Institution: Liverpool John Moores University

Unit of Assessment: 15

Title of case study: Phase Unwrapping Software.

1. Summary of the impact

Phase unwrapping is an **essential** algorithmic step in any measurement system or sensor that seeks to determine continuous phase. Instances of such devices are widespread: e.g. image reconstruction in magnetic resonance imaging (MRI), synthetic aperture radar (SAR) by satellite systems, analysis of seismic data in geophysics and optical instrumentation, to name but a few. Without successfully solving the phase unwrapping problem these instruments cannot function.

The topic is well developed and competition among algorithms is fierce. In 2012 alone, some 235 papers, most of which were describing potential new algorithms, were published in the area. But the continuing need for high-speed, automated and robust unwrapping algorithms poses a major limitation on the employability of phase measuring systems.

Working originally within the context of structured light 3D measurement systems, our research has developed new phase image unwrapping algorithms that constitute significance advances in speed, automation **and** robustness. The work has led to adoption by industry, as well as use in commercial and government research centres around the globe. Our approach since 2010 has been to make these algorithms freely available to end users. Third parties have gone on to translate our algorithms into other languages, widely used numerical software libraries have incorporated the algorithms and there are high profile industrial users.

2. Underpinning research

Our interest in the phase unwrapping problem began in the late 1980's and is on-going. This case study describes the development of a small group of automated algorithms which particularly focused upon improving speed **and** robustness.

In essence unwrapping phase is a simple problem involving the resolution of discontinuities in phase caused by the nature of the arctan function. In practice geometric complexity in the field variable, allied to the inevitable presence of noise, makes it an extremely challenging task to develop an automated unwrapper which is both fast and robust. In the case of a modest 512x512 pixel image, the algorithm must make over one quarter of a million correct assessments. One misclassification will lead to the corruption of the entire data-set. Scale this up into 3D stacks of larger images and the problem becomes even more difficult.

Our early work on this area was based on a strategy of simplification by dividing the full image into smaller sub-images. It was out of this approach that the algorithms which form the basis of this case study came about. The "divide and conquer" philosophy they represented was the starting point for what became known as "The Best Path" and "The Image Decomposition" approaches.

The Best Path Approach.

The idea here is that unwrapping is basically a point-to-point process; we start at one pixel in the image and we follow a certain path, resolving wraps as we go. We developed the new concept of a path that was in some sense "the best". We allow the path to meander through the image, constantly following the highest quality data. This process continues, with new paths being created and joined to existing paths, until it is determined that all of the data that it is possible to resolve has been dealt with [1]. This unwrapper was further developed and extended to non-continuous paths [2] – a significant improvement.

The Image Decomposition Approach.

In this method we start by selecting disconnected areas of the image that have data similarities, in this case similar phase values; resulting in the new idea of "iso-phase unwrappers". Once the iso-phase regions are identified we then start unwrapping in all of these areas independently, gradually expanding them outwards. The basis of the approach is that these areas will "fold" around corrupted data zones as they expand and eventually grow to confluence [3].

Further Development.

At this point we had two very fast, effective, 2D phase image unwrappers which solved some of the problems that caused other unwrappers to struggle. We then began work attempting to extend these successful 2D unwrappers into 3D form. This extension proved to be far from trivial and following five years of work we were successful in achieving the first extension of the Best Path Approach into a 3D form [4].

This 3D unwrapper was significantly ahead of any competitors, being very successful and widely adopted. However, we were aware that it had a limitation under certain conditions, primarily with one type of data (MRI), where it sometimes produced results that were geometrically inconsistent. We worked for a further two years to understand this problem, labelling the cause “singularity loops”, and then going on to write the final unwrapper in this suite which solves this problem [5].

In all GERI’s work on phase unwrapping has produced 12 PhD theses and over 25 journal papers since 1993.

Workers involved.
Prof Burton, submitted in this UoA, was the leader of this work. Dr Lilley was involved in the extension to 3D and is also submitted here. Prof Lalor retired from GERI in 2010. Dr Gdeisat was an ex-PhD student at GERI who became a staff member, eventually leaving in 2012 to take up a post at the University of Oman. Dr Arevalillo-Herráez was a PhD student supervised by Profs Burton and Lalor, later a PDR in GERI; he is now a lecturer at the University of Valencia and still maintains active links with GERI. All of the other named individuals were either PhD students in GERI or end-user-collaborators.

