Int J Adv Manuf Technol (2015) 81:1127–1138
DOI 10.1007/s00170-015-7178-z

ORIGINAL ARTICLE

Automatic part localization in a CNC machine coordinate system by means of 3D scans

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Received: 8 December 2014 / Accepted: 19 April 2015 / Published online: 17 May 2015

Abstract Due to the rough nature of surfaces produced by current additive metal processes, a deviation between the nominal and actual pose of the part arises when fixturing in an NC machine. Modern 3D scanning systems are capable of generating high density measurements that may be used to localize the part and compensate for these errors; but require that scan data be transformed from the scanner to the CNC coordinate systems. In this work, precisely located fiducial features are automatically detected in the scan data and used to compute the pose of the scanner. This information is used to register each scan to the CNC machine space, and thereby create a model of the workpiece as-built and as-mounted in the machine, for use in process planning and localization. An implementation of the system was built and tested against a machined part that was offset to simulate uncertain position and orientation. The initial performance evaluation of the system indicates that it is capable of successfully registering surfaces to the machine coordinate system with accuracy in line with the scanner performance specification.

Keywords 3D Scanning · Finish machining · Localization · Registration · Fiducial feature

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1 Introduction

The successful manufacture of parts on any machining system is predicated on accurate location, position, and form information of the workpiece. This is especially important when the workpiece is near net shape and has existing features against which tolerances are specified. In these cases, surfaces to be created by the CNC machine must be precisely located the surfaces must lie within the available workpiece material and be positioned correctly with respect to any features already present in the near net shape part. Traditionally, workpiece localization is performed in one of two ways: (1) the workpiece may be mounted in a specially designed fixture which ensures the workpieces location and orientation in the machine, or (2) by mounting the workpiece in a more general fixturing system such as a vice or a chuck and measuring the position and orientation of key features using indicator(s).

The selection of method is usually based on production batch size. When the batch size is large, fixtures tend to be the favored solution while manually locating the workpiece is favored when the batch size is small (down to single pieces). Both approaches have drawbacks—fixtures are time consuming and expensive to design and fabricate while general fixturing methods, require skilled operators and significant setup time per part. The clear solution to these challenges is the integration of an automated sensing system capable of measuring both the form and position of a workpiece as-built and as-mounted and in the CNC machine. This sensing system can be used to drive the generation of tool-paths that correspond to the part, thereby automating much of the setup process.

In common practice, the most used automated workpiece sensing system is the Touch Probe. Touch probing was first described by [1, 2]. Systems based on these patents are manufactured by [3] and are widely used commercially. Tactile probes can accurately measure the position of surfaces in the machine space. The probe is positioned adjacent to the surface to be measured and moved (by the CNC system) until the probe tip contacts the surface. The position at which contact occurred is recorded and the addition of precalibrated offsets, related to the probe's dimensions, to this position yields the position of the surface at the contact point. This process is repeated at different positions in order to capture multiple points from which surface form and position can be estimated. Several studies report on the use of tactile probing for workpiece localization. For example, [4] describe a system in which a touch probe, integrated with a CNC system is used for precision machining and inspection. [5] and [6] discuss the use of sparse measurements (as gathered by contact probes) together with CAD models for localization. Sahoo and Menq[7] discuss the use of tactile probing to localize complex sculptured surfaces while [8] further discussed the algorithm needed for localizing workpieces with point data gathered by touch probe. Other systems used for the localization and proper workpiece orienting using data gathered by tactile probing are described by [9, 10], by [11] and by [12]. These efforts further reinforce the need for automatic localization in CNC operations.

Challenges, however, remain in utilizing tactile probing as a workpiece sensing mechanism—for instance, toolpath design for probing is not completely hands–off, even when aided by modern probing software, requiring user intervention and decision making. Research to address this problem has been described in the literature by [13], by [14], and more recently by [15]. However, the authors are not aware of any commercial system that can completely automate the process of Touch Probing. Touch probes typically generate sparse surface data [6], while the successful localization of free-form surfaces, especially in the presence of high surface roughness, necessitates dense surface data. Gathering this data with a tactile probe is difficult and time consuming. Probing systems can be difficult to use when the workpiece contains occluded surfaces, as discussed by [13] or surfaces that are inaccessible due to probe length, probe diameter, and other limitations. It is also not clear how the accuracy of touch probes may be affected by the surface characteristics of rough, additively manufactured metal parts. It is likely that significant work will be required to determine and distinguish the expected versus the true point of contact and the cosine error. These characteristics render touch probes suboptimal for the measurement and subsequent localization of many classes of rough, near net shape parts.

Optical systems capable of capturing three dimensional data can overcome these limitations. These systems, sometimes referred to as '3D scanning', consist of a family of technologies that can capture three dimensional data of surfaces present in their field of view [16, 17]. The most common systems in industrial use rely upon the use of image processing techniques to analyze the distortion present in a pattern of projected light, caused by the pattern falling upon surfaces in the scanner field of view. The projection system is mounted offset from a camera and triangulation techniques are used to determine the position and form of surfaces that the projected light is incident upon. The projected light pattern can take the form of a single point of laser light, a laser line or stripe, or a more complex pattern produced by a video projection or grating system [18, 18–21]. Systems that rely on laser line stripes either include a means of sweeping the laser stripe across the target or must be mounted on a system in which the scanner and the target are moved relative to each other. The systems that utilize pattern projection can generally capture 3D measurements of all visible surfaces in their field of view, in a single frame.

