Modelling a Mini Unmanned Ground Vehicle via Additive Manufacturing

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Abstract: - The main objective of this study is to examine the technical issues and conditions for designing and manufacturing a mini unmanned ground vehicle, using Fusion360 CAD software and 3D printing, mainly for educational purposes and for assessing available tools, technologies and practices of rapid prototyping. In the beginning, a historical review of the first car design and CAD software is given. Then, the relationship between the design of the car, using CAD software, and a 3D printer is mentioned, as well as the theoretical model, which the study focuses on, and the basic principles of the forces exerted on it, i.e., force and torque are presented. Then, the steps followed to design the unmanned ground vehicle, using Fusion360 to create a 3D model, are described. This is followed by a reference to 3D printers and an exploration of the hardware to be used to implement the 3D model. During the work, a static stress simulation has been carried out to confirm the durability of the structure. Finally, the 3D model is programmed into the 3D printer, and along with the appropriate settings it is printed and manufactured.

Key-Words: - CAD software, Unmanned Ground Vehicle, modelling, additive manufacturing, 3D printing, simulation.

Received: March 8, 2026. Revised: July 11, 2026. Accepted: August 5, 2026. Published: September 29, 2026.

1 Introduction

Nowadays, CAD/CAE/CAM technologies are widely used and recognized in the construction industry. Personal computers have replaced expensive workstations that were mostly based on UNIX systems. 3D modeling has become commonplace and is even present in public applications, such as Google Maps, 3D building models, IMSI floor plans for home furnishings and garden design. Advanced analysis techniques, such as flow simulations and finite element method (FEM), which is used for structural analysis, are widely used in the design process. NC code is generated and sent to NC machines, and CAM systems are used to model and optimize the manufacturing process [1].

Historically, although the first numerical control programming tool, Pronto, was created in 1957 by Dr. Patrick J. Harranty, Ivan Sutherland is considered the father of CAD, because he created Sketchpad in 1963, as part of his doctoral thesis at MIT (Fig. 1). It was particularly unique because, at that time, computers operated only in batch mode, using punched cards and magnetic tape. In Sketchpad, the user could interact with the software using a light pen and a large CRT screen. In the mid-1960s, the manufacturer developed the first generation of CAD systems on the domestic market, mainly for 2D design applications. General Motors released DAC (Design Automated by Computer), followed by McDonnel-Douglas CADD (1966), Ford PDGS (1967) and Lockheed CADAM (1967). To reach the form it is today, CAD had to go through some design stages as mentioned below [2].

Technical drawings using 2D frame primitives (line, arc, B spline, etc.) were still created by design engineers in 2D. Many argue that the overhead (design engineers had to learn how to use computers and CAD) only slightly increased design productivity. However, it was easier to make changes and improvements, and as time went on, CAD software and systems became more reasonably affordable for mid-sized businesses. The functionality and usability of CAD applications improved in 1974.

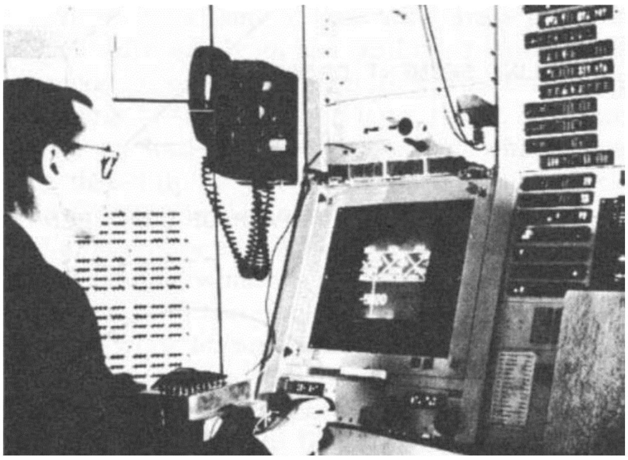

Figure 1: Ivan Sutherland with Sketchpad [3].

In the early 1960s, 3D frame features were developed, and in 1969 MAGI released Syntha Vision, the first commercially available solid modeling program. The 3D capabilities of CAD programs have greatly improved solid modeling. The mathematical representation of freeform surfaces, known as NURBS, first appeared on Silicon Graphics computers in 1989. NöRBS, an interactive NURBS modeling application for computers, was created by CAS Berlin in 1993.

