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Design and development of an Automatic Optical Inspection (AOI) system support based on digital manufacturing

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Abstract

Visual inspection of components, subassemblies and final products is an essential step to ensure the quality control of ready-to-market electronic components. In many manufacturing plants, including Bosch Car Multimedia S.A., typically automated systems for automatic optical inspection (AOI) are implemented at several workstations to perform visual verification and validation in between critical production tasks. At Bosch Car Multimedia S.A., the AOI system includes a metallic support frame that accommodates a series of components for the function of AOI. The support frame is attached to a robotic arm for controlled movement. As the AOI is a rather fast-moving process, deformation of components may occur during monitoring due to the high acceleration of the robotic arm while operating. In addition to this issue, the existent AOI system includes a high number of components and connections which increase complexity for assembly and disassembly operations. This paper presents the redesign for enhanced performance and functionality of a AOI metallic support frame by resourcing to the generative design (GD) exploration method. Furthermore, additive manufacturing technology, based in selective laser sintering (SLS) of polymeric powders, was used for the production of a new lightweight and reliable version of an AOI support frame. The alternative AOI support frame configuration consists of a single consolidated polymeric component that enabled an overall weight decrease above 30% and a reduction of main components and total number of parts of approximately 89% and ~77%, respectively.

Keywords: Automatic optical inspection; digital manufacturing; generative design; selective laser sintering; additive manufacturing, polyamide 12

1. Main text

The process of manufacturing electronic products is rather complex as there are various subsequent tasks (e.g., mounting, welding), typically at distinct workstations and performed by different operators and machinery. As electronic products integrate sensitive and fragile components, the evaluation and validation of performance, during several stages of the production process, is crucial to assure a correct function of the product [1-3]. Quality monitoring of electronic products helps the electronic industry to improve process and product efficiency which translates in an increased competitiveness [1,2]. Literature reports multiple quality monitoring techniques [1] being the most commonly employed the optical inspection. This monitoring technique can be performed manually by an operator or automatically, based on an automatic optical inspection (AOI) system integrating an image sensor and processor, being the AOI the most commonly employed for quality assessment [1,2]. Besides being automatic, this type of quality control system is also simple, non-destructive, fast and accurate. By consequence, it is less time consuming, less costly as it reduces the cost of human inspectors and more consistent

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and efficient as it can monitor beyond the limitations of the human eyes [4, 5]. Typically, an AOI system incorporates optics elements (e.g., lens, cameras, light sources), movement mechanism modules (e.g., robots, power supply), electronic control and vision software tool, to replace the human inspection and to process the signals acquired from the optics, based on an algorithm [5, 6]. Bosch Car Multimedia S.A. is a company that manufactures electronic assemblies for infotainment systems. In order to maintain the quality of the electronic products at a mass production competitive rate, Bosch Car Multimedia S.A. has implemented, at specific workstations, AOI quality monitoring systems. The currently implemented AOI system allows the visual inspection of printed circuit boards (PCB) for missing components or defects by resourcing to the scanning of a digital camera (In-sight 8405 from Cognex) that is fixed to a support frame (Fig. 1). The system is built with an aluminum alloy (AA5083) frame and plates, as well as, stainless-steel rods that support a light dome with light-emitting diode (LED) lights in its interior, that change color depending on the type of evaluation. The inspection process occurs with high acceleration (50 m/s2) of the robotic arm and inertia moment of the overall system. As the support frame lacks robustness and comprehends a considerable number of components and connections, the speed of the process may lead to deformations of the structure, mainly in the support legs, and consequently affect the position/alignment of some components. This issue will interfere with the stability of the image acquired by the camera which may become compromised. Therefore, this situation can be critical considering the amount of AOI systems present in line production working 24 hours per day and 7 days per week. To solve this problem, alternative approaches based on generative design combined with additive manufacturing were considered for design optimization, aiming for fewer components, weight reduction and increased robustness.