3. References to the research

1. Arevalillo-Herráez M.A., Burton D.R., Lalor M.J. and Clegg D.B., *“Robust, simple and fast algorithm for phase unwrapping.”*, Applied Optics, 35, No 29, pp5847-5852, 1996. [Cited 37 times]
2. Arevalillo-Herráez, M., Burton, D.R., Lalor, M.J. and Gdeisat M.A. *"Fast two-dimensional phase-unwrapping algorithm based on sorting by reliability following a noncontinuous path"*, Applied Optics, Vol. 41, No. 35, pp.7437-7444, 2002. [Cited 86 times]*
3. Arevalillo-Herráez M., Gdeisat M.A., Burton D.R. and Lalor M.J., *"Robust, fast, and effective two-dimensional automatic phase unwrapping algorithm based on image decomposition"*, Applied Optics, Vol. 41, No. 35, pp. 7445-7455, 2002. [Cited 25 times]*
4. Abdul-Rahman, H., Gdeisat, M.A., Burton, D.R., Lalor M.J., Lilley F. and Moore C.J., *"Fast and robust three-dimensional best path phase unwrapping algorithm.”*, Applied Optics, Vol. 46, No. 26, pp. 6623-6635, 2007. [Cited 29 times]*
5. Abdul-Rahman, H., Arevalillo-Herráez, M., Gdeisat, M.A., Burton, D.R., Lalor, M.J., Lilley, F., Moore, C.J., Sheltraw, D., and Qudeisat M., *“Robust three-dimensional best-path phase-unwrapping algorithm that avoids singularity loops”*, Applied Optics, Vol. 48, Issue 23, pp. 4582-4596, 2009.

* Indicates a main publication.

4. Details of the impact

Our interest in phase unwrapping originally stemmed from involvement in developing optical 3D surface-form measurement systems. What this case study illustrates is how the work that was embarked upon for the relatively narrow purpose of solving problems in an area of 3D optical metrology turned out to have very much wider applications and take-up.

In 2010 we started to become aware of significant numbers of citations of our unwrapping work in areas far removed from optical metrology. This was reinforced by requests for advice on implementation of the algorithms, coming from people working in geo-physics within the oil industry, medical technology (particularly MRI), aerospace sensing for SAR satellites, microscope technology in the life sciences etc. It was becoming clear that our work had a much wider potential impact than we had originally envisaged.

In direct response to the increasing level of requests, and to raise the profile of our algorithms to a wider industrial audience, we took the radical decision to make our C++ codes that implemented the methods available for free download from our website. As part of this strategy we developed a range of support material for users to consult [E1].

Over an 18 month period we logged 468 downloads from the website of these implementations of the algorithms described in Refs 2 to 5 above. Destinations included 15 countries (The UK, Germany, France, Italy, Spain, Poland, Israel, Russia, The United States, Canada, India, Japan, China, South Korea and Indonesia). The graph in Figure 1 shows downloads per month for the monitored period.

The codes have been available for free download since 2010 and remain freely available today. Based on a detailed analysis of our 18 month sample we estimate that in excess of 1,000 organisations have downloaded these algorithms since they were first made available.

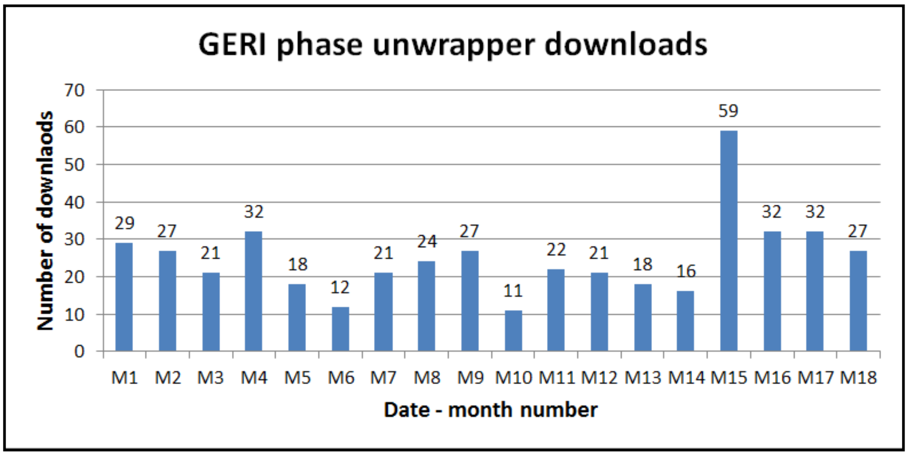

Figure 1 – Unwrapper Downloads over an 18 Month Period.

