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Reverse engineering as a modern methods of test bed modernization

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The main purpose of the work is to demonstrate the individual stages involved in the reverse engineering process by using a dynamometer equipped with a single-cylinder research engine AVL 5804 as an example. The project entails theoretical and practical aspects of measurements using 3D scanners. The Scantech KSCAN Magic hand-held optical scanner was used to obtain measurements of the geometry of the dynamometer. The CAD model was created in the Autodesk Inventor program, and its accuracy was verified by comparing it to the scan and generating a scale of deviations along with a color-coded representation of their size in the GOM Inspect program. The work was summarized with an example of upgrading the current stand based on a previously made design, which significantly shortened the process of modifying the intake system.

Key words: *modification of test benches, 3D laser scanning, research engine, intake system development, CAD modeling*

1. Introduction

The rapidly changing automotive market is forcing designers to integrate new technologies into vehicle construction. One of the primary reasons for this shift is the climate crisis caused by the harmful compounds emitted by internal combustion engines, mainly carbon dioxide. The concentration of CO_2 in the atmosphere is on the rise [10, 11], and it leads to an increase in the greenhouse effect. To address this issue, efforts have been made to enhance the efficiency of internal combustion engines. These include transitioning from multi-point injection to direct injection [7, 12], using variable valve timing systems [14, 21], engine rightsizing [9, 28], using exhaust after-treatment systems [18, 24], using exhaust gas recirculation [16, 27]. The current most developed direction of the powertrain evolution is the hybridization or electrification of drive systems [1, 4, 15, 17]. Previously mentioned trends are focused on lowering the fuel consumption of internal combustion engines and reducing CO_2 emissions. As a result of these innovations, the driving pattern of the vehicle is changing. To meet the challenges dictated by the automotive market, it is necessary to conduct tests on engine dynamometers as well as tests under actual RDE road conditions. Engine dynamometers ensure repeatable conditions during testing.

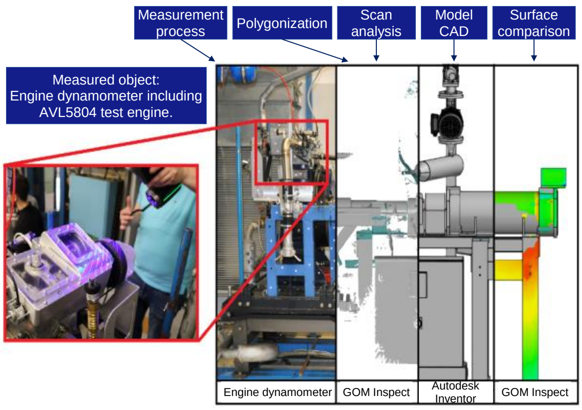

Fig. 1. Steps for obtaining a 3D model during scanning of a test bench

To accurately simulate operating conditions, test benches should be adjusted to current solutions, which require constant updates. Modifications of existing constructions create the need for careful planning of all related operations, which is why the CAD model can be useful. Through reverse engineering, it is possible to digitally recreate an existing object based on its physical form. While previous reverse engineering solutions have been focused on smaller-sized objects, it is now feasible to replicate significantly larger objects using laser scanners. The article presents the scanning process used to acquire a 3D model of an entire test bench (Fig. 1).

2. Object of study

The studying object is a dynamometer test bench with a single-cylinder research engine AVL 5804. This engine is located in the Institute of Combustion Engines and Powertrains at Poznan University of Technology. The dynamometer is used to simulate operating conditions for research purposes. The bench allows researchers to monitor the combustion process during engine operation.

The engine unit has a piston diameter of 85 mm and a stroke of 90 mm. Over the past few years, the research carried out at this test bench has focused on:

- using the ionization voltage signal to diagnose the combustion process of a spark ignition engine fueled with natural gas [8]
- assessing the impact of different CNG fueling methods on the stability of engine operation with a prechamber [26]
- research of new solutions for engine ignition systems and combustion of lean air-gas mixtures with the use of two-stage combustion systems [19, 20]
- investigating the potential of cold-flame-combustion while working with high Exhaust Gas Recirculation (EGR) rates [6].

