. In addition, some of these assembly items are actually very large and cannot be practically housed within a robot cell.

The challenge therefore lies in engineering both a practical as well as a safe robot cell that incorporates both the human operator and the industrial robot within the same shared workspace without the use of physical guards.

The aim of this piece of research is to determine the risk acceptability of a proposed human-robot collaborative robot cell, without physical safeguards, by the UK safety community.

Work has been undertaken at Cranfield University to integrate state of the art, off-the-shelf electro-sensitive protective devices (i.e. non-physical safeguards) with a large scale industrial robot arm – see Figure 20.

The robot cell is designed to simulate the process of attaching an assembly item to a counter-piece and is being offered as a conceptual generic solution for a handling task that involves direct human-robot collaboration – see Figure 19.
Figure 20
Large scale collaborative robot cell at Cranfield University.
The robot cell (also known as the test facility) incorporates an integrated and synchronised KUKA KR240-2 industrial robot, Pilz SafetyEYE and a SICK Scanner, a Projection System, a Facial Recognition System and Audio and Visual Warning System. The robot device is set to automatic mode with the speed limited at 10% (i.e. 0.25 m/s). The Project System highlights for the operator the zones around the robot that ought to remain clear during operation – see Figure 21. It is also used to prompt the operator to approach the robot safely at the appropriate time during the assembly process. The visual (i.e. a light tower) and audio warning system is used to inform the operator when the robot is in collaborative operation.

In order to validate the system, a number of test scenarios were designed and the behaviour of the system was logged. The test scenarios were chosen to simulate the most probable and foreseeable hazardous situations that could occur within the context of the test facility. This activity successfully demonstrated the safe functionality of this truly collaborative robot cell. Researchers have used both quantitative and qualitative methods to identify the hazards within the scope of the demonstration test facility. The associated risk was shown to be low and manageable based on the context of the integrated system at the test facility.

The robot cell and its risk assessments will form the study upon which the acceptability of the inherent risk by the safety community within the UK will be measured. Variables such as individual experience with robotics, safety culture of the organisation and types of risk assessments will be used to identify the factors that influence risk acceptability, and hence the readiness or uptake of this type of automated solution.
MANUFACTURING INFORMATICS

TOWARDS SMART AUTOMATION DEVICES & SYSTEMS

The Manufacturing Informatics theme is investigating information and communication technology solutions to reduce the integration effort of complex automation systems and extend their long term sustainability.

Models and protocols for rapid plug-and-produce of automation components have been defined over the years and now the focus is moving to methods to better utilise valuable data generated during the integration and operation of manufacturing systems. This is expected to be the foundation to enable future smart automation devices that can form smart production systems. Smart devices are expected to contain models and knowledge of themselves which they use to proactively help integrate themselves into new systems, adapt to new production requirements, and continuously optimise themselves.

The rise of the Internet-of-Things (IoT) and Cyber-Physical-Systems (CPS) paradigms is driving increased efforts to take advantage of interconnected systems. Systems-of-Systems thinking allows new approaches to address the inherent complexity of production systems. Also, the relationship between human and machine on the shop floor is being redefined. New production control systems are expected to maximise the relative strength of humans to adapt to change while leveraging the capability of machines to process large amounts of data and consistently perform complex processes.

Hence, this theme is investigating how to use information models, communication, interaction methods and advance data-driven methods to reduce ramp-up, achieve faster changeovers, extend the lifetime of production equipment and continuously optimise the performance of complex production systems. The foundation of these is seen to be smart, self-aware machines which are able to integrate themselves quickly into wider systems.

Current research is a combination of collaborative European Projects and PhD focused research with world leading companies and academic institutions.
European Projects

Co-operate, Communicate and Connect to Boost Smart Components for Tomorrow’s Industry

[EU-H2020 Co-ordination & Support Action: 637178]
01/01/2015 to 31/12/2016
http://www.cofactor-eu-project.org

Co-FACTOR is a Co-ordination and Support Action (CSA) funded by the European Commission under its Research & Innovation Program Horizon 2020 and aims at fostering the industrial impact of the current Factories-of-the-Future (FoF) projects I-Ramp, ReBorn, SelSus, T-Rex, INTEFIX and Power-OM.

The common research topic centres around “smart components” which comprises among other devices with innovative capabilities, machines with built-in intelligence, computer assisted and advanced manufacturing technologies.

Production Harmonised Reconfiguration of Flexible Robots and Machinery

[EU H2020 FoF Innovation Action: 680735]
01/10/2015 to 30/09/2018

This project will look at deploying service based architectures combined with agent-based planning and control methods in large and medium sized factories.

The ambition is to use results from previous successful research projects and industrialise them to a point that they can be deployed into actual production systems. This is expected to reduce changeover times and allow smaller economic batch sizes.

openMOS
Open Dynamic Manufacturing Operating System for Smart Plug-and-Product Automation Components

[EU H2020 FoF Innovation Action: 680435]
01/10/2015 to 30/09/2018

This is an SME focused project which explores common standards for rapid integration of smart automation devices. The Centre played a driving role in developing this project and will be responsible for creating an open manufacturing service bus which can link embedded smart automation devices with dynamic planning and optimisation methods on the MES level. The drive behind this project will be to create an open innovation platform for plug-and-produce automation devices based on a common manufacturing communication bus.

Co-operate, Communicate and Connect to Boost Smart Components for Tomorrow’s Industry

Project team: Steinbeis-Europa Zentrum (Germany), Instituto for Systems and Robotics (Portugal), Fraunhofer Institute for Manufacturing Engineering and Automation IPA (Germany), Loughborough University (UK), IK4-TEKNIKER (Spain), Harms&Wende GmbH & Co. KG (Germany).

