

## **Special Issue on: Machine Vision for Outdoor Environments**

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### **Editorial**

The successful application of machine vision systems to outdoor tasks offers a potential to automate many existing laborious, difficult or even dangerous manual activities, and in some cases has allowed the realisation of entirely new and useful mechanised activities not previously undertaken, such as the automated aerial monitoring of crops. While many outdoor tasks involve working within relatively unstructured and disorganised environments, seemingly typical of the natural world, the majority of research work published to date has been concerned with highly structured and predictable manufactured indoor scenes and tasks. A major reason for this comparative lack of application outdoors may follow from the perceived difficulties associated with effectively addressing the inherent complicating environmental factors that are very often experienced outside, such as dramatic changes in background light, exposure to the elements (e.g. heat, vibration, moisture and dust), the need to cope with and adapt to uncertainty and change (e.g. in lighting and in the nature and position of objects) and a capacity to handle and interpret unprecedented quantities of noisy or incomplete data. Other challenging issues, which are more specifically imaging and scene interpretation related, include the consequences of highly complex and busy scenes involving constantly changing parallax, perspective and occlusion, together with the angle and the nature of changing illumination.

These factors have traditionally made it difficult for researchers to produce sufficiently robust outdoor computer vision solutions that are able to reliably segment and measure scene features with a level of accuracy or with sufficient repeatability to enable useful real-world application - or even to allow their work to be quantitatively compared with the approaches of others. However, this situation is now changing, largely due to recent dramatic advances that have occurred in both the performance and affordability of the required machine vision hardware and software components. While these developments are too numerous to all be mentioned here, it is perhaps worth considering a few of the more salient technological improvements that are proving key in realising new capabilities in outdoor machine vision. In terms of the camera hardware itself we have seen major improvements in image quality, including improved dynamic range and low-light level performance – all concurrent with dramatic reductions in cost - together enabling a wider application of vision solutions. A move towards more affordable larger format sensor arrays has facilitated improved accuracy in image based metrology, and when accompanied by extended sensitivity at longer wavelengths, allows use of infra-red (IR) pass filters with matched light emitting diodes (LEDs) to assist in minimising the effects of outdoor ambient lighting. At the same time, LED illumination technology has also undergone a rapid development itself; so that for example, low-cost single IR diodes can now be purchased that produce as much light intensity as whole arrays of only a few years ago. Use of such high-intensity LEDs with matched cameras and filters can greatly reduce or eliminate illumination problems for many outdoor applications. Other examples of enabling camera developments include improved interfacing and data transfer via USB 3 (or above) and GigE, thereby obviating the need for expensive camera interface cards, while maintaining good bandwidth. There has also been a

marked reduction in costs and increased performance and availability of technology for 3D imaging that has attended the introduction of RGB-D cameras such as the Kinect, Kinect II and other similar related devices. Of the other enabling factors touched on above, coping with exposure to the elements has seen a greater use of innovation in terms of new forms of IP rated waterproof fixtures and enclosures; while imaging complications such as busy scenes, parallax, perspective, shadows, occlusion and changes in angle of illumination have been addressed by utilisation of now readily accessible 3D data, most recently together with increased traction via the deployment of artificial intelligence (AI) techniques.

The utility of AI in outdoor imaging has benefitted from a number of exciting machine learning innovations, one of the most significant being an explosion in the implementation of deep learning through the use of convolutional neural networks (CNNs). This has enabled dramatically improved automatic feature identification within complex outdoor scenes by effectively mimicking human scene appraisal and has been found extremely useful for identification of features of interest in busy images captured in nature and in overcoming many of the other complicating factors mentioned above. One potential drawback in the practical application of deep learning has been a requirement for a great deal of image data computation for training purposes (although not for consultation). However this has been addressed largely through two approaches: utilisation of pre-trained networks and a capacity to capture large amounts of data in the field – often labeled using crowdsourcing techniques. CNN training has also presented as a formidable task but here again developments in hardware are providing solutions, where, for example, the introduction of high-end personal computers (PCs) and graphics processing unit (GPU) accelerator cards are enabling relatively low-cost computer hardware to attain computation rates that are orders of magnitude above common PCs and which facilitate CNN training in an hour or two rather than the days or weeks of the past.

However, perhaps surprisingly, despite all the developments outlined above, utilization of machine vision for outdoor applications has proved to be far less widespread than may have been expected given the potential advanced capabilities on offer. In many ways the technology might be considered as a ‘caged tiger’ – i.e. something potentially very powerful that has yet to reach its full potential! The reasons for this are not entirely clear, although it may be that the prospective users’ perceptions of the limitations caused by the complications previously mentioned, coupled with an impression that computer vision is still somewhat of a lab based research activity rather than being able to offer commercially ready and economically attractive outdoor solutions, has biased potential user industries away from exploring the technology more so. An objective of this special issue has therefore been to help to alleviate this situation by illustrating how machine vision is being increasingly employed successfully in real-world unstructured outdoor situations. Furthermore, the papers included herein illustrate how the advanced vision techniques and equipment mentioned can be combined in innovative ways to generate useful quantitative and qualitative information that is sufficiently accurate and repeatable and which can have real advantageous impact and commercial value.