The AVL 5804 engine was updated several times. Initially, it was a self-ignition engine with direct injection into the combustion chamber with a rotary distributor pump. Now engine has a common rail injection system with a spark TJI ignition which enables it to work with gas and liquid fuels. Additionally, a variable valve timing system VVT-iE, which uses an electric motor to rotate the camshaft, has been added to the engine [3]. The engine head was modified to adjust for the variable camshaft phasing. In this case reverse engineering has been used. Optical scanning and computer tomography were used to create a project of the new cylinder head with VVT-iE. The external geometry of the engine head was measured using 3D scanning, while the internal structure data was acquired through tomography.

The reverse engineering process for the AVL 5804 engine head has been completed successfully. The knowledge acquired and documented during earlier tests will be used in the next process of reverse engineering, this time for the whole dynamometer bench. The dynamometer model was combined with the previously obtained cylinder head model to provide a complete model of the external dimensions of the research bench.

3. Measurement method

3.1. Selection of the measurement method

During creating a model of a dynamometer bench, it is crucial to know its external dimensions. For this purpose, it is necessary to select one of several measurement methods (Fig. 2). The dynamometer has complex geometry and is situated in a laboratory that restricts freedom of movement around it, therefore the non-contact optic method was opted for. There are various optical methods available, which can be divided into two types: passive and active methods [5, 23]. Passive scanners operate under natural light and therefore do not require an additional light source. Active scanners, on the other hand, need to be provided with an additional light source.

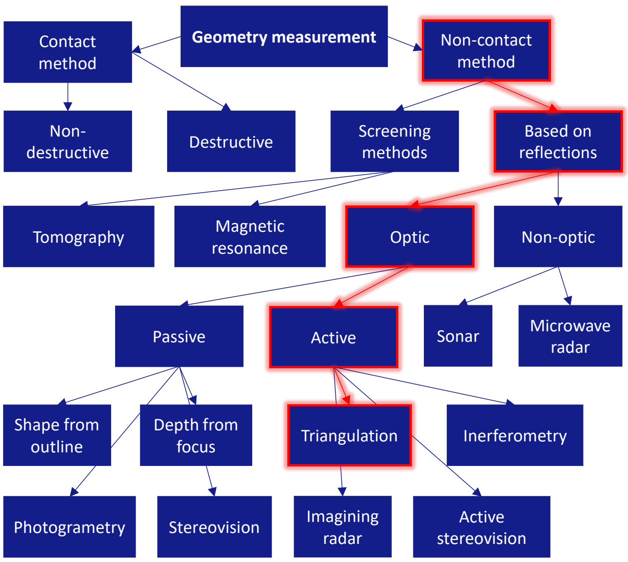

Fig. 2. Division of measurement methods along with an indication of the method used in the research (based on [5])

Passive methods include:
- photogrammetry
- shape from the outline
- depth from focus
- stereovision.

Active methods include:
- triangulation
- interferometry
- imaging radar
- active stereovision.

Due to the dynamometer's large size, limited space, and length of scanning process, only two methods were considered, photogrammetry and triangulation scanning.

Photogrammetry scanning works by processing multiple images of the surveyed object and accurately representing the geometric relationships between them [22]. Since the dynamometer bench is over two meters long, using photogrammetry would require taking numerous photos, which would be time-consuming. Moreover, there is not enough space in the laboratory to take pictures from every angle.

On the other hand, triangulation is a technique that uses the position and angles between a light source and recording devices to obtain geometry data (Fig. 3). A beam of light is sent at a suitable angle to the element under examination. The recorder captures the light reflected and distorted on the surface, sends the information back to the control unit, and the computer calculates the position of the surface [13]. Laser scanning has several advantages, including measurement speed (up to 1350000 measurements per second), high measuring accuracy (reaching up to 0.01 mm), and the ability to take measurements in confined spaces.

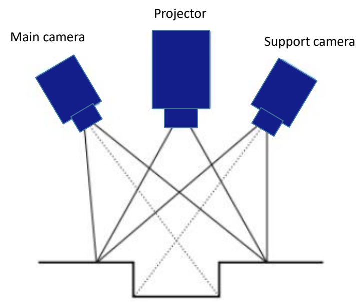

Fig. 3. The principle of triangulation [13]

For the reverse engineering of the dynamometer bench, a laser triangulation method was selected. This scanning process is presented in the following sections of the publication.

