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

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Abstract. 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 engineering students. The application can track and recognize 3D CAD models with the use of real-world markers printed on a hard copy of a Mechanical Drawing textbook which is used in class. Intuitively, the projected models can also be imported into a graphical user interface which provides trainees with advanced 3D transformation tools. These tools offer not only a mere visualization but an interactive understanding of the solid object and the underlying geometric transformations. Students often find it difficult to visualize a 3D model based on the standard views of the respective mechanical drawing. This application aims to overcome this problem using state of the art AR technology which is more appealing to the younger generation by simultaneously offering scientifically concrete 3D manipulations rendered on a mobile platform, based on computational geometry algorithms.

Keywords: Augmented Reality, Computational Geometry, Computer-aided Design.
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1 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 [10]. The potential of incorporating AR capabilities so that mobile platforms can be a crucial part of training is significant, opening challenging research questions in relation to mobile AR's usability, registration accuracy between real and digital and efficiency as a training medium.

In an educational context for Computer Aided Design and Computer Aided Manufacturing, 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 [8]. 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 [12]. Often, the views may appear abstract to the student and the 3D model could be hard to mentally visualize. The instructor is now required to draw a representation of the solid in order to help the student visualize it. 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 engineering students. The presented AR app is used along with a brand-new Mechanical Drawing textbook authored for the respective course [3]. 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 the most important of 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 offers additional functions such as the calculation of the surface's volume and weight of the solid object based on its material properties as well as access to its geometric characteristics such as its dimensions and triangle count. The users of the application may also store the model locally on their mobile device for offline editing. The mechanical drawing of the solid model can be visualized.

The application is developed with Unity3D game engine and EasyAR SDK Unity plugin providing the AR development tools [6]. 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.

2 RELATED WORK

AR technologies show potential for enriching educational and training processes with digital elements, in varied scientific fields. In [14] 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. Augmented Chemical Reactions is a chemistry teaching application which facilitates the understanding of molecules behavior and structure using a 3D user interface offering direct manipulation [11]. Students are able to get acquainted with different elements and learn about chemical reactions. In [13] an AR platform for electromagnetic education is developed, offering motivation and engagement for learning. AR training was deemed essential for smooth lecture flow.

AR educational apps often focus on 3D visualization of complex objects. For instance, a mobile AR application was developed for undergraduate anatomical education [7]. The application can track plastic heart models located in the classroom, without the use of observable markers. After recognition of the real object, text labels are depicted above specific anatomical parts of the organ. Using virtual representations of hearts, students are able to self-learn outside the classroom. A similar approach [4] teaches anatomy education by augmenting 3D models of organs on the users own body.

Since AR's beginning, combining hard copy material with AR showcased AR's positive effect in education. 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 [12]. AR technology has also been employed in the education and training of mechanical engineers. A recent AR approach superimposed 3D models of cutting, measuring tools and special equipment on a text book [2].

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 this work, a mobile graphical user interface is further implemented, facilitating the importing of projected 3D models for further geometrical transformations. The paper presents a complete visualization system which in conjunction with a mechanical drawing text book offers AR visualization and 3D manipulation of CAD models, thus aiding mechanical design training and understanding.

3 USER INTERFACE

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 [3]. 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 Figure 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. The Augmented Reality functionality is summarized in Table 1.

AR Functionality
Superimposition of a 3D model above a scanned marker printed on textbook
Support of simultaneous superimposition of multiple models
Selection and lock of a superimposed object to the screen center
Import of selected object to a processing environment

Table 1: List of Augmented Reality functions summarized.

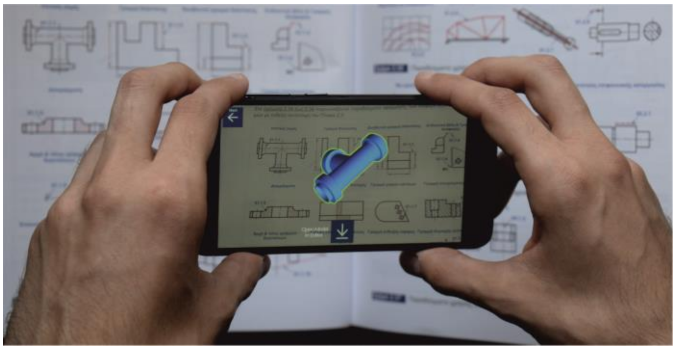

Figure 1: Selection of a 3D model through Augmented Reality based on textbook marker.