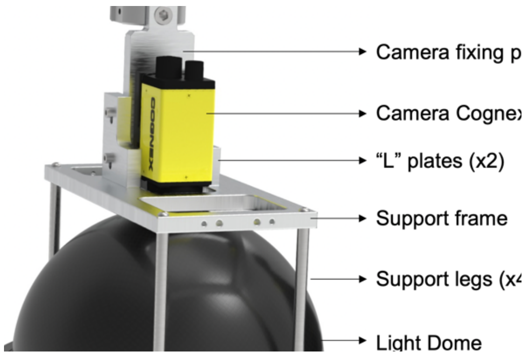


Fig. 1. Representation of the AOI support components.

1.1. Additive manufacturing and generative design

Conventional 3D design and traditional manufacturing methods lack the versatility to materialize complex models with internal cavities or cellular structures known for helping to create lighter parts without compromising their mechanical properties [7]. Furthermore, typical computer aided design (CAD) software does not fully consider the capabilities of additive manufacturing (AM) and restricts designers and engineers to traditional geometries. This situation will result in robust designs that are far from optimal in terms of rapid development, production time and costs [8, 9]. Therefore, AM as a competitive digital manufacturing process able to fabricate complex and functional geometries opens unprecedented opportunities for innovative products and for rethinking design, in a more efficient way [10-15].

A fundamental principle of large-scale product manufacturing is related to the prototyping phase across the whole product design and development process. Forasmuch as there is an incessant demand to reduce the lead time and the cost of products, AM is being selected as the technology to achieve that. This advanced technology allows the manufacturing of physical models by 3D CAD models along with the improvement of product design at early stages [10, 11]. Selective laser sintering (SLS) is an AM technology that uses powder materials to generate complex 3D parts layer-by-layer. This process selectively fuses powder particles of each layer together through the scanning of the powder bed with a high-power laser beam which moves along the x-y plane, creating a printed layer. After a certain number of layers, the 3D model is created. In contrast to other AM technologies, the SLS process does not require structural supports since the excess powder not sintered by the laser acts as support during the printing procedure, which is then removed by a post-processing process. Parts with overhanging and other complex features, such as lattice structures and porosities, can subsequently be easily produced by this technology [16]. Polyamide 12 (PA 12) is the most widely used laser sintering polymer, occupying 95% of the commercial market [17]. PA 12 is a semi-crystalline thermoplastic, easy to be processed and to be recycled with considerably low cost and tensile strength as well as elastic modulus comparable to their injection molded counterparts, thus it is a good material for prototyping [18, 19].

The design versatility that SLS, an AM technology enables, combined with design exploration methods, such as, generative design (GD) is a possible approach to overcome the manufacturing limits experienced by traditional methods, targeting a simpler design with associated manufacturability, substantial cost reduction, less time and material consuming [20]. GD is a novel form-finding procedure that allows the conception of novel, unconventional and complex structures and can be used in the initial design phase to autonomously generate multiple designs based on input parameters. This generative method optimizes the design in terms of the proposed needs and limits and provides results in numerous design alternatives at once. Besides that, GD also considers the intended materials, temperature tolerance, manufacturing technology along with mechanical properties that make the part capable of enduring stated efforts [21-24]. Therefore, the final design is optimized considering the proposed needs and limits. In general, the process of GD can be applied as follows: (i) establishment of the design area, design parameters (e.g. density, cost, thermal and mechanical properties of the material) and goals for optimization (e.g. lightweight, deflection or stress); (ii) generation of diverse design alternatives by using algorithms according to different parameters; (iii) investigation of the obtained structure solutions, iterating by modifying parameters and goals, and then identify the best design; (iv) manufacture the selected design by an AM process [21, 24].

In this context, the focus of this research relies on the re-design and production of an alternative and optimized support frame for the AOI system currently implemented at Bosch Car Multimedia S.A., by coupling GD and AM targeting a reduction of the number of components and overall weight while improving the robustness. Several solutions were defined and manufactured enabling testing in real context of use to evaluate the effectiveness of the mass reduction strategy applied in the study on the performance of the new solutions in comparison to the original AOI system.