3.2. Scanning process

In order to carry out the research, a handheld scanner called Scantech KSCAN Magic was used (Fig. 4). The scanner is constructed with two cameras and a source of vision-safe blue laser. On the back of the scanner is located a control panel that enables the user to adjust the operating mode while scanning. Additionally, an LED bar on the housing indicates the correct positioning of the scanner in relation to the object. When the LED light is green, the scanner is at the correct distance. If the distance between the scanner and the object is too large or too small, the light turns red.

The scanner also offers a photogrammetry function. While working in photogrammetry mode, the Scantech KSCAN Magic collects coded points based on photos, and then in reference to these coded points acquires geometric data using either blue laser light or infrared light. The scanner has four modes of operation (Fig. 5):

– fast: uses eleven blue laser crosses
– accurate: seven parallel blue laser lines
– deep holes: one blue laser beam
– large area: infrared light.

Fig. 4. Scantech KSCAN Magic construction [23]

The scanner uses a total of forty-one laser lines and takes measurements with an accuracy of 0.015 mm. The measuring speed of the scanner reaches 1350 points per second. Each mode of operation has its advantages and disadvantages, making scanning adjustable for different types of surfaces. For example, the eleven crossed blue laser lines are ideal for quickly measuring a big area, making it suitable for scanning large flat surfaces. Seven parallel laser lines are a perfect mode for scanning surfaces with different types of irregularities. A single line allows for scanning deep and difficult-to-reach pockets and holes. The infrared laser measurement is used for scanning large areas. The scanner also has a photogrammetry function for collecting reference points, which are used to decrease measurement error. During measurements, the scanner needs to be connected to a computer with suitable software.

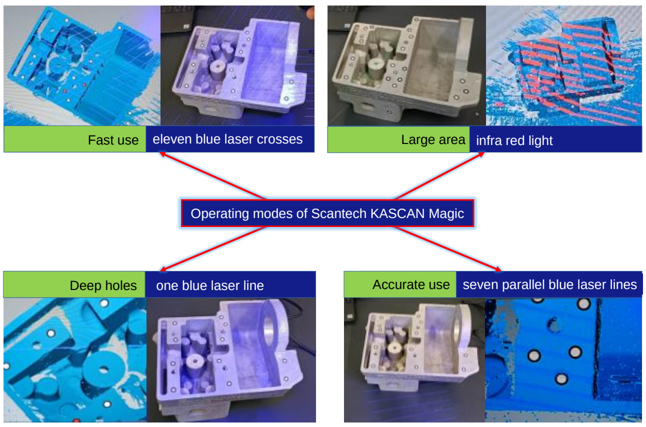

Fig. 5. Scantech KSCAN Magic modes

Before scanning, it is necessary to calibrate the scanner. To achieve this calibration plate must be scanned. The scanner measures the plates from different distances and angles. The computer monitor displays the actual position and positions where the scanner must be placed (Fig. 6).

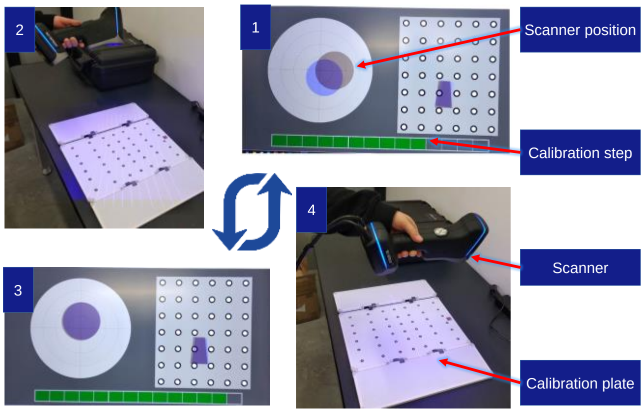

Fig. 6. Calibration process: 1 – the software indicates the angle and position in which to place the scanner, 2 – operator sets up the scanner, 3 – software indicates another angle and position to set up the scanner, 4 – operator repositions the scanner; the steps shown in the figure are performed repetitively until the end of calibration process

The calibration process of the Scantech KSCAN Magic involves fourteen steps that must be followed. During the process, the scanner should be positioned towards the calibration plate at the angle and distance indicated by the software. A progress bar at the bottom of the screen shows the progress of the calibration. Once completed, the software will display a calibration deviation, which is usually in the range of 0.0048 mm to 0.0075 mm for the Scantech KSCAN Magic (Fig. 7).