Parametric CAD software was first introduced by T-FLEX in 1989 and later by Pro/ENGINEER. When a model is parametric, it indicates that its parameters define it. To maintain the connection between all elements of the design, a change in the values of one dimension changes the other dimensions. At the same time, MCAD systems introduced the concept of constraints, which allow the user to specify how parts relate to each other during assembly. The "bottom-up" method, in which parts are first manufactured and then assembled, became popular among designers. It is easier to perform additional analyses, especially kinematics, and the modeling is more accurate and understandable.

Accordingly, the main objective of this study was to examine the technical issues and conditions for designing and manufacturing a mini unmanned ground vehicle (UGV), using CAD and 3D printing.

2 Methodologies

Many designers and manufacturers have been credited with being the first to design and build an automobile, but the one generally credited with this is Carl Benz. He demonstrated his first successful three-wheeled vehicle in 1885 in Mannheim, Germany, which he patented in 1886 and began producing for sale in 1888 (Fig. 2) [4].

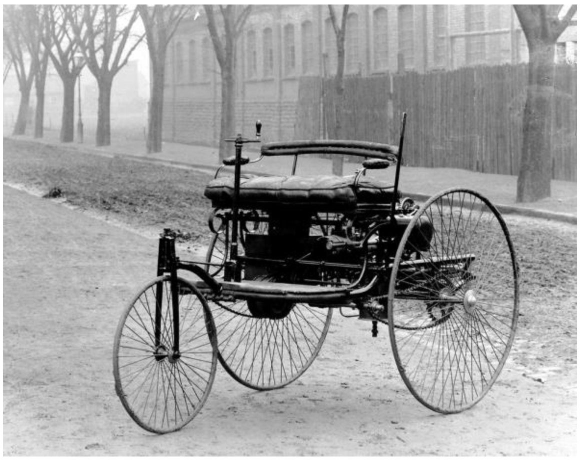

Figure 2: Benz Patent-Motorwagen in 1885 [5].

In the early days, car design was done using design methods such as technical drawing. Cars started with an idea and were sketched out with pens, pencils, and tape on a drawing board. The design process involved multiple iterations, including clay models, mechanical models, stereolithography, the precursor to 3D printing, and more. Designers used these methods to increase efficiency and the time of release to the market.

The use of CAD systems for automotive design now plays a central role in the automotive industry. Automotive development processes were characterized until the mid-1980s by a high degree of material optimization and prototype cycles. The entire vehicle development process at that time included three prototype phases and required about six years. The processes changed drastically when electronic, virtual approaches were integrated into the automotive development process. Engineering tasks, previously completed through hardware-based development, began to be replaced by computer-aided design and simulation in the mid-1980s. Networked automotive development was made possible in the last decades of the 20th century by integrated CAD/CAE software. Virtual prototypes were to replace physical prototypes, which they had existed until then. The application of virtual engineering to full vehicle development has promoted global collaboration by bringing together partners and markets from different countries and regions. Today, full vehicle development takes 4 years (in the case of derivative product development less than 3 years) and the trend is moving towards further reduction [6]. Well-known modern CAD tools are the SolidWorks, Fusion360, Onshape and Inventor.

Using CAD software, 3D printing is a technology that allows the rapid and flexible creation of tools, end-use parts, and prototypes (Fig. 3). It provides the ability to create parts of any geometry and from many materials, such as ceramics, metals, polymers, and synthetics. At the same time, the user can exercise local control over the material composition, texture, and microstructure of the surface. It belongs to the category of additive manufacturing, which is the process of manufacturing a physical object using modeling data [7].

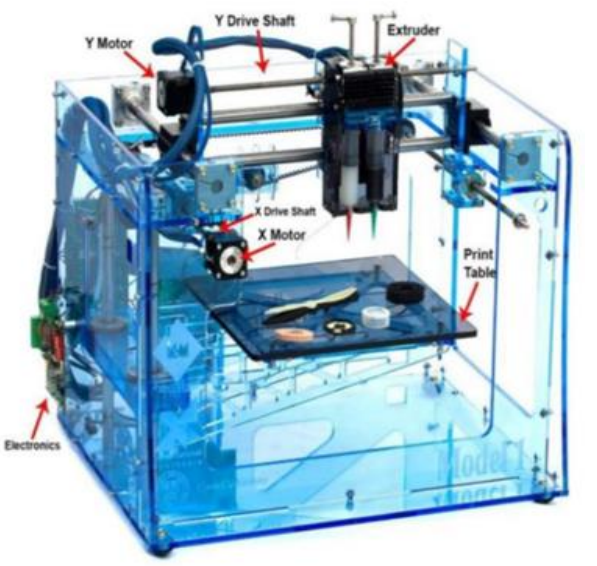

Figure 3: A 3D printer [8].

