Int J Interact Des Manuf (2017) 11:385–395
DOI 10.1007/s12008-016-0347-y

ORIGINAL PAPER

Augmented vision and interactive monitoring in 3D printing process

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Received: 5 July 2016 / Accepted: 22 August 2016 / Published online: 3 September 2016
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Abstract This paper describes the beneficial impact of an augmented reality based technique on the 3D printing process monitoring within additive manufacturing machines. A marker is applied in a fixed point of the rapid prototyping machine, integral with the component being manufactured; as an alternative, a markerless approach can be followed too. A virtual model of the object to be printed is superimposed to the real one. In this way, the shape of the object in different printing stages can be viewed. An interactive comparison between real and virtual model can be carried out both in manual and automatic mode. If manufacturing errors are detected, the building process can be stopped. Augmented reality technique allows an intuitive shape check of a part being printed with rapid prototyping technologies. In case of complex objects it helps the operator in the detection of possible errors along the manufacturing process; stopping the machine as soon as an error appears avoids waste of machining time and material. The average precision of the augmented reality is useful to find significant geometrical errors; geometrical deviations less than 1 mm can hardly be assessed both in manual and in automatic mode, and further studies should be carried out to increase the technique precision and range of application. To the best of the authors' knowledge it is the first time where experiments on the integration between augmented reality and rapid prototyping to interactively monitor 3D parts' printing have been investigated and reported in literature.

Keywords Rapid Prototyping · Additive Manufacturing · Augmented Reality · 3D printing · Design

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1 Introduction

The name "Rapid Prototyping" (RP), defined also with the more correct name "Additive Manufacturing" (AM) in the ASTM official terminology, refers to an ensemble of heterogeneous procedures, usually additive, implemented to manufacture in a short time physical components from CAD models [1]. Thanks to this technique, complex shapes can be built, so that the new paradigm "the shape follows the functions" can be applied to manufacturing. To this aim, Topological Optimization can be applied without the constraints on components' geometry typical of traditional subtractive machining. Exploiting this capability, strategies of minimal weight assuring a pre-set homogeneous Safety Factor or maximum stiffness can be implemented in a very effective way. The AM can be considered a "game changer" in the manufacturing process and technical literature suggests that a new industrial revolution is going to happen in the next years. The AM presents in fact the following advantages respect to the traditional subtractive methods based on CNC machines: there is no need for moulds (so you don't need to design, build, store it), complex shapes can be manufactured, time to market is reduced, changes in CAD models can be done along the production lots to improve the design, there is no need for spare parts and the warehouse is reduced to powders (or wires) stocks. On the other hand, the AM can't be considered a panacea of all the problems related to modern manufacturing processes since drawbacks still lie: high costs of materials and machining hour rate, no standardization for advanced applications (space, aeronautics, biomedical among others), high acquisition cost for the machines, economical advantage only with small lots, need to train technicians to "design for Additive Manufacturing" techniques, expensive experimental tests to check stress and strains and exhausting Non Destructive Inspections (NDI) on complex shapes.

Several techniques have been proposed in literature for AM [2] and are available on the market to print in a short time components [3]: a representative, but not inclusive, list includes early developed techniques like stereo lithography (SLA), fused deposition modelling (FDM), laminated object manufacturing (LOM), selective laser sintering (SLS), three dimensional printing (3DP) and newer metallic powders based strategies [which are commonly referred as powder bed fusion (PBF) methods] like electron beam melting (EBM), direct metal laser sintering (DMLS) and selective laser melting (SLM).

The manufacturing of an object with these techniques usually follows a common sequence of steps: the realization of a CAD model, its saving in STL format (where the geometry is meshed in triangles), the slicing of the model along its height, the computation of a trajectory to follow for a tool (laser, ejector, heated head) and its movement along the path, the shifting of the building plate (or head) in vertical direction to leave room for new slices of material to be deposed (or to be cured), and the movement of a rolling powder feeder in some techniques.

Just to provide some additional details, SLA is based upon the use of ultraviolet light (usually a laser beam) to achieve the selective polymerization of a photosensitive resin. This technique is capable of high details level and the surface finish is usually good; also thin bodies can be printed, even if shrinkage and curls can occur. However, it requires post curing and support structures (difficult to remove) are needed for undercuts and protruding zones of the object. SLS is a technique based on the melting of a metallic powder layer by layer [4]: it is widely used with materials like titanium. The un-melted material can act as a support for the protruding parts. Building times are quite fast and a lot of different materials can be used for powders; the strength and surface finishing of the parts are not so high. By implementing the FDM technique, an object is obtained by melting a thin wire (usually rolled on spools) of thermoplastic material [5] and deposing the filament along a series of horizontal paths. The building plate is lowered layer by layer and support material can be used in case of complex shapes. The wire can be made by ABS, PLA, solvable wax (useful for investment casting), medical grade materials and solvable materials. Also high strength materials like ULTEM 9085 are sometimes used in FDM machines for high value components, like that for space applications [6]. The FDM machines are usually cheap; the change of the wire once a spool is finished is simple and a running work can be resumed without problems. No post curing is necessary. On the other hand, the quality of small details is low, the building process can be long, large distortion can be noticed without a heated building plate or a hot printing chamber; the supports design (usually automatically computed by software) can fail with complex geometries. LOM is a now obsolete technique relying on the gluing of layers of adhesive-coated materials (usually paper, plastic, metal) whose shape is obtained through the cutting (with laser or knife) of a thin sheet.