In all cases, the data output from these scanning systems consist of 'point clouds'—sets of points represented as three dimensional Cartesian data that lie on surfaces in the scanner's field of view. In some cases, additional processing is needed to convert the raw scanner output to this form; while in others, additional information such as target color is also available. These Cartesian coordinates are provided in an internal scanner frame of reference and must be transformed to the machine coordinate system in order to be used for localization. In addition, multiple scans need to be taken with the scanner and the part at different positions and orientations in order to capture all critical part surfaces. These scans (each represented as point-clouds) need to be properly oriented, about the machine axis, with respect to each other, before being combined in order to properly represent the surfaces of the workpiece.

Scans are commonly combined by means of algorithms such as those discussed by [22] and [23] in which features and surface forms already present in the target part are used to align overlapping point clouds. In some systems, such as those discussed by [24] , fiducial markers are affixed to the target before scanning in order to simplify and improve the ability of the system to detect the relative positions of different scans. These methods, available as a part of many software packages, are inherently incremental in nature – one scan of the workpiece is aligned to the next and so on. Models generated in this manner, while accurate representations of the part form, do not provide for localization in a global coordinate system, as is required for detecting workpiece position, location, and form. It is therefore necessary to develop a system which registers each scanned point cloud to its appropriate position and orientation in a global coordinate frame, corresponding to the CNC machine axis. Scans registered using this approach will also naturally be registered with respect to each other.

The use of 3D scanning and related systems for global localization has been described in the literature as well as commercially implemented. Gordon and Seering [25] describe a system capable of performing accurate localization with a carefully located light stripe sensor. Habibi percaru [26] describe a patent for a system for training a robot to recognize and localize objects using 3D vision. Biegelbauer and Vincze [27] describe a system that used a 3D laser scanner to accurately localize bore holes for endoscopic inspection. Skotheim et al. [28] have developed a system that uses a laser line scanner mounted on a robotic arm for workpiece localization in assembly operations. Okarma and Grudzinski [29] have developed a system in which multiple scanners are used to generate an in-machine 3D model of the workpiece. More recently, [30] describe the development of a laser scanner-based localization system for automatic robotic welding. Several systems have also been developed for the wood and lumber industry—for automatic localization and workpiece analysis for bucking, debarking, sawing and sorting of logs [31–33].

In all these cases, the sensing system is mounted and calibrated such that the transformation from its measurement frame to the machine base frame is known. This approach is useful when the scanning system can be accurately and repeatedly mounted at a known location in the machine space. Often though, the workpiece requires scans taken from multiple positions and orientations in order for all surfaces to be captured. In such cases, the scanner has to be mounted upon a motion system that provides accurate location information. This system can take the form of a motorized robotic arm or a (manually) movable assembly that can report on its position. However, such systems can easily prove to be expensive and difficult to properly integrate into an existing CNC machine setup. It is therefore necessary to develop a system that allows scan data to be accurately localized (registered) to a global coordinate frame, when the scanner frame of reference is not well known.

This work is focused on the development of a system that can register scan data, captured by a 3D scanner arbitrarily positioned and oriented, to the machine coordinate frame. This registered scan data is then combined to create a high-density point model of the target workpiece in the machine coordinate frame. This located point model can then be used to determine the optimum position of the desired part surfaces within the material present, in the machine coordinate system.

2 Approach

In order to overcome the challenge of global registration of scan data, this work proposes the following system:

1. Several machined fiducial features, each possessing a unique geometry, are mounted and precisely located in the CNC machine space. These fiducial features are prismatic in nature and lend themselves well to localization by traditional means. They are also easy to manufacture and ‘universal’— the same features can be used for any part, eliminating the issues associated with traditional fixtures.
2. The workpiece is then fixtured in the CNC machine and scans are taken from multiple viewpoints until all reference surfaces on the workpiece have been adequately captured. The scans are taken such that they each contain one or more fiducial features along with the workpiece. The scanner may be arbitrarily positioned and oriented during this process. If the CNC machine is used to move or rotate the workpiece away from its nominal position, the machine position corresponding to each scan is recorded.
3. Each scan is then analyzed and the position and orientation of the fiducial features captured along with the workpiece are estimated. The estimates are compared to the known (measured) position and orientation of the fiducial features and a transform that moves the scanned point cloud from the scanner coordinate system to the machine coordinate system is generated. If the scan data was taken with the workpiece translated and/or rotated away from its nominal position in the machine, the transformation is modified to compensate.
4. Each scan is analyzed in this manner and the generated transformation(s) are applied. This results in a set of point clouds in which the point coordinates correspond to their location in the machine coordinate system. The points contained in all the scans are then combined to generate a single model that contains a point representation of all required workpiece surfaces. This model may then be analyzed to extract the positions of these reference surfaces and drive tool-path generation.

3 System description

An implementation of this system was developed to illustrate the processes and algorithms required for use of the system. The following sub-sections describe this setup.

3.1 CNC machining station

The CNC machining systems used, consists of a HAAS VF–3 [34] machining center within which a 2 axis truncation assembly is installed, giving the system 5 axis machining capability. Workpieces are mounted in three jaw chucks between the trunnion, rotated to 90 degrees, and a coaxial outboard support which is itself mounted on a Schunk Vero–S NSE plus quick change pallet system (Fig. 1). The workpiece, mounted in this way, can be rotated about the X axis, in addition to Translation in X, Y, and Z. The VF–3 is equipped with both a Renishaw probing system [35] and a Renishaw automatic tool setting system [36] , allowing for rapid, accurate workpiece, and tool measurements.

3.2 Fiducial features

Two parts, each with three plane mutually orthogonal surfaces that form a fiducial feature (two unique Cartesian coordinate systems) were machined. They are denoted here as ‘A’ and ‘B’ (Figs. 2, 3, 4 and 5). The fiducial feature surfaces on each component are easy to locate, and the parts were designed to be simple to machine. The fiducial features were designed to facilitate repeatable and accurate detection in the 3D scan data. Both parts were sand blasted to provide a matte surface finish. This was done as the scanner appears better able to pick up matte, as opposed to reflective, surfaces.