All the underlying technological advances outlined above are to some extent employed in the cutting-edge research described within the papers contained in this special issue, where they have been found to be enabling in providing advanced capabilities in a wide range of topical outdoor applications across a diverse set of industrial sectors. The response to the initial call attracted some 55 submissions from both academia and industry from which, due to limited space and time, only 28 papers have been progressed for inclusion in this special issue. All of

these papers were reviewed by independent referees and in the vast majority of cases were subject to several revisions before final acceptance.

The papers that follow may be considered to fall into two broad categories: firstly those which are primarily concerned with scenes captured from nature, or more specifically the arguably ‘pseudo-nature’ of human agricultural applications and secondly applications within unstructured environments on a boarder range of scales and sectors. In all cases, the successful application of any innovative technology often requires consideration of issues relating to the integration within and interfacing to existing equipment, processes and the wider business enterprise, and this is also reflected in several of the submissions.

## **1. Agri-tech applications**

Our first and the largest grouping of papers in this special issue address the application of machine vision to the solution of a range of pressing agricultural problems. Agri-tech represents a huge (possibly the largest) developing area of application for outdoor or highly unstructured indoor applications for machine vision. In addition to tasks such as harvesting of fruits and vegetables, where Brexit is driving renewed interest in exploring automation to replace lost migrant labour, machine vision is particularly potentially useful for tasks with an ecological aspect, such as automatic weed detection – since it offers potential to enable mechanisation that could provide many environmental and economic advantages, including the reduced use of harmful herbicides. Sabzi *et al.* address identification of weeds in potato crops in their paper “A fast and accurate expert system for weed identification in potato crops using metaheuristic algorithms”; while Ahmad *et al.* apply boosted classification to weeds in their paper, “Visual features based boosted classification of weeds for real-time selective herbicide sprayer systems”. The next two papers illustrate the advanced capabilities that can result from capturing 3D data in the field. In “Iterative individual plant clustering in maize with assembled 2D LiDAR data” Reiser *et al.* found that analysis of 3D data from laser scanning can enable detection of 100% of plants; while Hansen *et al.* show for the first time using a single device that 3D vision data can be used to determine cow body condition, lameness and weight, in “Automated monitoring of dairy cow body condition, mobility and weight using a single 3D video capture device”. Diaz *et al.* also report on generation of 3D data in their paper “Grapevine buds detection and localization in 3D space based on Structure from Motion and 2D image classification”, but here generated by a structure from motion method and combined with 2D data to detect grapevine buds. Luo *et al.* also apply machine vision to grapevines in “A vision methodology for harvesting robot to detect cutting points on peduncles of double overlapping grape clusters in a vineyard”, but here the challenge was specifically to identify cutting points on peduncles of overlapping grape clusters, during harvesting. Tangerine detection employing color-space transformation and ellipse fitting was achieved by Liu *et al.* in “Detection of citrus fruit and tree trunks in natural environments using a multielliptical boundary model”. In addition to fruit location detection, another important capability of machine vision is that it enables characteristics, such as ripeness, to be determined without physical contact with the fruit. Sajad and Arribas demonstrate this in the case of oranges in their paper “A visible-range computer-vision system for automated, non-intrusive assessment of the pH value in Thomson oranges”; while Ramos *et al.* show that 3D vision data can be used to detect ripeness of coffee fruits in “Measurement of the ripening rate on coffee branches by using 3D images in outdoor environments”. The demonstration of vision methods for plant analysis is continued by Smith *et al.* in “Innovative 3D and 2D machine vision methods for analysis of plants and crops in the field”, where case studies of weed and potato detection/measurement are used to show the utility of 2D and particularly

3D vision data in the field. The latter area is further explored by Zhang *et al.* in “Photometric stereo for three-dimensional leaf venation extraction”, where the authors describe their photometric stereo imaging system, which can capture high-resolution 3D data, thereby enabling extraction of detailed leaf venation architecture. As well as analysing plants, vision can be usefully applied to identification of farm animals, with potential benefits for both the animals and farmers, as shown by Hansen *et al.* in the above work on cow condition monitoring and also in “Towards on-farm pig face recognition using convolutional neural networks”. This paper illustrates the powerful discriminating capabilities of convolutional neural networks (CNNs) and this is a theme that is continued by Dias *et al.* with their application of CNNs to flower detection in “Apple flower detection using deep convolutional networks”. Tabb and Medeiros also address apple flower detection in “Automatic segmentation of agricultural objects in dynamic outdoor environments”; in this case employing superpixels to detect objects of interest in the presence of agricultural backgrounds. Such detection is also addressed by Sadgrove *et al.*, in “Real-time object detection in agricultural/remote environments using the multiple-expert color feature extreme learning machine (MEC-ELM)” but here two implementations of a multiple-expert color feature extreme learning machine are used. The theme of agricultural scene interpretation is continued by Bulanon *et al.* in “Machine vision for orchard navigation”; where they analyse the tree canopy and sky of an orchard row to autonomously navigate an unmanned ground vehicle. The final paper in this section is by Bosilj *et al.* and entitled “Connected attribute morphology for unified vegetation segmentation and classification in precision agriculture”. Here support vector machine (SVM) methods are applied to normalized difference vegetation index (NDVI) images of onions and sugar beets to successfully segment fine details of plant regions.