It is worth noting that also variable density structures [7] can be produced with some RP technologies (e.g. FDM and SLS), thus imitating what nature does in structurally efficient porous elements like bones. The most recent industrial technologies are focused on power bed fusion machines in which metallic powders of materials like Inconel 718, Ti6AlV4 titanium allow, AISI 304 steel are melted to obtain solid structures. All PBF based machines are based upon the layer by layer building of the component. Powders are spread over the already solidified layers, by using a roller or a blade, while the part is lowered to leave room for new material to be melt. High power lasers or electron beams are usually used to melt the powders, so that the manufacturing process followed by these machines is conceptually similar to soldering or melting.

Depending on the final application, all these techniques are being currently applied in manufacturing industry, in aerospace, in medicine and in cultural heritage fields thanks to the high customization which is possible. The use of RP in industry can rely on the realization of physical prototypes, typically used to evaluate a new product or a variant. The aerospace can benefit of the fast realization of models to be used in wind tunnel [8], and spare parts could be produced directly in space [6]. PBF techniques can be used in aeronautics to produce turbine blades, heat exchangers of complex shape, conveyors ducts in a single part instead of assemblies of parts joined with screws. Also the rapid prototyping with carbon/kevlar/glass filaments is now under study to allow the production of parts in composite materials, without the need for moulds and manual layup. The RP is widely used in bioengineering too; the building of anatomical dummies to train surgeon before an operation, the manufacturing of equipment to help the positioning of nails or the reconstruction of parts of bones in maxillofacial surgery or hips [9], bolts and screws in titanium alloys to be inserted in bones are typical applications. The cultural heritage operators appreciate the capability of obtaining accurate replica of sculptures once a CAD model has been obtained, eventually by scanning a real model.

Despite the flexibility and maturity of the RP techniques, some problems still lie in this technology [2]. As an example, a strong relation between temperature and errors in geometry is noticed in some FDM machines: if the RP machine does not include a hot chamber or a heated plate, deformations

[10] in large parts are possible due to the local material cooling and following shrinking. Also the automatic design and positioning of support structures can be considered a critical issue since its partial collapsing or lacking can produce deformations in the object: it can even cause the falling down of the part leaning beyond the main body of the model (undercuts). Gaps between the actual 3D part geometry and the nominal model can also lead to objects where the upper layers lean on the below ones in a wrong way. On the other hand, it is not easy to detect errors in the geometry of the part during the printing process: the user does not have references to evaluate whether the printed part is correct or not and there is no information on the correct shape of the component during the layer by layer manufacturing process. A huge waste in time and material follows if the printing isn't stopped once the building process starts failing. The cost of metallic powders for PBF can be up to five hundred of euros per Kg, and the cost of this type of machines can reach hundred thousands of euros, with high machining-hour expenses. From this introduction, it follows that one of the challenges to increase the efficiency of AM procedures passes through the reduction of waste in parts and early detection of errors during the printing process.

This paper presents a methodology which can be implemented in RP machines to interactively detect errors in the building process, allowing the operator to promptly stop the 3D printing. Our technology is based upon the use of the augmented reality (AR) to compare in real time the shape of the part being built and a virtual 3D model representing the ideal geometry of the object. The technique described in this paper is strongly related to the concept of interactive manufacturing. In the traditional workflow a part is machined and further controlled following the geometric dimensioning and tolerances (GD&T) requirements. In the methodology described in this paper, the control is performed in real-time with the manufacturing of the part itself: eventual problems can be detected during the layer by layer manufacturing, and components 3D models or machine settings can be updated accordingly to mitigate the problem and start a successful new print in short times.

The paper is structured as follows: after this introduction, a brief description of the augmented reality is provided in Sect. 2. A description of the proposed methodology and a layout of the architecture to implement it follow in Sect. 3; the benefits of the approach are included in Sect. 4; the illustration of a case study is reported in Sect. 5, conclusion and future work sections end the paper.

2 The augmented vision

The augmented reality (AR) [11] is a technique in which an image of the real world is manipulated in real-time via software to add to the scene a symbol, a writing, a label or a virtual object [12]. This technique is less invasive than the Virtual Reality where the user interacts with a completely virtual scene: with AR the operator has always a contact with the real world. The AR procedure is based on the following steps: (1) image acquisition, (2) calibration, (3) tracking, (4) registration, (5) display. The image acquisition can be obtained by an internal camera in case of mobile phones and PC or with external glasses fit by the experimenter. The Calibration phase allows to evaluate the internal parameters of the camera and to implement the adequate corrections to reduce the image distortion. The Tracking is the operation necessary to define the position in space and orientation of the camera respect to a fixed reference systems: it can be obtained using a maker whose shape and dimensions are known, or through the feedback of a series of sensors (ultrasound, encoders on boom, etc...), or with markerless solutions (see [13] for further details). The Registration implies the synchronization between the virtual scenario and the real world image. Finally, the display phase presents the real world image with the virtual object added to the scene in a pre-defined position: head up displays (HUD), see through (ST) lenses or screens are typical output devices. HUD is a sort of closed cask with an internal screen on which the image is projected; ST transparent lenses are mounted on glasses equipped with a camera and two miniaturized projectors capable of projecting the virtual scene on the lenses themselves. Registration is the most critical phase, and for an overview of the theoretical framework which describes this operation please refers to [14]. Just to provide an idea of the transformations lying upon the AR, the following Fig. 1 presents the relationships among the reference systems involved in the registration computations. If a simple pinhole model is selected, it is possible to find the position of a 3D point in a screen reference system and vice-versa using a simple math based on transformations between reference axis.