3D printing technology, as we know it today, dates back to 1984, when Charles “Chuck” Hull invented stereolithography. Applying one layer after another, this printing technique uses ultraviolet light to produce a three-dimensional object. Hull discovered that he could modify this method to print solid objects, while working for a company that applied thin plastic coatings to furniture using ultraviolet light [9].

The process of making tangible models or mock-ups of a product or component, before it is mass-produced, is known as prototyping. In the automotive industry, 3D printing for prototypes has become widely accepted and established. Prototyping is vital to automotive design and development, as it allows engineers and designers to test and validate their ideas, improve functionality and performance, as well as find and fix errors. 3D printing can facilitate rapid prototyping for automotive design and development, producing prototypes faster, cheaper, and more accurately than traditional manufacturing methods. More iterations, changes, and complex geometries can be achieved with 3D printing [10].

Using 3D printing for prototyping has many advantages, such as speed, cost-effectiveness, flexibility, and accuracy. However, it also has disadvantages, considering scalability, reliability, standardization, and regulatory issues. For example, 3D printing may not be able to meet the high volume and quality standards of mass production, even though the technology can quickly and cost-effectively create prototypes for small batches or individual pieces. In addition, 3D printing may not be able to ensure the same degree of quality and safety for the final objects, even though the technology can create accurate and reliable prototypes for testing. Therefore, based on their unique requirements and goals, automakers should carefully evaluate the viability and suitability of using 3D printing for prototyping [11].

3D printing is widely used by automakers to produce prototypes for validation and testing. For example, Ford prototypes various parts of its vehicles, including lettering, dashboard details, steering wheel trims, and safety features, using Formlabs 3D printers. According to Ford, 3D printing can reduce the time it takes to build prototypes from weeks to hours, resulting in monthly production cost savings of up to $493,000. BMW is another example; it prototypes metal parts for its engines, transmissions, and chassis, using 3D printing. BMW says that using 3D printing can improve the quality of its components, performance, and durability of parts. Another critical and growing use of 3D printing in the automotive industry is personalization. The adaptation of a product or service to suit the unique requirements or preferences of a customer or market segment is known as personalization. Customer satisfaction, loyalty, competitiveness, and differentiation can be improved through personalization. Because 3D printing can create customized or unique cars or custom parts without the need for expensive tooling or inventory, it can enable customization and personalization of automotive products and services [12].

3 Modelling

The model that has been designed consists of four wheels that rotate clockwise and generate forces and torques, which will be analyzed below. The two front wheels are connected to an axle, as are the rear wheels. All horizontal forces are inherent in the vehicle as a whole. Furthermore, the weight of the car is equal to the product of the vertical forces, exerted by the ground on it; therefore, in this definition of horizontal motion, both weight and normal forces can be ignored. The real issue is simplified for clarity, by ignoring air resistance and assuming that the contact of the wheels with the ground follows a line and not a surface. When the car is moving, the horizontal forces, exerted by the ground on the tires, are static friction forces, the magnitude of which, according to the *Amontons-Coulomb* law for friction of solid materials, cannot exceed $\mu_s N$, where μ_s is the coefficient of static friction and N the vertical force, exerted by the ground on the tire. The type of wheels (passive or traction) and whether the car is accelerating positively or negatively determine where these static friction forces are directed. Fig. 4 shows a front traction wheel in rapid rotation. Due to the torque exerted on the wheel, the point of contact with the ground, P, tends to slide rearward, resulting in a positive static friction force. Equation (1) is the equation for the rotation of the front wheel about the axis of rotation, if we represent this frictional force by F. The rest of the car produces a force, while the ground and the weight of the wheel exert zero torque:

$$M_0/2\text{-}FR=Ia \quad (1)$$

where I is the moment of inertia of the wheel, R is the radius of the wheel, and $a=\alpha R$ (no slip or smooth rotation condition) is the angular acceleration [13].

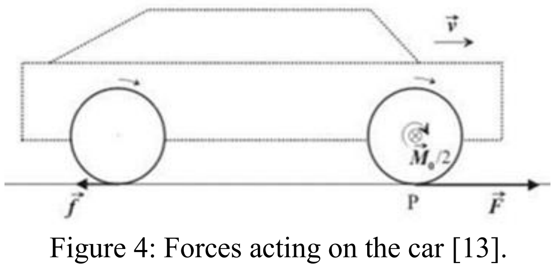

Figure 4: Forces acting on the car [13].

