

Title:

Augmented Reality for CAD-CAM Training Featuring 3D Interactive Geometric Transformations

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Keywords:

Augmented Reality, Computational Geometry, Computer-aided Design

DOI: 10.14733/cadconfP.2020.258-262

Introduction:

Augmented Reality has been shown to positively affect educational and development processes by engaging young trainees and integrating the latest display technology with traditional forms of learning, training and manufacturing [7]. In an educational context for Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM), students often have difficulties contextualizing 3D information through traditional ways of teaching and static visual material, digital or hard copy, often losing motivation to learn [5]. By not only superimposing 3D CAD models on the real world as in most previous approaches but also offering interactive 3D manipulation, AR has the potential to enhance the understanding of 3D object transformations, aiding trainees to conceive and process 3D complex information. As part of a mechanical drawing course, when given the basic views of a 3D object, a student needs to visualize the respective 3D solid [8]. Often, the views may appear abstract to the student and the 3D model could be hard to mentally visualize. AR can offer valuable training material of complex, accurately drawn models, releasing time for explaining and describing complex computational geometry processes related to CAD/CAM.

In this paper, a mobile Augmented Reality (AR) application is presented, employed to facilitate and enhance the learning processes and traditional text book material of the Mechanical Drawing course for undergraduate and postgraduate university students undertaking an engineering degree. The presented AR app is used along with a brand new Mechanical Drawing textbook authored for the respective course [2]. The novel AR content, enhanced with computational geometry processes, complements the extensive university-based Computer Aided Design (CAD) and Computer-Aided Manufacturing (CAM) training. The application can track and recognize 3D CAD models with the use of real world markers printed on a hard copy of the Mechanical Drawing textbook used in class. The projected models may also be imported into the mobile application for further geometrical processing.

After importing the displayed 3D models, a mobile graphical user interface provides trainees with advanced 3D transformation tools offering a detailed visualization and understanding of the solid object. The most basic functions include pan, rotation and magnification of the solid object. Adding to the standard functions, the technically challenging implementation of a section operation of a 3D model is central to the system's capabilities. The section operation is implemented through a series of computational geometry algorithms applied to the mesh of the examined model. The application is developed with Unity3D game engine and EasyAR SDK Unity plugin providing the AR development tools [4]. State of the art AR technology which is more appealing to the younger generation is shown to be beneficial for CAD training based on laboratory evaluation, offering scientifically concrete 3D manipulations.

AR technologies show potential for enriching educational and training processes with digital elements, in varied scientific fields. In [10] a mobile Augmented Reality Application was developed which aims to inform the user about the cultural heritage sites of the old town of Chania, Greece. This is achieved by superimposing historical buildings on real site locations and providing historical information through text and images. In [9] an AR platform for electromagnetic education is developed, offering motivation and engagement for learning. AR training was deemed essential for smooth lecture flow. AR applications combine superimposed AR models with touch, speech and audiovisual content. Overall feedback suggests that a book is much more likely to be read when combined with an AR application [8]. In summary, previous research focuses on superimposing AR elements onto hard copy text books, offering, though, limited interaction and off-line availability of complex 3D models for training. In our work, we go beyond plain visualization of AR content, putting forward a mobile graphical user interface facilitating the importing of projected 3D models for further geometrical transformations. The system presented enhances CAD-CAM mechanical drawing training.

Augmented Reality Visualization for CAD Model Manipulation:

A vital part of the application presented involves the selection of a 3D CAD model through a mobile Augmented Reality environment. Each model is associated with a target image (marker) which is printed on a mechanical drawing text book [2]. The user scans the target image with the camera of the portable device and the respective 3D model is recognized and superimposed above the marker. During that phase, the user may either view or select and import the model into the mobile app's environment, which provides further geometrical processing options. In Fig. 1 a 3D model is visualized in AR mode after it has been selected by the user in the AR environment. The user has now three options. Either deselect the object by touching anywhere on the screen, or return to the processing environment with or without importing the selected model.

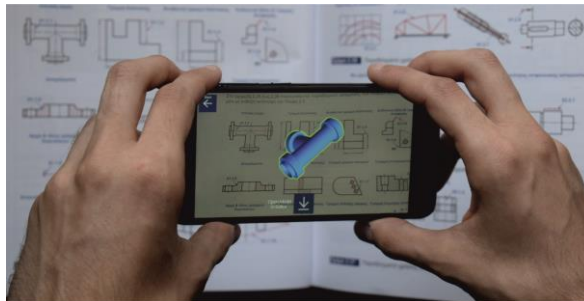


Fig. 1: Selection of a 3D model through Augmented Reality based on textbook marker.

User Interface:

The main processing environment offers the user the ability to interact with the imported 3D model and apply several functions which contribute to the understanding and visualization of the solid object. The geometrical transformations of the model are accomplished by touch inputs. Basic functions include rotation, zoom in or zoom out and pan of the object. In this section, the main capabilities offered by the application's User Interface (UI) will be described.

