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Multi-sensor Integrated System for Reverse Engineering

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Abstract

Application of multiple sensors in Reverse Engineering (RE) has been effective approach to meet increasing demands of both complexity and accuracy. However, methodology to plan RE steps using systems combining different sensors has been a serious challenge. This paper presents hybrid system that integrates laser line scanning probe and touch trigger probe of coordinate measuring machine for RE of complex part. As a result of integration, this system utilizes strength of one system to overcome limitation of other. In this paper, RE methodology using hybrid system has been described through a part case study. The primary objective of this paper is to retrieve lost 2D drawings as well as damaged portion of mechanical part efficiently and accurately using hybrid system.

Keywords: Reverse engineering; Coordinate Measuring Machine; laser line scanning probe; touch trigger probe; multi-sensor integrated system

1. Introduction

Reverse engineering (RE) is a design methodology where existing part is measured to gather information either in form of point cloud or simple geometries for reconstruction of CAD model [1]. It is a process where an existing part is engineered back to obtain its CAD model and finally its drawing [2]. RE comprises of two fundamental steps: 3D Digitization (data capture) and surface reconstruction as shown in Fig 1. The basic concept behind RE is to determine design intent of existing obsolete or worn out parts.

Fig.1. Steps for reverse engineering of an existing object

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The developments in RE methodologies and techniques have made RE an important process in design and production processes [3]. This design approach has recently gained lot of interest in automobile, aerospace, medical industries etc., because of high complexity and functional requirement of their products. RE can successfully be utilized to reconstruct obsolete, damaged or worn out mechanical parts. However, in many complex applications it has been observed that efficient RE requires integration of multiple 3D digitization techniques to capture complete part information. Sensor integration, which can also be called as hybridization not only simplifies measurement task but also utilize measurement techniques to their potential which yield accurate results in lesser time as compared to conventional RE process. Multi-sensor data integration can be defined as process of combining data from more than one sensor into a common format [4]. Main objective of multi-sensor data integration is to obtain quality data and capture all part features efficiently. Sensor integration can improve performance of RE process in following ways: completeness of data, better resolution, increased robustness to sensors, noise reduction and improved accuracy etc. These benefits of hybrid system have been realized through several past investigations such as of Motavalli et al. [5] who successfully implemented integrated system that combined contact and non-contact sensors to digitize part surface. In the same way, Reich et al. [6] carried out 3-D shape measurement of complex objects using system that combined photogrammetry and fringe projection techniques. Chen and Lin [7] also employed sensor integration between 3D stereo detection and contact digitization for RE of complex parts. It has been recognized that combined approach utilizing two sensors for RE of freeform surfaces can provide highly accurate CAD model in lesser time [8]. There has been lot of examples in literature where concept of hybridization has been utilized to successfully generate CAD model for complex parts. For instance, Menna and Troisi [9] integrated data from photogrammetric and laser scanning technologies for RE of complex objects. In this work, small screws have been used as test object to point out limitations and benefits of measurement techniques as well as feasibility of suggested approach. Similarly, Colombo et al. [10] presented an innovative approach to design prosthesis socket and to reconstruct 3D geometric model of stump. In this approach, they utilized laser scanning for external surface and medical imaging (CT or MRI) for internal structure. These two systems have successfully been integrated and implemented to obtain high quality digital model for prosthesis socket. Efstathiou et al. [11] also used combination of computer tomography and laser scanning for RE of metallic archaeological objects. They implemented methodology to retrieve CAD model for bronze suspension head. Complete geometry of head including invisible internal geometries has been captured using computer tomography to avoid any damage of the part. However, ineffectiveness of computer tomography to penetrate X-rays through thick metallic objects resulted in many missing regions on object's surface. Therefore, external geometry has been scanned using laser scanner to completely digitize the shape of bronze suspension head. In another work, Nashman et al. [12] proposed a system that fused data from machine vision and touch trigger probe to advance Coordinate Measuring Machine (CMM) measurements. In this work, it has been demonstrated that integration of vision and touch trigger probe provides more effective tool than either sensor individually. Similarly, Chan et al. [13] introduced novel concept to integrate two sensors for RE purpose. In this approach, they generated spatial information of part using stereo vision to plan movement of touch trigger probe for data collection. Although, application of multi-sensor fusion has several benefits but still it is crucial to have right RE methodology to deal with highly complex parts. There have been lot of works in literature that provide overview of multi-sensor technology in RE and its several benefits. However, literature regarding comprehensive RE methodology where integrated systems being implemented to get CAD models of complex parts has scarcely been available. This paper presents integration of multiple sensors to retrieve lost 2D drawing as well as recover worn out portion of mechanical part. A case study has been reported to illustrate integration of data from two different systems for RE. Main contributions of this work can be summarized as follows:

1. CAD-based methodology has been proposed to plan hybrid RE process for CMMs utilizing combination of touch trigger probe and laser line scanning probe.
2. Many issues related to 3D digitization as well as integration have been discussed and successfully negotiated.
3. Approach to recover damaged potion of a part has also been presented.

2. RE of Door attach fitting

Aerospace part shown in Fig 2 is a door attach fitting of main landing gear. This part is prismatic and non-symmetric in nature. Well established RE methodology has been critical for this part due to following reasons:

- It does not possess any technical drawing.
- The part is damaged on one side, so recovery of complete part geometry has been required.
- It is made up of regular geometrical features such as cylinder, planes as well as curvature, freeform shape, fillets etc.
- It comprises of block (shown in Fig 2) positioned at an angle to the vertical on rectangular base.

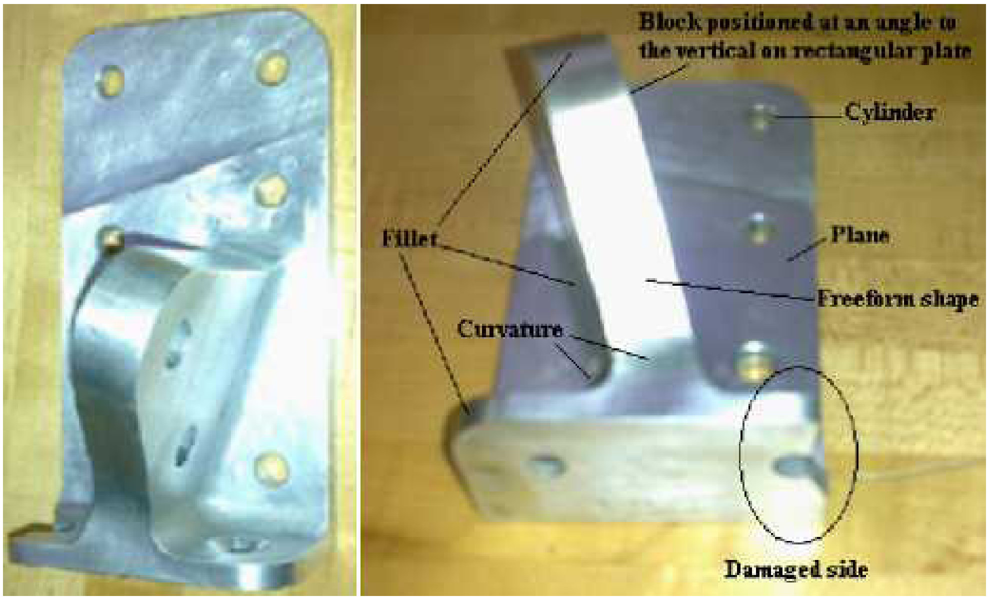

Fig. 2. Door attach fitting, its features and characteristics

2.1. *Sensor selection*

Methodology adopted for RE of this part has been described with workflow diagram shown in Fig 3. This part consisted of a combination of regular geometries as well as curvature and freeform shape therefore hybrid method seemed to be best solution. Application of proposed hybrid approach required data acquisition with both touch trigger probe and laser line scanning probe to capture all necessary information for generation of CAD model. Therefore, first step in multi-sensor integrated system required selection of suitable measurement technique for each feature based on following criteria [14]:

- Reliability of measured data i.e., sensor accuracy should conform tolerance requirement.
- Geometric feature types such as freeform surface, hole, plane, cylinder, shaft etc.
- Factors such as part complexity, material, surface finish etc.