Now on the rear wheels, only the friction force, denoted by f, produces a constant torque about the wheel center. For a wheel to move clockwise, as shown in the rear wheel in Fig. 4, the force must be negative. The equation for the rear wheel is:

$$fR=Ia \quad (2).$$

Finally, equation (3) depicts the motion of the car as a whole:

$$F_R=2F\text{-}2f=m\alpha \quad (3)$$

where the resulting external force is denoted by F_R. In contrast to the torque transmitted by the engine, a torque is now applied to the wheels if the vehicle needs to brake. In this case, the static friction forces F and f reverse direction, resulting in a decrease in the speed of the center of mass. The embedded abilities of the designing tool for modeling and simulation (see next subsection) make more theoretical details (e.g., Newton–Euler or Lagrangian mechanics) redundant.

3.1 Designing

To start designing the model, a design program must first be selected. One of the most well-known for modeling and simulation is Autodesk Fusion360, which is suitable for the design, since it provides a wide range of tool options, simulation capabilities, part of its calculations are based on the Cloud and is more user-friendly, as it does not require large computing spaces [14].

The process a user follows for the digital form of the model until its physical printing is the following:

- An object file is created by a CAD software or the file is downloaded from an online source.
- The object is saved as a stereolithography (STL) file, which allows it to be digitally sliced into layers.
- The STL file is transferred to the 3D printer and a plastic filament is fed to the heated print head.
- The molten plastic is ejected from the printer head layer-by-layer onto a platform, with movement in the x–y–z axis; This continues until the object is completed.

Fusion360 enables also the creation of construction drawings (Fig. 5). This serves to visualize the dimensions of the drawing and to observe them after construction, in order to ensure the proper functioning and application of the car components. The drawings should provide images from various angles and views, so that they are understandable to each user. The dimensions must be clearly visible and must be in millimeters.

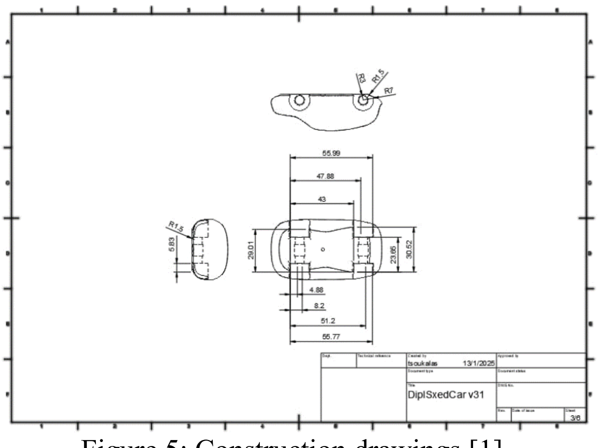

Figure 5: Construction drawings [1].

The next step is to convert the file to *stl* format, which is a file format native to stereolithography

CAD software, a necessary step for the 3D printer to be able to process it. Now the possibility is given for editing the construction, where in this case the size scale will be increased by 100% more, to make it easier to print and observe the model. It is important to place the supports, which have an important role in printing the model, with the appropriate settings. The last step is to print the model, where it should be mentioned that the body is printed separately from the wheels and axles.

3.2 3D Printing

A Fused Deposition Modeling (FDM) 3D printer was used to print the model designed in this work (Fig. 6). These printers follow FDM, that is, a continuous thermoplastic polymer filament is used to print layers of materials. The filament is heated at the tip of the piston to reach a semi-liquid state and is then extruded onto the printer platform or onto the previously printed substrate. The key property for the method is the thermoplasticity of the polymer filament. This allows the filaments to bond together during printing, resulting in them solidifying at room temperature, after printing. The advantages it offers and the reason it was chosen are high speed, low cost and ease of the process. The creation of fiber-reinforced composite materials via FDM has improved the mechanical characteristics of 3D printed models.

