Rapid Prototyping for Large-Scale and Complex Assemblies

Kuang-Hua Chang[1] and Tim Long[2]

[1]University of Oklahoma, khchang@ou.edu
[2]University of Oklahoma, timlong@ou.edu

ABSTRACT

This paper addresses the issue of creating physical prototypes of large-scale and complex assemblies using Rapid Prototyping technology. There are several technical challenges to overcome, both in software and the physical models. The challenges in software mainly stem from the fact that the mainstream CAD systems may not able to directly convert large-scale and complex assemblies to STL models. For the issues in the physical model, some of the components of the scaled assemblies are too small to fabricate using RP or too weak to produce viable prototypes for intended purposes. In addition, the paper presents information regarding support of relative motion between components in the RP model, which is desirable for demonstrating kinematics of the system. The paper proposes a systematic approach that addresses these issues and realizes quality physical prototypes serving intended purposes. Practical examples are employed in this paper, including a Formula SAE race car assembly that is used as the principle example for this study.

Keywords: rapid prototyping, large-scale assemblies, formula SAE.
DOI: 10.3722/cadaps.2011.357-371

1 INTRODUCTION

In most instances of fabricating physical models using rapid prototyping (RP) technology, a single part or simple assembly is produced. Typically, the RP process involves taking a CAD solid model, converting it to STL (Stereo-Lithography) format [1], creating build path using proprietary software of the RP, and then fabricating physical prototypes using RP. This process usually requires minimal work and a physical model can be fabricated with relatively little effort since the RP method and process for such applications have been well established. Fabricating large-scale and complex assemblies, such as a racecar shown in Figure 1, has not been studied extensively. Such assemblies usually are large in physical size and consist of thousands of parts with wide variation in their respective physical sizes.

A great deal of study has been performed on the creation of more efficient, or better performing algorithms for the creation of STL files from CAD geometry, as well as improving the performance of STL slicing algorithms in layer based manufacturing. In addition, Jingbin et. al [2] developed an algorithm for automatically creating assembly features that adapt to the geometry of a part to improve assembly quality. Although the work they have done aims at improving the quality of larger, more complex assemblies, the models used consist of only a few parts. In a related paper on the subdivision and refinement of large components, Medellin et. al [3] presented an algorithm which partitions components that are too large for the build volume of the RP machines. The process uses planar sectioning to cut the component into smaller chunks that are individually printed. In the process the interfacing surfaces are modified with alignment features to assist with assembling the components into the finished prototype. The work done by Medellin et al is certainly more complex in nature, but it still falls short in investigating the capability of RP systems to deal with massively complex assemblies.

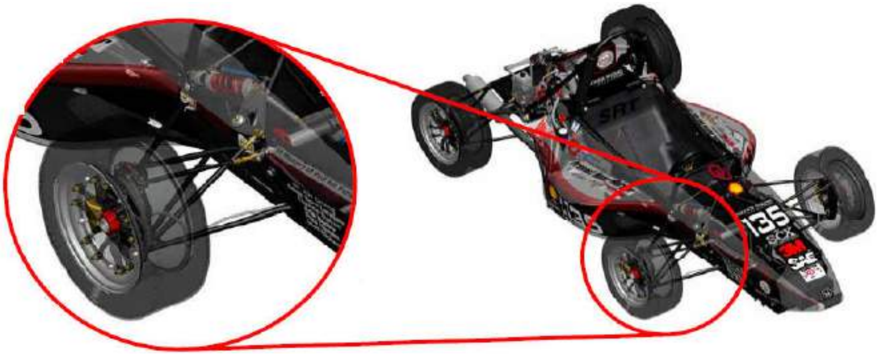

Fig. 1: The CAD model of the racecar: (a) Close up of front suspension, and (b) The entire car.

When dealing with large-scale assemblies many technical issues arise. One of the main issues is that the full assembly model in CAD has to be scaled down in physical size, which can mean that some features become too small for the machine to print accurately. All rapid prototyping machines have limits as to the minimum feature size they can create, and the variations between the different processes and machines can have a wide range of variance, as illustrated by the benchmarking work done by Kim et. al [4]. The range is anywhere from 0.01 in. for high precision SLA (Stereo Lithography Apparatus) machines, such as those from 3D Systems [5], to 0.06 in. for FDM (Fused Deposition Manufacturing) machines such as the Dimension 1200sst [6] from Stratasys, Inc. These limits can severely hinder the model durability when faced with small features such as tubing and thin shell. Even if small features can be fabricated, they may be destroyed or damaged during post-processing; e.g., removing the support materials. Furthermore, converting a complex assembly to STL models presents challenges due to the geometry complexity and feature size variations, as well as limitations in the capabilities of the computer hardware.

The objectives of this paper are to identify issues involved in fabricating complex and large-scale assemblies using RP, compose and propose a viable solution, and demonstrate the feasibility of the proposed method by fabricating durable and scaled physical models of large-scale assemblies. Issues involved in both software and physical prototypes are investigated.

2 REQUIREMENTS AND TECHNICAL ISSUES

Physical models fabricated using RP have been employed for a broad range of engineering applications, from design verification, marketing and presentation, to functional testing and surgical practices. In general fabricating prototypes for large-scale assemblies using RP mainly supports product marketing and presentation. In supporting such intents, four basic requirements on the prototypes are essential. They are, roughly in the order of their importance, model fidelity, appearance, durability and cost, and accuracy.

The scaled physical prototypes must have adequate model fidelity by retaining essential features that are sufficient to convey design concept and support demonstrating certain product functions. For some cases, the prototypes must allow relative motion between parts in order to demonstrate the kinematic characteristics of the product. For example, a single-piston engine shown in Figure 2 requires adequate clearance between mating parts in order to allow relative motion between components inside the engine case.

