Institution: University of Manchester		
Unit of Assessment: 12 (Engineering)		
Title of case study: Robotic and mechatronic manufacturing of 3D shell-shaped textile products to deliver medical and structural textile reinforcements		
Period when the underpinning research was undertaken: 2001 – 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:**
Prasad Potluri	Professor of Robotics and Textile Composites	1994 – present
Tilak Dias	Senior Lecturer	1992 – 2010
Anura Fernando	Lecturer (2010 – present) Research Associate (pre 2009)	1997 – present (one year career break in 2009)
Period when the claimed impact occurred: August 2013 – July 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Mechatronics and robotics research into 3D shell-shaped textile products undertaken at the University of Manchester has delivered benefits in two major fields of application:

Medical device development: Research into fabric behaviour, and technological manufacturing developments resulted in the creation of a novel compression garment technology – Scan2Knit. Scan2Knit is used globally in healthcare to treat patients needing compression garments, as well as in sport to increase post-exercise muscle recovery. Scan2Knit is now commercially licensed to Advanced Therapeutic Materials Ltd.

Advanced composites winding technologies; A 9-axis robotic winding device was conceptualised through this research. This novel technology has been transferred to Cygnet Texkimp, winner of the UK Composites Innovation of the Year Award 2017, and has boosted annual company revenue by GBP1,000,000.

2. Underpinning research

In 1988, Professor Porat at the University of Manchester (UoM), established research activity into novel computer-aided textile weaving solutions. Since 2000, these tools and techniques have been further developed to support the manufacture of complex woven/knitted patterns, shapes and geometries with strength and stiffness properties that enable manufacturing challenges to be addressed. This has collectively been applied in two areas: 3D knitting [1-4] and 9-axis robotic winding [5-6]. The common principle is to place the textile material in a helical path around a three-dimensional central axis. 3D knitting provides the basic approach here by constructing an expandable material suitable for providing external support, while 9-axis winding constructs a textile material that is an internal support for another engineering material.

i) Medical Devices and Garments

From 2001, UoM researchers investigated methods to model the (previously un-researched) interface pressure of knitted elastomeric structures for compression therapy. Using mathematical algorithms, they developed empirical data models that predicted pressure profiles of honeycomb-knitted elastomeric-fibre structures [1]. This demonstrated how simple CAD (computer-aided design) programming could predict the mechanical behaviour of knitted fabrics, in terms of structure and yarn properties.

As part of this body of work, in 2001, UoM researchers collaborated with the (then) Director of Vascular Studies Unit at South Manchester University Hospital, (SMUH). Wellcome Trust funding (GBP500,000) enabled them to develop the basic science and technology for the manufacture of patient-customised compression stockings with an engineered 3D pressure profile. This led to the development of 3 patents [2, 3, 4] and a fundamentally new approach to the manufacture of pressure control garments, named Scan2Knit [2].

The Scan2Knit CAD software created precise knitting templates for compression garments, capable of delivering a predetermined medically required pressure profile. This software included two key innovations. Firstly, the 3D scanning technology captured the surface geometry of affected limbs enabling the garment to precisely address the patient's need. Secondly, the 3D limb scan data allowed the calculation of both the knitting pattern and required length of yarn for the support sleeve. This influences the stitch length (through a precision yard feed device) and, as a result, the strain properties of the garment. Through these means, the desired shape and pressure characteristics of the garment can be defined.