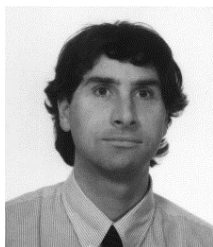
## **2. Outdoor scene analysis on a range of scales across different industrial sectors**

In addition to the specific agri-technology applications mentioned above, papers submitted to the special issue also addressed numerous outdoor machine vision applications that varied in both scale and sector. The work described by Strobl *et al.* in “Portable 3-D modeling using visual pose tracking” relates to medium-scale scene analysis; and presents low-cost scanning/tracking techniques that are mobile and so suited to recovering textures and morphologies of outdoor objects/surfaces. In their paper “Camouflage assessment: Machine and human”, Volonakis *et al.* describe methods that operate at a similar scale, which employ low-level vision principles to develop a model that performs as a human observer model for camouflage assessment. The paper by Bibi *et al.* is at a similar scale and is entitled “Automated multi- feature human interaction recognition in complex outdoor environments”. Here a vision system is presented for recognizing person-to-person interactions in public areas by considering individual actions and trajectory information in multiple camera views. The next paper at this human scale is by Jian *et al.* and is entitled “Comprehensive assessment of non-uniform illumination for 3D heightmap reconstruction in outdoor environments”, where the authors combine three methods for correcting non-uniform illumination for surface heightmap reconstruction when using photometric stereo. The final paper that recovers data at the medium scale is “Image super-resolution for outdoor digital forensics - usability and legal aspects” by Villena *et al.* Here super-resolution techniques are used to extract images from surveillance videos; and the outputs of the method are illustrated by employing a study of real-life cases of damage and theft. Our remaining papers that relate to outdoor scene analysis are on a larger scale and illustrate the diversity of the sectors addressed in the Special Issue. In the first, which is entitled “Towards an automated photogrammetry-based approach for monitoring and controlling construction site activities”,

Omar *et al.* describe a vision system for the continuous monitoring of construction activities, where their system is tested as part of a real-life case study within an in-progress construction site. Two of the remaining papers in this group relate to vision systems for autonomous vehicles and ensuring safety. The first is “Application of HDR algorithms to solve direct sunlight problems when autonomous vehicles using machine vision systems are driving into sun”, by Paul and Chung. They investigate the use of high dynamic range (HDR) imaging algorithms in a machine vision system of a research vehicle and measure how well the system performs in direct sunlight. The second is a paper entitled “On-board monitoring system for road traffic safety analysis” by Battiato *et al.*, who installed a system on public transportation vehicles that collects raw GPS information, video sequences and a stereo-based depth map. The collected data are analysed to compute surrogate safety measures. Other work in monitoring road traffic is presented by Al Maadeed et al in “Robust feature point detectors for car make recognition”. Here a range of techniques are explored for automatic vehicle make and model recognition (AVMMR) – effectively an extension to the well-established automatic number plate recognition Systems (ANPR) now in widespread use. This is followed by “Vanishing point detection for visual surveillance systems in railway platform Environments”, where Tarrit *et al.* propose a three-stage approach to accurately detect the main lines and vanishing points in low-resolution images acquired by visual surveillance systems in railway platform environments. The final paper in the group is entitled “Dynamic texture recognition and localization in machine vision for outdoor environments”. This describes work by Kalsta *et al.* that involves analysis of video sequences captured by surveillance cameras, where representations on both a local and global scale are usefully combined.

A major objective of this special issue of the Computers in Industry journal has been to provide a forum for the presentation of new state-of-the-art ideas and techniques within the context of highly unstructured environments and tasks; and to illustrate their effective use in solving real problems in a holistic sense. As demonstrated by the papers presented, applications of machine vision outdoors have been rapidly gaining ground in a range of industrial tasks that are well reflected in the breadth of submissions for this special issue.

The editors have very much enjoyed editing this special issue and it is hoped that the reader will find the work presented here informative and beneficial as a reference and as an indicator for future research directions. We would like to thank the Editors-in-Chief of Computers in Industry, Professor Hans Wortmann and Professor Harinder S. Jagdev, for the opportunity to publish this special issue on outdoor applications of machine vision and also all the authors, the referees and editorial office colleagues who have helped make this possible.



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