Institution: University of Portsmouth		
Unit of Assessment: UoA 11: Computer Science and Informatics		
Title of case study: Robotics research improves support for autism spectrum disorder and stroke patients		
Period when the underpinning research was undertaken: 2010 - 2019		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Prof Honghai Liu	Professor of Human Machine Systems	19/09/2005 - date
Prof Hui Yu	Professor of Visual Computing	01/10/2012 - date
Dr Zhaojie Ju	Reader in Machine Learning and Robotics	24/09/2012 - date
Dr Dalin Zhou	Senior Lecturer in Computer Science	16/10/2017 - date
Period when the claimed impact occurred: 2015 - 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Delivering care to children with autism spectrum disorder (ASD) and victims of a stroke is particularly time consuming and expensive. Deploying the results of our research provides a 20% cost reduction in the former and a 10% reduction in average treatment periods for the latter. The ASD research has so far benefitted over 300 patients globally. Our rehabilitation research also reached hundreds of patients globally and led directly to the expansion of a local health technology company. We achieved this through the development of new technology and the drafting and dissemination of practice guidelines, both nationally and internationally, for autism intervention and post-stroke rehabilitation. Our multi-sensory fusion, computational intelligence and robotics research has led to new facial-recognition techniques, robot-enhanced therapies, physiological sensing technologies, human behaviour analysis and multi-fingered robotic hand prosthetics by the University of Portsmouth (UoP). This has changed the way the health sector provides support for patients with long-term health conditions.

2. Underpinning research

The underpinning research focused on the development of multi-sensory fusion, computational intelligence and robotics for rehabilitation of patients with limb impairment, facial palsy from stroke and support of children with autism.

Rehabilitation Research

Context: The ability to detect and analyse the complex motions of the human hand or face is key to addressing several unmet needs related to active healthcare and stroke rehabilitation, and can improve recovery. Prof Honghai Liu and Dr Dalin Zhou's research, such as **(R1)**, was mainly done in collaboration with Shanghai Jiao Tong University, China. A portable 16-channel Electromyography (EMG) system for sensing and analysis of human hand motion (grasp types and multi-fingered manipulation) to actively support rehabilitation of the upper limb motor function in stroke patients was developed. It also assisted the recovery of amputees. At the core of the EMG system is its multi-modal fusion integrating pressure, position, haptics, ultrasound sensors plus the corresponding computational intelligence model (Fuzzy Gaussian Mixture Models). The system provides accurate recognition of users' intention for upper limb motion, enabling active rehabilitation. The research was supported by an EPSRC First Grant, for Liu **(G1)** with UoP as Lead Research Organisation and project partners Bristol Robotics Laboratory, Shanghai Jiao Tong University and Tokyo Metropolitan University. Prof Hui Yu's research **(R2-R4)** has developed easy to use facial palsy therapy technologies, which can provide automatic facial palsy grading and real-time feedback assessing treatment responses of patients. At the core of the system is a deep learning architecture combining a convolutional neural network and a Long Short-Term Memory (LSTM) network that can capture both asymmetric facial features and temporal information of facial movement for accurate facial palsy grading. Facial palsy management is expensive. The NHS National Clinical Guidelines for Stroke physiotherapy recommends 45 minutes daily facial therapy for patients with facial paralysis. To meet the guidelines, each patient would need daily face-to-face therapy for a period of at least 12 weeks (broadly defined as the

acute phase), costing the NHS £2,400 per patient. The developed technologies can provide patients with real-time feedback when undergoing therapy at home and thus could significantly reduce the time of visiting therapists for face-to-face feedback, and therefore costs to the NHS. This research has been supported by grants from EPSRC, Innovate UK and the Royal Academy of Engineering **(G2-G4)**

Findings: The research showed that multi-modal sensing and analysis can measure EMG-driven hand gestures and manipulation with high accuracy. The hardware design, combined with EMG and ultrasound sensors, and integrated computational intelligence algorithms of Fuzzy Gaussian Mixture Models can better capture limb-impaired users' motion intention. Likewise, facial rehabilitation research developed a novel two-step framework – Multi-subspace SDM as part of a facial tracking application that could track the user's face with 66 landmarks in real-time. This application can robustly track the face within a large range of head poses and facial expressions, while having low hardware requirements to run smoothly on an Android smartphone. Research (**R1-R4)** demonstrates the feasibility of our approach for applications such as prosthetic hand control, remote manipulation, virtual reality, treatment of neuropathic pain or stroke.