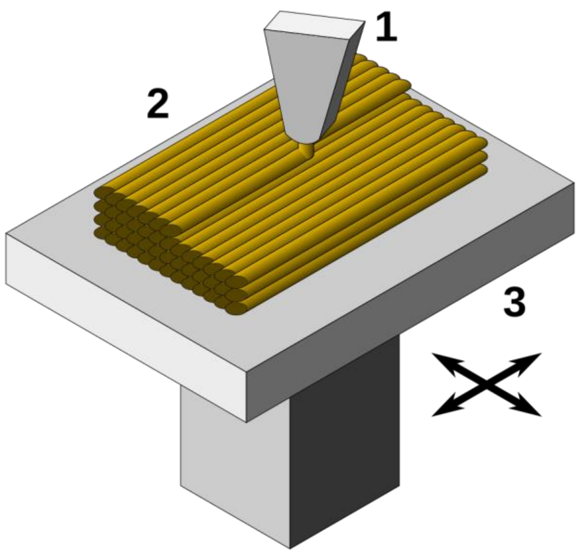

Figure 6: FDM 3D printer [15].

The reason why this specific method was used to give physical form to the model is the following advantages it offers to the user:

- *Efficiency*: Creating prototype models on 3D printers is easier and faster than other technologies.
- *Flexibility*: To manufacture 3D models, there is a wide variety of different materials that can be used by the user. This makes 3D printing technology useful for the construction of several projects in many industries.
- *Durable products*: The objects produced do not absorb moisture and do not deform over time, resulting in a longer lifespan.
- *Quality*: The objects produced by 3D printers have an excellent surface finish.
- *Low Cost*: This characteristic of 3D printing is what makes it easy for more users to access than other manufacturing technologies. There are several low-cost printers and materials on the market that can create reliable models.
- *Time*: With traditional manufacturing, different parts had to be joined together to form the final product; printing a 3D object can be done instantly, allowing large production runs to manufacture products in a matter of hours instead of days or weeks.

3.3 Materials

The choice of the construction material must be strictly based on some criteria that will be set. Initially, the material must be compatible with the printer and with the method chosen. Strength and reliability are two other criteria, so it is required to provide durability and elasticity. Finally, its low purchase cost is also desirable. The best choice for all these criteria is Acrylonitrile Butadiene Styrene (ABS plastic) [16].

ABS plastic belongs to the polymer family. The most popular materials for 3D printing are polymers, due to their affordability, adaptability and ease of use. They are made up of materials that include resins, polymers and rubber-like compounds, which can be melted and extruded into various shapes. The most widely used 3D printing technology is FDM, which is based on polymers. In 3D printing, various types of polymers are used, each with unique properties. Their properties arise from the polymers that compose them. More specifically, the styrene monomer allows for good processability, acylonitrile offers resistance to high temperatures and at the same time chemical resistance, and finally butadiene makes the model more durable and harder, even in low temperature conditions.

ABS plastic is also thermoplastic; this term refers to how it responds to heat. Thermoplastics can be liquid, specifically ABS at 105 ºC. They have the ability to be heated to their melting point, cooled, and reheated without significant damage. Such thermoplastics liquefy, instead of burning. This characteristic allows them to be easily injection-molded and then recycled.

ABS plastic ranges in color from white to ivory and is opaque, but can be colored with dyes for various applications and can be sanded and painted relatively easily. This makes it an excellent material for prototyping, one of the reasons why it is chosen for enclosures that often have glossy surfaces or different textures. Its cost is about $1.50 per kilogram, a cost that is quite cheap, so it is used by a wide range of industries.

In summary, ABS plastic is the best material for choosing to manufacture the model, as exposure to it does not pose a health risk, since it does not contain carcinogenic substances. Fusion360 allows us to see the properties of the material, for better control.

3.4 Simulations

At this point, a study needs to be done on the strength of the model. Autodesk Fusion360 provides this capability, as it has simulation tools. The first thing to be examined is the static stress for the resistance of the structure to the forces exerted. Next, is the second study for the resistance to ambient temperature, through thermal analysis. At the end of each study, it is examined whether the model will need any changes to its design, to be able to cope with these conditions.

Before the simulation, the theoretical part of static stress and how it works will be mentioned, through the official website of Autodesk Fusion360. Robert Hooke, in 1678, laid the foundation for modern finite element stress analysis with Hooke's law. An elastic body is compressed or expanded, depending on the force exerted on it. Mathematically, it is valid:

$$F=kx \quad (4)$$

where F = Force, k = Proportional constant, called stiffness, and x = Distance of expansion or compression.

Static stress analyses are one of the most common types of finite element testing. The model is subjected to a series of loading conditions and the resulting stresses, strains and deformations are analyzed to calculate the probability of design failure. Linear static stress analysis assumes that:

- The structure returns to its original shape;
- There are no changes in the magnitude or direction of the load;
- The material properties do not change;
- The stress and deformation are small.

