Institution:
University of Cambridge

Unit of Assessment:
UoA10

Title of case study:
Image Processing for Fluid Mechanics

1. Summary of the impact (indicative maximum 100 words)

Mathematically-based image processing techniques developed at the University of Cambridge have helped bring about a revolution in the ability to extract quantitative measurements from laboratory experiments in fluids. Techniques and software tools developed from this research and incorporated into commercial software are now used in engineering, physics and mathematics research laboratories around the world on projects ranging from fundamental research to ones with strong industrial connections.

2. Underpinning research (indicative maximum 500 words)

Fluid mechanics underpins many natural and man-made processes, and the immense challenge of understanding fluid flows relies on theoretical developments confirmed by experimental measurements. Dr Stuart Dalziel was one of the first to recognise the potential for extracting non-intrusive quantitative information from sequences of images for laboratory experiments in this context. Dalziel joined the University of Cambridge Department of Applied Mathematics and Theoretical Physics (DAMTP) in 1989 as a Postdoctoral Research Associate and has remained in the Department throughout the period (Assistant Director of Research from 1994, Lecturer from 2000, Senior Lecturer from 2001 and Reader from 2012 to present). In 1993, using ideas borrowed from operations research and graph theory, Dalziel developed not only one of the first practical ways of determining the velocity field through particle tracking velocimetry (PTV; Dalziel 1993), but also developed the first system that could be used readily by others.

While most pioneers of image processing for fluid experiments focused solely on velocity measurements, Dalziel recognised the importance of measuring other fields with comparable fidelity. Consequently, his ideas for the use of image processing as a laboratory tool expanded during the mid-1990s to provide a viable method for measuring the spatial structure and temporal evolution of density and/or depth fields based on light attenuation through dyes (Hacker *et al.* 1996). Although this technique proved highly successful, a desire to measure much weaker signals without the need to add any additional species led Dalziel to invent 'synthetic schlieren', with the first results published in 1998. This technique (Dalziel *et al.* 2000), based on the quantification of minute changes in the refractive index, is capable of measuring density fields (Sutherland *et al.* 1999) with unprecedented accuracy and spatial resolution. Dalziel has continued to develop synthetic schlieren over the last ten years to allow simultaneous density and velocity measurements (Dalziel *et al.* 2007), and to provide full three-dimensional measurement of density fields (Hazewinkel *et al.* 2011).

3. References to the research (indicative maximum of six references)

Particle tracking velocimetry

*Dalziel, S.B. 1993 Rayleigh-Taylor instability: experiments with image analysis; *Dyn. Atmos. Oceans*, **20** 127-153, DOI: 10.1016/0377-0265(93)90051-8.

Dye attenuation

Hacker, J., Linden, P.F. & Dalziel, S.B. 1996 Mixing in lock-release gravity currents; *Dyn. Atmos. Oceans* **24**, 183-195, DOI: 10.1016/0377-0265(95)00443-2.

Synthetic schlieren

*Sutherland, B.R., Dalziel, S.B., Hughes, G.O. & Linden, P.F. 1999 Visualisation and Measurement of internal waves by "synthetic schlieren". Part 1: Vertically oscillating cylinder; *J. Fluid Mech.* **390**, 93-126, DOI: 10.1017/S0022112099005017.

*Dalziel, S.B., Hughes, G.O. & Sutherland, B.R. 2000 Whole field density measurements by 'synthetic schlieren'; *Exp. Fluids* **28**, 322-335, DOI: 10.1007/s003480050391

Dalziel, S.B., Carr, M., Sveen, K.J. & Davies, P.A. 2007 Simultaneous Synthetic Schlieren and PIV

measurements for internal solitary waves. *Meas. Sci. Tech.* **18**, 533-547, DOI: 10.1088/0957-0233/18/3/001.

Hazewinkel, J., Maas, L.R.M. & Dalziel, S.B. 2011 Tomographic reconstruction of internal wave patterns in a paraboloid. *Exp. Fluids* **50**, 247-258, DOI: 10.1007/s00348-010-0909-x.

*References which best represent the quality of the underpinning research

4. Details of the impact (indicative maximum 750 words)

The research has had significant impacts through summer schools and public engagement, and the most significant impact has been through the development (by Dalziel Research Partners) of commercially-available, user-friendly, flexible software tools.

The development of particle tracking velocimetry and dye attenuation techniques drove the development (by Dalziel Research Partners) and marketing (through Cambridge Environmental Research Consultants Ltd.) of DigImage, a video-recorder based image processing system designed specifically for analysing fluid mechanics laboratory experiments. DigImage incorporated both specific techniques from Dalziel's published research and solutions to many technological hurdles that Dalziel overcame. Although development of DigImage ceased in 1999, its impact on the community was such that it continues to be used in at least three laboratories outside Cambridge and has had continued impact as new results obtained using it continue to be published (e.g. Ansong & Sutherland 2010; Corner et al. 2011; Read & Risch 2011) and otherwise influence science and technology (e.g. the incorporation of ideas originating in DigImage in a recent patent; Dey et al. 2010).