Production Harmonised Reconfiguration of Flexible Robots and Machinery

Project team: Introsys SA (coordinator, Portugal), Fortiss GmbH (Germany), Elcrest Automationssysteme GmbH (Germany), Ford Motor Company Ltd (UK), SenseAir AB (Sweden), Inotec Ltd (UK), Alag Automation AG (Switzerland), HSSMI (UK), UNINOVA (Portugal), KTH (Sweden), Linkopings University (Sweden), Masmec SPA (Italy), Electrolux Italia SPA (Italy), We Plus SRL (Italy).

openMOS

Project team: Intrasy SA (coordinator, Portugal), Fortiss GmbH (Germany), Elcrest Automationssysteme GmbH (Germany), Ford Motor Company Ltd (UK), SenseAir AB (Sweden), Inotec Ltd (UK), Alag Automation AG (Switzerland), HSSMI (UK), UNINOVA (Portugal), KTH (Sweden), Linkopings University (Sweden), Masmec SPA (Italy), Electrolux Italia SPA (Italy), We Plus SRL (Italy).

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Innovative Reuse of Modular Knowledge Based Devices and Technologies for Old, Renewed and New Factories
09/2013 to 08/2016
Niels Lohse, Vikrant Hiwarkar, Paul Danny

The ReBorn project is working towards achieving 100% reuse of production equipment by the accumulation of manufacturing knowledge for a 360° factory equipment life-cycle. The methodology adopted to achieve this goal is based on three key concepts as follows:

- Modular plug and produce equipment, in-line to adaptive manufacturing
- Innovative factory layout design techniques for adaptive reconfiguration
- Flexible and low cost mechanical systems for easy assembly and disassembly

ReBorn successfully passed the midterm review of the project with very positive comments: self-monitoring devices were successfully demonstrated; data driven reliability assessment methods have been created; strategies for rapid configuration of mechanical systems using custom printed components have been defined; requirements capture, lifecycle cost models and a configuration framework have been defined.

http://www.reborn-eu-project.org

This project has received funding from the European Union’s Seventh Framework Programme for research, technological development and demonstration under grant agreement number 609223

Project team:
- Harms & Wende (Germany)
- Fagor Automation (Spain)
- Critical Manufacturing (Portugal)
- Centro Ricerche Fiat (Italy)
- IEF Werner (Germany)
- Fraunhofer (Germany)
- Steinbus Europa Zentrum (Germany)
- W.E.H.S, Karlsruhe (Germany)
- University of Oulu (Finland)
- Gamax (Hungary)
- ISRP (Portugal)
- ISG (Germany)
- University of Madrid (Spain)
- Paro (Switzerland)
- ZEC (Switzerland)
- Technax (France)
- Loughborough University (UK)
Health Monitoring and Life-Long Capability Management for SELF-SUSTaining Manufacturing Systems

09/2013 to 08/2017

Niels Lohse, Mohamed Sayed, Peter Kinnell, Athanasios Anagnostopoulos

The vision of SelSus is to create a new paradigm of highly effective, self-healing production resources and systems to maximise their performance over longer life times through highly targeted and timely repair, renovation and upgrade. SelSus aims to embed these next generation of machines, fixtures and tools with extended sensory capabilities and smart materials, combined with advanced information and communication technologies (ICT) for self-diagnosis and prognosis, enabling them to become self-aware and a step closer towards supporting self-healing production systems.

Distributed diagnostic and predictive repair and renovation models are being embedded into automation devices to enable early prognosis of failure modes and component degradations. Self-aware devices will be built on synergetic relationships with their human operators and maintenance personnel through continuous proactive communication in order to achieve real self-healing capabilities. This will dramatically improve the resilience and long term sustainability of highly complex manufacturing facilities to both predicted and unpredicted disturbances and deteriorations and thereby reducing system downtime and minimising energy and resource consumption and waste. The SelSus vision is being achieved through the development of a new synergetic diagnostic and prognosis environment, which is fully aware of the condition and history of all the machine components within the factory and is in constant knowledge-enriched dialogue with their human personnel.

The scientific innovations of the project are continuously being demonstrated using four industrial cases from the project’s industrial partners: two cases for component-level demonstration, as well as two cases for system and factory levels.

http://www.selsus.eu

This project has received funding from the European Union’s Seventh Framework Programme for research, technological development and demonstration under grant agreement number 609382.

Project team:
- Fraunhofer IPA (coordinator, Germany)
- Loughborough University (UK)
- University of Nottingham (UK)
- Electrolux (Italy)
- Ford (UK)
- MTC (UK)
- IEF Werner (Germany)
- XETICS (Germany)
- Gamax (Hungary)
- ADP (Germany)
- Inatec (UK)
- Harms & Wende (Germany)
- Hugin Expert (Denmark)
- HSSMI (UK)
- ISR (Portugal)
Flexible Multi-Agent Systems in Automated Manufacturing

Spartak Ljashenko, Niels Lohse, Mike Jackson

The manufacturing industry is facing significant changes due to increased demand for highly customised products. Currently, robots are primarily used for mass-producing goods that require neither intelligence nor adaptation to variability. However, repositioning robots and programming and equipping them for sets of different tasks requires a great amount of time, skill and investment. Moreover, the complexity of modern systems is steadily increasing, leading to greater challenges in terms of flexibility and adaptation.

The traditional paradigms, based on single central processing units that control all operations in a given manufacturing environment, are becoming obsolete. In view of this, the manufacturing industry is interested in developing technology that can solve these challenges. However, it is evident that such systems are still in their early stages. Flexibility and adaptivity in manufacturing generally require an approach where each entity (or agent) has a partial view of the environment and makes its decisions autonomously. Multi-agent systems can allocate individual agents to manage disruptions, allowing the rest of the system to continue working, which leads to increased efficiency and utilisation of machinery.