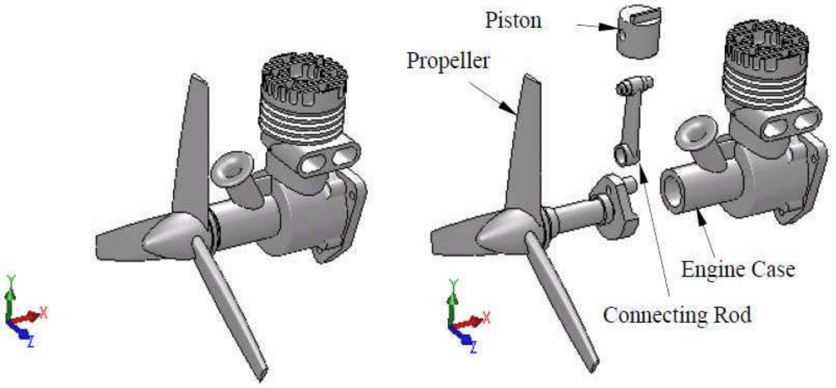

Fig. 2: Single-piston engine: (a) Unexploded view, and (b) Exploded view.

Also, the prototype must be reasonably durable and have adequate structural strength, enough for routine transporting and handling. In general, stronger and durable prototypes are more expensive. Cost is certainly an important factor to consider in RP. Finally, model accuracy in dimensions can be relaxed a little since the physical prototypes are scaled and not intended for form, fit, and dimension checking. However, they should not deviate too much from the design to affect the accurate communication of the design concept. Finally, the appearance of the prototype, such as color and surface finish, must resemble closely to the final product.

In order to fabricate physical prototypes that satisfy the requirements, several technical issues must be overcome. Most of the issues arise due to model size scaling and the fact that the assemblies are complex in nature.

The technical issues in software mainly stem from the fact that the mainstream CAD systems, such as *Pro/ENGINEER*, may not be able to directly convert large-scale and complex assemblies to satisfactory STL models that are required for RP. The conversion of the racecar used in this study to an STL was attempted with *Pro/ENGINEER Wildfire 4.0*. During the conversion process, the complex geometry can cause tessellation errors in the approximation of the surfaces using triangles. For example, in some cases the tubing that comprised the frame of the vehicle causes errors due to the very small wall thickness, compared to the size of the vehicle. Often the minimum chord height provided in CAD was too large (due to the size of the assembly) to adequately capture the geometry of the tube. The approximating triangles had a tendency to intersect, causing errors in the STL file.

Three methods were found to attempt to deal with these errors. First, such errors could be fixed by manually editing the model geometry using modeling capabilities in the CAD systems; for example increasing the thickness of the tubing. However, for an assembly of over a thousand parts, fixing these errors can be a tedious and difficult process, although it may be necessary if major parts of the model have problems being tessellated. Second, the problematic geometry can be excluded from the tessellation process, which is certainly a much simpler option compared to manually fixing the geometry. This method works well when the problematic parts are very small in size and do not contribute to, or affect the fidelity level or strength of the physical prototype. The third option is to use an intermediate file format, such as VRML (Virtual Reality Modeling Language) [7]. Once the VRML file of the assembly is created, converting it to an STL file usually goes quite smoothly, although the overall accuracy and smoothness of the geometry could be lessened. One instance we encountered is tessellating the first half of the racecar using *Pro/ENGINEER*, which provides limited controls on the size of the polygons of the VRML model. The STL model created via VRML is essentially tessellated twice (once in the VRML conversion, and again to convert that to STL), often resulting in a coarser geometry. A comparison between an STL model created from a VRML versus an STL created directly from CAD geometry can be seen in Figure 3.

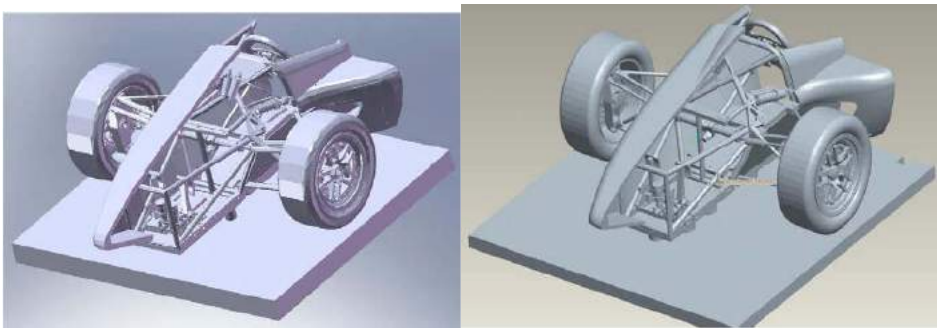

Fig. 3: STL models from two methods: (a) STL created by saving as VRML first, and (b) STL created by directly saving as an STL.

Issues arise also in proprietary software of RP that slices STL to 2-D layers for generating build path due to the size and complexity of the STL files. The slicing operations can be extremely memory intensive for the computer, and the proprietary slicing algorithm (comes with the respective RP machines) may sacrifice robustness in favor of speed. Very often in the process of slicing and generating tool paths for large STL files, a computer may run out of RAM and subsequently crash.

In addition, large assemblies tend to push the CAD software to its limits, causing software to significantly slowing down system responsiveness. The file sizes of the assemblies can get quite large, which can tax the limits of the computer software and hardware. For example, the model of the racecar in its native *Pro/ENGINEER* format has a file size of 293 MB. The converted STL files can be very large for the required accuracy, reaching a size of 75 MB for only the front half of the racecar model. In the converting process, the computer's RAM can be quickly used up, not only slowing down the system, but occasionally causing software to crash unexpectedly.

Furthermore, as assembly components are modified to improve their fidelity for the RP model, the placement constraints on them can often fail. For example, if a large hole is removed from a component to increase its strength, assembly constraints that referenced that hole will fail and need to be removed and re-constrained. Model modification and regeneration for a large-scale assembly in CAD can be unbearably slow. Usually, the scale of the model can be increased so that fewer small components need to be modified to improve their strength.

Problems revealed in the actual physical models are mainly due to the significant reduction of the model size from the assembly. The scale factor plays a critical role in prototyping large-scale assemblies. Adopting an excessive scale factor may cause some or most of the parts or features in the scaled model to become too small to fabricate using RP, or too weak to retain minimum strength for intended purposes. On the other hand, a small-scale factor may lead to a large and costly prototype. In any case, parts must be modified (or simplified), strengthened, and in some cases new parts must be added for additional structural support. One other issue is that the STL format does not retain information of colors in the parts and solid features.