ASD Intervention Research

Context: Liu led the development of the DREAM project, funded by the European Commission (EC) in 2014 to deliver the next generation of robot-enhanced therapy (RET) **(G5, G6)**. This was the first EU study with large-scale clinical trials to attempt to develop clinical interactive capacities for social robots operating autonomously under psychotherapist supervision. DREAM delivered the next generation RET with clinically relevant interactive capacities for social robots operating autonomously. It was developed through over 3,000 therapy sessions and over 300 hours of therapy **(R5)**. Conducted between 2014 and 2019, DREAM was led by UoP (Liu), with Ju, Yu and Zhou. Underpinning research involved collaborator and partner organisations University of Skövde, Vrije Universiteit Brussel, Universitatea Babeş-Bolyai, Plymouth University, De Montfort University, and Aldebaran Robotics. Studies **(R6 & R7)** on non-contact sensing, multi-sensory data fusion and smart environment design were to improve the autonomy of robots to enable the RET.

Findings: The core of the DREAM RET robot is its cognitive model which interprets sensory data (body movement and emotion appearance cues). It uses these perceptions to assess the child's behaviour by learning to map these to therapist-specific behavioural classes. It then learns to map these child behaviours to appropriate robot actions as specified by the therapists.

Cross-disciplinary research involved computer vision, robotics, child psychology and engineering. As a result, the UoP team, together with our collaborators in China, has made significant advances in multimodal sensing and interpretation based human behaviour analytics like visual focus of attention (**R8**) and body movement (**R9**). The sensing system automatically extracts and fuses sensory features such as body movement, facial expression, and gaze features, that are associated with therapist-specified child behaviours. Thus allowing the identification of data that characterises children with ASD as a human therapist would **(R6)**. Clinical trials comparing RET and standard human treatment (SHT) indicate that RET can obtain equivalent performance for children with ASD **(R7)**.

3. References to the research

R1	Yang, X., **Zhou, D.,** Zhou, Y., Huang, Y., & **Liu, H**. (2018). Towards zero re-training for long-term hand gesture recognition via ultrasound sensing. *IEEE Journal of Biomedical and Health Informatics, 23*(4), 1639-1649. 10.1109/JBHI.2018.2867539 (selected as the feature paper)
R2	**Yu, H**. & **Liu, H** (2014). Regression-based Facial Expression Optimization. *IEEE Transactions on Human-Machine Systems*, *44*(3), 386-394. 10.1109/THMS.2014.2313912

R3	Liu, X., Xia Y., **Yu, H**., Dong, J., Jian, M., & Pham, T. (2020). Region Based Parallel Hierarchy Convolutional Neural Network for Automatic Facial Nerve Paralysis Evaluation. *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 28*(10), 2325-2332**.** 10.1109/TNSRE.2020.3021410
R4	Lou, J., Cai, X., Wang, Y., **Yu, H**. (2019). Multi-subspace supervised descent method for robust face alignment. *Multimedia Tools & Applications, 78*(24), 35455–35469**.** 10.1007/s11042-019-08129-4
R5	Billing, E. et al**.** (2020). The DREAM Dataset: Supporting a data-driven study of autism spectrum disorder and robot enhanced therapy. *PLOS one*, *15*(8), e0236939. (20 authors including **Liu, H**). 10.1371/journal.pone.0236939
R6	Cai, H.et al. (2018). Sensing-enhanced therapy system for assessing children with autism spectrum disorders: a feasibility study. *IEEE Sensors Journal, 19*(4), 1508-1518. (13 authors including **Ju, Z.** and **Liu, H**.) 10.1109/JSEN.2018.2877662
R7	Cao, H.L. et al. (2019). Robot-enhanced therapy: development and validation of supervised autonomous robotic system for Autism Spectrum Disorders Therapy. *IEEE Robotics & Automation Magazine, 29*(2), 49-58. (27 authors, including **Yu, H**., and **Liu, H**.). 10.1109/MRA.2019.2904121
R8	Cai, H., Liu, B., Zhang, J., Chen, S., & **Liu, H.** (2015). Visual focus of attention estimation using eye center localization. *IEEE Systems Journal, 11*(3), 1320-1325. 10.1109/JSYST.2015.2441952
R9	Liu, B., **Ju, Z**., & **Liu, H**. (2018). A structured multi-feature representation for recognizing human action and interaction. *Neurocomputing, 318*, 287-296. 10.1016/j.neucom.2018.08.066

