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ICI - Inline Computational Imaging: Single Sensor Technology for Simultaneous 2D and 3D High Definition Inline Inspection

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Description of the innovation:

The innovation introduced here, the AIT Inline Computational Imaging (ICI), is a novel single camera industrial inline inspection system capable for simultaneous colour 2D and 3D inspection. The proposed solution is specifically developed for high-performance industrial inline inspection. The principle behind is a smart combination of light field (LF) and photometric stereo (PS) imaging techniques.

Light field and photometric stereo are so called computational imaging methods using several images of an object for 3D reconstruction. The light field consists of multiple images of an object obtained from different observation angles. The photometric stereo approach makes use of different illumination angles. The LF 3D reconstruction performs well in terms of the absolute depth accuracy but fails at fine scales, areas with little or no texture and on surfaces with specular reflections. The PS depth models are typically accurate in fine surface details but show limited global 3D accuracy.

Acquisition setup and working principle: The proposed AIT ICI combines the advantages of both techniques, light field and photometric stereo, together with line scan imaging. Figure 1 shows the hardware setup and acquisition concept. The image acquisition unit consist of one matrix camera fitted with a standard non-telecentric lens and two static light sources. Since ICI is especially developed for inspecting moving objects at high speed the camera is used in a multi-line-scan mode. Therefore, only a small number of lines (more precisely line-pairs because of the Bayer mosaic colour pattern) are read out while the object is moving underneath the camera. Each of these lines act as an individual line scan camera that captures the corresponding image line by line while the object is moving in front of the camera. This produces an image stack consisting of multiple images each seeing the object under slightly different viewing angle. It can also be seen, each single line not only see the object under different viewing angle but also under a slightly different illumination angle. The acquired image stack therefore contains light field information stemming from different viewing angles and photometric information stemming from different illumination angles. The AIT ICI therefore is a single camera solution for simultaneously acquisition of light fields and photometric stereo data.

High precision 3D reconstruction: The ICI 3D reconstruction algorithms are a tailored combination of depth analysis and surface reconstruction. For the light field depth analysis, the acquisitions are represented as an epipolar plane image (EPI) stack. The slopes (angles) of the EPI linear structures correspond to depths of each image position. Depth analysis is performed by using a multi-view correspondence analysis in the EPI domain with tailored image features that are robust against brightness and contrast variations to achieve robustness against various photometric effects. In the photometric stereo analysis, the surface orientations are derived from local shading information. Although, the surface geometry can be partly retrieved from surface orientations only, ICI method combines the depth estimation from the light field and photometric stereo analyses to achieve an overall improved reconstruction accuracy. Final 3D reconstruction is delivered as a point cloud together with measurement confidence values for each single captured point.

Independent from reflectance properties of the object: Combining the advantages of both mentioned technologies compensates also for their respective shortcomings. This makes the method to work largely independent from the objects surface reflectance properties. Figure 2 shows 3D reconstructions results of a scene comprised of a black zip tie, a glossy coin and a rough mostly dark file. Although this scene is an artificial one it demonstrates the capabilities of the proposed technology. The upper left image shows a photo of the scene. The upper right image shows a 3D reconstruction calculated using standard stereo approach from just two extremal views captured by our camera. The zip tie fails for 3D reconstruction and the high surface reflectance of the coin leads to reconstruction artefacts. Overall, the stereo imaging approach leads to unsatisfactory results for 3D sensing of challenging scenes such as this one. The lower left image shows a 3D reconstruction obtained by multi-view stereo approach using the entire captured light field. Here one can see, that using more than two views enhances quality of the result significantly so that all components are detected but still lacking fine surface details. Finally, the lower right image shows the 3D reconstruction obtained with our AIT ICI. As can be seen, within this image all objects can be precisely reconstructed, not only the fine details of the file's surface can be measured, but also the finest surface details of the glossy coin and even the ejection points of the texture-less black zip tie are clearly visible.