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. Through the **VIEWS** menu, the model can be observed from the six standard mechanical drawing views (Figure 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 (Figure 2(b)).

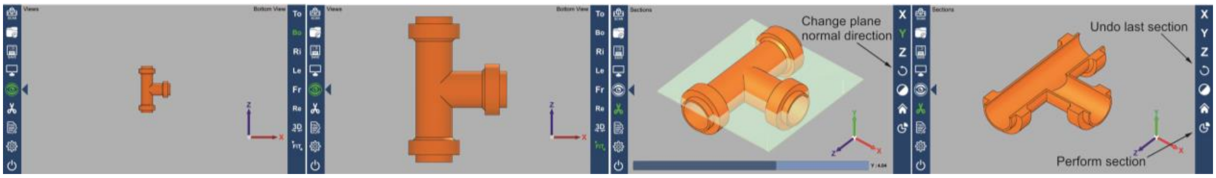

Figure 2: (a) Bottom View, (b) Fit Function, (c) Section in Y axis, (d) Section Result.

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. Figure 2(c) and Figure 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 (Figure 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 (Figure 4(b)). The surface of the model cannot be directly obtained from the mesh and has to be calculated. This is accomplished by computing the surface of each triangle of the mesh individually and, afterwards, the sum of the total calculated surfaces.

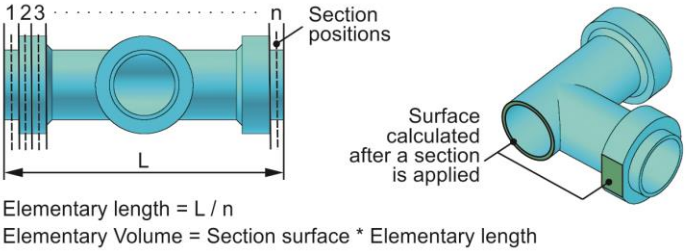

Figure 3: Calculation of Model's Volume.

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 contained in the mesh. 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 Figure 3. The partition parts are defined as 100 for optimal performance. In practice, it is found that this method can effectively approximate the object's volume, so more partitions are not essential. It is important to mention that the above methodology of volume calculation is not very accurate especially in complex objects, but offers a very close approximation of the volume. The purpose of the calculation is to show the user the change of the total volume before and after performing a number of sections to the model. Therefore, an extremely accurate calculation of the volume is 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.

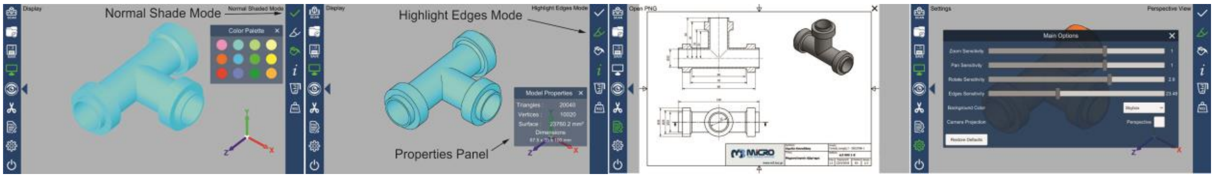

Figure 4: (a) Color menu - Disabled model edges, (b) Properties Panel, (c) Mechanical Drawing, (d) User Options.

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 (Figure 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 (Figure 4(d)).

4 SECTION OF A SOLID AGAINST A PLANE

The most technically challenging function of the developed application is the section of a solid model against a plane. 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. In Figure 5 a section of a triangle mesh along with the desired section result is depicted. By just applying a section on the model and without any other modifications of the triangle mesh, open areas are formed at the section position. 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. Achieving the desired section result is accomplished through a series of well-known computational geometry algorithms. These algorithms are described in short in the following paragraphs.