At first the relative position between the marker reference system (x_m, y_m, z_m) and the orientation and position of the pinhole reference system (x_c, y_c) is found; in the following, the virtual model of a 3D body can be superimposed to the external environment to find the Augmented image in the screen reference system (x_s, y_s, z_s). It is worth noting that AR is a real time technique since when the user moves the camera, the virtual object shape is updated to maintain the alignment with the real scene.

3 Integration of AR into RP

3.1 Layout and software

The system architecture to implement the augmented vision and interactive monitoring (AVIM), called AM-Viz, is summarized by the scheme presented in Fig. 2.

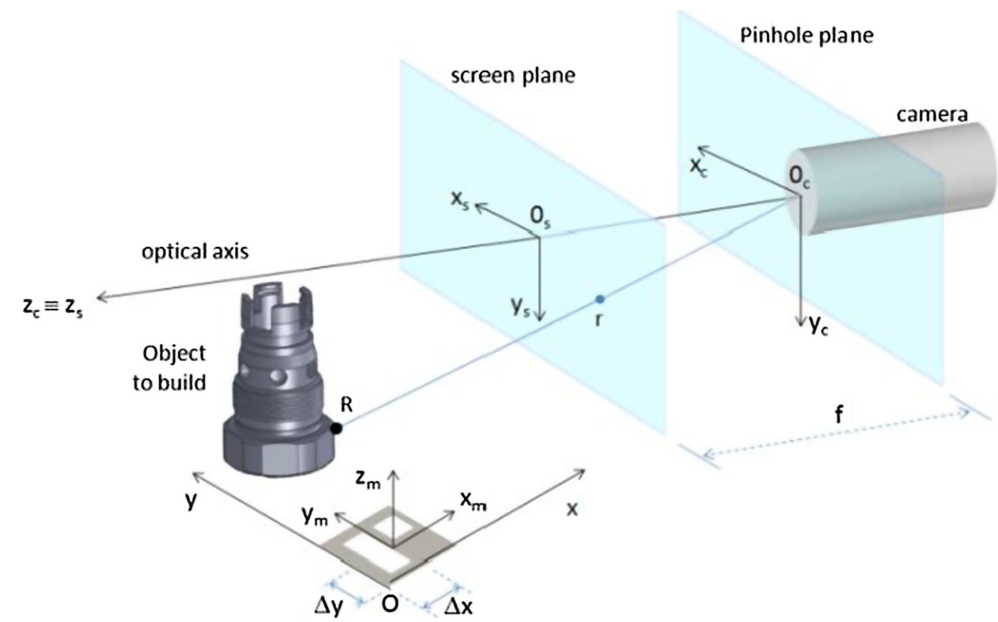

Fig. 1 Registration process

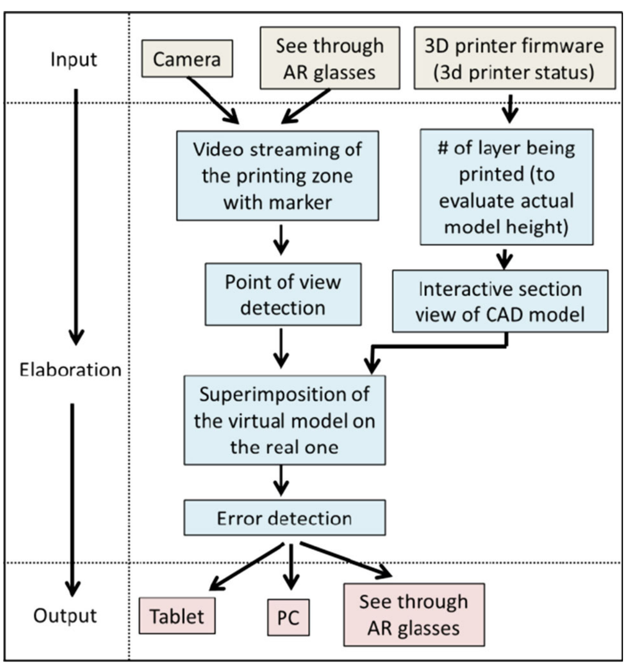

Fig. 2 Layout of the methodology

The AR has been integrated in the AM process by implementing an original system architecture, based on the available type of RP machine and final application. The use of marker instead of physical sensors to detect the position of the printing table reference system is more suitable than markerless approaches due to its precision and simple implementation.

Fig. 3 Marker used in tests

Several marker shapes can be selected to train the software to guess the position and attitude of the camera. For instance, a photo or a composition of white and black geometrical elements (see Fig. 3) can be used to the aim. Also an AR markerless solution can be adopted: in this case, the position and attitude of an object is found by comparing a picture of it taken from an unknown point of view with a set of images (whose point of view and position with respect to the camera is known) stored in a data base. The markerless solution seems to be less robust to the effect of shadows and different conditions of light, while the use of a marker can increase printing table complexity and interfere with the printing area. About the image capturing, a USB camera has been placed in the print chamber and connected to a PC. Alternatively, a pair of AR glasses or a tablet/smartphone can be used; in the first case only a fixed point of view can be

