Institution: Sheffield Hallam University

Unit of Assessment: 26 Sport and exercise Sciences, Leisure and Tourism

Title of case study: 3D measurement systems

1. Summary of the impact

The Centre for Sports Engineering Research (CESR) has developed new methods to allow accurate 3D measurement. These methods have evolved from lab-based to *in-situ* systems allowing real world measurements using multi-camera systems, object tracking, signal processing and planar calibration. This research has had four main types of impact:

- the implementation of camera-based analysis systems embedded within Olympic teams in preparation for London 2012 and Rio 2016;
- the implementation of systems at the International Tennis Federation (ITF) to allow that organisation to monitor the game of tennis and set its rules;
- the transfer of knowledge and systems to the commercial and health sectors;
- dissemination to the research community.

2. Underpinning research

Between 2008 and 2010, Allen, Choppin, Goodwill and Haake (references 1, 2) carried out industrially sponsored research (grant a) to develop an understanding of dynamic tennis shots using finite element or Newtonian models. These models were validated experimentally using a bespoke impact rig with 3D photogrammetry to measure the complex motion of the racket and ball. The finite element model in reference 1 was the first to simulate accurately oblique-spinning off-centre impacts with a racket.

Allen used his model to look at the effect of tennis racket parameters on simulated ground-strokes showing that mass distribution rather than racket stiffness was the most important parameter. The work also highlighted the need to measure what happens during real play on a tennis court and Choppin *et al.* (2010; reference 2) used two high speed cameras and the planar calibration method to determine racket and ball motion at Wimbledon qualifiers. The work required the development of in-situ techniques with minimal interaction with the player to produce detail 3D information on the motion and dynamics of the racket and ball during play.

In parallel to this between 2006 and 2010, research was sponsored by the ITF (grant b) to create a method of automatically measuring ball spin during play. The work was used to develop laboratory systems at the ITF to determine the overall physics of spin generation in tennis (references 4, 5) using the knowledge of real play conditions. This work determined the effect of impact spin, speed and angle on rackets with 6 different string types with a wide range of friction coefficients. Multiple regression analysis showed that rebound was extremely complex and depended upon whether strings slipped throughout impact. Thus, friction between strings was much more important than friction between the strings and the ball.

The work described here marks a transition from lab-based studies to measurement in real environments. References 1, 2 and 3, between 2010 and 2013, showed that capture of useful 2D and 3D information in the field relies on a robust and practical camera calibration system, for which the planar calibration system was developed. The research demonstrated that planar calibration was superior to Direct Linear Transformation (DLT) in many real-life scenarios because reconstruction errors were smaller, the calibration object was simpler to use and errors scaled with the environment.

The work has moved into the research of low-cost off-the-shelf systems using depth cameras (such as the Kinect). In 2013, Choppin and Wheat (reference 6) explored the potential of these systems to measure body segment parameters, body segment angles and player tracking over a large volume. They showed that the centre mass position over a principal moments of inertia could be measured with root mean square error to ±3% using a Kinect (compared to a 12-camera motion capture system). While the overall accuracy was not good enough for all biomechanical analysis, it was shown that systems are capable of useful field measurements which will become more accurate as hardware improves.

The status of the researchers at Sheffield Hallam University is:

- Allen T, Senior Sports Engineer, 1/6/09-1/9/11; Senior Lecturer 1/9/11 onwards;
- Choppin, S, Sports Engineer, 1/6/09 onwards;
- Goodwill, SR, Senior sports engineer, 1/3/06 onwards;
- Haake SJ, Professor of Sports Engineering, 1/3/06 onwards;
- Kelley J, Sports Engineer 1/8/10 onwards
- Wheat J, Senior Research Fellow 1/8/10-31/8/12, Principal Research Fellow 1/9/12 onwards.

3. References to the research

All outputs were published in peer-reviewed journals. References 5 and 6 are the only ones not submitted to the REF; however, both are published in international journals.

1. **Allen T, Haake SJ & Goodwill SR** (2010) "Effect of tennis racket parameters on a simulated groundstroke", *Journal of Sports Sciences,* 29(3), 311-325. Scopus SJR 0.909. (Allen REF submission 1);
2. **Choppin, S.B., Goodwill, S.R. & Haake, S.J.** (2010) "Investigations into the effect of grip tightness on off-centre forehand strikes in tennis", *Proc. IMechE Part P: Journal of Sports Engineering and Technology,* 224, pp. 249-257. Scopus SJR 0.274 - 0.616. (Choppin REF submission 1);
3. **Choppin, S.B., Goodwill, S.R. & Haake, S.J.** (2011) "Impact characteristics of the ball and racket during play at the Wimbledon qualifying tournament", *Sports Engineering,*13 (4), pp. 163-170. Scopus SJR 0.283. Cited 7 times. (Goodwill REF submission 4);
4. **Haake, S.J., Allen, T.,** Jones, A., Spurr, J. & **Goodwill, S.R.** (2012) “Effect of inter-string friction on tennis ball rebound”, *Proc. IMechE,* Part J: 226 (7), pp. 626-635. Scopus SJR 0.274 - 0.616. (Goodwill REF submission 2);
5. **Allen, T.,** Ibbotson, J. and **Haake, S.J.** (2012) "Spin generation during an oblique impact of a compliant ball on a non-compliant surface", *Proc. IMechE,* Part P: 226 (2), pp. 86-95. Scopus SJR 0.274 - 0.616;
6. **Choppin, S**. and **Wheat, J.S.** (2013). The potential of the Microsoft Kinect in sports analysis and biomechanics. *Sports Technology*, **6**, 78-85.