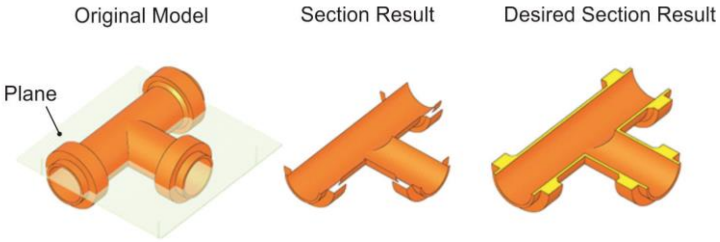

Figure 5: (a) Original model, (b) Section result without capping open areas, (c) Desired section result.

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. Thus, four main cases are distinguished as depicted in Figure 6.

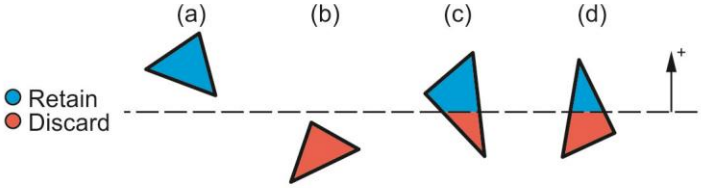

Figure 6: Main cases a triangle may be located in respect to the section plane.

As shown the whole triangle is retained if it lies in the positive half-space, else the whole triangle is discarded. If a triangle intersects with the plane, then a section has to be applied on the triangle as only the part in the positive half-space must be retained. As depicted in Figure 6(c) the triangle section may result in a quadrilateral, which has to be further divided into two new triangles by adding a diagonal.

After the clipping of each triangle, the intersection edges formed on the intersection plane have to be joined correctly. This is accomplished by the **polygon construction algorithm** thus creating the polygons formed on the section plane [1]. In Unity3D, each triangle of a mesh is rendered and stored in a clockwise direction of its vertices. A polygon may constitute either an outer boundary of the model or the boundary of hole that may exist in it. Consequently, each polygon representing an outer boundary of the model should have a counter-clockwise direction, whereas a polygon representing a hole should have a clockwise direction. As shown in Figure 7, the inner area formed by outer boundary polygons has to be capped in contrast with the inner area of hole polygons.

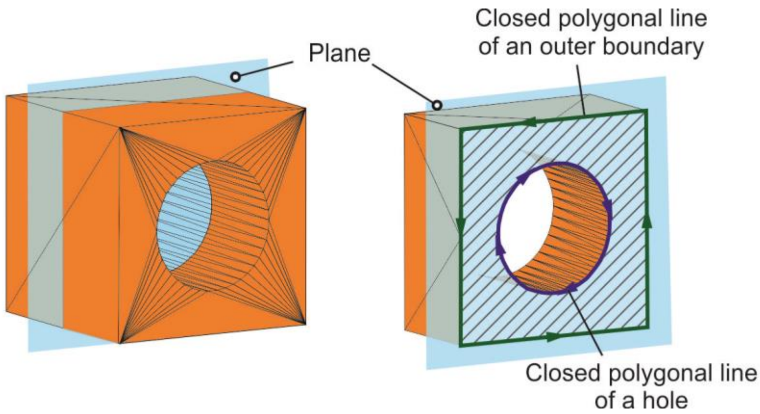

Figure 7: Polygons formed by the Polygon Construction algorithm. The hatched area has to be capped.

The **Ray-casting algorithm** [9] 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. A contour of a hole lies in the interior of a polygon which represents an outer boundary. 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. It should be noted that this algorithm does not work correctly if the examined point lies exactly on the contour of the tested polygon. Such cases are non-existent if triangle meshes are properly constructed, so the algorithm works correctly in every case.