The aim of this project is to consolidate the first steps in moving towards flexible and adaptive manufacturing systems. It will handle the specifics of varying production requirements, manage disturbances in the processes and eliminate bottlenecks on the production line.

Dynamic Energy Consumption Reduction in Flexible Manufacturing Systems – A Multi-Agent Approach

Abdulaziz Alotaibi, Niels Lohse

Manufacturing systems are currently changing rapidly with the significant growth in technology, business and industry. These systems are becoming more complex involving a variety of challenging issues, including variant services, customised products and unavailable machines. At present, there are limited models or approaches that deal with these complexities. Most of the scheduling models cited in the literature propose centralised approaches. Researchers are focused on reducing energy consumption in manufacturing due to the rising cost and environmental impact. Energy consumption factors have been introduced into scheduling research among other traditional objectives such as time, cost and quality. Although reducing energy in manufacturing systems is very important, few researchers have considered energy consumption factors when scheduling dynamic flexible manufacturing systems.

This project focuses on developing new models and algorithms for the dynamic multi-objective optimisation of energy use in flexible production systems. As part of this research project, new decision making and negotiation models for embedded multi-agent systems will be developed. This will allow complex production systems to robustly respond to demand fluctuations and other external and internal disturbances, while minimising their environmental impact.
Towards an Architecture for Cyber-Physical Production Systems based on Smart Components

Athanasios Anagnostopoulos, Niels Lohse

Modern industry needs to respond to varying unpredictable demands while being able to adapt to rapid changes in customer needs. These needs are driven by increasing customer requirements for more personalised products at a faster and more cost effective rate. Following this trend, the Industry 4.0 initiative is being proposed in order to move into the next industrial revolution; one that is based on the concept of intelligent responsive factories. These modern factories need to be focused on providing adaptability, efficiency and flexibility in response to varying demands.

The concepts of Cyber-Physical Systems (CPS) and the Internet of Things (IoT) are thought to be central enablers. Applying these concepts in a manufacturing system gives the opportunity to obtain the information of a required product, use the computation power that the cloud provides, and communicate with the physical part of a manufacturing system on the shop floor. This will allow the system to be controlled more efficiently while adapting faster to any required changes.

The aim of this research work is to create an architecture that will enable quick and easy configuration and reconfiguration of a manufacturing system. The focus is on investigating possibilities for real time communication between components with embedded intelligence that act as low cost device controllers on the shop floor, and the cloud where more advanced, computationally-intensive tasks such as planning and scheduling can take place. Additionally, the robustness of such smart, relatively low-cost control components is being investigated in order to establish the architectural and performance conditions under which industrially-viable control metrics can be achieved using these low cost devices.

Knowledge-Based and Reliability Focused Self-Organization Methodology for Modular Assembly Systems

Paul Danny, Niels Lohse

The aim of this project is to provide an automatic configuration and reconfiguration methodology for assembly systems which considers the characteristics and performance effects of using new, old or existing assembly systems, equipment or components for a given set of requirements. Traditional configuration methods are only price driven and do not provide any means to account for the lifecycle status of reused equipment when planning a new or reconfigured production system. This project investigates appropriate models and methods to account for the lifecycle effect of reused equipment. Heuristics will be developed to allow the early recognition of opportunities in a computationally effective manner. The key challenges will be to integrate lifecycle cost models into the configuration methodology and allow specific equipment modules to be selected based on their capabilities which have been determined from their operational and maintenance history. Models for reliability and maintenance effort which change over the lifecycle of equipment modules are being investigated and linked to optimisation methods to automatically explore large possible assembly system configuration spaces.

The proposed methodology aims to establish a knowledge-based and reliability centred self-configuration methodology for MAS, where the solution contains the bill of equipment modules that are best suited (optimal) to accomplish the given set of assembly process requirements. This would be the result of creation, addition or removal of modules depending upon its skills, interfaces and reliability. This PhD project is linked to the ReBorn project.
TOWARDS AUTONOMOUS MANUFACTURING PROCESSES

Adaptive manufacturing processes that react to measured variations in the environment, input materials, process machinery/tools and produced output are becoming more prevalent. The goal of the next decade of research is to extend the capability of adaptive machines to make autonomous decisions and associated actions in complex or unpredictable circumstances without reliance on human capability. One outcome of this future research is that an autonomous machine, such as an advanced robotic worker, will work co-operatively and intelligently with and also alongside a skilled human operative. The current EPSRC Centre research in this area is highlighted in the following examples. There are substantial research challenges that have been overcome already and there are many more to be addressed.

3D Vision Robotic Assembly

Phil Ogun, Karthick Dharmaraj, Zahid Usman, Matt Chamberlain, Mike Jackson

The main purpose of this research is to develop an established system that will give industrial robots the visual information feedback and the manual dexterity used by a skilled worker to perform complex assembly tasks. Robot workers of the future will be able to assemble components at least as well as human workers and without the use of application specific tooling, thus creating a rapid response to customised orders.

The robots will be capable of working alongside human workers to reduce physical and mental stress and increase productivity. The initial phase of this research investigates the limits of 3D Machine Vision enabled assembly. A test case has been created where three rings are to be assembled on a shaft. The shaft is tapered and the fit between rings and shaft are generous (~0.5 mm). The assembly robot, shaft and rings are shown in Figure 26.

Figure 26
The assembly robot, shaft and rings
A suitable vision system should be able to handle situations where the rings may be overlapping or placed one on top of the other in any order. Figure 27 shows examples of the various possible rings and shaft placements that the vision system should cope with. It should be able to recognise the topmost ring in the scene and also determine its pose.

