Joint Special Interest Group meeting between euspen and ASPE
Advancing Precision in Additive Manufacturing
Inspire AG, St. Gallen, Switzerland 2021
www.euspen.eu

Computer vision based zero point estimation for hybrid builds in metal additive manufacturing

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Abstract
This paper describes a novel computer vision system that is capable of performing automated zero point calibration for hybrid builds in additive manufacturing. This enables users to quickly and accurately locate and print on top of previously machined parts for part repair or hybrid builds jobs. The system was installed on an industrial laser powder bed fusion additive system and its performance evaluated. Results show that reliable zero point calibration can be obtained at high precision and accuracy and in few seconds, minimizing job setup time significantly.

Metal Additive Manufacturing, 3D Printing, Zero Point Calibration, Computer Vision, Hybrid Build, Process Monitoring.

1. Introduction

Metal based additive manufacturing (AM) has seen tremendous growth in the past years where specifically systems based on Laser Powder Bed Fusion (LPBF) have seen significant industrial adoption [1]. These systems can produce metal parts with complex geometries that would be impossible to manufacture using traditional machining or casting processes. A common application is to produce functional end parts that are made significantly lighter using topology optimization and infill meshing [2]. The geometrical flexibility offered has also proven to be an asset when producing tooling with integrated conformal cooling channels such as used in injection or vacuum forming molds. Though the manufacturing speed of such systems is improving with e.g., the addition of more laser units, traditional machining processes are often more accurate, faster and less expensive. To combine the strengths of these different processes, a hybrid build process combines these methods.

As a practical example, injection molds often have large functional sections for which LPBF is not the most efficient production platform. These sections are often flanges or interface regions. In these cases, where the design freedom of AM is not required, it is faster and more accurate to manufacture that portion of the part using milling or turning processes. Finally, the region benefiting for AM would be printed on top of the previously manufactured part. Figure 1 shows a simplified example of such a hybrid build. The system described in this paper is particular suitable, but not limited, to this use-case.

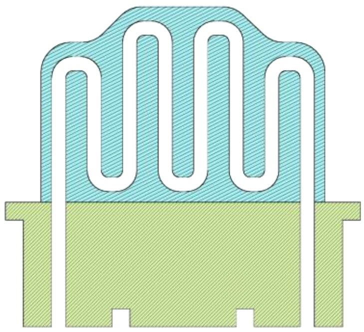

Figure 1. Example of a simple hybrid build design. Top section (blue) manufactured by AM, bottom section (base geometry, green) via traditional milling.

In order to be able to print on top of the pre-manufactured part, a zero point calibration needs to be performed on the work piece. This is the process of estimating the position of the hybrid part in the printer's frame of reference, or in other words the relative transform between the part coordinate system and the machines coordinate system. In traditional CNC machining, the machine will use a contact probe to probe the part or stock to evaluate its position within the machines reference frame. Such contact probe measurements are not possible inside of LBPF systems.

In the current approach to solving this, the part is fixed on the printer's build plate and registered using e.g., dowel pins. The printer's laser is thereafter used to mark or engrave a few visible features, such as crosses, that are visible to the human eye. As these feature positions are known in the printer's reference frame it is possible to take the hybrid part and measure the features relative to known features on the part itself. This measurement operation needs to be done using e.g., combined optical/tactical CMMs. The downside to this approach is that one needs to trust that the part is re-mounted at precisely the same location on the build plate, which is less than trivial. Furthermore, the method needs expert level know-how, expensive metrology equipment, is time consuming and special care needs to be taken regarding thermal expansion when going for the highest precision.

A less precise, yet much faster approach is to visually estimate the zero point offset using trial-and-error while the part is mounted on the build plate and inside the printer, preferably at operational thermal equilibrium. The offset can be entered in the printers print console and the engraving process repeated. This can be done iteratively until a desired result is obtained. For many applications, this method may be precise enough but remains time consuming.

This paper presents a novel approach of automatically determining the zero point using camera-based computer vision system with a camera inside the build chamber. When given a part geometry to search for, the system is within seconds able to accurately locate the part on the build plate and present its position in terms of the printer's coordinate systems. Our preliminary results show that the system significantly reduces setup time for hybrid builds without sacrificing accuracy.

2. Vision System

The optical system in question has been developed by Euler[1] as part of their off-axis quality assurance solution for LPBF systems. The hardware consists of an industrial camera along with a computation unit, show in Figure 2. The camera is mounted inside the build chamber as shown in Figure 3. In this position, the camera is outside of the laser region, and does not interfere with the inert gas flow inside the chamber. The camera is capable of operating at elevated temperatures up to *70* degrees C and is encapsulated in a housing to be IP67 ingress protected.

Figure 2. Vision system, comprising of an industrial camera and embedding computing system (mounting hardware not shown).

Figure 3. Vision system shown mounted in the build chamber of an EOS EOSINT M270 additive system.

2.1. Intrinsic Camera Calibration

This The camera is intrinsically calibrated by means of a precision calibration checkerboard target using the method of Zhang [3], followed by non-linear bundle adjustment optimization using the Levenberg-Marquardt algorithm. The sensor-lens system is modeled using the plumb-bob model [5] with three radial distortion coefficients, two tangential coefficients, unit aspect ratio and free principal point coordinates. The checkerboard fields are uniquely coded using ArUco binary markers [4], which allows for accurate characterization of the lens also at the image periphery.