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. Since solid models consist of triangle meshes, each open area has to be subdivided into triangles. 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 Figure 7. Initially, before the triangulation step the **y-monotone partitioning algorithm** is applied to partition a set of polygons (outer boundary or an outer boundary containing holes) into y-monotone sub-polygons. A polygon is called y-monotone with respect to the y axis, if every line orthogonal to y axis intersects the polygon at most twice. A **property** that holds for y-monotone polygons is, that a path along the polygon’s contour from the topmost to the bottom-most vertex, always has a downward or horizontal direction and never an upward direction. The purpose of the algorithm is to efficiently add diagonals in order to subdivide the original polygon (or a polygon containing interior polygons) into y-monotone sub-polygons. The algorithm moves an imaginary sweep line downward over the polygon, which halts at each polygon vertex it encounters. A diagonal is added whenever an encountered vertex eliminates the above-mentioned property of y-monotone polygons. This partitioning algorithm was considered appropriate as it can be successfully applied in cases of polygons with holes, which are present in the application. After the algorithm has completed its execution, a set of y-monotone polygons will have been created. In order to triangulate these set of polygons, 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 [5] offer a complete and comprehensive description of the last two mentioned algorithms.

The final result of the successive execution of the algorithms described above is illustrated in Figure 2(d). The final object after the section is performed represents a solid model, since every open area of the section has been capped.

5 HARDWARE REQUIREMENTS

Since the application makes use of 3D graphics, including Augmenting Reality functionality, 3D object manipulation as well as complex computations by modifying the object’s mesh, it would be important to mention the hardware requirements of a mobile device able to run the application smoothly. The application is developed for Android devices running Android version 4.2 or above with a minimum of 2GB of RAM, a dual-core processor and at least 100MB of free storage space. For an optimal performance 4GB of Ram and quad-core processor are required. A future version of the application targeted to iOS users is planned to be developed.

6 EVALUATION

Continuous feedback throughout the development of the system affected the design and feel of the AR and UI components. UI improvements included (a) using .png files for mechanical drawings rather than .pdf files requiring external readers, (b) introducing a central menu offering the main option of importing the 3D model visualized by AR, (c) setting the transparency level of the section plane rather than being opaque obstructing the visualization of geometry parts and (d) placing arrows at the edges of the section plane showcasing its direction so as not for them to be obstructed.

In order to test the educational effectiveness of this work, the application was distributed for further evaluation to undergraduate and postgraduate university students undertaking an engineering degree at the Micromachining and Manufacturing Modeling Lab (m3) and the Lab of Distributed Multimedia Information Systems and Applications (MUSIC) located at the Technical University of Crete. During lab time, students formed groups, gathered around the space of the CNC machines to study mechanical drawing concepts having available the text book material as well as the interactive app presented in this paper (Figure 8). The foundations of the 3D geometry transformations implemented in the app, for a wide range of CAD models, were available in the text book, simultaneously visualized through the app during lab time.

Figure 8: Group of students studying mechanical drawing gathered around a CNC Milling Machine.

Groups were asked to perform a number of tasks which related to the AR component of the application being able to recognize CAD models fast as well as perform a number of specified geometrical transformations, in the geometry processing environment. Overall, 3D recognition and 3D manipulation system response were fast and accurate, recognizing and handling a wide range of CAD drawings and associated 3D models. The section operation, central to the system's capabilities was found to perform very fast, cutting a model instantly without delay.

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. Most of these comments derived from the fact that studying the original textbook while using the application for further assistance through the AR system, was actually quite engaging when hard copy and AR were combined. The user interface was reported as "friendly" and "attractive" to the modern student; however, several users found the rotation of the model unpractical and fast at times. Some students proposed that apart from the textbook, the application could also import external custom 3D models for geometric transformations, so that the app could be used by a broader audience. Several suggested that an integrated manual should be provided with the application, as the textbook may not always be at hand. The text book in conjunction with the app is going to form a vital part of the undergraduate and postgraduate studies in mechanical drawing.

7 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. Through an AR interface, the user selects a target marker representing a CAD model printed on a hard copy of the text book. After visualizing in 3D superimposed on the printed page, the user imports the corresponding model to the main processing environment. 3D interactive transformations implemented on a mobile platform employing standard computational geometry algorithms include zoom, pan and rotation of the object. The technically challenging section of the model is also implemented and interactively visualized against a plane along the x, y and z axes. Additional implemented features include the surface, volume and weight calculation of the model as well as the projection of the mechanical drawing of the solid.

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