Optimized 2D images: Beside the 3D point cloud, provided are also pixel rectified colour images with an enhanced image quality over a standard 2D imaging. Figure 3 shows the ICI 3D model plus colour texture. Up to now enhanced 2D colour images for gloss reduction, shadow reduction, all-in-focus and high dynamic range are available. This makes ICI a single camera solution suitable not only for precise 3D measurement but also for more robust optical inspection and defect detection.

Compensation of motion artefacts: As mentioned before the AIT ICI technology is a multi-line scan imaging method. Line scan imaging enables high-speed and high-resolution image acquisition for linearly moving objects and, therefore, is an expedient choice when performing industrial quality inspection. However, when capturing moving parts, motion artefacts may arise when the movement is not precisely synchronized with the line scanning process. This can happen even when using high-end hardware components and becomes a serious issue especially when using high magnification optics. Therefore, AIT ICI comes with a tailored bundle adjustment algorithm for inline compensation of motion artefacts. This makes the solution very robust and allows for high magnification down to 4 μm per pixel lateral resolution.

Flexible and scalable for industrial needs: Finally, the proposed ICI technology also works with any number of lines used. Increasing the number of lines gives more detailed and robust results due to higher amount of data being captured, but at the same time require longer capture and calculation times due to lower multi-line scan rates. On the other hand, decreasing the number of captured lines leads to higher line rates, smaller amount of data captured, and therefore less detailed results at faster calculation time. The proposed solution works with lateral resolutions from 100 ?m down to 4 ?m per pixel. Achievable acquisition speed depends on the capabilities of the employed multi-line scan camera. Typically, the system runs at 20 kHz and 11 lines. Using just 4 lines and high speed xposure camera by AIT, the multi-line scan rates up to 150 kHz are feasible. This makes the ICI suitable for a very broad range of industrial inspection tasks.

Speed: All algorithms are a well-balanced trade-off between results quality and processing time and are the result of several years of research and development activities in algorithm enhancement as well as in runtime optimization. All algorithms are fast and accurate enough for high-performance inline inspection.

HW-supplier independent: Since the acquisition setup uses off-the-shelf hardware components only, ICI is a technology which can be used supplier independent. All outputs are provided in standard image formats so they can be easily processes further using standard machine vision libraries.

The AIT ICI is a rather simple yet powerful acquisition concept. In combination with smart algorithms it enables a new dimension in fast and accurate inline inspection

For more technical details on the AIT ICI, see the following research papers:

o Antensteiner, D., ?tolc, S. and Pock, T., 2018. Multi-line scan 3D sensing with a hybrid light-field and photometric stereo approach. In: Proc. of the 24th International Conference on Pattern Recognition (ICPR) 2018.
o Antensteiner, D., ?tolc, S. and Pock, T., 2018. A review of depth and normal fusion algorithms. Sensors, 18(2), p.431.
o Blaschitz, B., ?tolc, S. and Antensteiner, D., 2018. Geometric calibration and image rectification of a multi-line scan camera for accurate 3D reconstruction. In: Proc. of the Electronic Imaging, 2018(9), pp.1-6.
o Brosch, N., ?tolc, S. and Antensteiner, D., 2018. Warping-based motion artifact compensation for multi-line scan light field imaging. In: Proc. of the Electronic Imaging, 2018(9), pp.1-6.
o Antensteiner, D., ?tolc, S., Valentín, K., Blaschitz, B., Huber-Mörk, R. and Pock, T., 2017. High-precision 3D sensing with hybrid light field & photometric stereo approach in multi-line scan framework. Electronic Imaging, 2017(9), pp.52-60.
o ?tolc, S., Soukup, D., Holländer, B. and Huber-Mörk, R., 2014. Depth and all-in-focus imaging by a multi-line-scan light-field camera. Journal of Electronic Imaging, 23(5), p.053020.