For static stress analysis to be valid, the following conditions must apply:

- The loading should cause only small deformations or rotations. By "small", it is meant that the following conditions are met: (a) The deformation should not have a significant effect on the direction of the load, the location of the surfaces to which the loads are applied, or the magnitude of the loads; (b) The deformation should not change the boundary conditions (i.e., where and how the parts are constrained).
- The stiffness and strength of the material should not change.
- The dynamic effects of the loading conditions are not significant. Static stress analysis does not take inertial effects into account. However, the mass of the model is used to determine some static loads, such as gravity forces and rotational forces.

The simulation includes the material that will be used. So, through Autodesk Fusion360, the relevant tools it offers are used and the construction takes shape in ABS plastic.

The first stage of design ends with the final form of the car body that includes the position of wheels (Fig. 7).

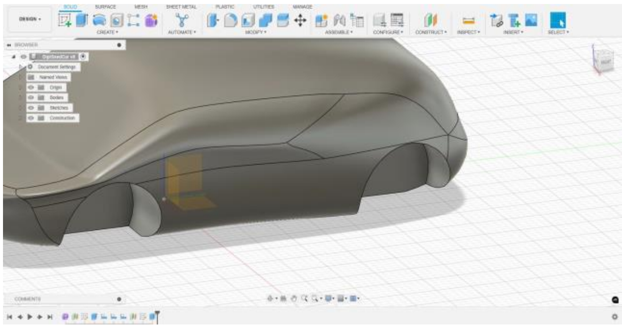

Figure 7: The final form of the car body [1].

The next stage includes the design of the wheels and their axles, by using the available integrated tools like "section analysis" and "combine" (Fig. 8).

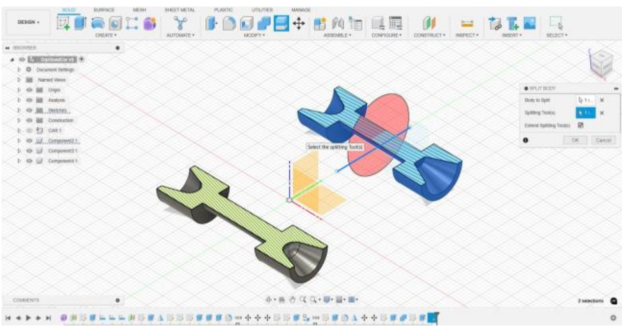

Figure 8: The front and rear axles [1].

Then, the fixed points must be set. That is, a fixed point is created, which will be the base of the model where the static stress will be applied. For this, the wheels are selected, as they are the points where the structure will be supported.

The next step is to select the points where the forces that will be exerted on the wheels will be placed. For the simulation, the model was tested with a force equal to 10 Newton and directed downwards.

3.5 Results

After the design and simulation of the model is finished, before proceeding to the stage of construction drawings and printing, Autodesk Fusion360 allows us to examine the final properties of the car, from the properties tab. As can be seen (Fig. 9), the car body has a length of 42.24 mm and a width of 76.44 mm. The height is 27.17 mm and the weight amounts to 51.75 grams.

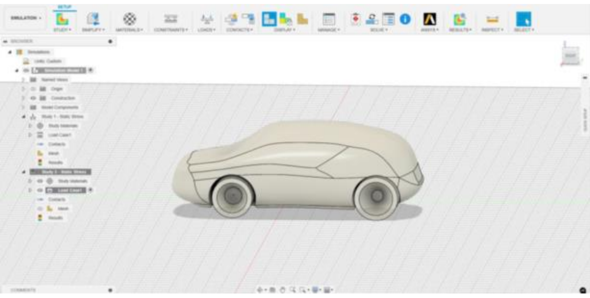

Figure 9: View of the model with ABS plastic [1].

The construction stage is the last one, as the parts of the model are ready: the wheels with axles and the car body that need to be joined. This is done through some glue that holds the parts and meets the specifications for the plastics used.

4 Conclusion

The usage of the Fusion360 CAD application and the 3D printer allowed the precise design and implementation of the UGV model with success and speed. By simulating the static stress, it was realized that the model is able to withstand the mechanical stresses that will be created. Then the material chosen, ABS plastic, was reliable, without great cost, highly durable and at the same time effective.

The design of the scaled model of a car and the implementation of this design is one of the most important issues that concerns the automotive industry. In this study, it was confirmed that the use of CAD software and 3D printing are reliable and ideal technologies for the production and development of durable and functional car models. Thus, this paves the way for future applications in the automotive industry, highlighting the usefulness of these technologies in car design.

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