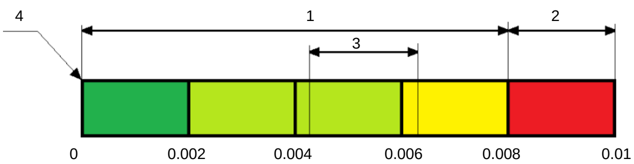

Fig. 7. Calibration deviations: 1 – acceptable deviation, 2 – unacceptable deviation, 3 – most frequent deviation, 4 – impossible to achieve deviation

Before measurement with the Scantech KSCAN Magic, it is important to properly set up the test bench. Since the scanner does not physically touch the measured component, it requires reference points to function accurately. In the measured area of the scanner must be placed at least three reference points. The reference points should be placed both on and around the object. Thanks to them scanner tracks the position of the component in space. The size of used reference points depends on the size of the object and the measurement area of the scanner. For example, points with an inner circle diameter of 1.5 mm are typically used for measuring areas of 320 mm × 320 mm, while larger areas require points with a diameter of 3 mm or 6 mm. However, using too many reference points can reduce measurement accuracy by approximating the geometry data at each point.

The next step is to scan the reference points so that the scanner would be able to accurately place data in three-dimensional space (Fig. 8).

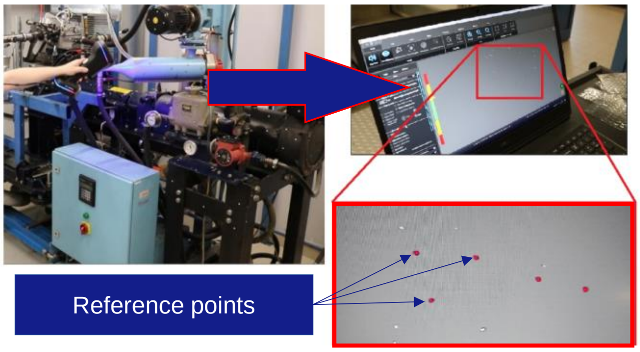

Fig. 8. Acquisition of reference points

After registering reference points, the scanner proceeds to acquire the geometry data. During the measurement process a fast triangulation mode with eleven crossed blue laser lines was used (Fig. 9). While measuring the scanner should move smoothly and steadily, gradually filling the point cloud with more data. The real-time preview allows the operator to see where data has not been collected properly and to return to those areas to gather more data. The final scan result was the acquisition of accurate data on the following systems:

- AVL 5804 engine
- shaft housing
- cooling system
- frame
- brake.

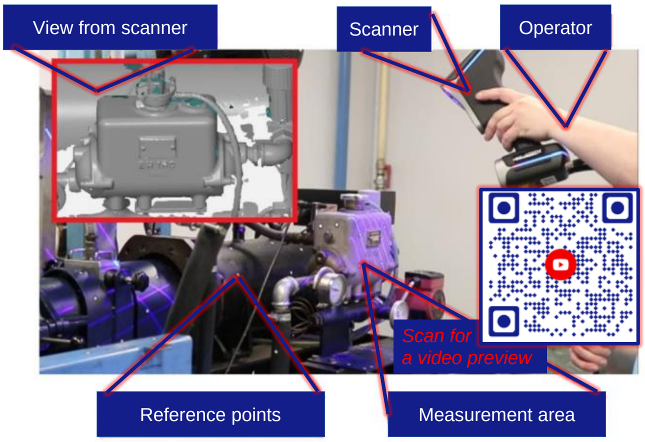

Fig. 9. Scanning process with eleven crosses blue line laser mode – to view a video of the scanning process use the QR code [25]

3.3. Model

After scanning and quality control of the acquired points cloud, the next step was polygonization. This process involves converting the cloud of points into a mesh [2] using specialized software and algorithms. During polygonization operator can only control a few parameters (Fig. 10) which are:

- optimization of the triangle mesh (max edges length)
- triangle mesh compaction (number of points)
- triangle mesh smoothing level (surface tolerance).