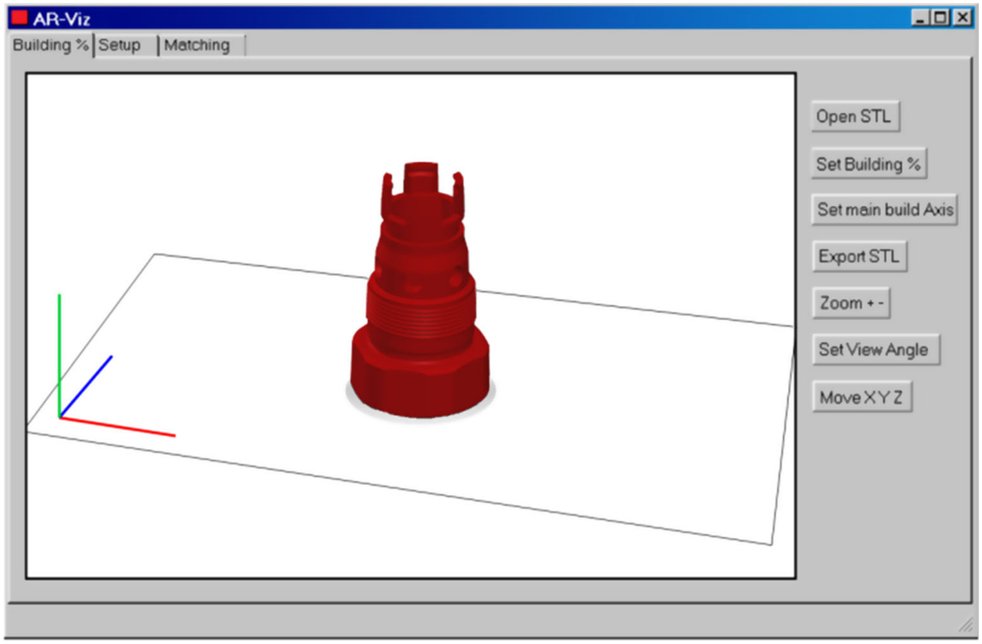

Fig. 4 AR-Viz software

available, but the augmented image can be visualized on the PC screen without the need of additional hardware. Using AR glasses [15], the user can move the point of view in an intuitive way and the augmented image representing the virtual part to be printed is overlapped to see-through lenses in real time by a set of miniaturized projectors. Data presentation with AR glasses provides a more immersive experience, but this hardware is quite expensive. Finally, the use of a tablet/smartphone allows to move the point of view dynamically, but the image is seen on a small screen, so that its quality is lower than in other cases. Whatever hardware is selected, the image acquired by the camera must frame at the same time the marker and the object (or the known scene and the object for markerless AR). It is worth to note that the monitoring of the shape is carried out in an interactively way since: it is a real time process providing an output as soon as a problem is detected; the user can evaluate the building process by changing in real time and interactively its point of view (with glasses); a sort of loop between CAD modelling, printing settings, monitoring with AR is implemented. Depending on the error detected during the AM process, the CAD model or the printing settings are changed accordingly up to fixing the problem. As it can be seen from Fig. 2, also a connection with the firmware of the printing machine is necessary to evaluate in real time the layer being printed (related to the shape of the part being partially manufactured). By computing the number of layer times the thickness of each layer, it is possible to obtain the height of the part being manufactured in real time along the printing process. In this way, it is possible to cut the CAD model at the correct height, so that the virtual model is aligned with the real one. As it will be better described in the next sections, also an automatic monitoring functionality has been implemented to detect errors between the CAD model and the part being manufactured: in this way, the user is supported in assessing failures.

3.2 Software

A software to support the AVIM, called AR-Viz, has been developed and tested in several case studies. The code is based on the ARtoolkit environment [16], whose functions have been enriched by a set of additional capabilities. In particular, AR-Viz includes: a user-friendly mask, a function to help the user in the setup of the AR; a tool to dynamically change the shape of the virtual object to be printed according to the percentage of the building process; a function based on the features detection to interactively compare the shape of the object being printed with the reference shape and compute the differences. Figure 4 presents a print screen of the software mask which allows to import an STL, to set a position in the building plate, to change the model accordingly to the percentage of the building process and to provide a digital model to be used in AR.

The AR-Viz environment import a standard STL file, and whatever CAD software respecting the ASCII or BIN coding for STL can be used.

3.3 Setup and calibration

An initial setup of the system is necessary to reduce the deformation errors due to the camera and lighting conditions which could affect the detection of the marker (or the scene in case of markerless solutions). The camera is placed in a set of already known points in the printing area framing a high contrast marker made by a chessboard with white and black squares. Correction parameters can be found to help registration precision and marker detection. Also a calibration process is necessary to precisely compare the differences between the real component being built and the virtual object. In this case, correction parameters can be applied to the scaling of the virtual object, or to its position and orientation: they can be found by tuning the superimposition of a virtual model with a sample real model (a parallelepiped with known size, position and orientation). It is worth noting that the setup and calibration depend on the features of the camera selected for the application, on the marker, and on the lighting conditions: if the hardware configuration isn't changed, there is no need for a new setup.

3.4 Automatic image comparison

The AR-Viz environment has been enriched by the capability of detecting printing failures in an automatic way. This is useful since an operator can supervise the work of several AM machines at the same time checking the printing only when an alarm starts; moreover, the implemented software can determine and highlight the zone of the model in which differences between real model being printed and CAD model are detected. In this way, the designer can understand the reason why the print fails and implement countermeasures useful to solve the problem. Aim of the image comparison is to detect differences between the images of the part being printed and an image of the CAD model taken from the same point of view. To perform this operation, a procedure based on several steps has been followed, as Fig. 5 shows.