3 PROPOSED METHOD

There are four major steps proposed to address the issues identified. They are scale factor determination, model modification, model conversion and model fabrication. Issues involved in each steps and solutions proposed are described next.

3.1 Scale Factor Determination

The first step is to determine the scale factor. Scale factor is the most important parameter that significantly affects the fidelity, quality, strength, and cost of the physical prototypes to be fabricated. The first and the most important consideration in determining the scale factor is the model fidelity; i.e., the level of detail to be retained in the prototype. The level of fidelity is application dependent, which will have to be determined by the designers considering the intended usage of the prototypes.

For example, critical parts and features, such as suspension components of the racecar shown in Figure 4, must be identified and the size of the smallest features or parts must be acquired. Small parts that will cause problems in fabrication, such as fuel line (Figure 5c), accelerator cable (Figure 5b), and wire harness (Figure 5d), must be also identified. Parts like these can be completely ignored while determining the scale factor. Parts that are decorating and not contributing to enhancing the level of fidelity; e.g., odometer of the instrumentation panel (Figure 5a), can also be ignored.

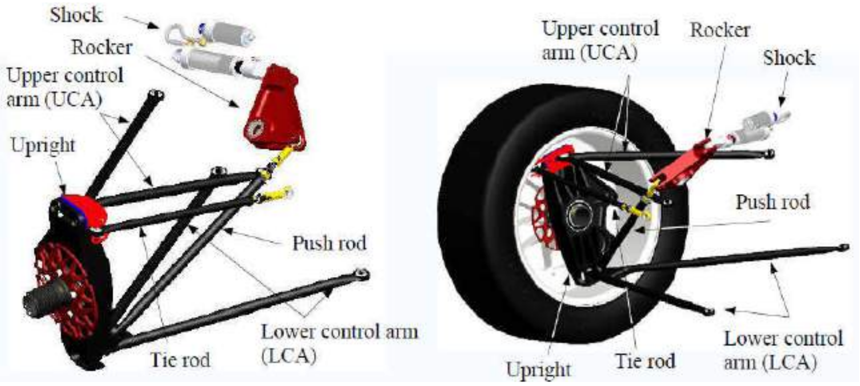

Fig. 4: Essential suspension components of a racecar: (a) View 1, and (b) View 2.

The second aspect in determining a scale factor is the capabilities of the RP machines to be employed. One important factor is machine resolution that determines, in theory, the minimum feature sizes that can be fabricated. However, in practice, the smallest features to be fabricated are much greater than the machine resolution, considering the strength of the parts fabricated and steps involved in post-processing. RP machines that require building support in fabricating overhangs, such as Dimension 1200, could cause significant damage in small parts while removing the support. Similar issue may appear in retrieving prototype from a powder bin using, for instance, ZCorp RP machines [8].

Once the scale factor is determined, small parts that fall below the threshold of the viable physical size will have to be removed from the assembly. From examining several prototypes fabricated by the Dimension 1200 3D printer, it was found that for a reasonable level of fidelity, a thickness of 0.06 in. was necessary as a general rule of thumb. Features smaller than this tend to be extremely weak and fragile. The scale factor s can be calculated by

$$s = A/a \tag{1}$$

where A is the size of the smallest features in the assembly to retain, and a is the size of the smallest feature that can be fabricated with adequate strength using an RP machine. After the scale factor is determined, the envelop of the actual prototype size $\ell \times w \times d$ can be calculated by

$$\ell = L/a, \quad w = W/a, \quad \text{and } d = D/a \tag{2}$$

Where L, W, and D are the length, width, and depth of the envelop of the original assembly, respectively.

Note that if the prototype size is too large to handle, a different RP machine may be considered to increase the scale factor. For example, RP machine using selective laser sintering (SLS) such as Sinterstation [5] of 3D Systems, produces stronger parts; therefore, may allow for smaller features to be built. Another possibility is to reduce the level of fidelity by removing more parts and features, which is, however, less desirable in general. If the physical model size exceeds the build envelop of the

RP machine, the model can be split into pieces. They can be built separately and physically assembled afterwards. In this case, interlocking features must be added to the CAD model before fabrication to assist in aligning and joining the separate pieces of the prototype.

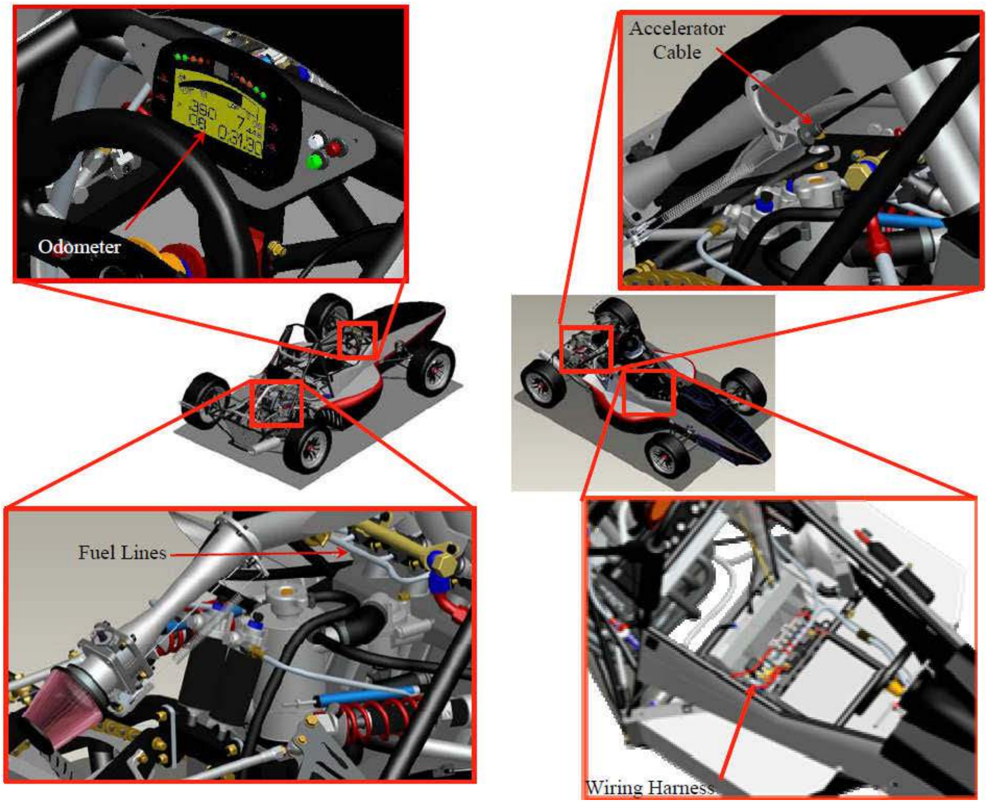

Fig. 5: Small components to be removed: (a) Odometer, (b) Accelerator cable, (c) Fuel lines, and (d) Wiring harness.