Grants associated with the impact (*a-b cited in section 2; c-f cited in section 4*)

a. SJ Haake: Prince Racquets, £30,000, 1st Jun 2006 to 31st May 2009, PhD sponsorship of Tom Allen “Finite element model of a tennis ball impact with a racket”;
b. SJ Haake: International Tennis Federation, £30,000, 31st Oct 2006 to 30th September 2010, PhD sponsorship of John Kelley “Measuring ball spin rates in match play tennis”;
c. SJ Haake: UK Sport, £209,181, 1st Apr 2008 - 31st Mar 2012, UK Sport Innovation Partnership;
d. J Kelley: UK Sport/English Institute of Sport (EIS), £60,808, 1st Aug 2011 to 31st July 2012, Elite Sport Training Tools;
e. SJ Haake: UK Sport/EIS Research and Innovation Team, £260,000, 1st Apr 2012 to 31st Mar 2014, Innovation Partnership;
f. J Kelley: UK Sport, £25,000, 1st Dec 2011 to 31st December 2012, UK Sport Ideas for Innovation Competition – iSwim automated tracking of swimmers;
g. J Wheat: GB Cycling/EIS, £6,780, 1/3/13-1/7/13. Monitoring the morphology of athletes using a depth camera based scanning system;
h. J Wheat, The Royal Derby Hospital, £10,000, 1/1/2012 to 31/12/2012, Development of a portable measurement system for breast clinics.

4. Details of the impact

Supporting UK Sport and Team GB

In 2008 UK Sport made CSER a UK Sport Innovation Partner to implement performance analysis technologies using its research expertise (grant c) in the lead up to London 2012. CESR used the camera and photogrammetric expertise developed in tennis to create calibrated measurement systems for use in day-to-day training and coaching. These systems used the planar calibration technique (references 2, 3) to allow measurement in large volumes and tracking algorithms (reference 5) developed in tennis to track athletes. Systems generally had the following characteristics: coaches found them simple to use; they employed automated video analysis; they provided storage and retrieval; and the analysis they generated gave a performance advantage.

Examples are as follows:

- GB Boxing required CSER to instrument the new GB Boxing Gym at the EIS in Sheffield with a 5-camera system called *iBoxer*. The system allowed boxing analytics to be developed over and above tracking across the ring. This included punch rates during a round and the strategic analysis of opponents. The GB Boxing performance analyst said "*the data suggests that this kind of preparation increases the boxer's success rate by around 25%*" (http://www.bbc.co.uk/news/technology-18735629). GB Boxing won 5 medals at London 2012.
- GB Taekwondo installed iTaekwondo at its gym in Manchester and was a derivative of iBoxer. The EIS performance analyst said of the system, "*It has been a pleasure collaborating with you on the project to produce a very innovative, and truly world leading product that I can confidently say puts GB Taekwondo and myself at the cutting edge of the sport in the run up to 2012*" (by email, 11th Feb 2010). Taekwondo won 3 medals at London 2012.
- British Gymnastics required a camera and review system for its gym at Lilleshall. CSER developed a system with calibrated cameras and simple player tracking to allow coaches to review technique and actions of its gymnasts. The EIS performance analyst said, "*iGym has enabled video feedback during training for all squad gymnasts providing them with a tool to aid skill development and polishing of routine work. The high speed automatic capture system on two vaults is the most impressive part of the system which serves as such a powerful tool replaying the fast movement to both gymnast and coach…A very successful project.*" Gymnastics won 3 medals at London 2012.

Over 30 systems have been developed for UK Sport (source 1) and this success has led to further UK Sport/EIS funding (grants d, e) and a UK Sport Innovation Prize (grant f). Following London 2012, Dr Goodwill received a personal letter from the CEO of UK Sport (1/11/2012: source 2) which said, "*Without a doubt, the projects delivered have contributed to the medal success we have seen in London, Vancouver, Beijing, Turin and as far back as Athens in 2004. In the current funding review process as part of the Rio vision, many of the sports have highlighted the support and the benefits of the numerous projects in partnership with Sheffield Hallam University and the team of scientists and engineers. It is no coincidence that your name is continually linked to these projects.*"

In March 2013, Wheat was commissioned by EIS Manchester to design and build a bespoke apparatus using low-cost depth cameras to measure the body shape of Olympic athletes (grant g). The first prototype was tested in July at EIS Manchester and is being used to track the development of elite athletes. Additionally, CSER was awarded the following peer-reviewed prizes for this work: (1) Sports Analytics Innovation Awards, Sports Analytics Research Institution of the Year Award (March 2013); (2) PODIUM Awards, RCUK Award for Exceptional Research Contribution. Silver Medal (May 2012).