2. Design process

2.1. Construction of references

The design iteration for the optimization of the AOI support frame was performed using Autodesk Fusion 360 software with GD tools to aid in the freeform modelling, optimized for the predefined geometrical and mechanical inputs. The first step in the GD exploration was to select the geometry needed to be preserved from the current AOI support CAD file. The geometries to preserve are related to the fixing connections for the robotic arm, as highlighted in green in Fig. 2 (left). The second step was to identify the obstacles (components of the AOI system) that will be in contact with the support geometry to be designed, such as the camera and the light dome (highlighted in red in Fig. 2 - right).

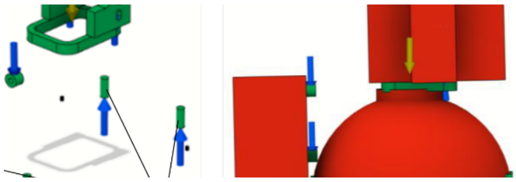


Fig. 2. Geometry to be preserved in the GD outcome (left image) and obstacle's geometry (right).

Consequently, the third step of the design exploration was to define the objective and limits for the redesign: (i) minimize final mass with a target of 0.4Kg; and (ii) safety factor of 2. The fourth step was to select the manufacturing process and material. AM was defined based on SLS with polyamide 12 (PA12) as the building material. For this process, it was considered a minimum thickness of 3 mm. Thereafter, it was established the applied loads and constraints. The loads comprise a set of commons loads, including forces, pressures and bearing loads (i.e., distinct set of load cases) and the constraints, which can be the screws that connect the different components to the structure. Fig. 2 (right) depicts the constraints (highlighted in green) and the loads applied to the geometry (blue arrows). The loads, that the system is subjected to, were established by calculating them at two points of the structure. Zone A related to the load caused by the Cognex camera, its fixing plate plus the dome, and Zone B related to the load that the dome induces. Table 1 lists the values of the distinct efforts at each point of the structure frame. The sixth, and last step, was to run the software for the generation of the design results and the subsequent selection.

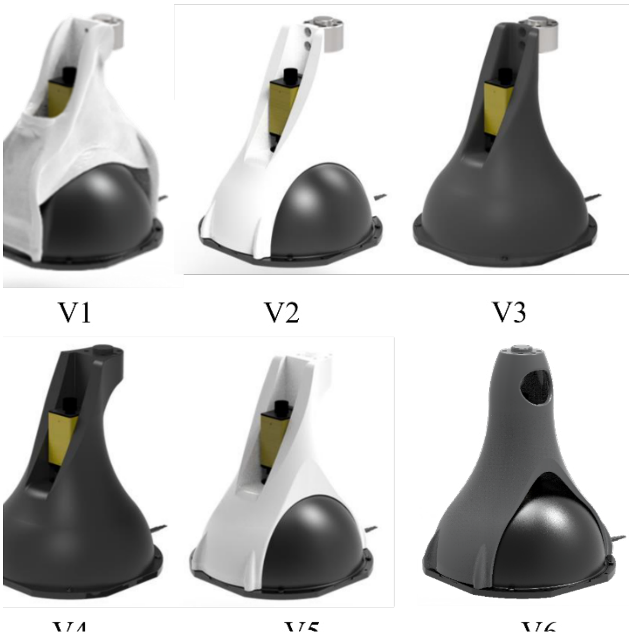
Table 1. Values of mass, acceleration and forces undertaken by AOI system.

Point of structure	Mass (Kg)	Acceleration (m/s^2)	Force (N)
A	1.425	50	71.27
B	0.391	50	19.55

2.2. CAD Modelling

The selected model (Fig. 3, Version 1(V1)), obtained through GD, was used as a foundation for the development of new designs by fine-tuning the generated geometries with the CAD software SolidWorks®. By recurring to the CAD software capabilities, a few iterations of modelling based on the GD study were created. Five versions (Fig. 3) were modelled with some particularities, either by merging the gripper to the robot and the light dome, or aligning the structure to the robot gripper axis.