There are adhesives made for use on virtually every material that may be used to permanently join pieces together, such as common glues for plastics and metals. More specifically, SLA parts are joined by dispensing UVBOND SL-Lo [9] along the length of the bond line and applying UV light source to cure adhesive. Also, Pro-Weld plastic bonding agent and sealant from Ambroid [10] can be applied to bond models fabricated using Dimension RP machine. In general, SLS prototypes tend to be better suited for bonding. Due to the porosity of an SLS part, the adhesive penetrates the part surface to form a bond that is stronger than that found when joining SLA or PolyJet sections.

3.2 Model Modification

After the scale factor is determined, the assembly model in CAD must be modified. First, non-datum surface features must be suppressed or removed in order to avoid errors in tessellating non-solid entities. For example, the boundary blends used to create body panels of the racecar must be suppressed to prevent them from being present in the VRML or the STL models.

Small parts and features will have to be either deleted or suppressed. While deleting parts or suppressing features in CAD could cause failure in part or assembly regeneration if parent parts or features are involved. Parent/child relationships in CAD must be examined carefully in advance in order to minimize such problems.

Modification also involves strengthening weak parts by varying their sizes; for example, increasing the thickness of a thin shell, solidifying hollow tubes, etc. From time to time, parts will have to be added as support or reinforcement to add rigidity to the prototype.

Another type of modification involves cutting out some parts or portion of the assembly to allow the internal structure to become more visible. For example, a front left quarter of the body panel in the race car is cut out to reveal the design of the brake system and steering column, etc., as shown in Figure 6a. Also, portion of the engine case is cut off to reveal the internal parts of the single-piston engine, as shown in Figure 6b.

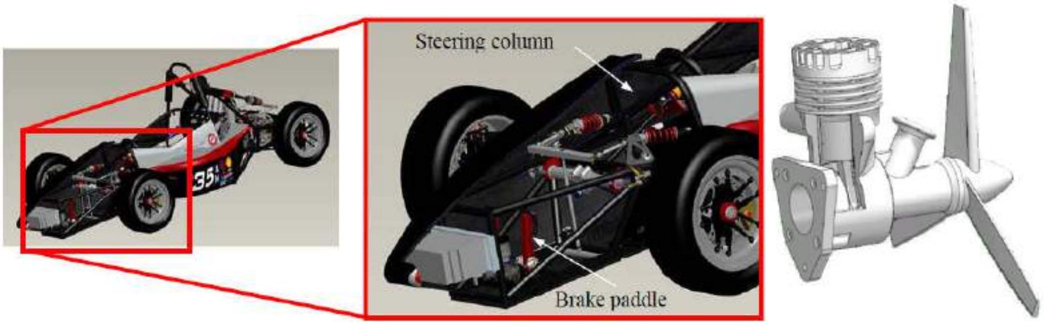

Fig. 6: Portion of the part or assembly removed to reveal internal structure: (a) Front cover partially removed on race car, and (b) Engine case partially removed.

In some cases, adequate clearance must be provided for mated parts, such as when relative motion between them in the physical prototype is required. The amount of clearance to choose depends on the RP machines employed. For Dimension 1200, a clearance of about 0.02 in. is needed to allow breaking the support materials filled in the gaps between parts. This was first tested by using socket joints of a shaft in a HMMWV (high mobility multi-purpose wheeled vehicle) shown in Figure 7. Socket joints provide all three rotational degrees of freedom between the two ends of the shaft and parts they respectively connect. Clearance was provided in CAD for a working prototype that demonstrates the relative motion of the socket joints.

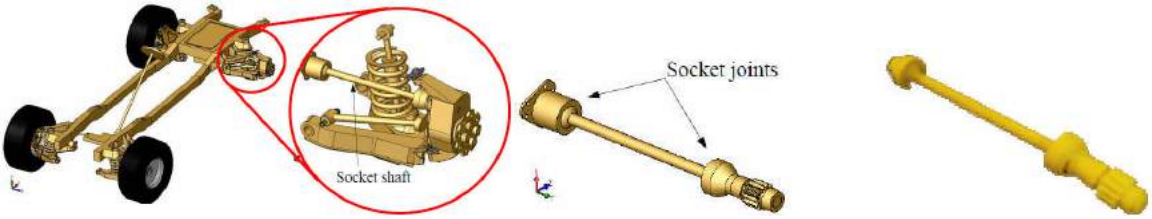

Fig. 7: HMMWV suspension and socket shaft: (a) HMMWV suspension in *SolidWorks*, (b) Socket shaft in *SolidWorks*, and (c) Physical model.

3.3 Model Conversion

Because of the size and complexity of the assembly, *Pro/ENGINEER* experiences problems with converting CAD assembly directly to the STL format. The issues confronted in *Pro/ENGINEER* are associated with the tessellation process, and the size of the files. Tessellation errors often appear when the software breaking the geometry into triangles makes an error, causing surfaces to intersect. This tends to happen more as the ratio of the distance between two surfaces to the chord height of the triangles gets smaller. For example, as the software breaks a small, thin walled tube down into triangles that approximate its surfaces, if the size of the approximating triangles is too large, it may cause the process to create an intersecting surface. Figure 8 shows a cross section of a hollow tube as solid circles, while the dash line indicates the incorrectly tessellated profile of the outer cross section of the tube. The dashed line representing the outside of the cross section; that is, the square shape is intersecting the circle, which is the representation of the interior surface of the tube. This surface intersection is what causes the errors in generating the STL file. In general, decreasing the chord height reduces the number of tessellation errors in geometry, resulting in smoother surfaces. However, reducing the chord height typically generates larger file sizes. The large file size not only means that the software takes a great deal of time to open, save, and export the files; but also editing any geometry in the model to prepare it for printing may become substantially longer than usual. As the files get very large the software may have the tendency to crash unexpectedly; especially while opening, saving, or exporting a file.