The measurement data file before the polygonization process was 895,100 KB (0.85 GB) in size and required considerable computing power for its analysis. The mesh thinning process performed reduced the file to a size of 177,771 KB, which is less than 20% of the original file size. This procedure makes it possible to work on the model on a computer with minimal hardware requirements for design software such as GOM Inspect or Autodesk Inventor. Such a large reduction in file volume was realized by increasing surface tolerances, reducing the number of measurement points by 80% and extending edge lengths. Depending on the design demand, the above treatments are justified or omitted.

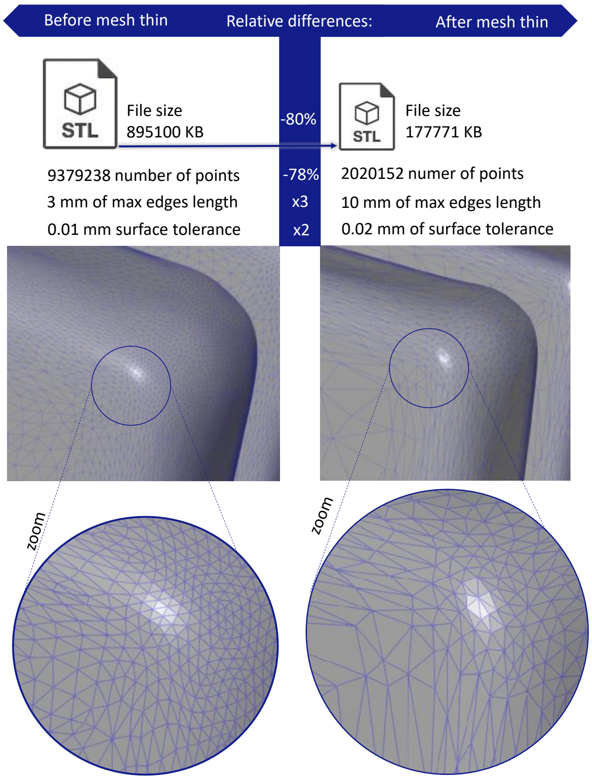

Fig. 10. Mesh before and after thin

The mesh file serves as a geometrical representation of external geometry, allowing reverse engineering to be made. The CAD model was created using Autodesk Inventor software, and the dimensions of the dynamometer bench were measured using the GOM Inspect program (Fig. 11).

This CAD model contains both internal engine structure and external information about the entire dynamometer bench. To obtain the external geometry of the bench, 3D scanning measurements were utilized, while 2D documentation was used to get knowledge about the engine's internal structure (Fig. 12).

The documentation did not contain any information regarding the modified engine head. Therefore, the previously created model of the cylinder head for the GasOn project at Poznań University of Technology was used to complete the CAD model of the bench. The first created component of the unit was the AVL 5804 engine, which includes a working crank-piston system. Next, the frame and brake were made. After the cooling system was reproduced.

Following that, a model of the control room was added to the 3D design. The dimensions of the control room were determined through traditional contact methods (Fig. 13).