Support for the International Tennis Federation

The ITF has implemented much of CSER's research within its systems for monitoring the nature of the sport. The work on the measurement of spin (references 4, 5) has been implemented in the software *SpinDoctor* which has been used by the ITF to monitor the game: it was used at the Davis Cup (2010, 2011, 2012), the ATP Masters in London (2012, 2013) and at Wimbledon (2011, 2012, 2013) with a total of 3,437 shots analysed. The spin rig used in references 4 and 5 has been coupled to a database to allow the ITF to assess the effect of new strings and stringing methods on spin generation by specific rackets. The results of this work were presented to the ITF Technical Commission (source 3) from 2010 (on which Prof Haake is a voting member) whose role it is to monitor the game and assess the appropriateness of the rules of tennis to technology. The use of *SpinDoctor* and the spin rig showed that spin generated by professional players is significantly less than that of the 'spaghetti racket' which was banned in 1980; the ITF will continually monitor the amount of spin in the game, using Rule 4 (The Racket) to temper excessive spin. Prof Haake's expertise in performance analysis systems and experience from UK Sport were used to inform the

Technical Commission and the introduction of a new rule to tennis (Rule 31) at its AGM on 12th July 2013. This rule allows the use of performance analysis technology in tournament play for the first time and will come into force on 1st January 2014.

Supporting commercial and health organisations

The understanding of dynamics developed in references 1 and 2 and funded by Prince (grant a) was used by Prince to improve its understanding of tennis racket performance from 2006 onwards and supported its growth to number one racket manufacturer by 2010. The improvements in measurement techniques described in references 2, 3, and 5 were developed by CSER staff into tools that could be used by our commercial partners.

SpinDoctor was sold to Prince, IsoSport and adidas to use in their labs (with the ITF receiving 25% of royalties) to allow the measurement of scalar spin in the field. adidas requested a further system for its football testing with the ability to give 3D spin vectors and used the camera calibration and tracking systems outlined in references 3 and 5. Since 2011, footballs have been tested using the system, enhancing adidas' ability to develop its products (source 4). Tracking and signal processing techniques (reference 3) were also used to develop an iPhone application for adidas (*Snapshot*) to automatically measure the speed, angle and trajectory of a kick. The application had been downloaded around 300,000 times (31/7/2013) and is the first analysis App developed by adidas.

CSER is also working with Labosport to test the Goal-Line Technology systems being installed at Premier League clubs around the UK. The work uses techniques from references 2, 4 and 5 to measure simulated goals according to FIFA protocols. CSER staff have been accredited by FIFA to carry out the work and all 2012-13 Premier League clubs have been assessed and passed by CSER according to the FIFA specifications.

The depth-camera work has also been transferred into the commercial and health sector. Wheat (grant h) has been commissioned to build a low cost scanning device for Oxylane (Decathlon) for installation in its stores and also for breast clinics in collaboration with a Senior Breast Surgeon at the Royal Derby Hospital (grant h; source 5). The significance of the latter work allowed it to win 3rd prize in the 2012 Health Enterprise East Awards, Medical Technology & Software category. Heller used depth cameras to allow older people to enhance their physical capabilities by interacting with virtual worlds ("2nd Lives for the 3rd Age). This work has been used as a case study to inform the research community on the future of research through a Parliamentary report on 'Assistive Technology 2010-11' and a RCUK report (6/2011) on 'UK Research that will have a Profound Effect on our Future'.

Dissemination of research findings to the research community

The work of Goodwill, Choppin, Haake and Kelley showed that planar calibration was superior to the more commonly used DLT for *in situ* environments. A full suite of applications was made available as open source software (http://www.check3d.co.uk/default.html) to allow the research community to benefit from the enhanced accuracy of the planar method. Since the site went live in Sept 2012, the research has had more than 600 views and by 31/7/2013 the software had been downloaded over 200 times by those seeking to benefit from the enhanced accuracy it brings.

A further website (http://www.depthbiomechanics.co.uk/) made the 3D software available to the research community to allow others to benefit from the research. From 8/11/2012 to 31/7/2013, the software has been downloaded 46 times by researchers in North America (40%), Europe (44%) and Asia and Australasia (17%); the majority are university researchers but also benefiting are companies such as Casio. The researchers come from a range of disciplines including software engineering (53%), biomechanics (30%), physiotherapy (10%), and psychology (7%).

5. Sources to corroborate the impact

1. Senior Manager, Performance Solutions, English Institute of Sport;
2. Chief Executive Officer, UK Sport;
3. Executive Director, Science and Technical, The International Tennis Federation;
4. Senior Manager, Football Development, adidas Innovation Team;
5. Senior Breast Surgeon, The Royal Derby Hospital.