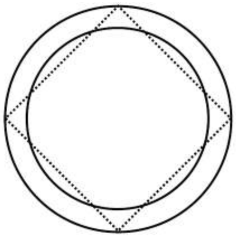

Fig. 8: Cross section of a tessellated section of tubing having intersecting facets.

The size of the files and complexity of the assembly can cause problems with proper conversion to the STL format, especially on computers running a 32bit operating system and software. This is because the amount of RAM available is much more limited on a 32bit system as compared to a 64bit computer. The additional RAM can make an enormous difference in not only the time it takes to convert a file, but also determine whether the conversion can be completed without crashing the computer. It may be possible to get around some file conversion problems relating to RAM usage by using an intermediate file format, such as VRML, and then saving the VRML file to the necessary STL format.

Another issue is retaining colors created in CAD assembly model. The STL file format does not include colors. On the other hand, VRML files are capable of retaining the various colors that have been applied to the parts and features of an assembly in CAD. Note that it is important to check if the slicing software of the RP systems accepts VRML models. The *CatalystEX v4.1* software [11] used with the Dimension 1200 RP machine accepts only STL models, or the CMB files that it produces from STL models. However, the *ZCorpZEdit Pro* software [12] has the ability to import a number of different file formats, including VRML.

3.4 Model Fabrication

RP machines that produce prototypes with adequate strength are primary choices for such tasks. Commercial RP systems, including SLA 7500 and Sinterstation (selective laser sintering) [5] of 3D Systems, as well as Dimension 1200 of Stratasys (fused deposition manufacturing), that offer high precision, excellent strength prototypes, are desired. Among them, Sinterstation that produces porous metal parts is especially attractive due to excellent prototype strength. The Dimension machine offers an alternative at a lower cost. The machine uses ABS thermoplastic materials and produces relatively strong physical parts.

Advanced RP, such as EBM (Electron Beam Melting) [13] or Solidica [14], produce metal parts that are as strong as regular metals. However, they are not suitable for large-scale assemblies. The problem is that these methods are not capable of producing parts with overhangs. Also, the EBM process is not capable of producing very fine details that are necessary for intricate assemblies. Although the aforementioned RP machines produce high quality and strong parts, they do not have the ability to create color models. Only single-color prototypes can be produced. The prototype will have to be painted by hand to create an appearance that resembles the final product.

At this point, the only commercially available RP machine that produces color prototypes is the ZPrinterZ650 [15]. The Z650 is capable of 24-bit color and can complete four layers per minute. The main problem is that the prototypes fabricated using plastic powders and adhesive bonding materials in the Z650 are usually weak and are easily damaged. By using their infiltrate systems the model may be made stronger and their elastomeric polymer infiltration could be used; for example on suspension components of the racecar, to help avoid stress damage from flexing.

Many RP systems utilize some form of support material to assist in the fabrication of parts with overhangs or hollow geometry. Depending on the type of support material, there are typically a number of options for support removal. For parts fabricated using Dimension RP machine, support removal ranges from manual removal with hand tools such as knives, brushes, pliers, or the use of a Dremel or similar tool; to more autonomous commercially available solutions of chemical bath [16], or ultrasonic [17] support removal systems.

4 EXAMPLES

4.1 Single-Piston Engine

The single-piston engine shown in Figure 2 is employed to demonstrate the capabilities of the Dimension machine to print an assembly with moving parts. The CAD geometry was created in *SolidWorks*. The engine example consists of four major components, case, propeller, connecting rod, and piston. The overall size of the engine is 6.68 in.×8.98 in.×8.02 in. and was printed at full scale to the CAD model. The model took 33.5 cubic inches of model material and 20.2 cubic inches of support material. It was printed using the smallest layer thickness of 0.01 in., and with the “sparse” support material option, offered by the system, and took 50 hours to complete printing. The STL was generated using default settings in *SolidWorks*, which entailed a chord height, or deviation, of 0.00809 in., which resulted in an STL file with 51,942 facets.

To prepare the model for printing, the locations where clearance for moving parts would be necessary were identified and the mate constraints were modified to allow for 0.02 in. of clearance between the surfaces of moving parts. The interference checking capability in *SolidWorks* was used to verify that there was no interference that would cause problems for the moving parts. The model was then exported to an STL file, sliced, and printed on the Dimension machine. Figure 9a shows the orientation of the engine model in the build chamber in *CatalystEX*. Figure 9b shows the printed prototype. The most challenging thing with this model was getting the support material removed from inside the cylinder of the engine. The very small space made it difficult to break away the support material, so the primary method of removing the material was to let it dissolve in the WaterWorks [18] solution. After the support material was removed, it was found that the cylindrical shapes that were oriented in the vertical direction had much better accuracy and smoothness for the allowance of motion compared to those surfaces oriented in a horizontal direction. The reason for this is due to the rougher surface present on the horizontally printed curves, and due to the thickness of the individual layers of material. Slightly more clearance may be necessary for horizontal cylindrical shapes due to the reduced surface quality.

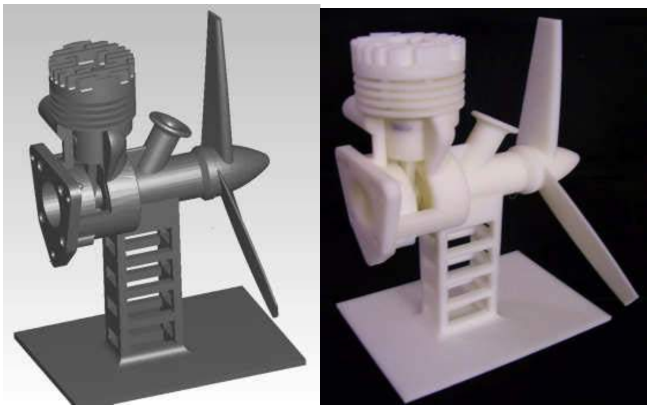

Fig. 9: Physical prototype of the single-piston engine model: (a) Original STL, and (b) Physical prototype.