RE techniques using laser line scanning probe creates CAD model from point cloud data which are mathematical ‘best fit’, but this CAD model may be an inaccurate representation due to noise contained in the model. Moreover, large file size of point cloud data degrades computer speed and performance which slows down processing steps. Therefore, data handling is quite a hefty task in case of laser line scanning probe. On the other hand touch trigger probe creates CAD model by capturing part details in the form of planes, cylinder etc. The curvilinear profile, freeform shapes cannot be defined efficiently and easily using primitive shapes measured by touch trigger probe systems. Moreover, processing of complex profiles is time consuming and cumbersome task in case of touch trigger probe. To meet these challenges, systematic approach based on hybrid method has to be adopted in a comprehensive manner to acquire relevant information on the part. Therefore, in this work touch trigger probe has been selected for regular geometries and laser scanning for curvatures and freeform surfaces.

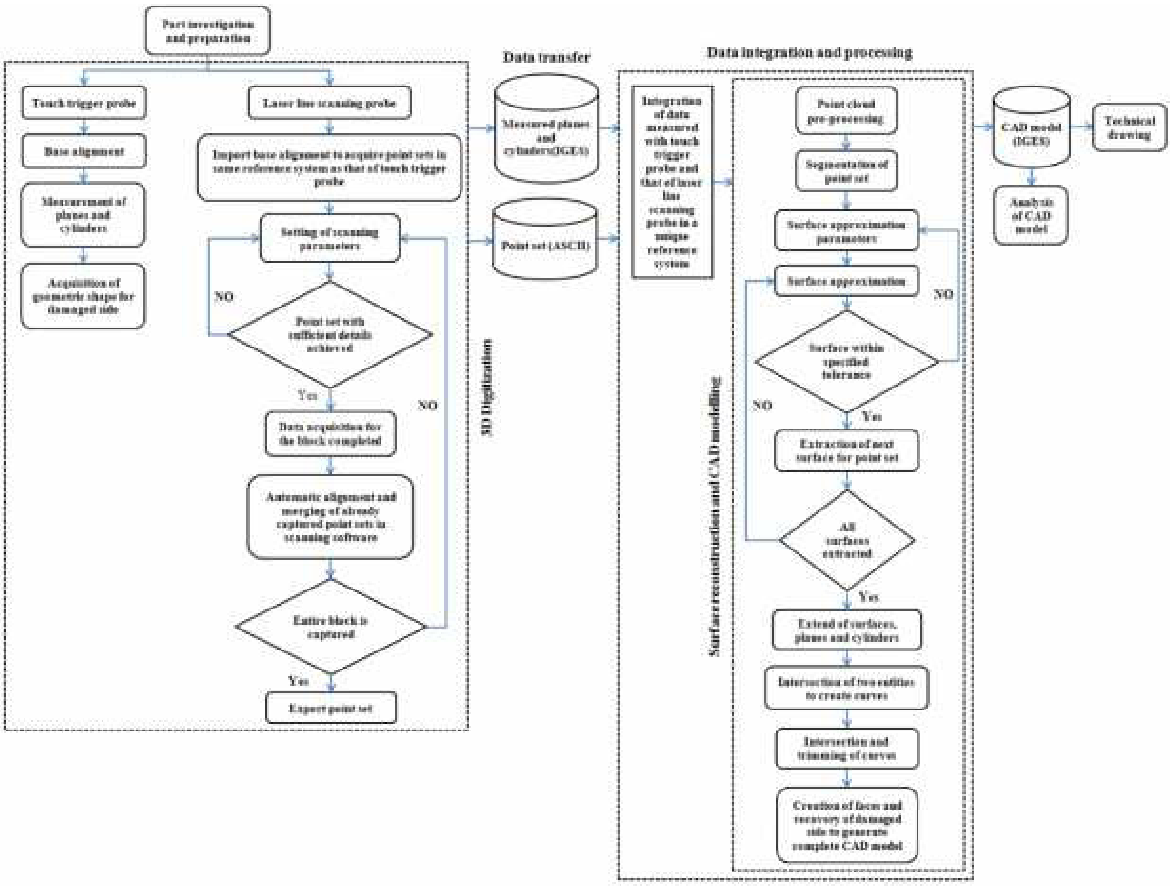

Fig. 3. Workflow diagram for RE of door attach fitting part

2.2. *Data acquisition process*

First and foremost requirement for measurement process has been cleaning of machine table, probing systems, part in consideration and calibration sphere to remove any dust particles. Cleaning has to be followed by calibration of measurement system, positioning and fixing of part on machine table. Subsequently, part base alignment has been created to define common coordinate system for data measurement with both touch trigger probe and laser line scanning probe. Features captured for base alignment comprised of bottom plane, front plane and left plane as shown in Fig 4 (a). Bottom plane prevented spatial rotation and movement in z-direction whereas front plane restricted planar rotation of part and movement in y-direction. Moreover, movement in x-direction was restricted by left plane. Finally, coordinate system was placed at the bottom left corner of the part as shown in Fig 4 (b).

(a) (b)

Fig. 4. (a) Features describing base alignment and (b) reference coordinate system

2.2.1. *Touch trigger probe*

Touch trigger probe has been calibrated at two different angle of rotations A0B0 and A0B90 as shown in Fig 5 to acquire all relevant information on the part. In fact, angle A represents angle of rotation in horizontal plane whereas angle B represents angle of rotation in vertical plane. Measurement of features such as planes, cylinders resulted in volumetric representation of part as shown in Fig 8 (a). Moreover, regular