The two machined features were mounted, using bolts, to a Schunk Vero–S PAL–S (399 x 159) mounting pallet . The pallet was drilled and tapped with an array of holes, spaced at 50.8mm (2 inches) to facilitate easy mounting of the parts, in multiple orientations and positions. A dial indicator was used to ensure that both fiducial features were aligned to the CNC machine axis. Run–out was within 0.0254 mm (0.001 in) over approximately 50 mm in both cases. The Renishaw probe was then used to measure the position (single point measurements) of the three planes that form the fiducial features on each part. These measurements were processed to compute the position of local origins of each fiducial feature (in both cases, the point where the three planes intersect) in the CNC machines coordinate space.

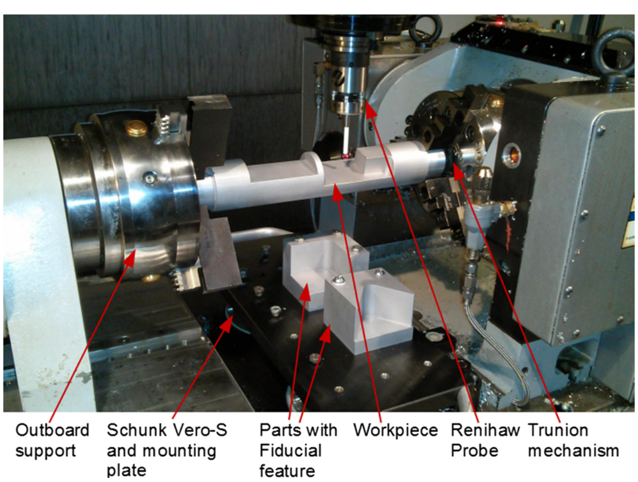


Fig. 1 Setup in a HAAS VF–3. Trunion assembly, outboard support, workpiece, pallet system, fiducial parts and Renishaw probe are visible

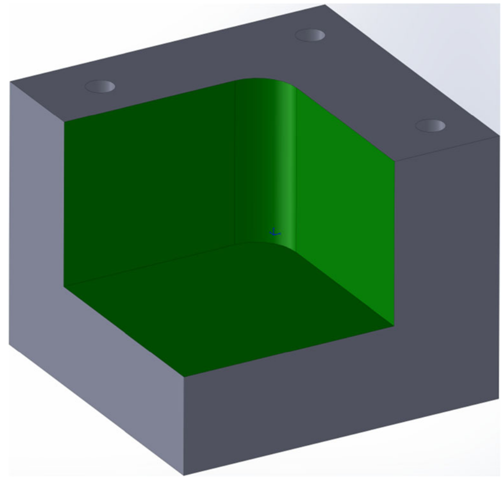


Fig. 2 Fiducual Feature ‘A’ Highlighted in green

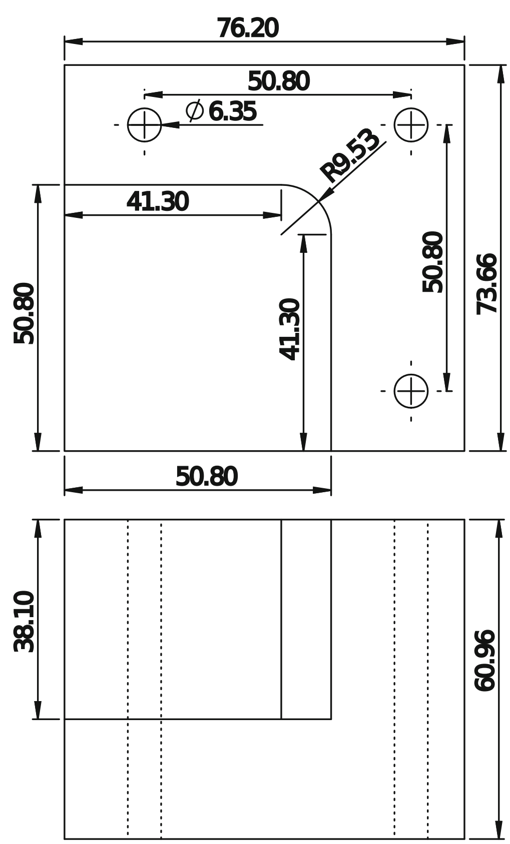


Fig. 3 Part with Fiducual Feature ‘A’; all units in mm

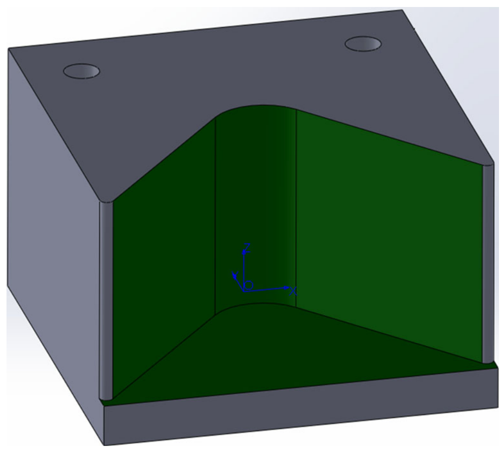


Fig. 4 Fiducual Feature 'B' Highlighted in *green*

3D point models of the fiducial features were then prepared:

1. The part models were transformed such that fiducial feature origin on each corresponded to [0,0,0]
2. The models were exported as STL triangulated representations with units in meters.
3. The STL models were imported into MeshLab [37, 38]
4. The reference surfaces were extracted. These are indicated in green in Figs. 3 and 5. The remaining surfaces were deleted.