4.2 Formula SAE Racecar

The race car model shown in Figure 2 is employed to demonstrate the feasibility of the proposed method. This is a Formula SAE (Society of Automotive Engineers) style racecar designed and built by engineering students at the University of Oklahoma (OU) during 2005-2006. Each year engineering students throughout the world design and build formula-style racecars and participate in the annual Formula SAE competitions [19]. The result is a great experience for young engineers as a meaningful engineering project as well as an opportunity to work in a dedicated team environment.

The detailed CAD model of the racecar shown in Figure 10a was created in *Pro/ENGINEER*, consisting of about 1,400 distinguished parts; many are under ¼ in. diameter or thickness. The racecar was designed and later built in its full size (see Figure 10b) for the competition. The wheelbase of the car is 68 in., and the front and rear tracks are 49 in. and 48 in., respectively. The CAD model was created in such detail that it was within 0.7 lb. of the as-built car, which weights 445 lb. The computer used on handling the front half of the car ran 32bit Windows XP Pro, with 2.7Gb of RAM, a 2.67 GHz dual core processor, and *Pro/ENGINEER Wildfire 4.0*. The computer which was used for the more complicated back half of the car ran 64bit Windows XP Pro, with 4Gb of RAM, and a 2.95GHz quad core processor, and *Pro/ENGINEER Wildfire 4.0*.

Fig. 10: Formula SAE race car designed and built by students: (a) Race car designed in *Pro/ENGINEER*, and (b) Race car revealed and on display.

4.2.1 Scale Factor

The smallest features to be retained in the model were identified by measuring a number of the smaller details of the model, such as body panels. Most of which measure around 0.375 in. in the full-size CAD model. To identify the scale factor to be used, this number was divided by 0.06 in., which corresponds to the minimum feature size that the rapid prototyping machine can create with reasonable strength. This yields a scale factor of approximately 6 to 1. Since the car has a length of 115 in., the prototype length of the car will be approximately 19.2 in. Given that the work envelope of the Dimension 1200 measures 10 in.×10 in.×12 in., the model was split in half, yielding two halves, which measure approximately 9.6 in. in length.

4.2.2 Model Modification

Based on the scale factor, a number of components were either modified, or removed from the model completely in order to improve the structural integrity of the model. Parts that are small and do not contribute to the fidelity of the physical model were removed. These parts include small parts such as fuel lines, wiring harness, and accelerator cable, similar to those shown in Figure 5. A total of 36 parts or assemblies were removed. In many cases, these components could be removed without causing constraint failures in the CAD model. In the instances where constraint failures were unavoidable, the problem constraints were redefined to alternate geometry that would be persistent in the model. For example, if a brake rotor required a constraint to a brake line, the constraint would be modified so that the rotor would be constrained to the steering knuckle, or another larger component that will be retained in the printed model.

Twenty-three parts were modified. The modifications include increasing thickness in shells and panels, filling cavities or holes, and altering part dimensions to increase their strength in the physical model. The main body components such as the nose cone, and side pods of the car, as well as the under tray and cooling ducts are very thin, approximately 0.0625 in. thickness in the CAD model, as shown in Figure 11a which were also thickened. There were six major panels that were thickened to about 0.75 in. in the CAD model, which will result in a wall thickness of approximately 0.125 in. on the prototype. Also, the cavities inside the brake fluid reservoirs, shown in Figure 11b, are filled. In addition, the sizes of the spokes on the wheel centers (Figure 11c), as well as the sprocket (Figure 11d), were increased such that the minimum cross sectional thickness was greater than 0.06 in. in the printed model. Also, the diameter of the damper (Figure 11e) was increased to the diameter of the coil spring, minus half the diameter of the wire in the spring in order to provide more support for the coil that was easily broken while breaking away support material. In addition, the gap between the shock absorber and the linear displacement sensor, which is depicted as a small cylinder above the coil spring in Figure 11e, was filled with a thin extrusion measuring 0.5 in. in thickness. The 28 tubes of the frame shown in Figure 11f were completely solidified in the model, since the tubing thickness is far too thin for the 3D printer to create. The tubes along the bottom of the frame, located under the driver could not be completely solidified, as the center of the holes is referenced extensively by other geometry. To quickly get around this, the inside diameter of the tubes was minimized to 1/8 in. in CAD. This does not affect the fidelity of the physical model, yet adding strength to it.