geometrical features have been probed using 1.5 mm diameter probe to measure all critical planes, cylinders and their position with respect to base coordinate system. Measurement with touch trigger probe also estimated the shape of damaged side. The thorough investigation as well as measurement of surrounding area of damaged side indicated shape of cylinder as shown in Fig 8 (a) and it has been captured manually using touch trigger probe.

Fig. 5. CMM measurement of damaged part using touch-trigger probe

2.2.2. Laser line scanning probe

High-density point cloud has to be captured to determine the shape of block. Therefore, block shape has been acquired using laser line scanning probe mounted on CMM. Laser line scanning probe scanned the block surface from one point to another point through two scan passes. There have been important parameters that needed to be set to overcome problems of shadowing, inaccessibility, occlusion, noise, improper reflection. Scanning parameters considered were laser power, shutter time, threshold for reflection, measuring field and orientation angle of laser probe etc. Initially, this part was scanned at different combinations of scanning parameters to find most appropriate combination of parameters. Best result for this part has been obtained at laser power of 15 mW, shutter time of 5 ms, threshold for reflection value of 100 and a standard measuring field. The problems of shadowing, occlusion, inaccessibility have successfully been dealt using different angle of rotations. Angles A0B0, A135B45, A45B45, A-135B45, and A-45B45 have been calibrated to capture complete block shape. Measurement of the block has been a tedious task because of its positioning on the rectangular base. It has been positioned at an angle to the vertical which caused serious problems of shadowing, occlusion and inaccessibility to corners during measurement. Initially, acquired point set was incomplete with many gaps and holes. Therefore, to overcome these problems, combinations of various angles of rotation for laser line scanning probe and degrees of freedom for fixture system have been utilized simultaneously. Angle for laser line scanning probe and rotation of fixture system has been set so that inaccessible areas could be reached without causing problem of shadowing, occlusion and improper reflection. It should also be noted that if fixture system has sufficient degrees of freedom it is always better to change positioning of part rather than changing angle of laser line scanning probe as shown in Fig 6. Angle of rotation for laser line scanning probe greatly influence measurement results and added up to total measurement error.