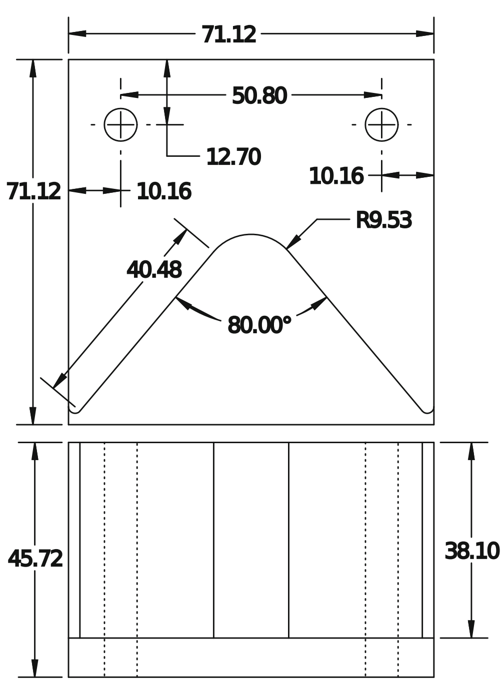


Fig. 5 Part with Fiducual Feature 'B'; all units in mm

5. A point representation of the surfaces was generated by sampling the remaining surfaces in MeshLab using the Poisson sampling filter [39]. Sampling was performed with an explicit radius of 0.0005 m (0.5 mm). Poisson disk sampling was selected as it was found to generate well distributed samples.
6. The point models were exported as ASCII PLY files.

3.3 3D scanner

The scanning system employed is a NextEngine HD laser scanner [40]. The NextEngine is a low cost commercial scanning system with a stated accuracy of 0.381 mm (0.015 in). This was deemed sufficient for initial proof-of-concept validation. A more capable scanner, capable of measurement accuracies under 0.025 mm (0.001 in) will be necessary for the accuracy required in a commercial implementation of the system.

The scanner was mounted in a custom-built assembly and suspended from an aluminum beam bolted to the HAAS machining center (Fig. 6). The scanner mount was designed to permit the scanner to be freely positioned and oriented with respect to the target part and fiducial features, in conjunction with the motion capability provided by the CNC system itself. The NextEngine scanner was controlled using the associated ScanStudio software in order to capture scans.

3.4 Software

The localization software was written in C++ with extensive use of the PCL library [41]. The software is implemented as a set of constructs. Each construct performs a specific task and has well-defined methods and input/output formats. It is envisioned that these constructs will eventually be used as building blocks for a complete automated localization system, integrated with a CNC machining station .

Fig. 6 NextEngine laser scanner mounted in CNC machine

3.4.1 Scan localization algorithm (processor construct)

The construct designed to perform localization is the processor. The processor construct functions by attempting to fit known models of the fiducial features present, to the scan data. If a fiducial feature model is successfully fit to the scan data, the transformation that produced the successful fit can be inverted to give a transformation that fits the scan data to the machine coordinate system.

Each fiducial feature model is fit to the scan in two stages—an initial global fit, which transforms the fiducial feature model to its approximate location in the scan and a final fit, which uses least squares methods to accurately fit the feature model to the data present. In this work, the Sample Consensus Initial alignment (pcl::SampleConsensusInitialAlignment) [42] algorithm is used to perform the initial, global, fit, and the normal ICP (pcl::IterativeClosestPointWithNormals) algorithm is used as the final, accurate, fit algorithm. Both are implemented as a part of the PCL library.

This registration process is performed against each fiducial feature model and the computed transform is stored. After each fiducial feature model is fit, a performance metric is computed. This metric (1) is the inverse of the average distance between the points in the (registered) fiducial feature model and the corresponding (as per ICP) points in the scanned data.

$$N_f / \sum \left(P_f , P_s^f \right) \tag{1}$$

Where N_f represents the number of points in the fiducial feature model, P_f is a point in the fiducial feature model, and P_s^f is the corresponding point in the scan. A larger metric indicates a more successful fit. Once each of the fiducial feature models has been fit, the largest metric is compared to a threshold. If the (corresponding) metric exceeds the threshold, the corresponding fit is considered 'good'. In this way, this system is robust to bad fits and occlusions of the fiducial feature.

After the best fit is identified (assuming at least one fit passed the threshold metric), the overall registering transform is computed:

$$T_r = T_f^{-1} T_o T_d \tag{2}$$

Where T_r is the overall registration transformation, T_f is the (best) fiducial feature fit transformation, T_o is a transformation that represents the measured displacement of the fiducial features in the CNC machine coordinate frame and Td a transformation that represents the CNC machine position (translation and rotation) when the scan was taken (Fig. 7).

The output of the processor construct consists of an instance of a view construct. The view construct