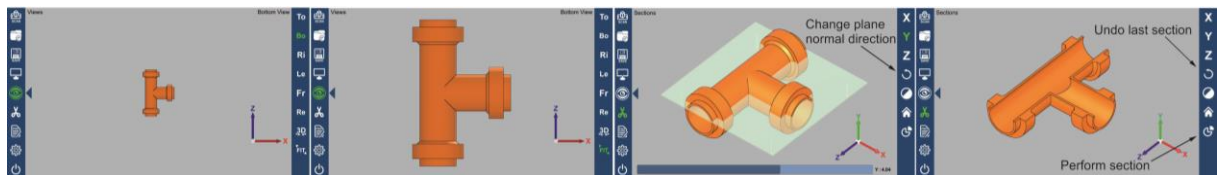


Fig. 2: (a) Bottom View, (b) Fit Function, (c) Section in Y axis, (d) Section Result.

Through the **VIEWS** menu, the model can be observed from the six standard mechanical drawing views (Fig. 2(a)). The model can be restored to the default 3D perspective view or the fit function may be applied. The fit function re-positions the model to the center of the screen so that it fits to the bounds of the screen, in case it may have been removed by extensive zoom or pan (Fig. 2(b)).

Through the **SECTION** menu, the user may apply a section to the model along the basic three axes X, Y and Z. Through a graphical slider the user may move the intersection plane along the selected axis. For each plane, the direction of the plane normal is specified. The plane normal vector defines the part of the model that will be retained after the section is performed. Since the user has applied a section, an undo option is available through the respective button. If desired, a user may perform two or more successive sections. The Home button restores the model to its original form before any sections. Fig. 2(c) and Fig. 2(d) depict the section menu and a random section of the model in Y axis.

The **DISPLAY** menu offers simple functions related to the model's appearance and its properties. Such functions include model color change, deactivation of model's edges (Fig. 4(a)) and display of a panel with mesh properties. This panel provides information about the mesh triangle count, the total surface of the model and the model's dimensions (Fig. 4(b)). The surface of the model is calculated by computing the surface of each triangle of the mesh individually and, afterwards, the sum of the total calculated surfaces.

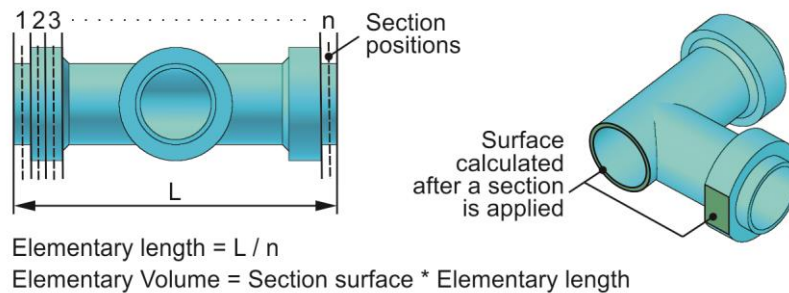


Fig. 3: Calculation of Model's Volume.

This method of surface calculation provides a close approximation of the real model's surface. The accuracy of the calculation is further increased by increasing the number of triangles the mesh contains. The **DISPLAY** menu also offers the object's volume as well as weight calculation for a specific material. In order to calculate the object's volume, the solid object is partitioned in *n* parts by performing successive sections along the z axis. For each part an elementary volume is calculated. The final volume is the sum of each elementary volume. For each section, a surface is calculated which is used for the elementary volume calculation as depicted Fig. 3. The partition parts are defined as 100 for optimal performance. In practice, it is found that this method can effectively approximate the real object's volume, so more partitions are not essential. The weight calculation follows a similar method. The only difference lies in the calculation of an elementary volume which has to be multiplied by the material's specific weight.

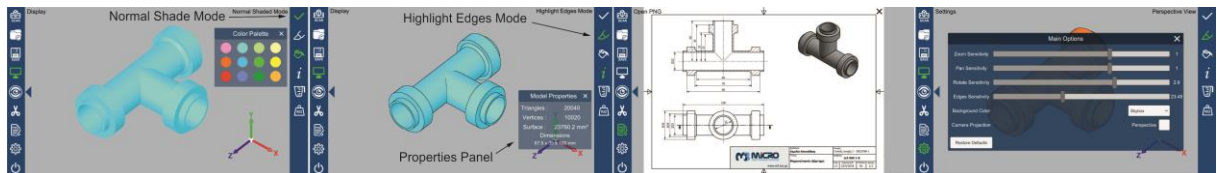


Fig. 4: (a) Color menu - Disabled model edges, (b) Properties Panel, (c) Mechanical Drawing, (d) User Options.

The application allows the user to save a model locally on the device. In case a section has been performed to the model, the save function stores the final model after the section. For most models, the application offers the opportunity to display the mechanical drawing of the model for educational purposes (Fig. 4(c)). The drawings are stored online under a .png format and are downloaded on the fly when the user selects the corresponding option. Finally, through an OPTIONS menu, the user may adjust the speed sensitivity of the pan, rotate and zoom functions, toggle the camera projection mode as perspective or orthographic and change the background color (Fig. 4(d)).