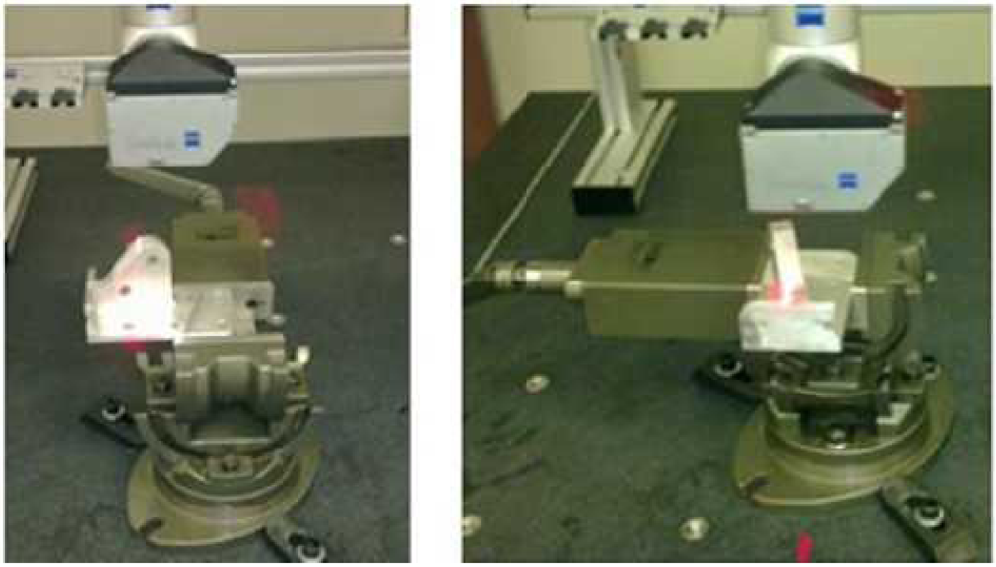

Fig. 6. Scanning of part at different degrees of freedom for fixture system

Data acquisition of complete block at different angles of rotation for laser line scanning probe and fixture system has been shown in Fig 7. Laser line scanning probe has been integrated with scanning software to capture block shape in the form of point set. The accomplishment of complete point data required total of six scans which has been achieved through different angles of rotation for laser line scanning probe. Since, part has been scanned in multiple views therefore merging and alignment of different point sets into one point cloud has to be carried out.

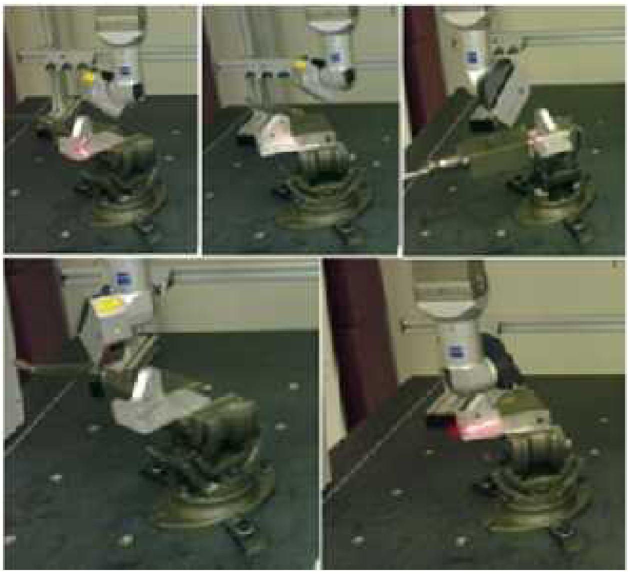

Fig. 7. Data acquisition of block at different angles of rotation for laser line scanning probe

Two types of data sets using two measurement techniques needed to be measured in same reference system for efficient integration. Therefore, coordinate system used for measurement with touch trigger probe has been imported into scanning software for capturing block shape using laser line scanning probe. The point set from scanning software and regular geometrical features from measurement software have been exported in ASCII and IGES format respectively to processing software. Measured data using both measurement techniques has been shown in Fig 8.

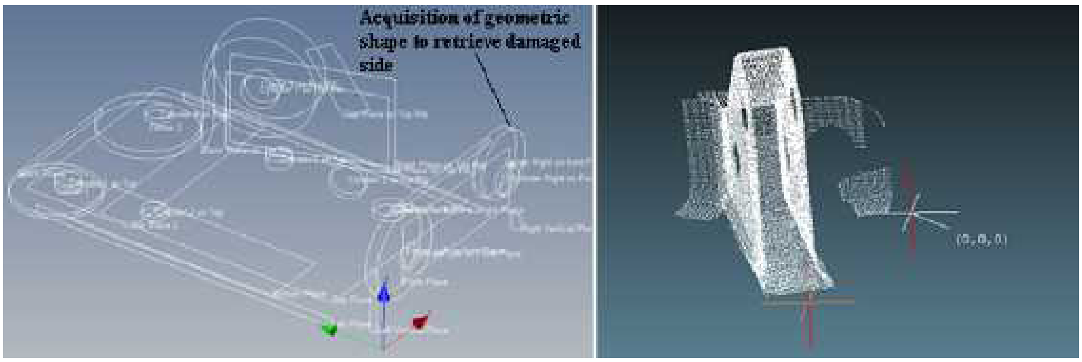

Fig. 8. Measurement data using (a) touch trigger probe and (b) laser line scanning probe