Scan2Knit included the development of a yarn feed device [3], capable of delivering precise lengths of yarn - from supply to use point - at a rate required by that use point. Simultaneously, a needle-tracking innovation for knitting machines was developed [4], ensuring the yarn delivery system remained synchronised with the needle's yarn requirements during the knitting process. Collectively, [3] and [4] prevented the over-extension of elastomer yarn during knitting, avoiding distorting the desired garment shape and pressure profile. This enables Scan2Knit garments to avoid pressure necrosis occurring through incorrect pressure profiles.

ii) Advanced Composites

UoM 3D shell-shaped textile research has also contributed to the development of rigid structural composites within engineering. Composite materials provide various mechanical, electrical and corrosion advantages over conventional material systems such as metals, and are engineered using high-performance textile reinforcements. However, traditional textile machinery such as filament winding has limitations in developing multi-axis shell shapes, such as 'A' pillars or cant rails in motor vehicles or handlebars for racing bicycles. Traditionally, 3D shell-shape textiles for engineering composites are made using 2-axis filament winding machines. However, complex shape composites require multi-axis fibre layup winding. Commercially available filament winding machines use multi-axis fibre delivery systems with one axis of movement for the composite. This one-axis rotary movement is a key limiting factor for producing complex shapes through traditional winding: more advanced winding machines are expensive and time intensive.

In 2005, UoM researchers conceptualised a 9-axis robotic winding design, developing a prototype with support from Festo GB Ltd. The 9-axis winding concept has six axes of movement for the material, with three axes of fibre manipulation capability [as applied in 5, and shown in Figure 1].

This concept removes the limitations of traditional single axis concepts, enabling greater production speeds. This design enables the machine to produce otherwise unprecedented complex engineered shell-shaped structures for various industries including aerospace, automotive, sports, and building construction. As part of an Innovate UK Knowledge Transfer Partnership (KTP), the 9-axes rotating bobbin/spindle technology was integrated with a multiaxial robotic arm at Cygnet Texkimp, which resulted in a 3D winding system capable of winding complex shapes [6].

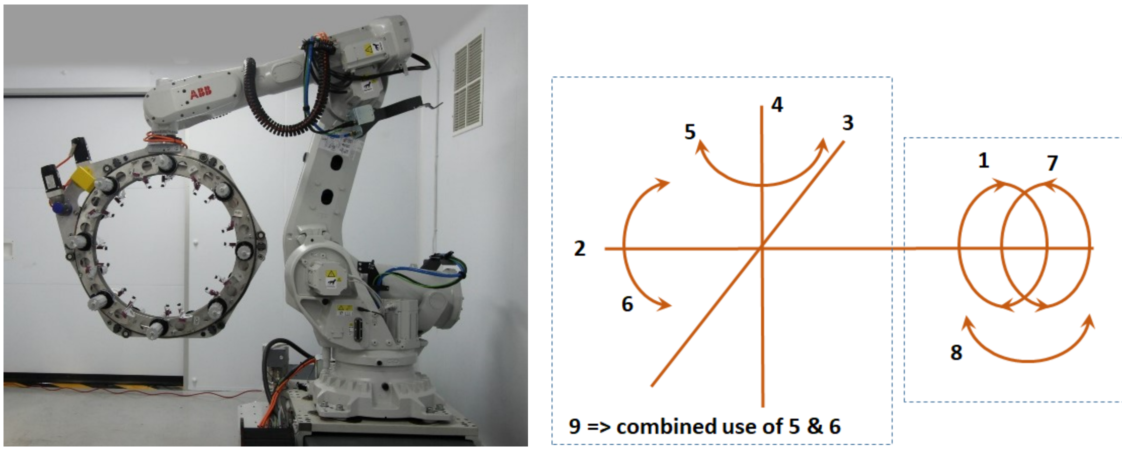

Figure 1. 9D winding device with schematic of rotations

3. References to the research

This research was published in international journals [1, 5] and presented at leading international conferences in the field [6]. The work also resulted in 3 patents [2 – 4], and was funded by the Wellcome Trust (GBP500,000), and UK Government Department of Health (GBP313,000). The advanced composites work has been funded by the (former) UK North West Regional Development Agency (GBP2,300,000, 2007-09), InnovateUK (GBP1,600,000, 2009-11) and an InnovateUK KTP (GBP235,000, 2015-18).