2.2. Laser Calibration

To perform alignment in the printer's laser focus plane, the extrinsic parameters describing this plane are estimated in the following way. A flat black anodized aluminium plate is placed on the build plate and its top surface brought into the laser focus plane. A dense asymetric circle grid pattern of known geometry is then engraved onto its surface by means of a low-power laser exposure. This circles grid is detected in the camera image and a rectifying homography is estimated between detected circle coordinates in the undistorted camera image and their metric 2D coordinates in the laser's coordinate frame. It is therefore possible to geometrically rectify image pixel coordinates and get the corresponding laser coordinates, corresponding to coordinates in the input CAD geometry.

2.3. Zero point calibration

Zero point calibration in this setting corresponds to an alignment or image registration task, in which a 2D rigid transformation (translation vector *(x,y)* and angle (θ) are to be estimated. Our approach is based on a non-linear optimization in 2D rigid transformation space, which maximizes the overlap of the CAD contour with strong image gradients. Analytical derivatives for this objective function are also utilized, which results in quick and robust convergence if an approximate pose is known (to within a few millimeters).

Specifically, the base geometry STL file is loaded and edges at its top surface are identified as those edges which are shared by triangular faces with a significant angle between normal vectors. These edges are linked, and points are sampled uniformly on the entire edge. We found 2000 points be sufficient for repeatable and accurate results.

Non-linear optimization using the Levenberg-Marquardt optimization scheme is then employed to maximize the squared sum of gradient magnitude below the sample points. The free variables during this optimization are (x,y) and θ. By sampling the gradient magnitude image using a spline interpolator, we can derive an analytical Jacobian of the objective function which

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we found to yield much more robust convergence than numerical derivatives. With a reasonable starting guess around 2mm from the goal, our procedure converges in all cases. Our platform allows the user to interactively provide parameter values for this rough alignment if necessary.

Inspection of the steepness of the objective function at the solution also allows for estimation of uncertainty of the parameter estimates. Mathematically we do this by estimating the covariance of the solutions as fthe inverse of $J(x^*)^T J(x^*)$, where $J(x^*)$ is the Jacobian matrix at the found solution x^*. Typical values are 20µm for translations and 0.01 degrees for the rotation.

3. Operation

The zero point system is operated through a front end web interface which can be accessed from either the computer attached to the AM system, or any other computer on the same network or even over the internet. The interface is shown in Figure 4. It presents the user with a live feed of the camera and allows for upload of STL based geometries for part detection. The alignment functionality can then detect and register the top contour boundaries of this geometry in the current camera image. Estimated transform parameters are presented within seconds. The user can the use these resulting zero point values in the printer's software or perform the coordinate correction at a model level in a modelling or slicer software of their choice.

4. Results

The zero-point system was evaluated on a use-case where tooling inserts are to be printed on top of EDM cut kernels. The input STL geometry is the insert fixture seen in Figure 4. By numerous trials, it was determined that the system recovers the zero point transform with accuracy of at worst *50-100* µm. This result was affected by the galvanometer laser system being slightly out of calibration (material dependent scaling factors were slightly wrong in EOS software). Nonetheless the accuracy is comparable to that obtained by a skilled operator by means of trial-and-error.

The estimated time saving of using the system for one such setup is between *40* to *60* minutes. It was determined that the system can recover transformations up to a few millimeters autonomously, but this number depends on the exact geometry and strength of image gradients.

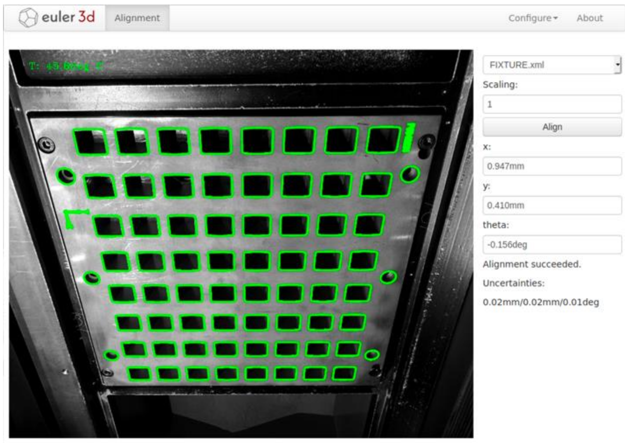

Figure 4. Web interface used to interact with the system, upload CAD geometries and perform zero point calibration. Detected alignment visualized with a green contour.

5. Conclusion

This paper has described the zero-point capabilities of the Euler off-axis print monitoring system and described the use-case of hybrid builds in which structures are printed on top of machined parts. Results show accurate alignment results and a significant time saving. An additional feature of the system is that it can be used to monitor print progress and quality remotely. More information is available at http://www.*euler3d.com.*

Acknowledgement

Part of the work presented in this paper has been funded by the Icelandic Technology Development Fund (Grant nr 188341-0611) and the Manufacturing Academy of Denmark (MADE).

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