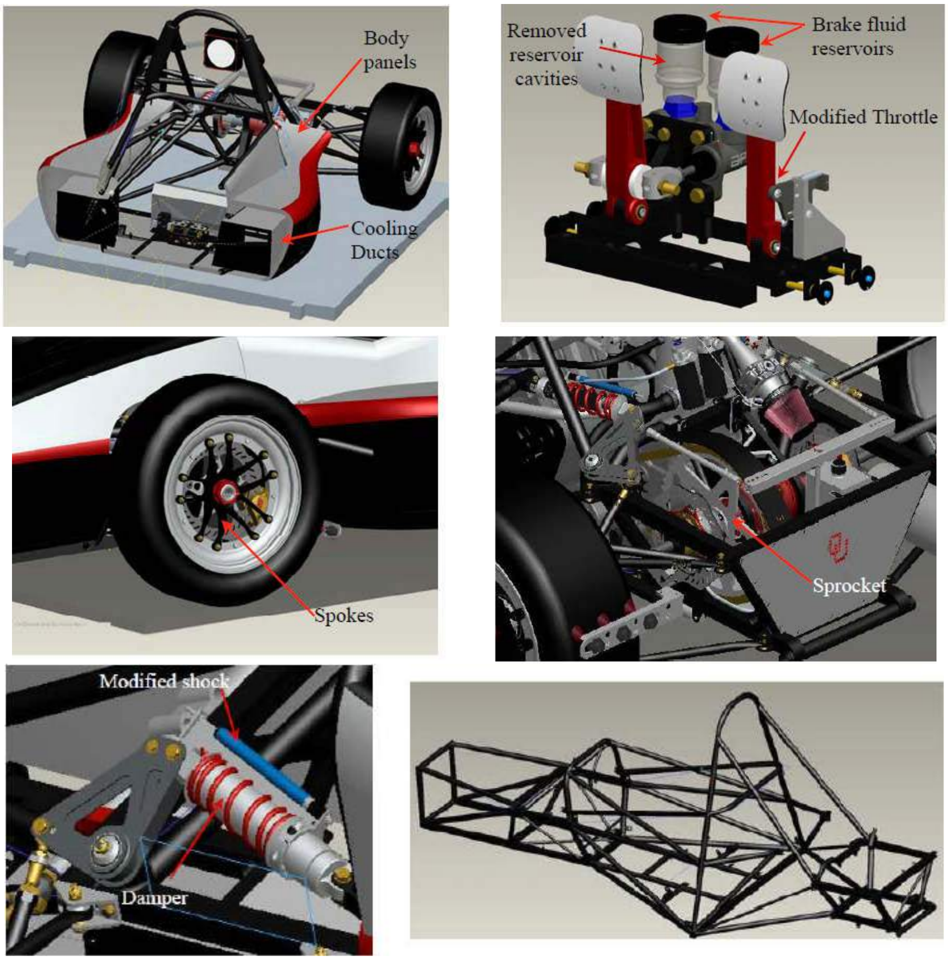

Fig. 11: Parts and assemblies removed or modified: (a) Body panels and thin shell parts thickened, (b) Brake system, (c) Spokes of the wheel center, (d) Sprocket of the transmission, (e) Shock and damper, and (f) Solidified frame tubes.

Note that while altering such parts, potential model interference could appear. For example, the accelerator pedal was very weak; to improve its strength the bracket to which the pedal was pinned was altered, as can be seen in Figure 11b. The space between the tabs of the bracket was filled, so that the pedal in the model would physically interfere with the bracket, increasing the structural support of the component, while having a minimal impact on the overall detail of the component. In addition, a base was created in the model to provide a rigid platform for the delicate geometry of the car to sit on. To improve the rigidity of the model, five small support columns measuring 0.375 in. in diameter were added underneath the floor pan.

The CAD model of the front half before and after modification is shown in Figure 12a. Some of the major differences include the frame tubes that are solidified, cooling ducts and body panels that have been thickened or partially removed for visibility, the reinforced steering column and steering wheel, and finally, the extruded base the model sits on. In addition, alignment notches were added, as shown in Figure 12a.

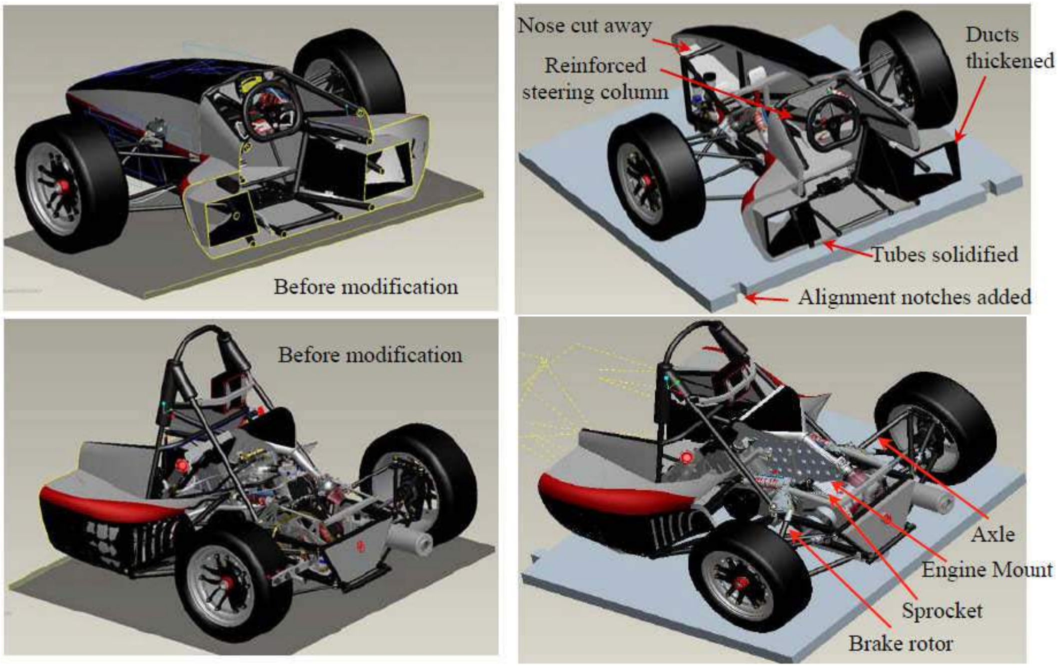

Fig. 12: CAD models of the racecar before and after modifications (a) Front half before modification, (b) Front half after modification, (c) Rear half before modification, (d) Rear half after modification.

The rear half of the car was treated in much the same manner. The rear shocks were modified in the same manner that the front were, all brake lines, cables, and hoses were removed from the assembly. Very small components such as the throttle return spring and switches on the dash panel were also removed. The thickness of many of the drive train components was increased in order to strengthen them. Examples include the rear sprocket, brake rotors, engine mounts, and axles, as shown in Figure 12b. These components had their smaller cross sectional dimensions increased such that they would have a printed model size of greater than 0.06 in.

4.2.3 Model Conversion

Once the components had been modified or removed, it was necessary to convert the *Pro/ENGINEER* model to an STL to be printed. There are two methods tested; direct conversion to STL from CAD and conversion via VRML.