[1] **Dias T.**, Yahathugoda D., **A. Fernando** and Mukhopadhyay SK. (2003) Modelling the Interface Pressure Applied by Knitted Structures Designed for Medical-textile Applications, *Journal of the Textile Institute*, **94**:3-4, p77-86, DOI:10.1080/00405000308630630

[2] **Dias T**., Cooke W.D., **Fernando A**., Jayawarna D., and Chaudhury N., *Pressure garment (patent)*, US7043329, WO03040449, JP2005508456, EP1444393, March 2005

[3] Challis S; **Fernando A**; **Dias T**, Cooke W, Chaudhury N H, Geraghty J, and Smith S, *Precision delivery system (patent)*, US6745598B2 June 2003

[4] **Dias T**., Cooke W.D., and **Fernando A**., *Improved knitting machines and methods of knitting (patent)*, GB2400861, US2007180863 , US7421860, JP2007501338, WO2005014903, 2005

[5] Roy SS., **Potluri P**. and Soutis C. (2017) Tensile Response of Hoop Reinforced Multiaxially Braided Thin Wall Composite Tubes. *Applied Composite Materials*, **24**, p397–416, DOI: 10.1007/s10443-016-9570-8

[6] Liu Y., **Potluri P**., Roy, SS., Li X., Taylor, C., Shah R., Whitham A., and **Fernando A.** (2018) *Comparative evaluation of braiding and 3d complex winding for automotive chassis frames*, ECCM18 - 18th European Conference on Composite Materials Athens, Greece, 24-28th June 2018

4. Details of the impact

The mechatronics and robotics research has resulted in benefits in two main applications:

Medical devices improve patient treatment and outcomes

Conditions such as leg ulcers, deep vein thrombosis (DVT) and lymphoedema are traditionally treated by compression therapy; four layers of elastic compression bandaging tightly wrapped around the affected area. These can be uncomfortable and must be applied by trained medical staff once or twice weekly to ensure the required levels of pressure. Leg ulcer treatment costs the NHS over GBP400,000,000 per year, with 1.5% of the elderly population affected [A]**.** The costs for treating venous insufficiency, which may follow DVT, are even greater with approximately 2.24% of the UK population suffering from this condition at any given time (1,500,000 people) [A].

In response to these challenges, the Scan2Knit system (developed between 2001-2005) produces made-to-measure compression stockings that can be pulled on and off like conventional stockings [1-4]. In 2004, with the support of UMIP (UoM service to support the commercialisation of research, now University of Manchester Innovation Factory), the Scan2Knit system was licensed commercially to Advanced Therapeutic Materials (ATM) Ltd. ATM started commercial production of compression garments (under the registered trademark Isobar Compression garments) for the medical and sports industries [B]. [Text removed for publication].

The garment is engineered to the exact profile of an individual patient's limb, with a pressure profile specific to the patient's clinical needs [C]. Alternative compression methods are unable to achieve this specificity. As confirmed by Isobar's Chief Medical Advisor:

> *""Now, for the first time, we are able to deliver the precise pressures needed for each indication, whether increasing performance and recovery for elite athletes, DVT prevention, or treating lymphoedema and leg ulcers. This is something that cannot be achieved by any existing compression stocking or bandaging system."[D].*

[Text removed for publication].

Whereas traditional ulcer bandage treatments must be changed twice a week, accounting for at least 1 hour per week of clinical time, Isobar Compression garments can be changed less frequently, due to the custom pressure profile [B]. Based on the bandage costs alone, it is estimated the Isobar treatments are cost effective within 12 weeks of treatment [E]. [Text removed for publication].

Further, as a Leg Ulcer Specialist Nurse at the Wythenshawe Hospital has confirmed, "*Using the Isobar hosiery [they] have empowered many patients to self-manage their ulcer care*" [E]. Wythenshawe Hospital in Greater Manchester started using the Isobar Compression garments in February 2017. Between then and July 2020, over 250 patients have been scanned for the treatment [E].