The research has two main elements. The first element is the 3D visual perception and the other is the robot-vision integration. The fundamental task in the visual perception is the development of a 3D vision system for recognising and estimating the full pose of randomly placed objects within a robot workspace. The first problem to be solved is the identification of the right sensors for imaging the workspace. Imaging in manufacturing applications is more challenging than in other applications because some of the parts are made of metals (shiny objects), which produce specular highlights that corrupt the point cloud quality generated by 3D sensors. A number of different sensor technologies have been investigated and laser scanners have proved to be the most robust in terms of point cloud quality.

The solution that has been developed works by matching the CAD models of the parts with the point cloud data of the scene in which the parts are located. The point cloud of the scene is acquired from a laser scanner mounted on the robot gripper that moves across the scene. The comparison gives an indication of the pose of the part in the scene.

The parts are transformed using the estimated poses and then overlaid on the scene point cloud. Figure 27a shows a sample point cloud of the scene and Figure 27b shows automated matching of the parts in the scene.

The pose estimated from the point cloud matching represents the transformation of the parts in the sensor coordinate system. Hand-eye calibration is required in order to determine the transformation between the sensor and the robot tool co-ordinate system so that the poses of the parts can be determined in the robot co-ordinates. This enables the robot to grasp the parts and move them accurately within the workspace as required. The overall robot grasping accuracy obtained so far is good enough for safe and reliable manipulation of the parts. Although the accuracy is sufficient for the chosen assembly task, it requires further improvement for tighter tolerance fits such as transition and interference fits. In order to achieve this, force-torque control will be used to augment the visual feedback information from the vision system.
The purpose of this research is to understand the human skill applied by expert TIG welders. The longer term goal is for creation of intelligent, adaptive and autonomous welding systems for difficult manufacturing challenges. Thin complex geometries with minor variation are considered amongst the most challenging, especially where exotic metals are involved. Welding complex shapes (3D, variable gap/thickness) requires accurate seam tracking, intelligent decision making capability and adaptive weld process control similar to that of a skilled manual welder.

This can be achieved by using feedback about the weld path geometry for the adaptive control of the weld process parameters to achieve better controllability over the weld pool position and shape. The work carried out within the EPSRC Centre has addressed these requirements, with the primary research objective of the work being the development of a fully adaptable and intelligent TIG welding robot which can perform challenging welding tasks with a similar quality to that of a skilled manual welder.

Following human factors based research, which was carried out to rate the performance of novice, semi-skilled and skilled welders against autonomous welding equipment, a real-time position based closed loop system was developed for a six axis industrial robot (KUKA KR 16) fitted with a laser triangulation based sensor (Micro-Epsilon Scan control 2900-25) in front of the welding torch.

A National Instruments data acquisition system (NI DAQ) was used to capture sensor inputs and produce control outputs. A Fronius Magicwave welding system was used with a push-pull wire feed system to perform welding. The KR 16 moves the laser scanner over the approximate position of the weld gap to produce a point cloud of the scene. A novel algorithm was developed for finding joint profiles and path tracking of a three dimensional (3D) weld path. Algorithms were also developed to extract joint features in real-time. Empirical models were developed to predict important weld quality characteristics and to estimate weld machine settings based on the weld joint geometry.

The developed robotic TIG welding system is able to carry out welding of a variable gap weld joint with satisfactory results. Using visual appearance, in the form of weld bead dimension, the automated outputs are closely related to those of skilled manual welders.

The next phase of this project focuses upon further human factors research using only highly skilled operatives. Utilising not only the conscious efforts of personnel in carrying out tasks but also latent knowledge gained through experience, Skilled human welders make minor corrections and changes throughout the course of the process to optimise the output quality of the welded joint. It is highly desirable to gain this information and introduce it as control inputs into an intelligent control system for welding automation. This will help to enable advanced functionality during the automated welding process, including adaptation to differing conditions as they arise.
The purpose of this research is to understand the complex activity of a skilled panel forming worker that uses simple hand tools to create 3D sheet metal components with little or no bespoke tooling. The research aims to use this understanding to create new approaches to die-less automated panel forming.

The research methodology was developed in three stages, consisting of capturing human skill, semi-automated system and fully automated system. This work included several modelling and experimental process analyses.

Initially, experienced panel beaters were closely observed and their tacit human skill was analysed. It was identified that consecutive shrinking and stretching (through hammering) of sheet metal produces a sheet with uniform thickness. It was also determined that imposing repetitive kinetic energy through hammering allows better control over producing shapes incrementally by consecutive stretching and shrinking without fixtures.
This method is also believed to improve release of residual stresses during the forming process. The constructive methodology used by the panel beater improves the quality of the sheet metal by maintaining the uniform distribution of material.

The methodology developed uses a sequential hammering mechanism, the Eckold Kraftformer KF 170 PD. The mechanism incrementally forms the sheet metal which is held and manipulated by a robot to form the required shape. The developed approach includes an in-process monitoring system using machine vision. The vision system feedback is used to control the formation of sheet metal accurately to the three dimensional shape required.
Measurement of the impact force and kinetic energy involved in panel beating of sheet metal was carried out using an instrumented mallet and high speed video to capture data during manual hammering tests conducted in a structured laboratory environment. Based on the impact force determined and corresponding kinetic energy, a hammering machine capable of producing the required force and able to operate at the required frequency was investigated. The Eckold Kraftformer KF 170 PD was purchased, as this met the requirements for the automated panel beating test cell.

The semi-automated system utilises the Eckold Kraftformer and manual manipulation of the sheet metal blank between the hammer and the anvil during automatically repetitive hammering to progressively form the desired 3D shape. During the action of forming the shape, a Vicon 3D imaging system was used to capture and analyse the movement of the sheet metal blank. Based on several experimental trials, the most suitable movement pattern and path was determined to be used as an input to the robotic manipulation.