Evidence for the quality of research

The underpinning research is published in high quality international peer-reviewed journals. The research behind the RET robotic system **(R5-R9)** is the first effort to facilitate intervention for children with autism. It also offers a 20% reduction in human resource requirement compared with SHT. Our work sets the standard for the next generation of RET systems. The outcomes in **(R1)**, which was selected as a feature paper, are leading international research in wearable ultrasound sensing.

Research grant funding

G1	**Liu, H**. *Exploring human hand capabilities into multi-fingered robot manipulation.* Funded by the Engineering and Physical Sciences Research Council, March 2010-September 2013 (GBP295,150).
G2	**Yu, H**. *4D Sensing System for home-based facial palsy therapy*. Funded by the Engineering and Physical Sciences Research Council, September 2016-August 2018 (GBP100,609).
G3	Cox, G. & **Yu, H**. *SEEM: Sensor-Enabled Emotion Monitoring Eyewear*. Funded by Innovate UK, November 2017- April 2019 (GBP135,776 in total, GBP35,450 to UoP).
G4	**Yu, H**. *Dynamic Facial Expression Reconstruction from Upper Half-face Data*. Funded by the Royal Academy of Engineering, September 2018-December 2018 (GBP20,148).
G5	**Liu, H**., **Ju, Z**. & **Yu, H**. *Development of Robot-Enhanced therapy for children with AutisM spectrum disorders (DREAM)*. Funded by the European Commission, March 2013-August 2018 (€8,721,727 in total, GBP695,415 to UoP).
G6	**Ju, Z.** & **Liu, H**. *Development of Robot-Enhanced therapy for children with AutisM spectrum disorders (DREAM) -Extension.* Funded by the European Commission, October 2018-March 2019 (GBP145,243).

4. Details of the impact

Research undertaken by the University of Portsmouth on both ASD intervention and motor function rehabilitation enhances people's lives by improving their health outcomes and accelerating the timescale of therapies. The research also reduces the cost of the therapies to healthcare providers and therefore society. Dissemination activity has increased awareness by practitioners of the benefits of technology enhanced therapy as a better way to help patients, particularly for children with ASD and patients with limb impairment or facial palsy.

Rehabilitation

Post-stroke motor function rehabilitation context

The Stroke Association states that, in the UK, 100,000 people have strokes each year, and there are 1,200,000 stroke survivors. Post-stroke impaired motor function in adults leads to serious social and economic impacts with an annual cost to the public purse of an estimated GBP8.6 billion for the UK. The recovery of motor function helps patents to return to work and enables them to be economically active more quickly after rehabilitation.

Since 2017, our motor function rehabilitation research output, the EMG-ultrasound multimodal sensing and analysis device **(R1)**, has been adopted for hand motion recognition by healthcare providers in a rehabilitation centre and a hospital in the UK and China. So far, over 300 patients have benefitted. The sensing and recognition device provides a more robust estimation of the patient motion intention during rehabilitation and enables active upper-limb motor function rehabilitation **(S1)**. The active training enabled by the motor function rehabilitation research is recognised by Hobbs Rehabilitation Limited (HOBBS) **(S2)** whose staff benefit from "*knowing a better way to help the patients*" and by Ruijin Hospital, China (RUIH) in "*an easy-to-follow hint in practice of both stroke research and patient recovery*" **(S3)**.

Economic and health impacts of rehabilitation intervention

Health impacts include a faster recovery for patients. [Text removed for publication] HOBBS quantifies the benefit, stating "*The intelligent sensing and recognition of motion intention is estimated to reduce the average treatment period for each patient by 10%, equivalent to 1 month. This means that patients are able to return to their lives and their families quicker by recovering sooner*." **(S2)**. A qualitative indicator of our impact is improved patients' experience of "*a more natural rehabilitation protocol to follow and perceive*" at RUIH **(S3)**.