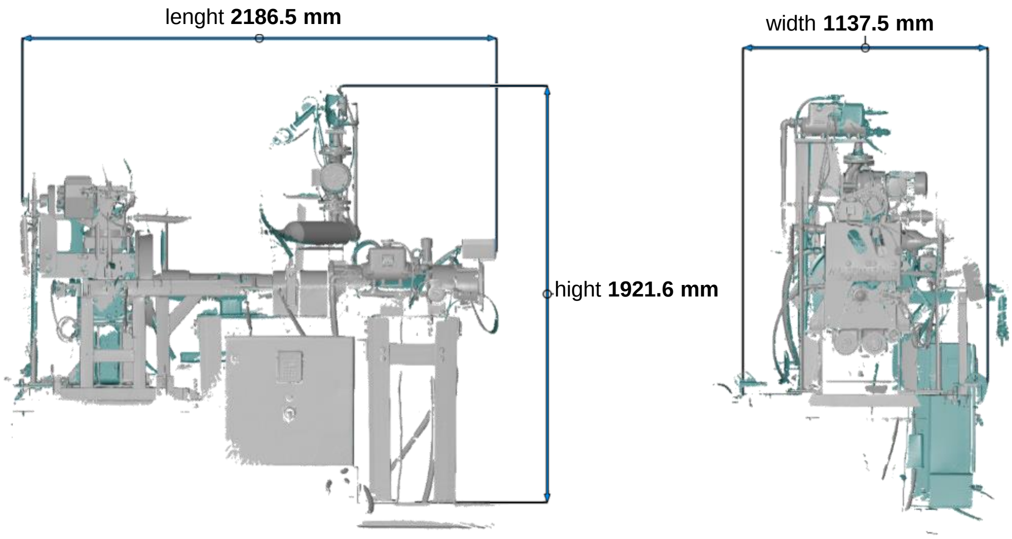

Fig. 11. External dimensions of dynamometer

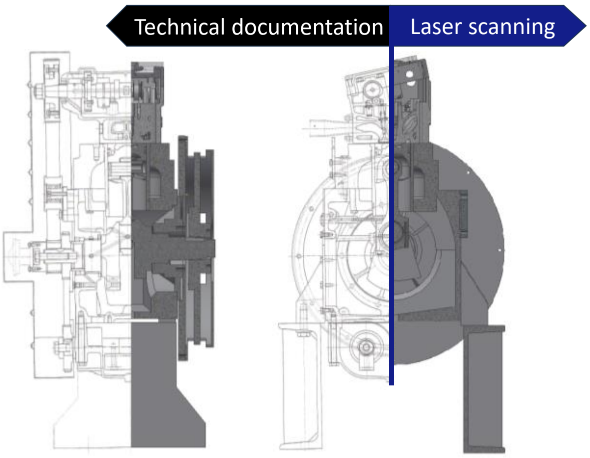

Fig. 12. Comparison of the completed CAD model with available manufacturer's technical documentation

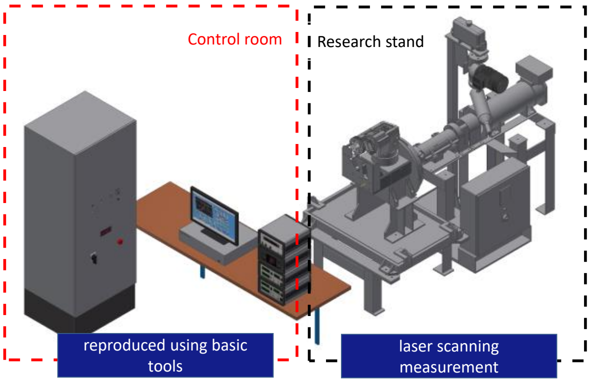

Fig. 13. View of the complete model of the engine dynamometer with the control room (control room made with basic measurement methods)

The performance section of the bench consists of four components: the engine, the frame, the brake and the oil cooling system. Each assembly was modeled separately before being combined together (Fig. 14). The oil and coolant pipes were not included in the model since there was insufficient data on their geometry collected during the scanning process.

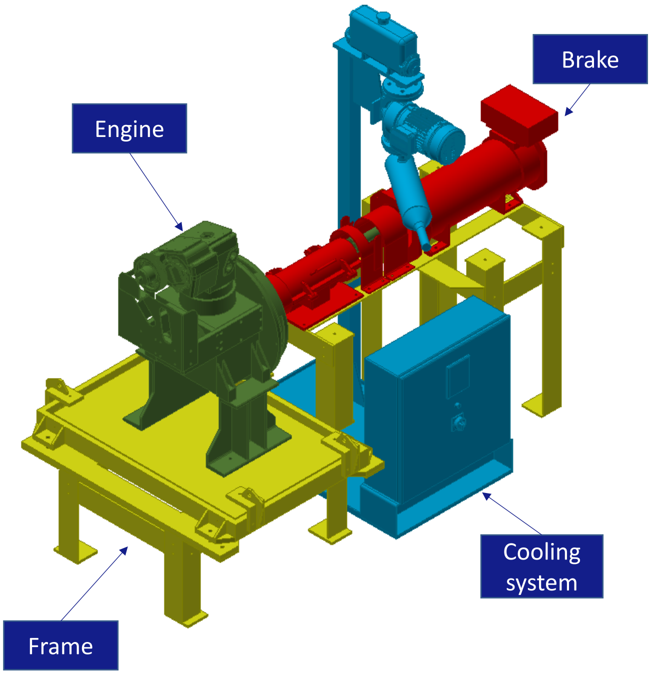

Fig. 14. Dynamometer bench CAD model with color-signed systems: green – engine, yellow – frame, blue – cooling system, red – brake

4. Model analysis

The final product of the reverse engineering process is a CAD model of the studied object. The model can be used to create technical documentation or relevant analysis, for example strength analysis. The GOM Inspect program allows for comparison between the model and scan by opening both files in a single project. The files must be aligned in a common coordinate system. A color deviation map is then generated on the scan surface (Fig. 15).