In the first step, two images are obtained: the picture of the real part being printed, and the virtual CAD image which is projected in AR. The images match and overlap themselves. It is important to note that the point of view of the CAD model and real part are the same, as well as the dimensions. A link between AR-Viz and the software supervising the printing provides a real time indication of the printing process: in particular, given the thickness of each layer and the number of the layer being printed, it is possible to compute where to section the CAD model in order to synchronize the two models. The printing is in fact a real-time process keeping under control the errors during all the part printing, from the beginning up to the end of the manufacturing. As a further step, being available the position of the model in both the images, the zone in which the virtual CAD and real part are positioned is cropped, so that a large part of the background is deleted (this help the algorithms used in the following to detect features). The two images are then converted from an RGB to a greyscale coding. In the following, a speeded

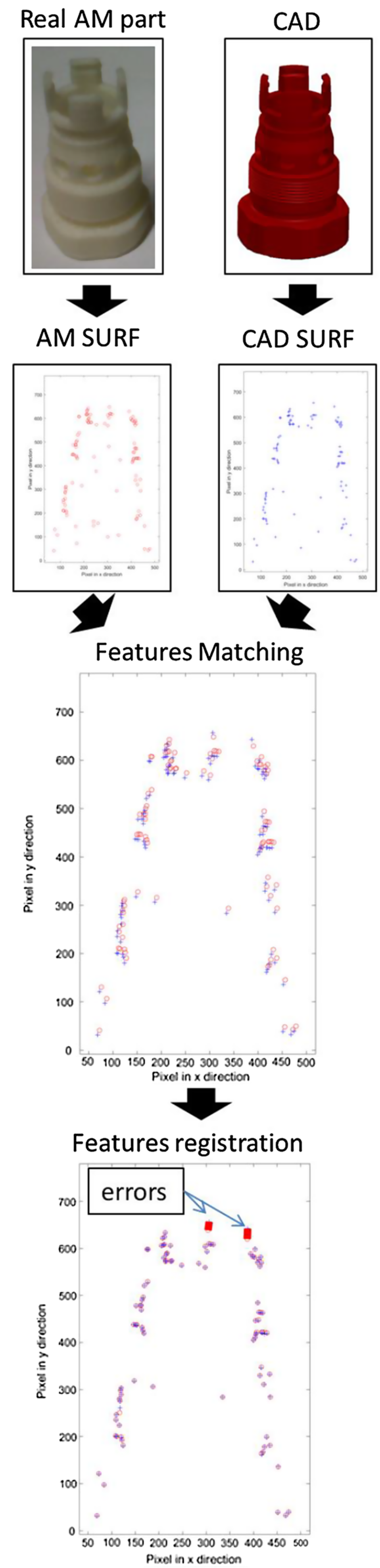

Fig. 5 Printing failures detection procedure

up robust features (SURF) algorithm is applied. The SURF algorithm, as explained in [17] is a powerful scale and rotation invariant procedure useful to detect interest points in an image (corners, edges, points with sharp changes, etc...). This effect is obtained in a very robust way through relying on integral images for image convolutions: this method is similar to scale-invariant feature transform (SIFT) methodology [18], even if it is faster.

An Hessian matrix-based measure is used for the detector, and a distribution-based descriptor follows. Several methods have been recently introduced by other authors to enhance the original SURF algorithm, but all the procedures are mainly based on the Hessian matrix. According to the paper by Bay et al. [17], once defined the position $p = [x, y]$ of a pixel in an image I, the Hessian matrix $H(p, \sigma)$ in p at scale σ (greater the value of σ, greater the blur) can be defined as:

$$H(p, \sigma) = \begin{bmatrix} L_{xx}(p, \sigma) & L_{xy}(p, \sigma) \\ L_{xy}(p, \sigma) & L_{yy}(p, \sigma) \end{bmatrix} \tag{1}$$

The $L_{xx}(p, \sigma)$ operator represents the convolution of the Gaussian second order derivative $\frac{\partial^2}{\partial x^2} g(p, \sigma)$ with the image I in point p. The same is for $L_{xy}(p, \sigma)$, $L_{yx}(p, \sigma)$, and $L_{yy}(p, \sigma)$. The $g(p, \sigma)$ operator can be expressed by:

$$g(p, \sigma) = \frac{1}{2\pi\sigma^2} e^{-(x^2+y^2)/2\sigma^2} \tag{2}$$

The SURF algorithm iteratively applies a blur to an image. Later on, images with different levels of blur are subtracted each other to extract features. Thanks to SURF, a vector containing the coordinates of the features detected in the CAD and real part images is obtained. These two sets of points are compared to detect the correspondent points in the images (in a sort of points' matching procedure). Only the common points obtained by SURF in the two images are selected, while the other points are neglected (RANSAC methods [21] can be used to perform this operation). The average difference in x and y direction between correspondent pixels in the two images is computed; one image is translated as to perfectly overlap the two set of points. In support to the set-up procedure necessary to tune the AR system (which should assure this perfect correspondence between real and virtual), it is useful to provide this additional correction to enhance the precision of the system when dealing with image processing.

At this point, the distance between correspondent points is low when the zones of the CAD and part to be printed are coincident; if the shape of the printed part starts changing from the CAD model, this distance typically increases layer by layer up to crossing a threshold value which can be set by the operator. The points of the image in which the correspondent pixels position differs from a quantity exceeding the threshold are highlighted. In this way, as soon as a difference is noticed, an alarm starts; moreover, the user can have an idea of the zone of the part in which the defect originated. The OpenCV library [19] implements SURF and other algorithms for image analysis in functions available in c++ environment, while Matlab® [20] can be used to test these algorithms and to prototype procedures and combination of these algorithms in short times.