The development of an automated system included the integration of an Eckold Kraftformer and Yaskawa SDA10D on a common control platform. This approach synchronised the sequential hammering of the Eckold Kraftformer with the forming manipulation pattern executed by the robot. A gripper was designed similar to the holding-area of a human grip in manual forming process. The gripper was installed on the robotic arm to be able to hold the sheet metal and provide the required manipulation.

Based on this set-up, experimental trials were conducted in developing an automated sheet metal forming process. These trials based on forming a bowl shape were successful and repeatable after several analyses and modifications. Information obtained from trials where skilled panel beating operators were observed performing their tasks, resulted in improved robot performance. Considering the throat depth limitations of the Eckold Kraftformer being used, the automated system has less than 5% deviation in shape form compared to the target form and is 98% repeatable.
An Intelligent Automated Polishing System

Eugene Kalt, Jamie Everitt, Radmehr Monfared, Sarah Fletcher, Mike Jackson

The purpose of this research is to understand what skilled workers do when polishing complex components. The project aim is to understand and capture human operations as quantifiable values (e.g., forces and polishing patterns) as a pre-cursor to creating automated polishing solutions.

A fixture (shown in Figure 32) has been created, equipped with three precision sensors to capture force, torque, position, orientation, and vibration of the part undergoing manual polishing. A set of computer functions have been developed to analyse captured data and specify the motion of the manual polishing process. The captured data is then interpreted as a polishing pattern with known force applied and speed for certain geometrical features of the part being polished. The research will then be extended to apply the data captured to an automated system, (e.g., a robotic arm), to reproduce the same pattern.

Currently, the fixture has been developed and tested within the Centre, and is now being tested by skilled operators. These experiments are carried out in collaboration with another researcher working within the Centre on human skill capture.

Figure 32
Manual skill capture using the fixture
The aim of this collaboration is to capture and understand the manual process by providing key parameter and data before automation. Typical output from the fixture is shown in Figure 33.

First results are showing that the skilled operator is following the geometry of the workpiece and control the quality of the surface frequently. Some, operators will carry out the operation the same way until the quality of the part is satisfactory, whereas other operators will change the force applied and the speed of movement depending on the type of defects.

The experiments also reveal that defects and marks are removed in a few attempts at the beginning and the rest of the operation is spent on improving the surface finish of the part as much as possible.

Overall this research will determine and document the human skills used for manual polishing operations and develop a recommended system for automated polishing process. First results of this investigation are promising and point towards further development of novel intelligent automated system using knowledge captured from the manual operation.
Automated Freeform Assembly of Threaded Fasteners

Karthick Dharmaraj, Radmehr Monfared, Mike Jackson

This research is aimed primarily at investigating and creating a freeform automated assembly system to carry out controlled fastening in an unstructured environment without the use of application specific tooling.

The approach taken for this research is to perform fastening of bolts automatically and to address control issues (e.g. torque and force to avoid cross threading) and lack of positional precision (e.g. co-ordination and orientation of target components to eliminate need for complex fixtures).

The proposed methodology includes using machine vision to identify a fastener and the target component with threaded fastening hole located randomly in the workspace. It also involves picking up the fastener and aligning it with the corresponding hole to perform torque controlled fastening.

A laboratory demonstrator has been developed, which includes a bolt holder, a circular disc with different sized holes on multiple planes, a tightening system, vision components, a robot and a personal computer. The scope of the research is limited to ferrous material bolts with a hexagon head ranging from M5 to M12.

In an industrial free-form assembly scenario, fasteners may be located at random positions, i.e. in three dimensional (3D) space, and therefore require 3D positional information. It is also important that the 3D sensor should be able to provide accurate visual perception of the objects in random environment. An evaluation of 3D sensors with different technology was conducted to find the suitable vision sensor for assembling fasteners in random 3D environment. The results show that laser scanners provide more accurate visual perception of objects in the work area and are less prone to negative effects of surface finish of objects and variable lighting condition. Despite their advantage of high accuracy, the laser scanners only have a small field of view and require multiple scans for large size objects. This trade-off between accuracy and field of view/speed is necessary for developing an optimal solution.
The final stage of highly complex fastener assembly was carried out using the laser scanners to obtain 3D work area information. The major challenges involved in this scenario are identifying fasteners (i.e. bolts) in random and possibly overlapping orientations, identifying hole features in 3D surfaces and manipulating the fasteners to carry out accurate assembly. The location of bolts and threaded holes in 3D has to be determined accurately to avoid misalignment during assembly. Established algorithms available for identifying hole features are few in number and, whilst accurate, tend to require more time for processing. This led to the development of a novel hole feature detection algorithm which is accurate and at the same time faster. An evaluation of the hole feature detection algorithm was carried out to analyse and validate its performance.

The results achieved are promising with an accuracy of less than 1 mm and 1 degree in position and also the hole feature was detected within 1.2 second. Experiments were carried out to assemble bolts in a random environment and the results are highly successful. The developed 3D assembly method was able to assemble the bolts with high accuracy and robustness and is therefore suitable for industrial applications.

Figure 34
Detection and manipulation stages (L-R)

Bolt exchange between robot arms

Bolt fastening

Assembled bolt
Mobile Robots

Tom Bamber, Jianglong Guo, Laura Justham, Mike Jackson

As part of the core research of the EPSRC Centre, there are two PhD candidates whose research focus is that of mobile robots. One is working towards the creation of a multi-legged outreach demonstrator and the other is developing a next generation crawler robot for manufacturing applications. Their research is an excellent example of scientific endeavour within the EPSRC Centre as they have made fundamental breakthroughs in the understanding of electro-adhesion, and are at the forefront of this field within the UK. It is also a strong case study of how the EPSRC Centre is building new connections with academia and industry.