The deviation scale includes the maximum and minimum deviation. The maximum deviation, located on the oil cooler system, is +12.60 mm, while the minimum deviation is placed on the base of the engine frame and it is –12.93 mm. The extreme deviation values occur where oil lines are placed, that were not included in the CAD model due to insufficient data.

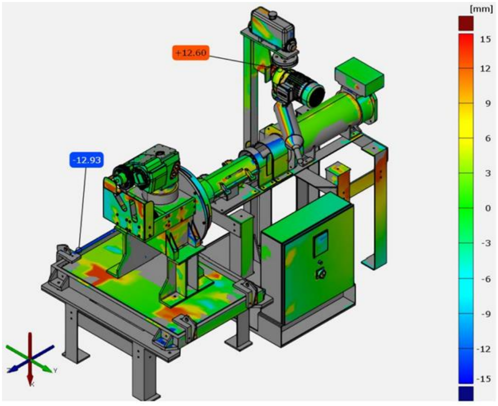

Fig. 15. Surface comparison with colored deviation map; maximum and minimum deviation

The GOM Inspect program can display a histogram of the deviation, allowing users to determine how much of the object falls within a given range of deviation. The standard deviation for the measured deviations is approximately ±6 mm. In the measurements presented here, this result was obtained for 66% of the scan area (Fig. 16).

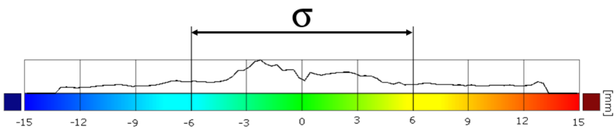

Fig. 16. Deviation histogram

5. Modification of the intake system

A CAD model proved to be helpful during modifying the inlet system of the AVL 5804 engine. This modification aims to adapt the intake system to burn gas mixtures using both direct and indirect injection. The 3D design allows the intake system to be made using 3D bending technology, thus ensuring continuous flow without interference from uneven welding (Fig. 17).

6. Conclusion and directions for further work

The presented method used for reproducing a test bench as a CAD model simplifies future upgrades of the studied object. The advantage of this method is that it acquires a large amount of data in a short time, thanks to 3D scanning. The complicated geometry of the dynamometer and the limited space around it cause measurement problems that cannot be resolved without a handheld 3D scanner. However, the disadvantage of this method is that the internal structure of the test bench cannot be reproduced as a CAD model without technical documentation or additional measurements using an appropriate method such as computer tomography.

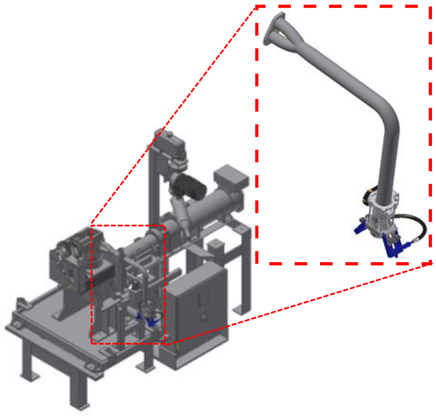

Fig 17. New intake system

The final product of the reverse engineering process is a CAD model of the whole test bench. Due to time limits and low demand, part of the scan was done in a cursory manner. However, this did not negatively affect the obtained 3D model. An adequate definition of the area of interest reduces measurement time and model size. Future research work and modifications necessary to carry it out will use the presented test bed model. The current model does not take into account the electrical connections and the cooling system, intake and exhaust pipes, which will probably be completed in future works.

Acknowledgments

This work was supported by the Reversesolutions company, which provided the equipment and software that made it possible to perform the reverse engineering process described.

Nomenclature

CAD Computer Aided Design
CAE Computer Aided Engineering
CI compression ignition
CNG compressed natural gas
DI direct injection
FEM finite element method
LPG liquified petroleum gas
SI spark ignition
STEP standard for the exchange of product data
STL standard triangulation language
VVT-iE variable valve timing-inteligent by electric motor

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