4 Benefits

Aims of the AVIM of 3D printed objects are: (a) to allow an interactively monitoring of the parts to be printed, which can be obtained by superimposing a virtual model of the model to be built in a whatever stage of the printing process to the real part; (b) to monitor along the 3D printing deviations of the real part shape respect to the virtual model (representing the "ideal" shape to obtain) so that a part validation during manufacturing is obtained (c) to provide information to the user about the building point where the real model starts differing from the CAD model; (d) to allow the user to immediately stop the building process as soon as a significant error is detected, sparing materials and machine time; (e) to provide an automatic alarm system which alert the operator when large differences between CAD model and part being printed arise. After the experience gained in several case studies, one of which will be presented in the next section, the advantages of this approach have been assessed: there is a complete control during the 3D printing process and the designer can benefit of the information which can be retrieved by the AR-Viz software environment to change the CAD model or the 3D printer parameters to avoid manufacturing problems. It is worth to note that the automatic system to detect errors can be used to suggest an inspection by the user (so that a single can supervise a set of AM machines at the same time), and to detect the critical zones during the printing process. Moreover, the automatic error detection system suggests to the user where to change the CAD model or the printing settings (e.g. thicken walls to increase strength, or increase the temperature of the building table to avoid local shrinking and deformations).

5 Case study

The methodology has been applied to the 3D printing of the main body of an hydraulic valve. The following Fig. 6 shows from the right to the left: the original valve body in steel, a 2D CAD model with some reference dimensions, a 3D CAD model, and finally the part obtained by RP technique in a FDM printer.

This component is geometrically made by a bolt on the base, and by a series of pretty cylindrical elements with dif-

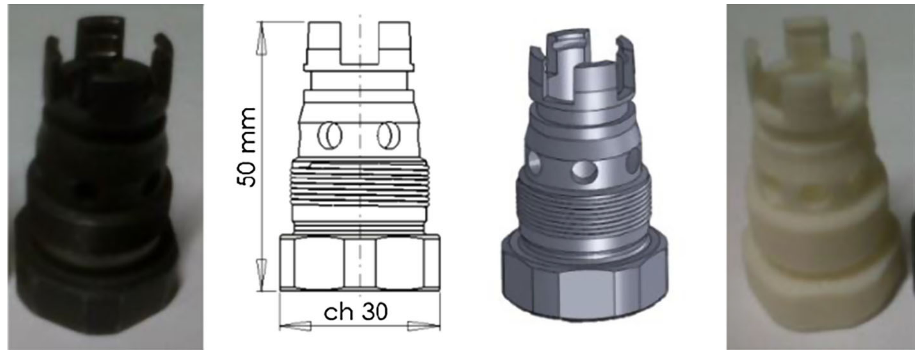

Fig. 6 Valve body to be produced by AM

ferent diameters and small wall thickness up to the top, where 4 small wings protrude the solid. Some problems can occur during the manufacturing of the part, like bending of the valve axis, irregular shapes in the zone of the holes, local twisting or folding in the zone of the four upper wings, thickening or thinning of the valve walls.

The FDM machine used in this research is a MakerBot Replicator 2×. It is a RP machine which implements the Fused Deposition Modelling technique to manufacture objects.

The plate of the machine can be heated and the building volume is 0.25 × 0.16 × 0.15 m (length, breadth, height). The average layer resolution is 0.1 mm, while the diameter of the ABS or PLA filament is 1.75 mm. The machine is managed by the MakerWare software environment which allows to import the CAD models in STL format; the slicing of the model, the computation of the paths of the extruder heads, and the support material geometry are automatically computed by the sotware. Several settings can be adapted to the model being built, among them: single/double head print, raft option (support base for the object), supports option (to manage undercuts), infill patterns (to change the internal structure of the modelled object). As Fig. 7 (top) depicts, a marker has been placed in a known position on the building plate of the machine (the base on which the model to be printed lies); also a camera framing the marker together with the printing chamber has been installed. As an alternative, a pair of Wuzix glasses can be used instead of the camera, as Fig. 7 (down) shows.

The virtual model of the part being printed can be overlapped to the video streaming from the camera or glasses using AR technologies. The Fig. 8 presents the printing chamber of the RP machine with a marker and the part in ABS being manufactured.

Also the automatic detection of errors have been tested. In this case, one of the 4 small wings on the top of the valve body have been intentionally stretched of 5mm in the CAD model to introduce a difference between STL model to be printed, and reference CAD model. As the following Fig. 9 shows, the SURF algorithm is able to detect this error (see

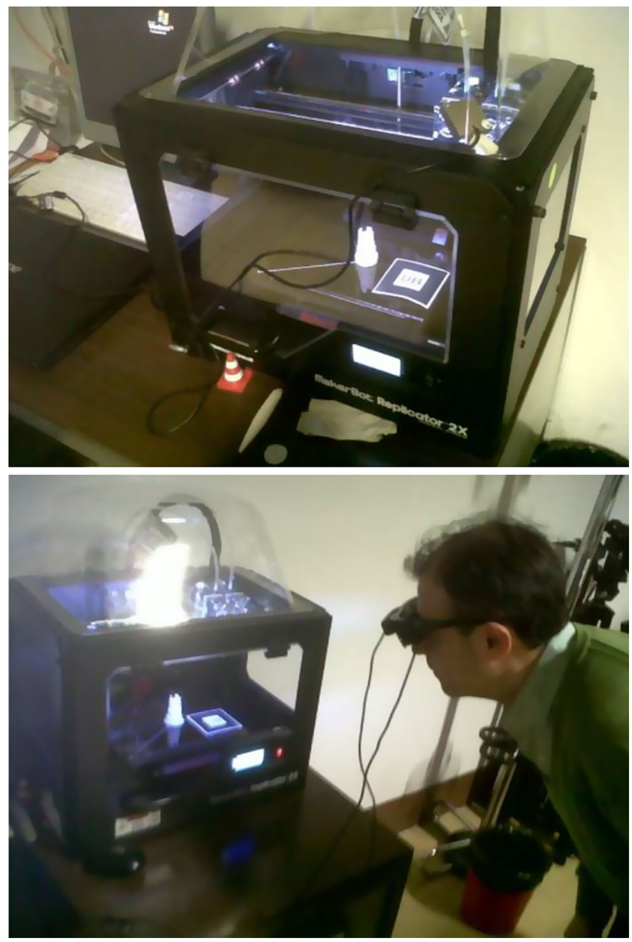

Fig. 7 Printing machine with camera (*top*) or Wuzix glasses (*down*)

the thick lines connecting correspondent points in the wing whose position differs from a length over the threshold).