Fig. 3. Rendered concept designs developed based on the obtained GD model.



The gripper (Fig. 1) is a part that allows the connection of the AOI system to the robotic arm by four screws M5 with a 0.8 pitch, aiding this way in the orientation of the AOI system during inspection. Version 2 (V2) is the most similar geometry to the output geometry from the GD study (V1). Version 3 (V3) was modelled by integrating the light dome in its geometry, while version 4 (V4) design merged the gripper to the robotic arm and the light dome to the rest of the structure frame. Version 5 (V5) includes the gripper to the robotic arm but kept the dome as an independent component. Version 6 (V6) was an alternative approach to V5 with the overall system aligned with the robotic arm gripper, unlike the others.

After making a critical analysis of all the designs, it was found that only V5 and V6 fulfilled all the requirements to continue for production and experimental testing. V2 and V3 were discarded because, without merging the gripper to the structure, the stabilization of the structure would be inferior. Furthermore, after checking the light dome details, it was found that it is a complex and standardized metallic component with integrated LEDs and electrical circuits making the merger planed in V3 and V4 an impossible task.

3. Production of prototypes

The selected versions for the AOI support frame, V5 and V6, were produced by means of the SLS process with an EOS P396 equipment. The selected building material was a PA2200 (PA 12) supplied by EOS GmbH, with a powder mixture ratio of 70-30 % (recycled - virgin material). This powder material presents an average size of 56 μm and laser-sintered parts typically provide a density of 0.93 g/cm3, an Izod notched impact strength of 4.4 kJ/m2 and a shore D hardness of 75 [25]. The main parameters of the production process were the same as reported in Lopes et al. [19]. Post-processing activities include removing non-sintered powder with brushes and pressurized air. Fig. 4 presents a photographic registry of the manufactured prototypes.

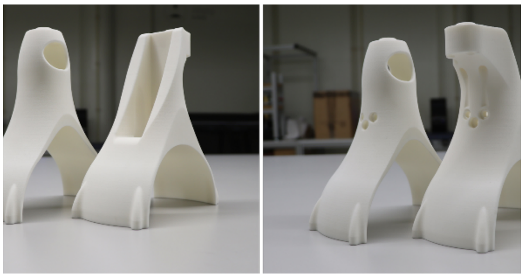


Fig. 4. Fabricated prototypes for testing (on the left of both images is V6 and on the right is V5).

4. Experimental Test

After production, a brief comparison between the mass and the number of components of the baseline AOI support frame (V1) and the versions manufactured was done (Table 2).

The total mass for the baseline that includes the complete metallic structure is 0.442 kg. For the geometries obtained with GD and CAD modelling, the total mass of the V5 and V6 prototypes is 0.237 kg and 0.188 kg, respectively. The mass reduction for the new structures design in relation to the baseline is noticeable, being more than 45 % lighter for V5 design and more than 55 % lighter for V6. Regarding the number of components, it is evident that the GD approaches with subsequent CAD modelling provided more consolidated geometries, drastically reducing the number of components down to 1 (approximately 89% reduction). If the total number of parts (including screws and other fixing parts) is considered, the new designs have almost 77% less parts than the baseline.

Table 1. Key performance indicators for the created prototypes.

System	Total mass (Kg)	Δ mass (%)	Quantity of main components	Δ Main components (%)	Total parts *	Δ Total parts (%)
Baseline	0.442	-	9	-	34	-
V5	0.237	-46.4	1	-88.9	8	-76.5
V6	0.188	-57.4	1	-88.9	8	-76.5

* Including screws and other small elements

The experimental tests simulating real context of use with prototypes V5 and V6 were performed in an experimental workstation equipped with a robotic arm, at Bosch Car Multimedia S.A. facilities (Fig. 5). The test simulated displacement movements that are typical during visual inspection of electronic assemblies.