Many industrial robots are large units that operate in fixed positions. Manufacturing tasks are brought to them, such as automotive builds on an assembly line. However, there is a lot of potential for much smaller industrial robots that can work autonomously, moving to where they are needed, climbing and even within structures to perform tasks.

The current phase of the PhD research is focused on path planning, collision avoidance and electro-adhesion.

Path Planning and Collision Avoidance

For any mobile robot to perform tasks they must have an awareness of their working volume. On-board and off-board sensors are the two ways of providing this information. Numerous 3D camera systems could be used on-board a mobile robot, however none of the currently available systems provide accurate enough depth information for our industry relevant manufacturing applications. If the working environment is known then an off-board system such as the Vicon system can be used and in this case using path planning and collision avoidance algorithms become imperative. Collision avoidance is different from path planning, because in high level path planning you can assume that you have complete knowledge of the other vehicle or obstacles that you are avoiding. In collision avoidance you are limited by the sensors available. Collision avoidance is most applicable to the safety or low level trajectory planning.

An example algorithm for solving the collision avoidance problem is the Potential Field method. Potential Field theory works on the principle that hills, or spikes, (areas of high repulsive potential) are obstacles, and dips (areas of high attractive potential) are targets. This means that the vehicle is pulled around the obstacles. It is possible to visualise the potential field as if a ball is rolling down a hill towards the goal. The ball will not go into the obstacle, because it is impossible for it to climb the spike in the centre (‘the obstacle’).

A Potential Field test plan for a route between the points \([0,0]\) and \([0,1]\) then \([1,1]\) then \([2,1]\) then \([0,1]\) and finally \([0,0]\) was carried out and is shown in Figure 35.

Simulations have been used in this project as they are the safest way to initially implement algorithms that the user is unsure of. The results of running the planned path in the simulation are shown in Figure 36.

Once simulations have been carried out and the user is happy that the results are acceptable, then real world testing is carried out. Within the EPSRC Centre we have done this testing using a buggy and a Vicon Bonita system, a CAD representation of this test scenario can be seen in Figure 35.
Figure 35
Potential field test plan

Figure 36
Simulation results
**Electroadhesion**

In order for the mobile robots to be able to perform in any orientation the challenge is climbing and one component of climbing robots is adhesion. There are a number of different mechanisms that could have been chosen, but the active low power consumption of electroadhesion means it has been chosen for development within the EPSRC centre.

Electroadhesion is the electrostatic effect of attraction between two surfaces subjected to an electrical field. Electro-adhesion contains three components shown in Figure 37:

- Conductive electrodes connected to a high voltage supply
- Dielectric material to which the electrode is attached (the pad)
- Substrate to which the pad is to be attached to (aluminium, carbon fibre etc).

The charge from electrodes applied with high voltages generates a strong electric field which can polarise the dielectric materials and induce equal and opposite charges on the surface of the substrates. The electro-adhesive force is formed between the electro-adhesive pads and the wall substrate. Modelling, experimental testing and manufacturing of electroadhesive pads is being carried out within the Centre. Results of which will be published shortly.

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**Collaborative Research**

The EPSRC Centre team are now working closely with Sheffield Hallam University and an automation SME to further develop this work on electroadhesion and to explore new industrial applications. PhD student exchanges have been completed with time spent at both universities to share knowledge and best practice. Working closely with the SME, project work has been extended to understand new real world challenges. The team are building relationships and scoping out future collaborative research opportunities.

As a National EPSRC Centre, a core aim is to develop relationships with academia and industry. By engaging through core project streams such as our work on mobile robots, we are supporting the broader growth of intelligent automation research across the UK.
BUILDING THE INTELLIGENT AUTOMATION COMMUNITY

The EPSRC Centre has developed a significant outreach programme that includes youth engagement from primary school to university level, funding support for new academic research and the provision of expertise to wider industry, with a particular focus on SMEs.

Youth Outreach: Our Goal for a Sustainable Future

At the EPSRC Centre, we know that a strong future pipeline of well-qualified scientists and engineers is critical to help ensure a sustainable automation workforce. Our youth outreach programme has gone from strength to strength. Our involvement with the Institute of Engineering and Technology (IET) continues to develop whilst we have also established firm links with Big Bang UK Young Scientists & Engineers Fairs.

We hope that our outreach programmes will inspire people to study STEM subjects (Science, Technology, Engineering and Mathematics) and show them the life-long opportunities that STEM careers can offer, particularly within the growing field of intelligent automation.

The work we do at a national level is rivalled by very few research institutions in the UK and provides a model for good practice that we hope will be adopted by others.

Our success is only possible because of the unique contribution of our STEM ambassadors who are undoubtedly integral to our continuing and rapid development. Our ambassadors include students, researchers and academics from both Loughborough University and Cranfield University and staff from our industrial partner institutions. Our volunteers are encouraged to be great role models, promoting STEM careers and developing their own skills through their involvement.

By investing in STEM education we hope to widen the talent pool from which we - and partner institutions - will recruit in the future, ensuring that we have the best people with the right skills to help fulfil our future responsibilities.

We have a broad range of STEM outreach activities, including:
FIRST LEGO League

In addition to being one of the primary sponsors for FIRST® LEGO® League (FLL®) UK, we also host the regional and national competition which has been held at Loughborough University for the last two years. This is a global science and technology competition with over 250,000 young people between the ages of 9-16 years taking part each year. Through this work the EPSRC Centre has engaged strongly with the Rt Hon Nicky Morgan MP, Secretary of State for Education, who presented her own award at the FLL national final.