The circles in Fig. 9 represent the features found in the CAD model, while the crosses represent the features detected in the real image of the component being printed. All the correspondent points present the same position except that located on the feature in which the error has been introduced.

Figure 10 shows the AR-Viz software while displaying the real scene inside the printing chamber of the RP machine.

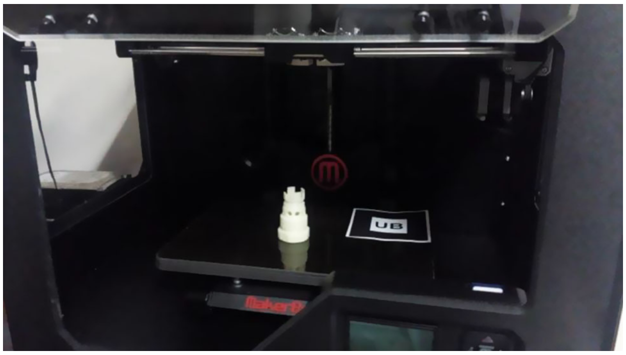

Fig. 8 Printing chamber

Fig. 9 SURF points on the CAD model

As Fig. 11 illustrates, it is possible to overlap a CAD virtual model in a used-defined stage of the modelling to the real model being built: the AR-Viz tool can be used to assist the user in the preparation of the virtual model.

Semi-transparency level and colour of the virtual part can be changed by the operator to help comparison with real model in background.

The integration of the augmented reality into the machines manufacturing objects through additive techniques allows a continuous checking during the building of the component. Also the virtual model of the part to be manufactured at different printing stages can be used, if it can help the user. For instance, in an early phase of the printing, the user can visualize the complete 3D model to have an idea of the final result. The output image (AR virtual + real model) can be presented in several ways: AR glasses, Tablet application [22], PC screen (see Fig. 12). In this latter case, a frame of the video output with the virtual model overlapped to the real part could be integrated in the proprietary software used to manage 3D printers by AM machines producers.

As a final remark, the method we developed can be used to detect the differences between a reference 3D model (CAD) and the model being produced in AM machines. It is possible to stop the building in case of errors, and to detect the initial point where the print starts failing.

Also coarse errors like conversion between inches and millimetres, or scale factors can be detected by comparing the initial layers of the real model printing with the 3D CAD reference model representing what the operator expects to obtain at the end of the process.

After an experimentation campaign on several case studies, some comments on this methodology can be reported: these statements are based on the feedbacks by several users involved in the research. The methodology is useful to increase the control of the printing process; the capability of superimposing the virtual CAD model (in a printing step defined by the user or synchronized with the building process) to the real part increases the end-user evaluation capability in phases where the logic of layer deposition is unintuitive, or the section of the body complex. Moreover, overlapping the complete CAD virtual model to the real model being printed can provide a more intuitive evaluation of the time needed to end the printing process. The automatic AR/real shape differences detection can be a useful feature, even if a very accurate setting is required, the lighting should be accurately set to avoid problems in image brightness, and the body geometry must have features which can be easily recognized by the SURF algorithm. The orientation of the camera in case of fixed positioning is crucial: in this case it is of paramount importance to orient the part to print so that a significant view with the highest number of details is framed and critical zones are not shadowed. The addition of more than one camera to obtain a 360° framing of the part to build may solve this problem.

6 Conclusion

This paper proposes the application of the AR technology to supervise in real time the printing process of parts obtained through AM technologies. The interactive superimposition of a virtual part to the real part being manufactured