Technical details and advantages of the innovation:
Today, there is a broad variety of state-of-the-art machine vision approaches for 2D and 3D industrial inspection such as standard area- and line scan imagers, laser sectioning, active structured light scanners, shape-from-focus systems, time of flight cameras, light dome-based photometric stereo setups, and last but not least also light field systems. These methods are either fast but not very precise (e.g. laser sectioning), or precise but slow (e.g. shape-from-focus microscopes). Moreover, many existing methods tend to be bulky and inflexible, failing in non-textured or glossy regions, with objects containing large reflectance differences (i.e. both dark and bright regions comprised in one scene), offering only low-resolution readouts as a result of the technical solution or operational speed.

One of the most common 3D technology used in industrial inspection is laser sectioning. This triangulation based technique uses a laser line being projected onto the object and captured by a camera at an angle. The deformation of the profile is a direct function of range. To collect a complete 3D model the object is moved under the camera and the laser line and a sequence of individual 3D profiles are simultaneously scanned. Nowadays these systems are deployed as compact sensors which are easy to integrate in existing production lines. Laser speckle effects are limiting these technique to resolutions of typically 100 ?m. Furthermore, it struggles delivering useful 2D intensity/colour data and needs to be parametrized for reflectance properties of the inspected objects. The 3-D Vision Ranger by Sick is among the fastest and one of the most prominent products for laser sectioning currently on the market.

Aiming for higher optical resolutions, technologies such as shape-from-focus (SFF) or confocal microscopy (CM) are used. Both SFF and CM reaches high optical resolution down to micro- or even nanometer ranges, but have very limited lateral field of view. These techniques take multiple images at each measured position with different focal planes and analyses each object point for optimal focus. The main drawback of SFF method is the necessity of (i) a textured scene as the focus measure is based on the high frequency content of the scene, and (ii) a large number of acquired images. These technologies are mainly used in the lab for high precision sample testing. Products using these technologies are, e.g. the SFF system InifniteFocus by Alicona and the CM system µsprint by Nanofocus.

Our solution, the AIT ICI technology, aims to close the gap between systems offering either high optical resolutions or high inspection speeds, combined with a compact and easy to use hardware setup. In comparison with conventional 3D scanning systems, the AIT ICI simultaneously considers multiple viewing and illumination perspectives and thus enables more robust 3D sensing and thus higher defect detection accuracy. The proposed imaging system consists of only one multi-line scan camera coupled with a standard machine vision illumination, nevertheless, still enabling for traditional and novel imaging applications via advanced data capture and processing. The main strength of the AIT ICI lies in a clever fusion of multiple computational imaging techniques such as the light field imaging for robust large-scale 3D capture and the photometric stereo approach for sensitivity to fine surface details and material reflectance properties. Instead of using multiple physical cameras or additional optical arrangements such as micro-lens arrays in front of the sensor, the AIT ICI employs a fast multi-line scan camera that yields all advantages of the traditional line scan imaging, but captures multiple line scan images at the same time and so enables for computational imaging. Such an approach brings light field imaging into the inline use cases without imposing any substantial compromises on the capture speed or quality. Additionally to light fields, the AIT ICI provides also photometric stereo information by exploiting multiple illumination angles that are inherent in this setup. By analysing the captured reflectance properties in each captured object point, fine surface details as well as information about its material can be recovered. Both methods complement each other enhancing the overall accuracy and robustness of the final method. The system allows for flexible choice of the number of views, which gives the user a possibility to decide dynamically on the ratio between speed and accuracy.

The most significant advantages of AIT ICI over the state of the art are:
o simultaneous capture of 2D and 3D information with the pixel-precise registration,
o simultaneous capture of multiple viewing and illumination angles,
o advanced 2D texture images with (i) increased signal-to-noise ratio, (ii) all-in-focus enhancement, and/or (iii) extended dynamic range via digital post-processing,
o adaptive dark / bright field imaging for special inspection task

Relevance and application possibilities of the described innovation for the machine vision industry:
Current industrial trends show that 3D shape alone is not sufficient for a large variety of applications, and shape must be complemented with 2D texture maps. The proposed AIT ICI technology exactly solves this task. It provides not only detailed 3D information but also high-quality colour texture images exactly aligned to the 3D model. Since the AIT ICI is not only a 3D measurement system but at the same time a high quality 2D line scanner it can be used for nearly all kinds of optical inspection tasks. The flexibility in choosing the number of lines used makes it easy to adopt to changing requirements in terms of speed and quality or changing surface properties. Over all, ICI is a highly flexible solution for high-performance inline inspection. It is the only system know combining light field and photometric stereo together with line scan technology.