To accommodate the development of synthetic schlieren along with the transitions to digital video and 32-bit Windows, Dalziel replaced DigImage with DigiFlow in 2005. This new system (now available directly from Dalziel Research Partners with licences costing up to £14,000) has been widely adopted internationally, with in excess of 370 licences being issued to research laboratories at 163 sites across 36 countries (around 160 of these over the period 2008 to June 2013). Based on the Times Higher Education Rankings for in 2012/13, DigiFlow is used in seven of the top ten and over half of the top twenty universities (these figures apply whether considering the rankings for Engineering, Physical Sciences or Reputation). The installed base of DigiFlow users continues to grow with major new installations during 2012 in China, Russia and two Baltic States, in addition to the more traditional western economies.

The flexibility and capability of the tools developed through Dalziel's research is also reflected in recent publications by DigiFlow users. These span the range of fluid flows ranging from natural ventilation to oceanic internal waves. They continue to exploit Dalziel's key underpinning research of velocity measurement (Drazen *et al.* 2011; Park *et al.* 2012), dye attenuation (*e.g.* Hunt & Coffey 2010) and synthetic schlieren (Peacock *et al.* 2008; Wang *et al.* 2012), although a complete list of the uses to which DigiFlow is put is much broader.

The influence of Dalziel's research, through its commercialisation by Dalziel Research partners, has had an enduring impact. As one academic user (Professor of Fluid Dynamics, University of Dundee) says, "*I have colleagues and collaborators at other institutions across the UK and all over the world who have had a similar experience and come to utilise or rely on DigiFlow for many of their laboratory diagnostics…. the use of DigImage and DigiFlow has had a profound, continuing impact not only on my own research, but the geophysical and environmental fluid dynamics communities as a whole across the world*". This influence extends beyond academia, with industrial use of DigiFlow ranging from the oil industry to ship building. Here, the advanced algorithms and pioneering techniques developed by Dalziel are particularly valued: "*We have invested in very expensive equipment and software for Particle Image Velocimetry, but have additionally chosen to invest in DigiFlow on the grounds of a higher quality software with superior capabilities and better access to support… We are applying this technique [synthetic schlieren] to measure both surfactants and crystals… which are of extremely high industrial importance in many*

process systems." (Department Head, Process Technology and Fluid Flow, Institute for Energy Technology, Norway). Indeed, even the first techniques developed by Dalziel are finding new uses in industry as illustrated by Schlumberger-Doll Research Center's recent purchase (July 2013) of DigiFlow to undertake particle tracking measurements.

5. Sources to corroborate the impact (indicative maximum of 10 references)

DigImage

Recent references demonstrating continued use despite development ceasing in 1999

Ansong, J. K., & Sutherland, B. R. 2010 Internal gravity waves generated by convective plumes. *J. Fluid Mech.* **648**, 405.

Read, P. L., & Risch, S. H. 2011 A laboratory study of global-scale wave interactions in baroclinic flow with topography I: multiple flow regimes. *Geophysical & Astrophysical Fluid Dynamics* **105**(2-3), 128-160.

Dey, S., Wong, D., Wen, J., Takebuchi, Y. Arole, P. & Panigrahi, D. 2010 Digital content buffering for adaptive streaming. *United States Patent* **US007743161B2**

DigiFlow

Selection of recent publications where DigiFlow has provided the main diagnostics

Hunt, G. R., & Coffey, C. J. 2010 Emptying boxes–classifying transient natural ventilation flows. *J. Fluid Mech.* **646**, 137.

Drazen, D., Lichtsteiner, P., Häfliger, P., Delbrück, T., & Jensen, A. 2011 Toward real-time particle tracking using an event-based dynamic vision sensor. *Exp. Fluids* **51**, 1465.

Park, Y. S., Liu, P. L. F., & Chan, I. C. 2012 Contact line dynamics and boundary layer flow during reflection of a solitary wave. *J. Fluid Mech.* **707**, 307.

Peacock, T., Echeverri, P., & Balmforth, N. J. 2008 An experimental investigation of internal tide generation by two-dimensional topography. *J. Phys. Ocean.*, **38**, 235.

Wang, T., Chen, X., & Jiang, W. 2012 Laboratory experiments on the generation of internal waves on two kinds of continental margin. *Geophys. Res. Let.* **39**, L04602.

User testimonials

Illustrating the value to both academic and industrial users of DigiFlow.

Department Head, Process Technology and Fluid Flow, Institute for Energy Technology (Norway)

Professor of Fluid Dynamics, Civil Engineering, University of Dundee (UK)