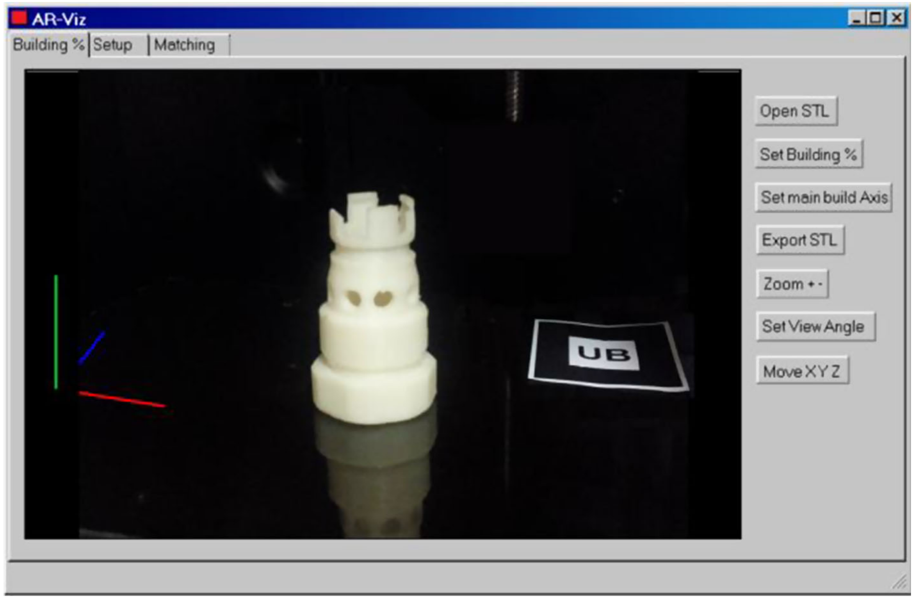

Fig. 10 Printing part visualization in AR-Viz

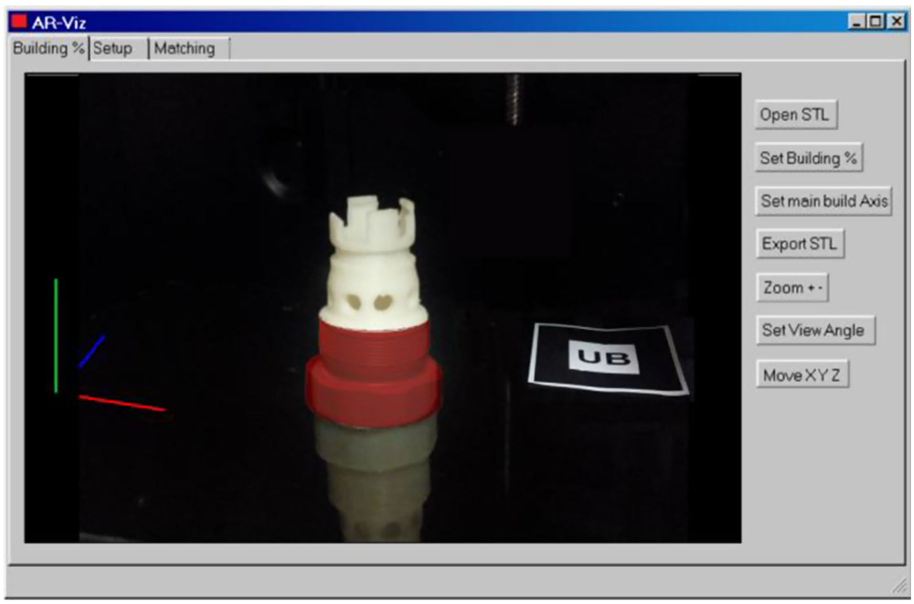

Fig. 11 Virtual and real model overlapping

is obtained through an AR based software environment: it allows an alignment between real and virtual worlds using markers or markerless technology, options of different semi-transparency levels, colours, and selection of shape at pre-set printing stages for the virtual model. Also an automatic strategy to find differences between real part being under building and CAD model have been implemented: it is used to suggest the need for a check to the operator. In this way, a single operator can supervise the work of several machines and inspect the building process only when needed. In case of failures during the printing, the point where the problem lies can be detected so that correction actions on the CAD model (or AM machine settings) can be carried out. Also an automatic stop of the printing process can be implemented without human intervention if previously enabled.

After several experiments with real case studies, the pros and cons of this approach has been evaluated. The application of the AVIM into the new generation of RP machines could provide advantages with a negligible implementation cost: basic implementation of the technique requires a camera framing the printing area and the integration of the AR code on the software of the printers. The implementation of this methodology in machines working with metallic powders could assure a reduction in machining time hours and material waste. Following the experience of the authors, an average 5–10 % of parts being manufactured in AM for the first time in companies fails. The average precision of the Augmented Reality is useful to find significant geometrical errors; precise evaluation of differences between virtual and real object can't be assessed. However, the automatic monitoring of the

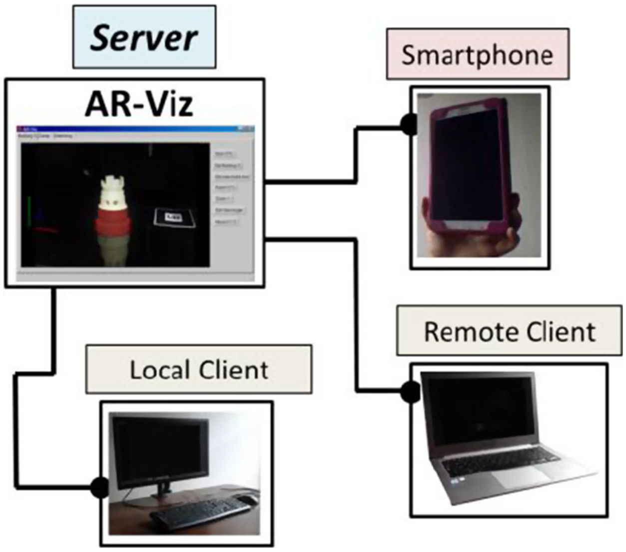

Fig. 12 Output for the printing scene added by virtual model on smartphone and local/remote client

printing process can be useful to suggest the stop of the manufacturing and provides an indication on the zone where the AM started to fail. The SURF algorithm works when parts with recognizable features are considered, but it fails when a too short number of common features is recognized in real and CAD images. This paper describes a preliminary study on the topic of the integration of AR and AM, but the methodology we propose will change with attended progresses in the fields of image analysis techniques and hardware computing capabilities. Future works include an accurate assessment of the range of errors which can be detected and an extensive on-the-field application of the methodology with a commercial RP machine to evaluate economic viability and pros and cons of the application. Several companies are developing facilities in which dozens of AM machines work at the same time: the automatic monitoring of several machines with a single operator could be an interesting challenge to test the methodology herein described. Moreover, the implementation of the AR-Viz tool as an add-on within commercial CAD software packages [23] or 3D printing software could provide interesting scenarios for a smart integration of features useful to support additive manufacturing into traditional design tools.

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