Section of a Solid against a Plane:

Applying a section to a 3D geometry (triangle mesh) results in open areas formed on the intersection plane. These areas cut a model open, eradicating the illusion of a solid object. It is required to connect and 'close' the mesh after performing a section in order to maintain the illusion of a solid object. Performing a section is the most technically challenging function developed in the application. It is often used in CAD applications and in certain cases two or more successive sections are required. Performing a section to a model containing one or more holes provides information about the interior of the solid, the depth and internal characteristics of the holes. Achieving a section is accomplished through a series of well-known computational geometry algorithms. These algorithms are described in short in the following paragraphs.

Initially, the **triangle section algorithm** describes a process for clipping a triangle mesh [1]. The algorithm examines the triangles of the model's mesh and determines their position in respect to a plane given as input. The plane divides the space into two half-spaces. The positive half-space is defined by a normal vector that is perpendicular to the plane. The part of a triangle lying in the positive half-space is retained, while the part in the negative half-space is discarded.

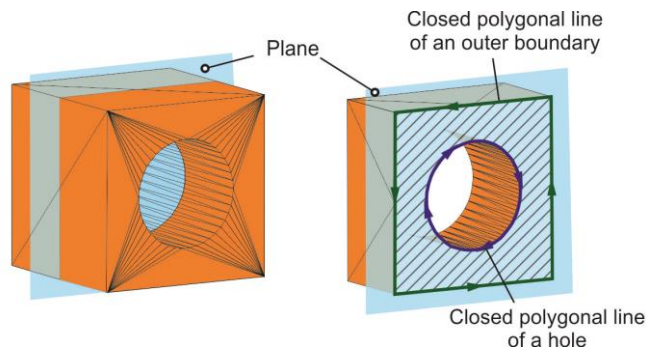


Fig. 5: Polygons formed by the Polygon Construction algorithm. The hatched area has to be capped.

After the clipping of each triangle, the intersections edges formed on the intersection plane are joined correctly. This is accomplished by the **polygon construction algorithm** thus creating the polygons formed on the section plane [1]. A polygon may constitute either an outer boundary of the model or the boundary of hole that may exist in it as depicted in Fig. 5.

The **Ray-casting algorithm** [6] is broadly used to determine the position of a point in respect to a polygon. In our work, this algorithm was used to determine which polygons contain other polygons in their interior. The polygons created by the previous algorithm may constitute an outer boundary of the model or a contour of a hole. Hole polygons should lie inside outer boundary polygons. Since polygons are non-intersecting, in order to determine if a polygon lies in the interior of another polygon, only one arbitrary point of the polygon has to be examined.

The polygon construction along with the ray-casting algorithm have managed to create and store every polygon formed on the intersection plane along with all possible hole-polygons it may contain. The final step for the successful completion of a mesh section requires the capping of open areas in the mesh created by the triangle section algorithm. For this purpose, two more algorithms are used in order to effectively triangulate the open areas. It is important to mention that hole polygons should

not be triangulated as depicted in Fig. 5. Initially, the **y-monotone partitioning algorithm** is applied to partition a set of polygons (outer boundary or outer boundary containing holes) into y-monotone sub-polygons. This partitioning algorithm was considered appropriate as it can be successfully applied in cases of polygons with holes present in our application. After the algorithm has completed its execution, a set of y-monotone polygons will have been created. These polygons need to be triangulated, so that the final mesh can be rendered inside the Unity3D engine. For this purpose, a greedy **triangulation algorithm for y-monotone polygons** is used. In practice it is found that the algorithm runs fast enough in modern mobile devices, despite its greedy behavior. De Berg et al [3] offer a complete and comprehensive description of these algorithms.

The final result of the successive execution of the algorithms described above is illustrated in Fig. 2(d). The final object after the section is performed represents a pseudo-solid model, since every open area of the section has been capped. The total response time of the algorithms executed was found to perform very fast, cutting the model instantly without delay.

Conclusion:

In this work, an Augmented Reality application for mobile devices is developed, which provides the opportunity of applying geometric transformations to 3D CAD models, in the context of a Mechanical Drawing course, thus aiding the educational process. In order to test the educational effectiveness of this work, the application was distributed for further evaluation to university students. The overall reviews were positive and surprisingly enthusiastic, with many student reports stating that the application greatly assists the educational process of the Mechanical Drawing course by providing faster means of learning and direct visualization of CAD models. Additionally, when given solids containing one or more holes, students had difficulties understanding and visualizing the internal part of the model. In those cases, a section operation at the middle of a hole was of great importance as it immediately resolved most of student visualization and comprehension issues.

Acknowledgement:

This research has been co-financed by the European Union and Greek national funds through the Operational Program Competitiveness, Entrepreneurship and Innovation, under the call RESEARCH – CREATE – INNOVATE (project code: T1EDK-01469).

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