Big Bang UK Young Scientists & Engineers Fair

Through the Big Bang UK Young Scientists & Engineers Fair we showcase a wide range of interactive stands that show young people (primarily aged 7-19) the exciting and rewarding opportunities out there for them with the right experience and qualifications. We also support those who influence young people’s learning, including teachers, parents and youth leaders. A new youth focused interactive exhibition stand is developed each year, and then showcased at additional venues including schools and science fairs.
This year the EPSRC Centre intends to strengthen its commitment to FLL by sponsoring and participating in the UK’s maiden Junior FIRST® LEGO® League (Jr.FLL®) UK competition making STEM subjects fun for children aged 6-9. The aim is to capture young children’s curiosity and direct it toward discovering the wonders of science and technology.
Robogals Loughborough

We are committed to engaging with a diverse audience particularly those in under-represented groups, including women. To help us with this initiative we have partnered with Robogals’ Loughborough University chapter who visit girls’ schools to run robotics workshops. In these fun and educational classes, students learn the basics of engineering, robotics and programming.

Work Experience Opportunities

The EPSRC Centre offers exciting opportunities for students, including work experience and internships. We also engage with students through various university programmes.

This year we had two undergraduate students, Hans Tang and Edd Macey, from the Wolfson School of Mechanical and Manufacturing at Loughborough University who were a part of an eight-week internship programme.

Hans worked on a project that evaluated the SICK Ranger E camera when running at high profile speeds and its effects on the quality of the image and data output. Whereas Edd was involved in one of our industrial outreach projects that focused on developing a prototype design for a percussion instrument.

“Being involved in an internship at the Centre has allowed me to integrate skills I’ve developed during my placement year and my degree through research in a challenging environment.”
- Hans Tang

“The exciting range of projects running at the Centre combined with its welcoming ethos, makes it an ideal place to experience the world of engineering research. Thanks to the Centre’s strong links with the University, I have been fortunate to spend two Summers here experiencing first hand cutting edge work and make my own contribution. I have learnt a huge amount from my five months here and will be taking forward many of these skills into my next opportunity.”
- Edd Macey
Academic and Industrial Outreach

A core aim of the National Centre is to build the intelligent automation community in the UK by identifying and bringing together academics and industry in knowledge sharing relationships. We strongly believe that for the work of the National Centre to have maximum impact it should not exclusively benefit those who can contribute the most, but should help to build a knowledge base that can support the development of world leading innovative manufacturing practice across the country, scaled appropriately to individual needs.

As part of the commitment to academic outreach, two feasibility study calls have been launched to date. Groups from across the UK have been able to apply for funding of up to £50,000 to explore new areas of intelligent automation research. In the first call funding was offered to four teams (Total £140,000):

- **Machine-Learning of Vision-Guided Bi-Manual Grasps, for Adaptable Autonomous Manipulation in Manufacturing Environment**
  
  Dr Rustam Stolkin, University of Birmingham

- **Soft, Safe and Variable Stiffness Continuum Manipulators for Intelligent Automation**
  
  Professor Samia Nefti-Meziani, University of Salford

- **Use of Gaming Interface Technology for Decision-Making in Intelligent Automation System**
  
  Professor Ashutosh Tiwari, Cranfield University

- **HRI Team Work Study**
  
  Professor Tony Pipe, Bristol Robotics Laboratory

A further call was launched in 2015 from which 3 additional feasibility studies will be funded by the end of the year.

**SME outreach utilises the capacity of academic staff and researchers to explore opportunities for EPSRC Centre work to benefit the wider industrial community. Through our outreach programme, we have continued to identify automation issues for smaller manufacturers, capturing data on human skill for individual processes and exploring ways to address their automation challenges.**

Projects have included the design of a system for automated percussion beater winding and the assessment of automation potential for a furniture manufacturer. Where appropriate, funding routes such as Knowledge Transfer Partnerships, are explored to enable SMEs to benefit from longer term engagement with the EPSRC Centre.

Collaboration with SMEs has both created new areas of research within the Centre and provided inspiration for extending existing projects, such as further development of our work on electro-adhesion, within the mobile robots research stream.
Figure 46
Quality Furniture Company shop floor.
European Robotics Challenges

EuRoC

This competition is funded from the European Union’s Seventh Framework Programme under grant agreement no. 608849. The initiative is divided into three industry-relevant challenges. The EPSRC Centre is competing in Challenge 2: shop floor logistics and manipulation. We have successfully progressed through to Stage 2 of the competition. Of the five teams selected from Stage 1, our team includes the only UK competitors across all the challenges. The team consists of four members: Loughborough University, the University of Birmingham, the MTC and Airbus in Hamburg as an End-User of the proposed technological advancements. We are focused upon the development of dexterous grasping and supporting human operators during repetitive manufacturing tasks using a mobile robot unit and lightweight robot arm.
Third Annual Meeting of EPSRC Manufacturing Fellows

Since February 2012, EPSRC’s Manufacturing the Future (MtF) theme has operated a successful Manufacturing Fellowships scheme. This scheme is designed to encourage researchers in industry to make a successful transition to an academic research environment and in so doing, become a recognised leader in their field. Dr Peter Kinnell hosted the third annual meeting of Manufacturing Fellows at Loughborough in April this year. The meeting was attended by 14 fellows, who took part in a workshop to discuss how intelligent technology, including robotics and autonomous systems, are most likely to impact on future manufacturing. Modelling, experimental testing and manufacturing of electroadhesive pads is being carried out within the centre. Results of which will be published shortly.
ONE TO ONE INTERVIEWS

To maintain the UK’s global research standing in the context of increasing international competition, the EPSRC awards Fellowships in support of individuals who have the most potential to deliver the highest quality research which meets UK and global priorities.

Three members of staff within the EPSRC Centre have the distinction of being awarded these Fellowships. In interviews below each award recipient discusses their strategic priorities, areas of focus where growth is required and where they can integrate their work into the wider landscape.