The AIT ICI is tailored for high-performance industrial inline inspection. Defects at the ?m-range can be reliably detected. The method works largely independent from the surface properties of the inspected parts and can therefore be used for simultaneous inspection of matt, glossy, textured, non-textured, bright and/or dark objects. A special advantage lies in the method's flexibility. The number captured lines, which define how many observation and illumination angles are acquired, can be defined dynamically based on user's current needs. It is the adaptability and flexibility of the ICI technology that makes it the right solution in many areas of the industry, such as quality inspection of metal surfaces, coins, print, packaging, micro-electronics, rails, silicon wafer, etc. Figure 4 shows a small section of possible application fields for ICI.

Industrial needs:

High system requirements
o high speed and accuracy,
o inline inspection of moving parts,
o flexibility and adaptability,
o working in harsh environments.
High data quality and robustness
o simultaneous 2D and 3D imaging,
o high resolution and optical detail,
o high dynamic range.
Challenging inspection tasks
o highly reflective materials,
o security print with optical variable features

AIT ICI value proposition:

Simplicity / Speed / Quality / Flexibility
o system consisting of only one multi-line scan camera and a standard machine vision illumination,
o multi-line scan camera paired with smart algorithms makes the approach applicable in real-world inline applications,
o more accurate and robust alternative to other state-of-the-art methods, thanks to combination of multiple proven computational imaging principles,
o flexible ratio between speed and accuracy.

Applicability / Scalability
o enables (semi-)automatic inline quality inspection,
o simultaneous 2D and 3D measurements,
o detection of ?m-range defects,
o material recognition and classification.

Video:

https://youtu.be/5I4Y9LCeTAQ

Images:
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39603_figure_2_-_kabelbinder_-_feile_-_m__nze.jpg
39603_figure_3_-_ici_3d___ici_3d___textur.jpg
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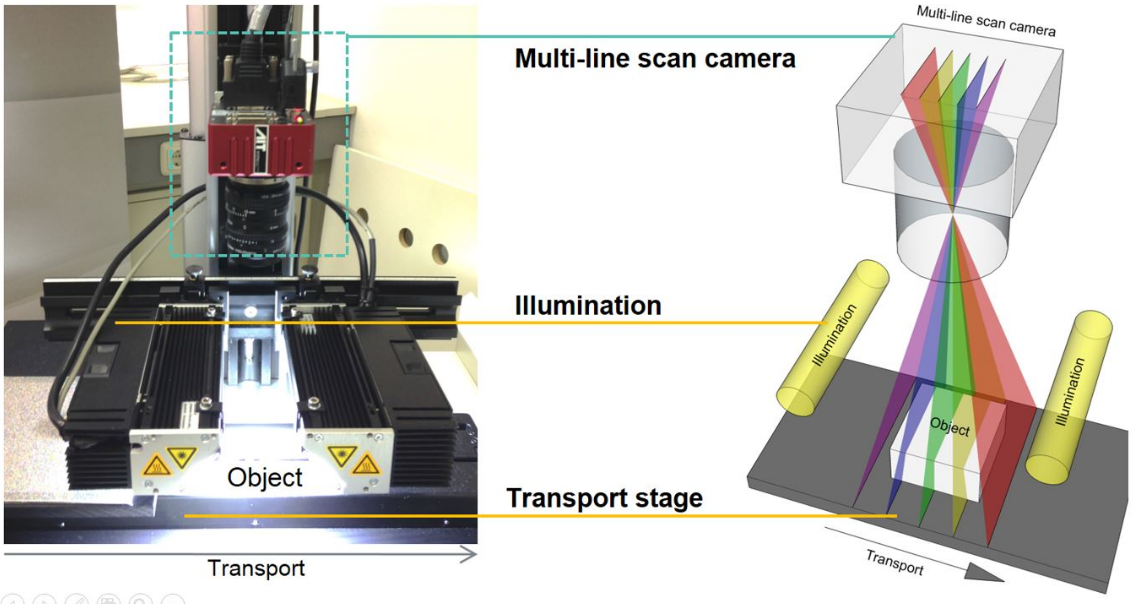