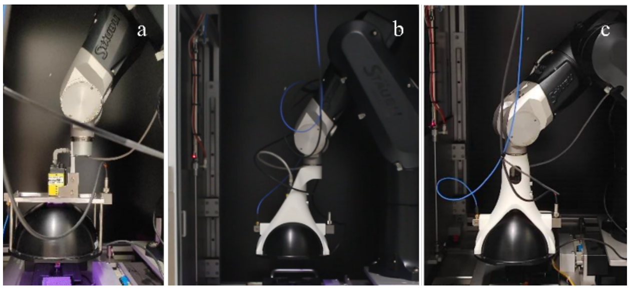


Fig. 5. Baseline AOI and prototypes V5 and V6 during experimental test.

To acquire data, two accelerometers were used, a capacitive accelerometer (PCB instruments 221B01) to measure the acceleration during robotic arm displacement and a piezoelectric triaxial accelerometer (PCB Piezotronics 356A14) to monitor system vibrations after the robotic arm displacement is stopped. The experimental test consisted on a comparative study between the baseline AOI support and the prototypes obtained by AM.

The values of acceleration in the time domain were captured by an LMS Scadas Mobile spectrum analyzer. Monitoring the time-domain response of the systems in free-vibration allows the correlation between the instant values of acceleration and the stabilization of the images that are captured by the camera. The stabilization of the images was determined by capturing frames from a chessboard control pattern (Fig. 6) and estimating their blurriness by converting them from greyscale to binary colors. Blurriness was determined by the aspect ratio of the dark and light squares from the chessboard control pattern. For this effect, it was imposed a to-an-from 30 mm dislocation (Fig. 6) in the robot dislocation (ZZ axis) and the frames were captured in the return movement. Through this test, it was possible to compare the dynamic response of the system, whenever it was subjected to sudden acceleration changes, and the impact on stabilization time required before carrying out the inspection with the Cognex camera.

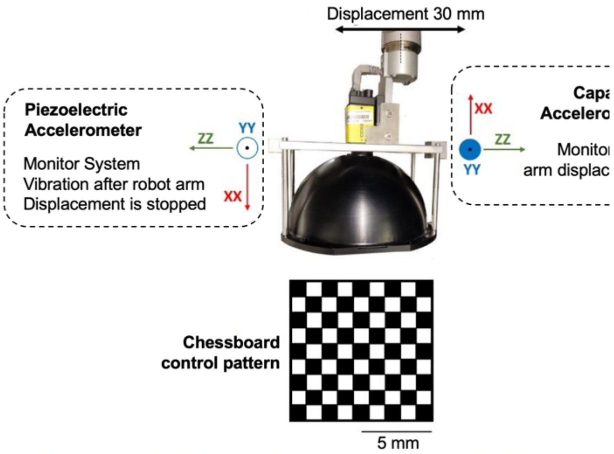
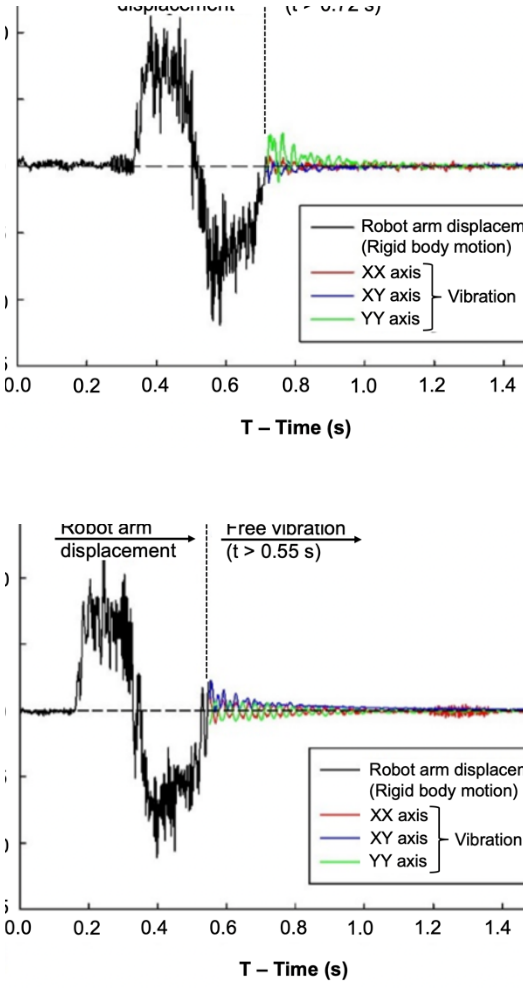


Fig. 6. Apparatus for in-situ vibration testing.