2.3. *Processing of measured data*

Registration is one of the most important and decisive steps of multi-sensor data integration where measured data captured in respective sensor’s coordinate system are aligned and transformed to common coordinate system. Since, output format of measured data did not accord with format of the processing software. Therefore, format of measured data output has to be transformed into format accepted by processing software. Integration of point cloud obtained using laser line scanning probe and regular features planes, cylinders captured using touch trigger probe in common reference system took place as soon as both data were imported into processing software. The pre-processing of point cloud is a key step of RE process and its results directly affects quality of CAD model reconstruction. Therefore, reduction of noise, outliers, gaps, overlaps has been carried out to get clean and well-defined point cloud set. The block comprised of complex contour surfaces and whole shape could not be approximated by single mathematical surface, therefore pre-processed point cloud has to be subdivided into many sections (segmentation) as shown in Fig 9. Segmentation is carried out to partition original point set into patches to ease the task of surface approximation and extract desired information efficiently. Subdivided data simplifies processing of data as well as improve precision of point cloud set.

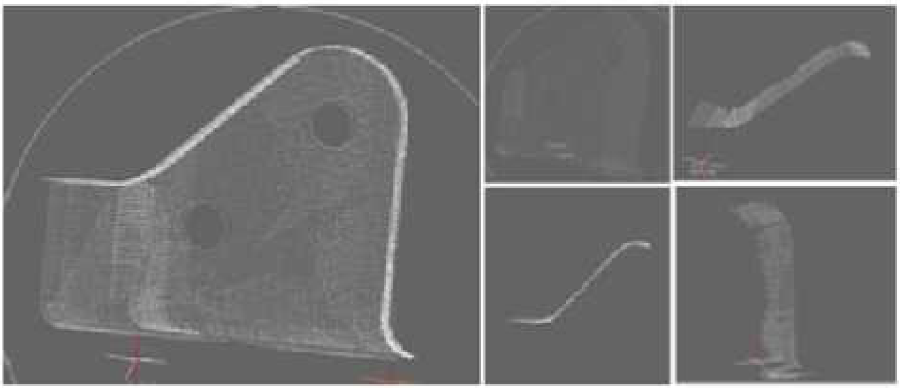

Fig. 9. Segmentation of pre-processed point cloud

Consequently, each of the segmented point sets has been approximated to create NURBS. Surface approximation is an iterative procedure because it finds optimum surface approximation parameters (number of patches in x-direction (u) and number of patches in y-direction (v)) to generate most accurate surface. The distance point analysis of surfaces and corresponding point sets shown in Fig 10 proved that surface approximation parameter of (u = 40 and v = 40) and (u = 10 and v = 40) resulted into surface with more than 80% points well within specified tolerance of ±50 µm for given part.