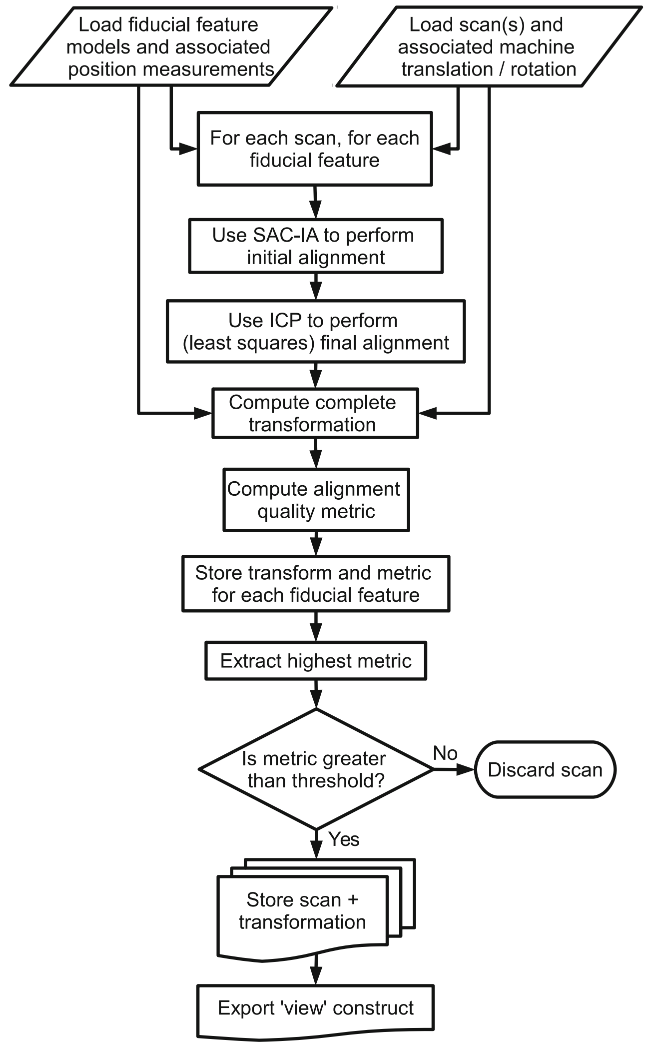


Fig. 7 Processor (registration) flowchart

functions as a storage mechanism and holds references to a set of (scanned) point clouds and the associated localizing transforms.

3.4.2 Workpiece localization (Part construct)

The part construct contains methods that reconstruct a model of the entire part, generate a dense point model of the workpiece surfaces and use the generated model for localization. The part construct works in a series of stages.

The set of view constructs (registered scans) are loaded into an instance of the 'part' construct. Along with these, a point-model of the workpiece reference surfaces at their nominal position is loaded into the part construct instance. The nominal position of the workpiece coordinate system, corresponding to these reference surfaces, is also provided to the part construct. The workpiece point-model was

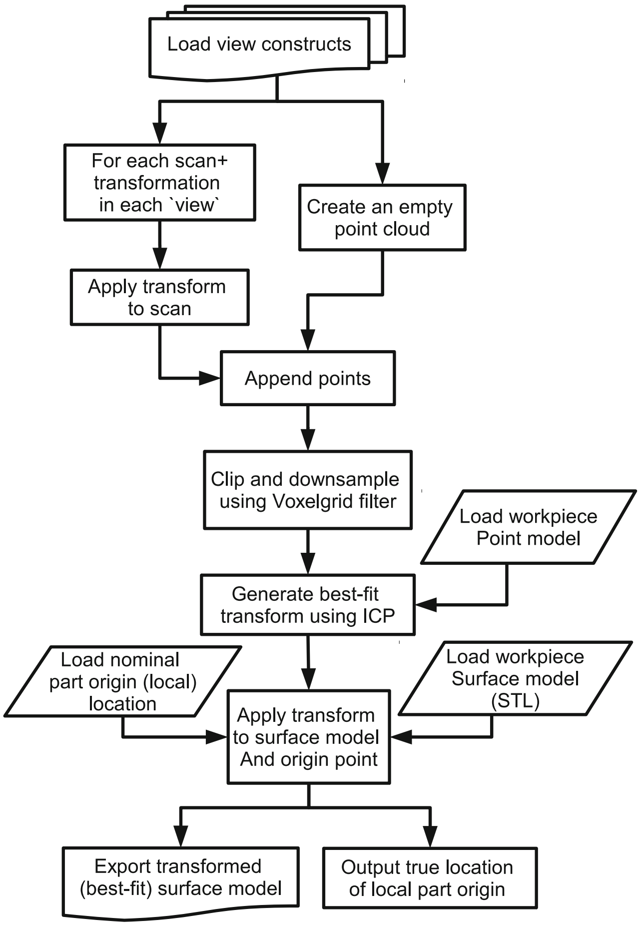


Fig. 8 Part (localization) flowchart

generated in a similar manner to the fiducial feature models—the cad file corresponding to the workpiece model was positioned at its nominal position in the machine coordinate system and its surfaces were sampled using the Poisson disk sampling function in MeshLab.

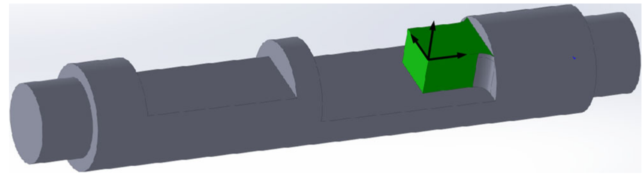
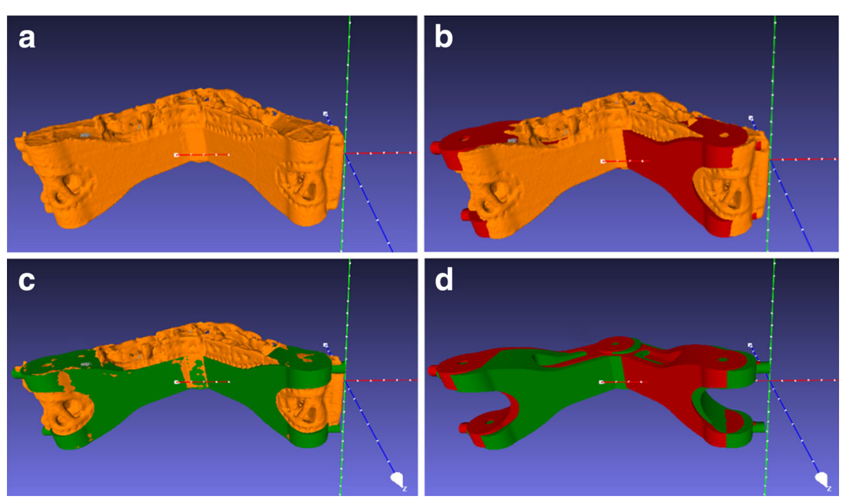


Fig. 10 Test workpiece and coordinate system; reference surfaces highlighted in *green*

The construct uses the computed registration information in each view to align each scan with respect to the others as well as the CNC machine coordinate system. The aligned scans are combined and clipped to generate a complete point model of the workpiece. The nominal workpiece model (reference surfaces) is transformed (using the ICP algorithm) to fit the model generated from the scan data. The true orientation and position of the workpiece (in the machine coordinate system) is extracted by applying this best-fit transform to the nominal workpiece coordinate system (Fig. 8).