Economic and health impacts result from having a more efficient protocol for recovery, which is demonstrated by its clinical application and evaluation both nationally and internationally. 30 post-stroke patients in HOBBS and 50 post-stroke patients in RUIH have received active rehabilitation of motor function. The economic impact is reflected by the benefit of "*saving the human resource and cost*" presented by HOBBS **(S2)**. Patients' early return to economic activity reduces the burden on the public health system and individual families, which is supported by "*an earlier return to well-functioned daily activities by an average of 20% less time consumption*" observed in RUIH **(S3)**.

The underpinning research, in particular **(R2-R4)**, has also led to impact in the commercial sector, through Liu and Yu's work with a Brighton-based health technology company, Emteq Ltd. [Text removed for publication] **(S4)**.

Autism Spectrum Disorder intervention

Autism is a neurodevelopmental disorder characterised by impaired verbal and non-verbal communication, compromised social interaction, and restricted and repetitive behaviour. According to the Centre for Disease Control and Prevention (CDC), the prevalence of autism is increasing, with about 1 in every 54 children reported as identified with ASD in 2020 compared with 1 in every 110 children in 2012. The prevalence and significance of autism led to its identification by CDC as an 'urgent public health concern'.

Since 2018, our ASD intervention research **(R5-R9)**, an intervention robot platform, has been deployed internationally to support over 300 children with ASD. The platform with the DREAM

robot enhanced therapy functions as a diagnostic and intervention tool mediating between therapists and ASD children by collecting clinical data. Novel guidelines were created for ASD diagnosis and intervention, and provided with the DREAM RET. These have so far been followed for child behaviour monitoring in Shanghai Ciyuan Rehabilitation Hospital (SCRH). In addition to monitoring children's behaviour individually, the RET has been used in clinical trials for ASD diagnosis and intervention in the Children's Hospital of Fudan University (CHFU).

Economic and health impacts of ASD interventions

Our ASD diagnosis and intervention has reached 80 children in CHFU who stated "*facilitating repeatable, consistent child-specific interventions across sites did improve the cognitive training quality*" **(S5)**. The ASD intervention provides economic benefit to the healthcare provider by reducing the staff time required. This is achieved by cost-effectively capturing multi-sensory data which replaces current labour-intensive techniques involving paper and pencil or manual video analysis. The impact is international and reflected by the statement from therapists of SCRH that "*Increased autonomy of robots can enhance the quality of the digital description of children with ASD by 30%*", which improved outcomes for 40 children with ASD at SCRH. [Text removed for publication] CHFU [text removed for publication] states that "*The robot platform increased effectiveness and efficiency of intervention by 20% that can reduce cost and free up human resources by 20%*" based on the intervention involving 120 children and 6 therapists.

The RET enabled by the ASD intervention research provides CHFU with "*a great way to free the doctors from repetitive observations in ASD diagnosis and intervention with improved efficiency*" **(S5)** and SCRH with "*a useful tool to capture ASD children's subtle behaviour changes*" **(S6)**.

Since 2015, the ASD intervention research outcomes have been disseminated helping us to drive and increase the impact. This has been done through events and peer reviewed publications, to the public through media reports **(S7)**, and to practitioners in four international conferences with recognition of best paper awards and finalists **(S8)**. In the UK, we have updated healthcare providers and their stakeholders (such as rehabilitation centres) of the economic impact through networking events **(S9)**.

5. Sources to corroborate the impact

S1	Letter of support from the University of Waterloo for employing the wearable ultrasound sensors
S2	Letter of support from Hobbs Rehabilitation Limited (the motor function rehabilitation centre) for post-stroke patients' recovery
S3	Letter of support from Ruijin Hospital for post-stroke study and patients' recovery
S4	Letter of support from Emteq Ltd outlining some economic benefits [text removed for publication]
S5	Letter of support from Children's Hospital of Fudan University using the complete RET for children with ASD 18/09/2020
S6	Letter of support from Shanghai Ciyuan Rehabilitation Hospital using monitoring part of the RET for children with ASD
S7	Media reports, including an exclusive article in the Daily Mail and subsequent popular science articles and social media activity relating to the DREAM project.
S8	Best paper awards and finalists in scientific conferences of HSI2015, HSI2016, and ICIRA2017.
S9	Reports of IEEE SMC Portsmouth Chapter sponsored and locally organised events. These attracted both an expert audience from academia, industry and clinics and the public whose interest and awareness in the therapy was raised 13/11/2020.