Regarding the results of the in-situ production line testing, Fig. 7 displays the acceleration versus time plots that detail an initial stage (black plots) in which the acceleration corresponds to the robotic arm rigid body displacement and a second stage (red, blue and green plots) that correspond to the free vibration of the models after the rigid body movement is stopped.



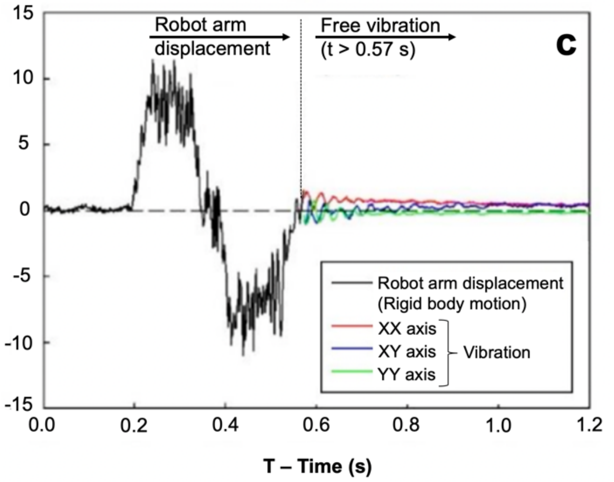


Fig. 7. Acceleration vs time plots of: (a) baseline, (b) V5; (c) V6 prototypes

It is noticeable that V5 prototype presents the lowest stabilization time, 0.55 seconds, followed by the V6 prototype with 0.57 seconds. The baseline took longer to stabilize 0.72 seconds. Thereby, V6 prototype shows a similar stabilization time to the V5 prototype value, it exhibits poor damping during the free vibration stage, since there is a lot of noise and vibration oscillations. Taking into account the fact that to replace the current structure, there is the need for a more stable structure, V5 appears to be the most appropriate option.

4. Conclusions

GD software capabilities were used to generate diverse design concepts for the mechanical structure of a baseline AOI system, in a relatively short time. After selecting one concept from the GD task, the concept was fine-tuned by CAD software. The 3D modelling was used to deepen a better solution by developing newer concepts with an overall smoother surface and adequacy for production by AM. At the end of the re-design process, prototypes of the most viable solutions were manufactured by SLS technology with polyamide 12. The AOI support frame consisted of a single consolidated part, significantly reducing the number of parts composing the baseline by up to an 89% reduction of the main components and 77% of the total number of parts. The new design and the replacement of a metallic structure with a polymer-based structure provided a mass reduction above 30% and improved the structural stability while in operation. The experimental tests with the use of accelerometers provided the information that the V5 polymeric prototype was the best choice to replace the current metallic AOI support since this had shown to be the more stable, taking less time to stabilize, and consequently to take the inspection picture. This means that, after a large number of inspection moments, this low stabilization time will have a great influence on the total time. For instance, after 100000 inspection moments, the current AOI support takes 1200 minutes and the V5 prototype takes approximately 917 minutes, so the gain by introducing this V5 prototype in the production line is almost 24%. By using GD and AM processes, it was possible to fulfil all the requirements to improve the baseline AOI system and implement the improved and lightweight solution at the workstations of Bosch Car Multimedia S.A. In future work, research will be centered on the development of personalized and task-specific robot end-effectors such as grippers, since the potential of digital manufacturing can enable fewer geometric constraints, reduced weight and shorter time-to-market.

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