Once the best fit transformation and corresponding true position of the workpiece have been extracted, the part construct generates two additional models—a triangulated surface reconstruction of the workpiece in the CNC machine and a surface model of the desired final part, transformed by the computed best-fit transform. It is expected that in the final system, these will be fed to a suitable CAM system in order to generate tool-paths for finish machining the transformed model of the desired final part will be used as a 'desired surface model' and the reconstructed workpiece as a 'stock model' (Fig. 9). It is intended that with further development, the part construct will become capable of determining the optimum position and orientation of the desired target part, to fit within the workpiece material present while maintaining orientation for machinability.

Fig. 9 Demonstration of system with test part: **a** Scanned and reconstructed model (*orange*), **b** reconstruction with workpiece (*red*) at nominal position, **c** workpiece transformed (*green*) to fit material present, **d** displacement between transformed and nominal part models



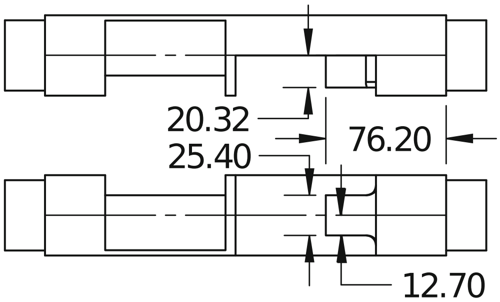


Fig. 11 Test workpiece; all units in mm

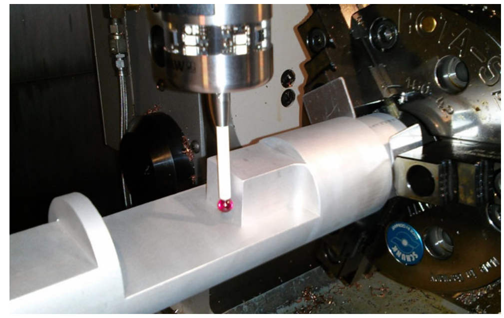


Fig. 13 Measurement of workpiece reference surfaces

4 Experimental evaluation

The purpose of this experimental evaluation is to determine if the system is capable of registering multiple scans, taken from arbitrary positions and orientations, and can be successfully registered to the machine coordinate frame. The accuracy with which a target part may be represented is also tested. In order to evaluate this, a test specimen (workpiece) was designed and machined from Aluminum (6061) bar stock. The specimen was sand-blasted to improve its visibility to the laser scanner. As described in Section 3.4.2, the reference surfaces of the part were extracted from the CAD model and sampled using the Poisson disk sampling algorithm in MeshLab. The samples were generated with an explicit radius of 0.0005 m (0.5 mm). Figure 10 shows the test workpiece, the reference coordinate system is formed by the intersection of the three highlighted planes. The nominal location for this coordinate system (corner), as designed is (-76.20, -12.70, 20.32 mm) referenced from the origin of the rotational axis—formed by the rotational axis and the jaw face.

The test specimen was shimmed and rotated before fixturing to simulate the effect of an uncertain workpiece location. The shim positions, thickness, and the angle of rotation were varied each experiment. After fixturing, the positions and orientations of the reference surfaces on the shimmed test part were measured using the Renishaw probe (Figs. 11, 12, and 13).

The Renishaw probing system was used to collect three data points on each reference plane (nine points in total). These points were processed, compensated for cosine error, and the position and orientation of the coordinate system formed by the three planes was extracted. The position of the part coordinate system was extracted by finding the (least squares) point simultaneously closest to all three planes. The probe is expected to be significantly more accurate than the current implementation of the scan-registration system. Therefore, the location of the part coordinate system extracted, determined by probing, is treated as the true location.

Six scans were taken of the test specimen. Two each at a rotations of 0 degrees, two at 45 degrees, and two at 90 degrees. The scans were taken from different positions, each position chosen by the operator in order to best capture the test parts surfaces. None of the positions were fixed or predetermined.

These scans were processed using the processor and part constructs as described in Section 3 (Figs. 14, 15 and 16). A