Sarah Fletcher
Senior Research Fellow, Cranfield University

The launch of the EPSRC Centre in 2011 is important as it signifies the UK’s imperative to augment developments in intelligent automation in order to improve manufacturing efficiency and global competitiveness. The Centre’s recognition of the importance of human factors also reflected the relevance of incorporating social science with engineering and physical science to establish effective developments. This recognition has not only enhanced the relevance of my work, but has enabled cross-disciplinary collaborations with engineers, both of which have given me particular satisfaction and motivation.

From the Centre’s inception, we have pursued two principal human factors research themes: human-robot collaboration and capture of human skill for automation. Two Centre researchers, George Charalambous and Jamie Everitt, have worked on individual PhDs for these themes and have, at key points, worked in collaboration with other researchers. As one of these PhDs has now been successfully completed, and the second is due to be completed later in the year, it is now an important challenge for us to continue to explore these key themes and develop further collaborations and joint outputs. I want to see collaborative endeavours between engineering and social science researchers not only continue to grow in the future, but become more instinctive and automatic. So, there is a challenge for us to keep developing opportunities for cross-disciplinary collaboration within these two themes and to try to reach the point where our researchers habitually consider human factors integration.

In October 2014 I won an EPSRC High Value Manufacturing Catapult Fellowship to conduct research with the Advanced Manufacturing Research Centre at Sheffield University for integration of human factors into the design of industrial augmented reality (AR) systems. This three-year programme of work, which began in March 2015, will specifically investigate the key physical and cognitive factors related to wearable optical head-mounted displays (e.g. intelligent glasses for the presentation of information) and adaptive assembly workbench systems (shop floor workbenches with on-screen and projected visual indicators to aid assembly tasks). Although this work is not directly related to manufacturing robotics/mechatronics, it links well to the EPSRC Centre work because we know that manufacturing systems are going to become increasingly digitised and, as part of that, industrial AR systems will be key elements that provide essential intelligent informatics to both human and technical processes.
In the UK we have an excellent track record of creating innovative automation solutions. However, there are still many challenges that are simply not feasible. To remain globally competitive as a manufacturing nation, we need new approaches - building more intelligent automation solutions will be a critical part of this.

Having experienced research and development in industry, both creating new ideas and transferring technology from academia, I have first-hand experience of how difficult it is to take good science and convert it into a good product or process. As it is rare for any one team to handle the full technology creation process, for me a critical factor in the creation of new technology has to be communication and the rigorous transfer of knowledge and experience gained by successive research and development teams. What I really like about the EPSRC Centre is that it has built very strong links with the engineers at the MTC to make sure new knowledge is successfully communicated to the next stage of the development cycle.

The Centre over the last year has really started to focus on creating fully integrated automation systems. There have been a number of really great outputs related to very exciting technologies. I have been particularly impressed by the work undertaken to create multi-sensor approaches to robot mounted metrology and inspections.

Linked to the Centre’s activities, I have recently started a five year EPSRC Manufacturing Fellowship entitled Collaborative Metrology for High Value Manufacturing. The aim of the project is to investigate how manufacturing processes can be monitored and controlled by combining more effectively the wide range of sensor, instrument and quality data that are typically available in modern manufacturing environments. Within the Centre, the main focus will be on how robot mounted sensors may be more effective deployed in factory environments, and how 3D vision sensors may be combined with other sensor technology to improve robot capability.

I am looking forward to extending our activities in the area of machine learning and autonomy. We have some really exciting plans for new research projects in these areas.

Peter Kinnell
Senior Lecturer, Loughborough University
The EPSRC Centre has been provided with 400 square metres of dedicated lab space at Loughborough University along with access to state of the art research facilities in a further 400 square meters of lab space at Cranfield University. Academics and researchers work collaboratively across the two sites and out with industrial partners, sharing their complementary expertise to develop truly multidisciplinary research.

The laboratories house a range of industrial robot cells. These include a pair of Yaskawa twin arm robots mounted in a cooperative working cell for complex assembly operations. This is a unique capability within the UK and represents a key investment within the EPSRC Centre. These 15-axis dual-arm robots provide “human-like” flexibility of movement and are able to replace operations that are traditionally performed by humans. This exclusive facility is being used for various projects where human dexterity is being replaced by automation. The general application domains include, fixtureless and tool-less operations, such as assembly tasks and manufacturing.

The EPSRC Centre is fortunate to have many other robots from a range of manufacturers, including Comau, ABB, FANUC, Kuka and Universal. The core equipment also extends beyond industrial robots to include a range of devices such as force and torque sensors, adaptive grippers and a range of both 2D and 3D cameras and systems which are integrated by the research team.

The Centre also has a number of real world application cells. These include, but are not limited to, 3D weld seam tracking and TIG welding and polishing of complex geometry and surface inspection cells; all of which are fully integrated into the robot system giving added value to our industrial partners.

Increasingly, the EPSRC Centre builds and commissions bespoke equipment to meet the needs of a unique portfolio of projects.

Central to the human factors work, there is also a suite of equipment utilised to better understand how people complete manufacturing tasks. Key purchases include eye-tracking glasses and a motion capture suit. The glasses are used for analysis of eye movement and visual attention in task performance. They also provide vital insight into awareness during safety critical activities. The suit is used to measure biomechanics and kinematic motion. As it utilises a non-optical system, it can be used to analyse activity within hidden internal locations such as when an engineer needs to climb into a large structure that they are working on, or within. We are the first research group within the UK to have a fully functional link between the Haption suite and the Delmia suite of software, allowing us to import real human movements into CAD models and perform offline reruns of tasks.
Journal

Publications

2015


2014


2012


Conference Presentations

2015


2014


2011


### European Engagement

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