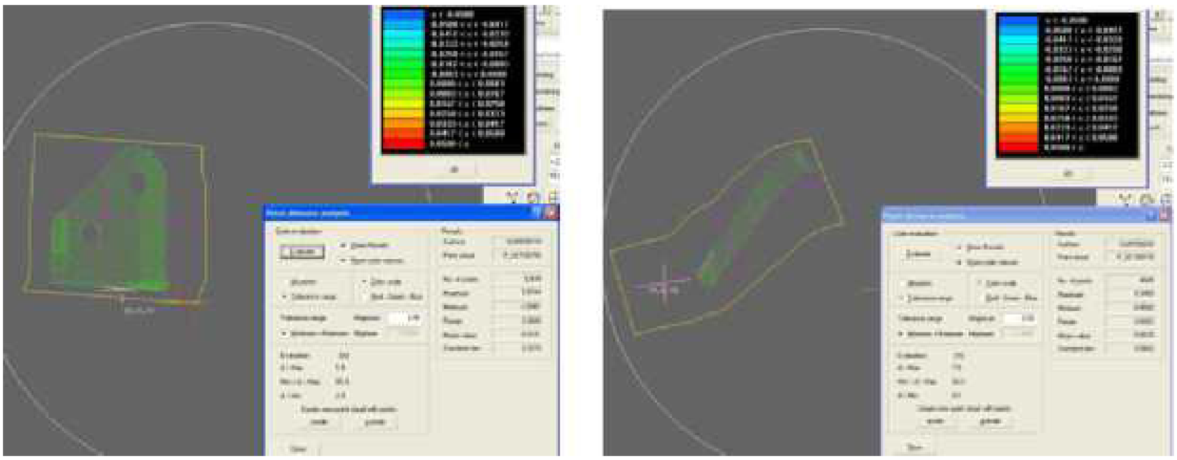

Fig. 10. NURBS and surface-point analysis - door attach fitting

2.4. *CAD modelling and analysis*

Approximated surfaces, planar surfaces and cylindrical surfaces have been extended and trimmed to get curves (as shown in Fig 11). In fact, these curves have been generated through intersection between two surfaces.

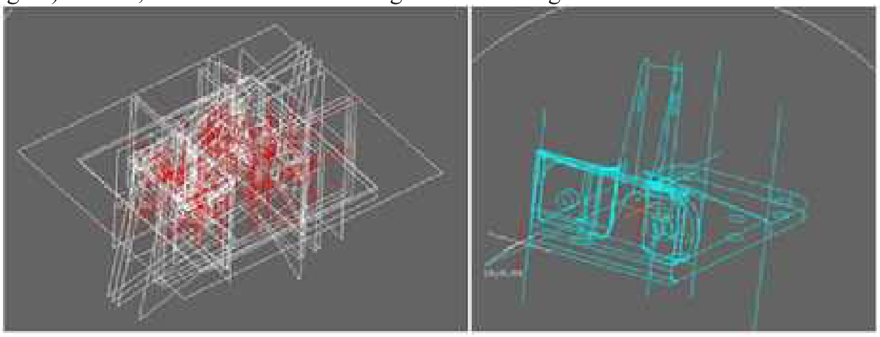

Fig. 11. Extended surfaces and curves obtained after intersection

Creation, stitching and manipulation of curves generated different faces which ultimately created CAD model as shown in Fig 12 (a). The CAD model has been translated to IGES file format and imported to measurement software for analysis.

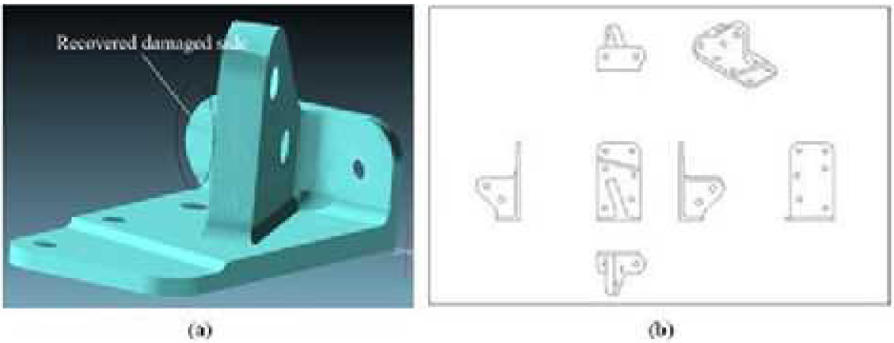

Fig. 12. (a) CAD model and (b) Different drawing views

CAD model of part in processing software has been imported to Catia and then to MasterCAM in *.dwg* format to get technical drawing and dimensions of part. Different views of part obtained using MasterCAM after cleaning and deleting drawing for double lines, unwanted lines and arcs can be seen in Fig 12 (b). Analysis to find out deviation between CAD model and original part has been performed using touch trigger probe of moving bridge type CMM. Comparison between actual part and corresponding CAD model resulted into maximum deviation of 60 µm. This maximum deviation has been observed for cases of fillet between block and vertical face and recovered geometry of the part. The dimensions and positions of all critical elements on part such as holes, length and width of part, positions of different features etc has been retrieved accurately and efficiently with most of deviations within 10 µm. Moreover, time taken during complete RE process is as follows: Total measurement time (both techniques): 1 hr 40 minute and Processing time to get CAD model: 2.3 hr.

3. Conclusion

- Multi-sensor integration has proven reliable method which provides efficient tool for RE of complex parts.