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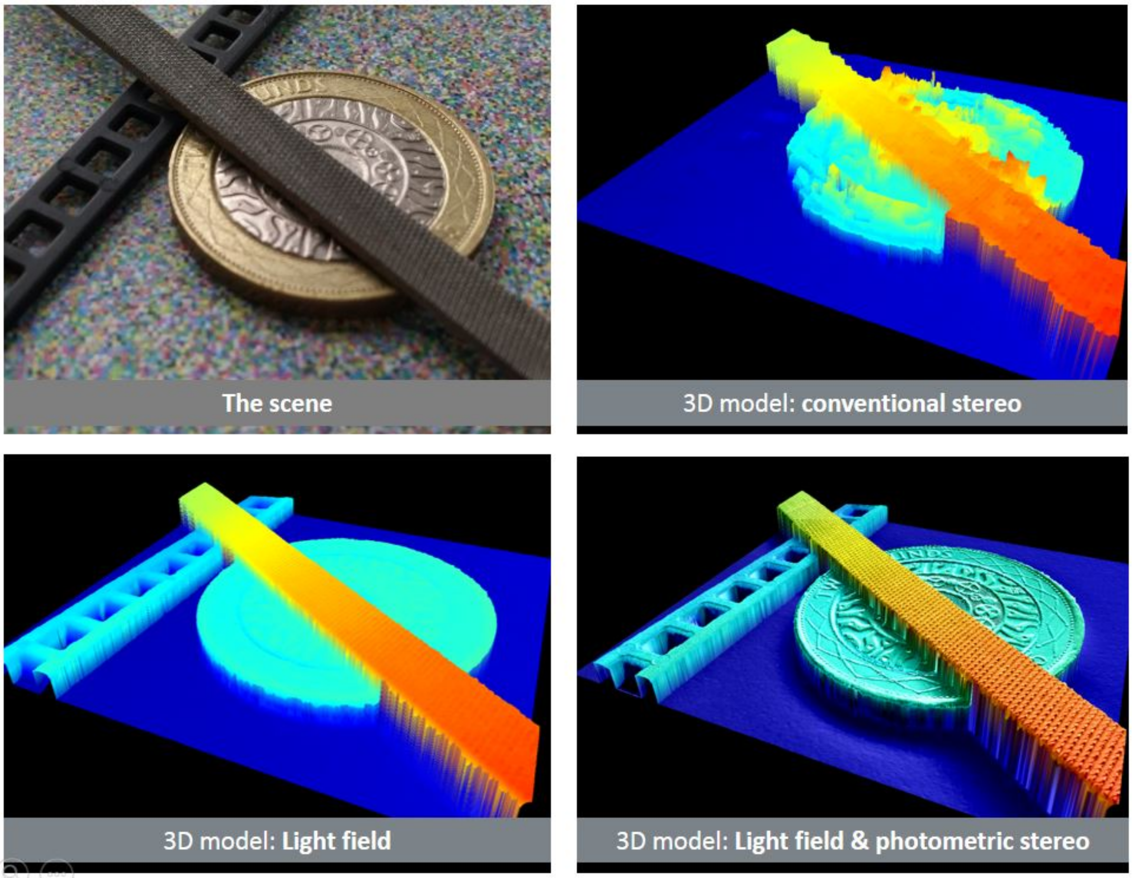