The downloads are a mix of academic and non-academic end-users and, based on a sample, approximately 40% are industrial users. The algorithms are used in a wide variety of ways. In the case of instrument developers it is often in the development of new instruments, but sometimes it is to replace previous under-performing algorithms in existing instruments. In some cases, in MRI for neuro-science for example, the user is actually driven by a need for the phase data in their own work and the algorithms simply offer a reliable, high-performance, “off-the-shelf” solution. We regularly follow-up with industrial organisations in order to better understand their use and future needs. Some samples of what we have learnt from these organisations are given below:

> **Laser Optical Engineering Ltd., UK.** LOE are an SME specialising in the commercialisation of new technologies in the area of optical sensing. Established in 1996, their list of existing clients include major industrial organisations such as: Rolls Royce, JCB, Mattel, Bureau Veritas and Corus. Prestigious government clients include: The Forensic Science Service and Trading Standards. They have used the unwrapping algorithms described here within two products designed to help locate IED’s and landmines. These products have only recently been declassified and were exhibited at DSEI in ExCel in Sept 2013. The CEO of Laser Optical Engineering said *“The products received a fantastic response from the world’s armies. We are in the throes of the final customer trials when we hope to see substantial sales volume which will reflect in your unwrapping.”* [Corroborative witness ID=1]
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> **The Max Planck Institute for Biological Cybernetics, Germany.** An Institute member says *“I use the 3D best path unwrapper for anatomical MRI phase imaging. It is a very efficient unwrapper.”* [Corroborative witness ID=2] [Note: According to their website “The Max Planck Society for the Advancement of Science is an independent, non-profit research organization.” They are not HEI’s or part of the HEI sector, nor are they government organisations in any form.]
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> **Shell International, USA.** A Team Leader, Seismic Processing, states: *“Shell International Exploration & Production Inc. have evaluated GERI’s phase unwrappers in our seismic processing software, overall we can say we have been satisfied with the stability and efficiency of the algorithm”* [Corroborative witness ID=3]

We have selected these three examples as they illustrate the scope of the impact both in terms of sector (new product development, life sciences and oil/energy); and geography (UK, Europe and USA).

As well as these direct users, there has been considerable further promulgation of the algorithms within the technical and software communities by third parties. Examples of this are given below:

- The algorithms have been translated independently into Java for implemention as part of the ImageJ library. ImageJ is a public domain image processing program developed at the US National Institutes of Health, whose website has received over 10 million hits. [Supporting evidence: E2 & E3].
- The algorithms have been translated into Python, again independently of GERI, and have been included in Scikit-Image (a part of the SciPy library) by users in Austria and South Africa. [Corroborating witness ID=4 and Supporting evidence: E4 & E5].
- Take up in the application area of Neurological imaging has been strong, particularly in the USA thanks to the championing the algorithms by one prominant medical user who states: *“the algorithms are now available to clinicians right across the United States and beyond through NITRC”* (The Neuroimaging Informatics Tools and Resources Clearinghouse). [Corroborative witness ID=5 and Supporting evidence E6].

These libraries and distribution networks are very significant. They are widely used by software developers and so the incorporation and dissemination of our software through these mechanisms greatly increases our outreach to users. However, due to this third-party distribution we have no precise data on just how great the penetration of these algorithms is in total, all we can say is that the figure of 1,000 user organisations, based on downloads and quoted earlier, is a minimum.

One way to form a picture of the scale of this impact may be to consider the range of application areas of phase measurement systems, all of which require an unwrapper. These include, for example:

- **Biomedical:** catheter guidance, tissue imaging, dental caries, MRI.
- **Instrumentation:** Low-coherence reflectometry, tomography.
- **Films, Coatings and Adhesives:** coating, adhesive and film thickness measurements.
- **Pharma & Chemical:** Particle sizing, scattering measurements.
- **Security:** Perimeter intrusion/detection systems, detection of explosives.
- **Smart Structures:** stress and strain measurement.
- **Oil & Gas Services:** Dynamic seismic sensing of geophysical properties.
- **Photonics:** Laser characterisation, interferometry.
- **Digital:** Displacement sensing for computer hard drives.

The extent of our penetration into these sectors is perhaps reflected in the fact a Google Search using the search-string “phase unwrapping” lists our website as the top three results (accessed 5th Nov 2013).

In a competitive arena, with a great many unwrapping algorithms published each year, these algorithms have established themselves as being among the leaders in their field; we are not aware of *any* other single algorithms, worldwide, that have such extensive and diverse adoption.

5. Sources to corroborate the impact

E1 - http://www.ljmu.ac.uk/GERI/90202.htm (GERI’s Phase Unwrapping Web-Resource)
E2 - http://rsbweb.nih.gov/ij/features.html (Evidence: ImageJ feature page establishing its significance and a US National Institute of Health initiative)
E3 - http://www.openmicroscopy.org/site/support/bio-formats4/users/imagej/ (Evidence: An example supporting the fact of ImageJ’s wider adoption by bio-imaging users.
E4 - http://www.scipy.org/ (Evidence: Role and significance of SciPy as a software development tool)
E5 - https://github.com/geggo/phase-unwrap/tree/master/unwrap2D (Evidence: translation of algorithms by third parties and incorporation on GitHub for incorporation in SciPy)
E6 - http://www.nitrc.org/ (Evidence: the significance of incorporation in this national and international distribution network)