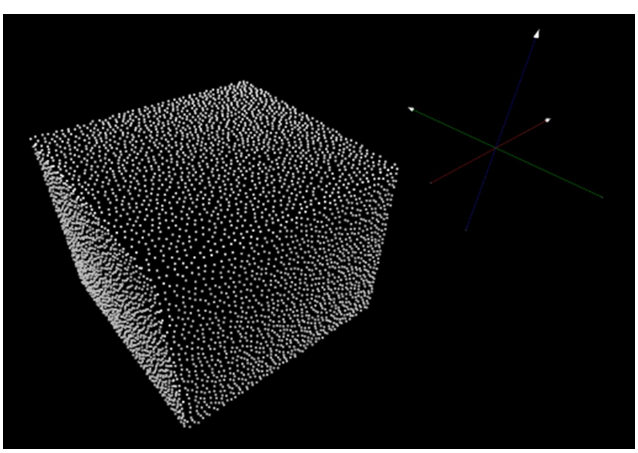


Fig. 12 Reference surfaces, extracted, and sampled

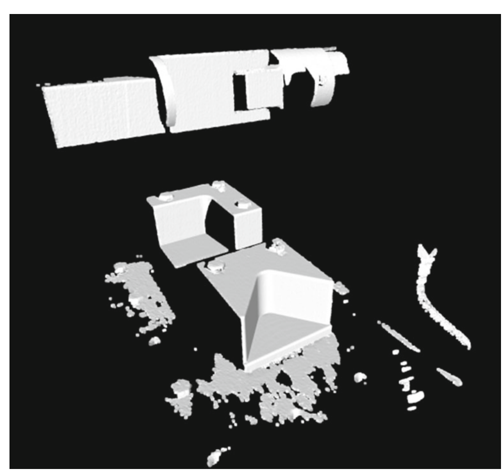


Fig. 14 Example of scan data

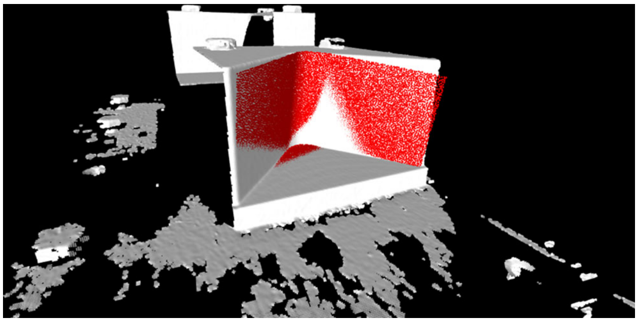


Fig. 15 Initial fit (SAC–IA) of fiducial feature model to scan data

value of 6,250,000 was chosen as the 'successful fit' threshold metric for the processor construct. This corresponds to an average point correspondence distance of 0.0004 m in (0.4 mm). This value was selected as being slightly less than the average point density of the fiducial feature models (0.5 mm) and scan data (4400 points / in^2). An average distance of 0.0005 m or greater would likely correspond to an improper fit. The parameters for ICP, SAC–IA, Normal Estimation on scanned data, and Scanning were selected by trial and error as well as the authors' experience. The values used are given in Tables 1, 2, and 3. Future work will include a scheme for analytic selection of parameters bases on scanner and system performance specifications.

The constructs functioned as expected and produced a combined point cloud, located in the machine space (Fig. 17). The reference feature model was successfully fit to the combined point model and the transform that resulted in the best fit was exported. It should be noted that a simultaneous fit on all three planes was used here. Ideally, the position and location of the coordinate system should be determined by performing a least square fit individually on each plane and treating them as primary, secondary, and tertiary datum. The simultaneous fit was deemed sufficient as the planes are machined surfaces created in the same operation and are therefore expected to have a (high) degree of planarity and orthogonality—sufficient for the simultaneous fit method.

Table 1 ScanStudio settings used

Setting	Value
Positioning	Single
Points / in^2	4.4k
Target	Light
Range	Wide

Table 2 Function parameters used in processor construct. All length units are in meters

Parameter	Value
Normal estimation radius	0.001
Downsampling radius for fiducial features	0.004
FPFH radius for fiducial feature models	0.02
Downsampling radius for scan data	0.004
FPFH radius for scan data	0.02
SAC–IA number of samples	3
SAC–IA correspondence randomness	2
SAC–IA maximum iterations	4000
ICP maximum iterations	400
ICP maximum correspondence distance	0.005
ICP termination transformation Epsilon	$1e-09$
ICP termination fitness distance Epsilon	$2.54e-6$

Table 3 Function parameters used in part construct

Parameter	Value
ICP maximum correspondence distance	0.005
ICP termination transformation Epsilon	$1e-09$
ICP termination fitness distance Epsilon	$2.54e-6$
ICP maximum iterations	600
MLS search radius	0.002 m
MLS polynomial fit order	3
MLS square gauss parameter	0.002^2m
Final Voxel–Grid filter radius	.0005

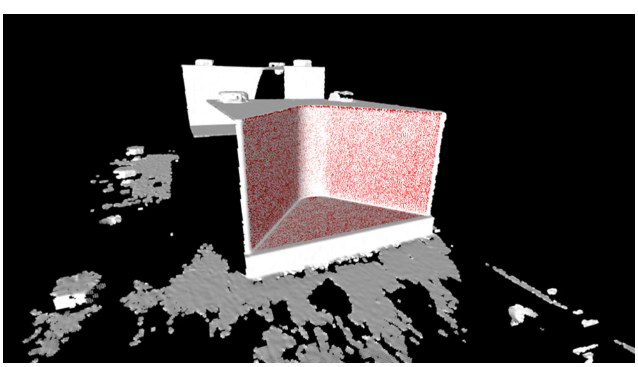


Fig. 16 Final (least squares fit with ICP) of feature model to scan

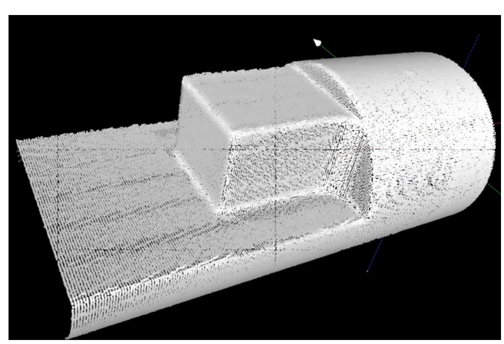


Fig. 17 Complete set of scans, registered, and clipped

The transformation was used to determine the position (X, Y, and Z displacement) and orientation ($\Delta\alpha$, $\Delta\beta$, and $\Delta\gamma$) of the coordinate system formed by the three reference planes (Fig. 10) as determined by the scan-based localization system. The position and orientation are determined as follows: given the reference surface fit transformation 'R', and a local workpiece coordinate system C consisting of an origin 'o' and unit axis vectors x , y, and z $C \equiv o, x, y, z$ the located coordinate system C' is given by:

$$R = \begin{bmatrix} R_{11} & R_{12} & R_{13} & R_{14} \\ R_{21} & R_{22} & R_{23} & R_{24} \\ R_{31} & R_{32} & R_{33} & R_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$C' = R \times C = \begin{bmatrix} R_{11} & R_{12} & R_{13} & R_{14} \\ R_{21} & R_{22} & R_{33} & R_{24} \\ R_{31} & R_{32} & R_{33} & R_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} o_1 & x_1 & y_1 & z_1 \\ o_2 & x_2 & y_2 & z_2 \\ o_3 & x_3 & y_3 & z_3 \\ 1 & 0 & 0 & 0 \end{bmatrix} \quad (3)$$

5 Results

The experimental procedure was repeated a total of five times with the part being re-fixtured to a new position each time. The results from each case—the measured (probed) and the located positions of the planes are listed in Table 4.

Table 5 contains the mean (absolute) and standard deviation of the errors (the difference between located and measured position). The average error in Table 5 was calculated as the average of the difference between the measured and located positions of the workpiece coordinate system $\bar{X} = \frac{\sum(X_M - X_L)}{5}$; $\bar{Y} = \frac{\sum(Y_M - Y_L)}{5}$; $\bar{Z} = \frac{\sum(Z_M - Z_L)}{5}$. The overall error was then computed as the average of the vector sum of the error $\|X, Y, Z\| = \frac{\sum(X_M - X_L)^2 + \sum(Y_M - Y_L)^2 + \sum(Z_M - Z_L)^2}{5}$.

Table 5 System performance, units in mm

Dimension	Average error	Standard deviation
X	0.07	0.060
Y	0.35	0.13
Z	0.35	0.02
$\|X, Y, Z\|$	0.50	0.12

6 Discussion and conclusions

The objective of this work was to provide an initial demonstration of the feasibility and utility of 3D scanning for workpiece localization and stock model generation. The NextEngine scanner used had an error in position of ±0.015 in. We feel that an industrial quality scanner would significantly reduce the error values. As such, the methods, algorithms and parameters used in this study were selected for expedience and ease of use rather than performance, accuracy or compliance with equivalent traditional practices. It is also standard industrial practice to design fixtures with 10 times the dimensional tolerance of the workpiece. In the system described here, the fiducial features can be thought of as machining fixtures and the scanning system the workpiece–fixture compliance. Since the fiducial features were manufactured to a tolerance of approximately 0.025 mm (0.001 in), it is unreasonable to expect localization tolerance better than 0.25 mm (0.010 in). This is expected and observed.

In this paper, we show that the described system can be used to register scan data to a CNC machine coordinate system (subject to the scanner performance specification) and thereby produce high density point models of workpieces in the CNC machine. The system does not require a precisely located 3D scanner or a precision motion system registration to the machine coordinate system is performed using the scan data itself. This scheme can therefore be used to integrate a 3D scanner into a CNC finish machining system without substantial additional equipment or modification.

Table 4 Experimental results. All units are in mm. X_M etc. refer to measured (true) coordinates while X_L etc. refer to the coordinates as located by the scan based localization system

Test #	X_M	X_L	Y_M	Y_L	Z_M	Z_L	α_M	α_L	β_M	β_L	γ_M	γ_L
1	−77.47	−77.52	−12.79	−13	20.67	20.99	0.5	0.7	−0.1	0	0	0.2
2	−80.06	−80.13	−10.41	−10.95	21.08	21.49	−6.8	−6.6	0.1	0.2	0	0
3	−78.81	−78.91	−12.16	−12.44	20.31	20.63	−1.9	−1.9	0.3	0.4	0	0
4	−80.9	−80.97	−11.59	−12.01	21.71	22.11	−3.1	−3	0	0	0	0.1
5	−78.78	−78.85	−13.86	−14.16	19.75	20.03	4	4.2	0	0	0	0.3

The point models produced by this system are located in the CNC machine coordinate space and can be used for offset generation, tool–path planning and in–process inspection. As manufacturing increasingly moves toward the production of small lot sizes of customized parts with greater complexity and free–form surfaces, approaches like this will be required in order to meet industry accuracy requirements while maintaining low lead times and costs. This is particularly important in the context of manufacturing systems that aim to exploit the capabilities of additive manufacturing while maintaining the accuracies and surface finishes required by industry. Given the high cost of materials and machine time, it is important to minimize material wastage and cycle times while simultaneously detecting failure early, before significant time is spent processing a part that cannot meet final requirements. The system described in this work, is well suited for such applications.

In order to evaluate the true performance of scan based localization systems, it will be necessary to rebuild this system with a high performance 3D scanner, precision machined fiducial markers and algorithms that better comply with traditional locating practices primarily the use of hierarchical datum features and incremental (as opposed to simultaneous) registration. A thorough validation study with such a system is necessary in order to evaluate scan based localization as a viable alternative to traditional approaches. Further, along with position, it is necessary to evaluate the ability of this system to accurately represent the form of the workpiece. A thorough understanding of the tolerance chains introduced by the scanner and by each of the procedures and algorithms used will also need to be developed and validated. This understanding may subsequently be used to drive scanner selection based on the required process tolerance. The development of this improved, high performance, system and the modeling and validation of its performance is the subject of future work by the authors.

Acknowledgements This work was made possible by support from the National Science Foundation, Division of Civil, Mechanical, and Manufacturing Innovation, under the project "Hybrid direct manufacturing production", #1161926 2012-4.

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