- Definition of appropriate part coordinate system is very important for effective multi-integrated system. Moreover, merging and registration of two data sets are critical steps because these operations aligns and transforms data captured in respective sensor's coordinate system to common reference frame.
- Results have indicated that proposed methodology based on hybrid method is adequate which can provide good accuracy.
- Presented methodology have successfully recovered damaged geometry and retrieved drawings with minimum effort and time.
- Results of investigation have also indicated that proper RE approach and well-established strategy can minimize digitization issues, improve process accuracy and ease task of processing data to generate CAD model.
- Most common digitization issues that have been identified include inaccessibility, shadowing, improper reflection, scattering, occlusion, damaged geometry, highly curved profiles etc.
- Selection of data acquisition methods for any part is primarily governed by different geometrical features and level of complexity and part details requirement.
- Well-defined strategy of RE for any part comprises of part investigation, selection of suitable data acquisition method, positioning of part on machine table, definition of optimum part coordinate system, procedures to minimize digitization issues and processing steps to generate CAD model.

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References

[1] Yuan, X., Zhenrong, X., Haibin, W., 2001. Research on integrated reverse engineering technology for forming sheet metal with a freeform surface, Journal of Materials Processing Technology 112, p.153-15.

[2] Vezzetti, E., 2007. Reverse engineering: a selective sampling acquisition approach, International journal of manufacturing technology 33, p. 521-529.

[3] Sokovic, M., Kopac, J., 2006. RE (reverse engineering) as necessary phase by rapid product development, Journal of Materials Processing Technology 175, p. 398–403.

[4] Weckenmann, A., Jiang, X., Sommer, K-D., Neuschaefer-Rube, U., Seewig, J., Shaw, L., Estler, T., 2009. Multisensor data fusion in dimensional metrology, CIRP Annals - Manufacturing Technology 58, p. 701–721.

[5] Motavalli, S., Suharitdamrong, V., Alrashdan, A., 1998. Design model generation for reverse engineering using multi-sensors, IIE Transactions 30, p. 357-366.

[6] Reich, C., Ritter, R., Thesing, J., 2000. 3D shape measurement of complex objects by combining photogrammetry and fringe projection, Opt. Eng. 39, p. 224-231.

[7] Chen, L-C., Lin, G.C.I., 1997. Reverse engineering physical models employing a sensor integration between 3D stereo detection and contact digitization, Three-Dimensional Imaging and Laser-based Systems for Metrology and Inspection - Proc. SPIE 3204. Pittsburgh, USA.

[8] Carbone, V., Carocci, M., Savio, E., Sansoni, G., De Chiffre, L., 2001. Combination of a Vision System and a Coordinate Measuring Machine for the Reverse Engineering of Freeform Surfaces, Int J Adv Manuf Technol 17, p. 263–271.

[9] Menna, F., Troisi, S., 2010. Low cost reverse engineering techniques for 3D modelling of propellers, International archives of photogrammetry, remote sensing and spatial information sciences. Newcastle, UK.

[10] Colombo, G., Bertetti, M., Bonacini, D., Magrassi, G., 2006. Reverse engineering and rapid prototyping techniques to innovate prosthesis socket design, Three-Dimensional image capture and applications VII, Proc. of SPIE-IS&T electronic imaging.

[11] Efstathiou, K., Varitis, Em. , Mansour, G., Efstathiou, C., 2009. Modeling of an ancient bronze suspension head by means of reverse engineering technique, Annals of "dunarea de jos" University of Galati Fascicle XIV Mechanical Engineering, ISSN 1224-5615.

[12] Nashman, M., Yoshimi, B., Hong, T.H., Herman, M., 1997. A Unique Sensor Fusion System for Coordinate Measuring Machine Tasks, Proceedings of the SPIE International Symposium on Intelligent Systems and Advanced Manufacturing.

[13] Chan, V.H., Bradley, C., Vickers, G.W., 2001. A multi-sensor approach to automating co-ordinate measuring machine-based reverse engineering, Computers in Industry 44, p. 105-115.

[14] Zhao, H., Kruth, J-P., Van Gestel, N., Boeckmans, B., Bleys, P., 2012. Automated dimensional inspection planning using the combination of laser scanner and tactile probe, Measurement 45, p. 1057–1066.