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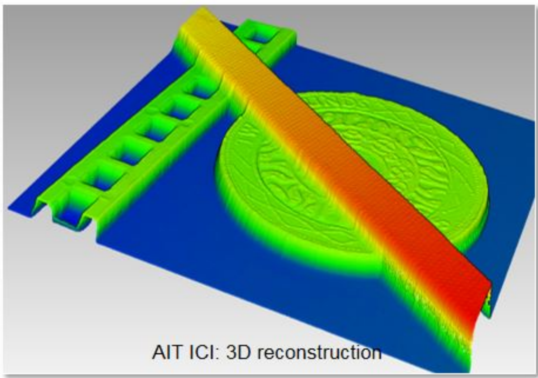

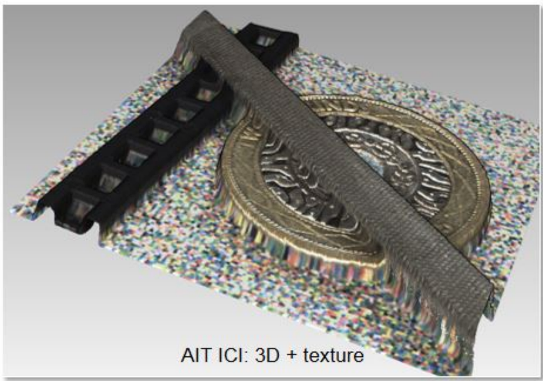

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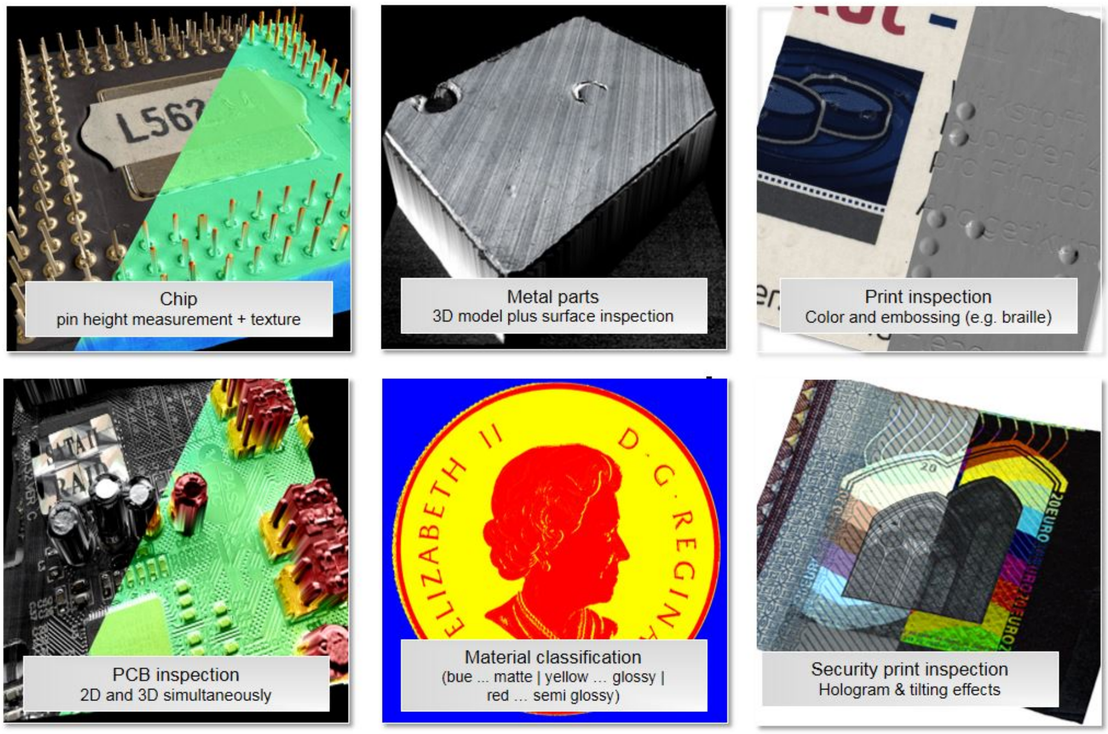

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