Isobar compression garments also produce sports specific products to enhance performance and, prevent DVT. Professional athletes including Olympic gold medal triathletes Alistair and Jonathan Brownlee, Ultra-endurance specialist Jasmijn Muller and Team GB bobsleigh athlete Bruce Tasker endorse the Isobar compression garment [D]. Likewise, the Lead Physiologist for British Cycling and English Institute of Sport states:

> *"From an applied sports science perspective, there are two main pro's* (sic) *of the Isobar garment. The 3D scan guarantees a perfect fit and the garment provides an effective level of compression to reduce venous transit time and reduce leg volume"* [D].

Enabling innovation in the Advanced Composites industry

Between 2016 and 2018 the 9-axis robotic winding device [5, 6] was transferred to Cygnet Texkimp through the InnovateUK funded KTP programme [F]. Cygnet Texkimp provides specialist knowledge and bespoke machinery for the global technical fibre and fabric, paper, plastic, foil and film processing markets, with more than 95% of sales resulting from international export to over 30 countries globally. As a result of the KTP, Cygnet Texkimp developed a robot-assisted multi-axis filament winding machine, capable of quickly, robustly and continuously winding carbon fibre composite structures. At the time Cygnet Texkimp were not aware of any commercially available product that offered this combination of complexity, accuracy and speed [G]**.** This 3D winder technology, earned the company the UK Composites Innovation of the Year Award (2017) [G].

The KTP between UoM and Cygnet Texkimp increased the company's product portfolio by expanding their knowledge of dry fibre placement systems. Specifically, Cygnet Texkimp have attributed the following to the 3D Winder device that resulted from the UoM research [H]:

- The filament winding device has provided income to date of approximately GBP1,000,000;
- Since 2016, annual exports have grown by approximately GBP250,000 per year;
- Cygnet Texkimp employed the UoM KTP associate directly following the end of the KTP, showing the value they place on the knowledge, skills, and in-house R&D stimulated from this research;
- Cygnet Texkimp secured new clients and contracts that have either directly resulted from the filament winding, or more generally from being able to demonstrate this equipment in action.

Indirectly, Cygnet Texkimp have also attributed further benefits from the original research into the 9-axis robotic device [5,6]. Cygnet Texkimp have confirmed that as a result of expanding their product range, they have been able "*to tender for new business that [they] previously were not equipped to supply*", which has also increased the resilience of the company to market fluctuations; "*due to the increase in product streams [Cygnet Texkimp] have been more robust during some challenging periods*" [H]. The machinery demonstrated their ability to tackle bespoke equipment challenges, and also provides a useful sales tool. Cygnet Texkimp have said, "*we would not have been able to complete this work alone, nor have a leading global-market edge, if it were not for the initial transfer of research from the University of Manchester*." [H].

5. Sources to corroborate the impact

[A] Medical stockings press release (2006) Confirming the cost of NHS treatment. [Available at https://bit.ly/3p9BGMC]

[B] Letter of support from Director, Advanced Therapeutic Materials Ltd (for the Isobar Compression Garments), September 2020

[C] Case studies booklet confirming the technology used in the Scan2Knit product: UMIP (2007) *Case studies of licensing: Reputation and value through intellectual property*, University of Manchester, Manchester,

[D] Compilation of online articles attesting to benefits of Isobar Garments [Available at https://www.isobar-compression.com/news]

[E] Letter of support from Leg Ulcer Specialise Nurse at Wythenshawe Hospital, Manchester, November 2020

[F] UoM-Cygnet Texkimp KTP009891 Final Report

[G] Cygnet Texkimp press release (November 2017) "*UK Composites Innovation of the Year Award*" [Available at https://cygnet-texkimp.com/award/]

[H] Statement of support from Technical Manager, Cygnet Texkimp, January 2021