The front half of the car was converted first to VRML, and then to an STL. This process was successful and repeatable with zero tessellation errors encountered. This method was used because with the available computer hardware directly creating the STL was not possible. Due to the large file sizes and RAM limitations, *Pro/ENGINEER* would crash during the conversion process to the STL file type. While using the VRML as an intermediate file format provided a successful method of creating the STL file, the accuracy of the STL file to the original model suffered since the model is tessellated twice. The VRML was created using the "high" quality setting in *Pro/ENGINEER*, while the STL created from this VRML was created using the default chord height and angle control given by *Pro/ENGINEER*; i.e., 0.2943 and 0.5, respectively. These settings resulted in an STL file size of 74Mb, with 1,572,467 facets. Due to the hardware restrictions, a smaller chord height could not be used to generate the STL file.

The rear half of the car was converted to an STL directly from *Pro/ENGINEER* directly. The back half features a smoother overall appearance than the front due to the direct STL conversion. The differences are most notable on the rounded surfaces of the wheels, and body panels as can be seen in comparing Figures 3a, and 1b, as previously mentioned. The STL of the back half of the car contained 885,100 facets, with a file size of 43.8Mb.

4.2.4 Model Fabrication

The STL was brought in to *CatalystEX*, the printing software used by the Dimension 1200. The STL model of each half was scaled down to 1/6 to fit into the work envelop.

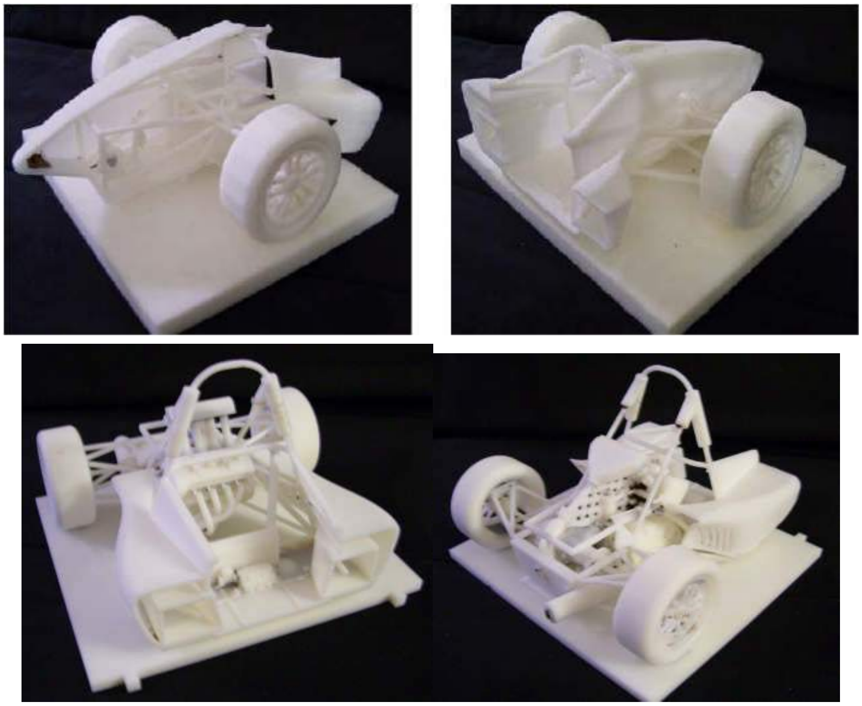

Fig. 13: Physical models of the printed race car: (a) & (b) Front half of car, (c) & (d) Rear half of car.

Once the part was oriented, the print settings were adjusted. The Support Fill option was set to *Sparse*, the Layer Resolution to the finest 0.01 in., and the *Model Interior* option to *Solid-Normal* for the front half of the car. The *Support Fill* option for the back half of the car was set to *Minimal*. This setting generates simpler tool paths for the support material, and also uses a build pattern which is much easier to break away; although, the build pattern does require the use of more support material. For the back half of the car, the ease of removing the support material was well worth it. The STL model is then sliced and sent to the Dimension machine for fabrication. It took about 60 hours for the Dimension machine to fabricate the front half of the vehicle, while the more complicated rear half with the engine took about 100 hours to fabricate. The models were then cleaned up by breaking away support materials, as shown in Figure 13. Figure 14 shows the overall process of converting CAD to physical models.

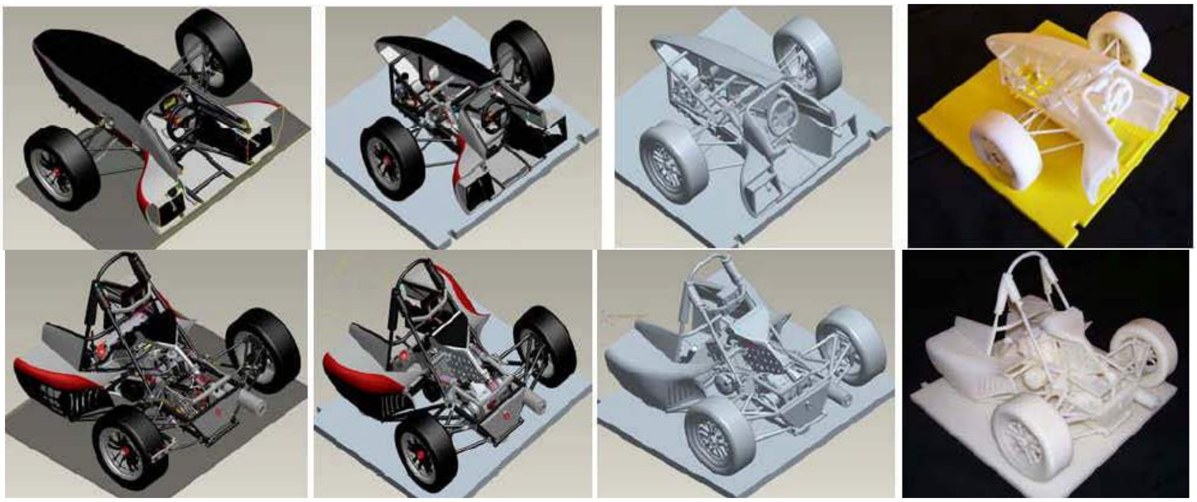

Fig. 14: The overall process of converting CAD to physical models: (a) First column, original geometry, (b) Second column, Modified CAD model, (c) Third column, STL model, (d) Last column, Printed model.

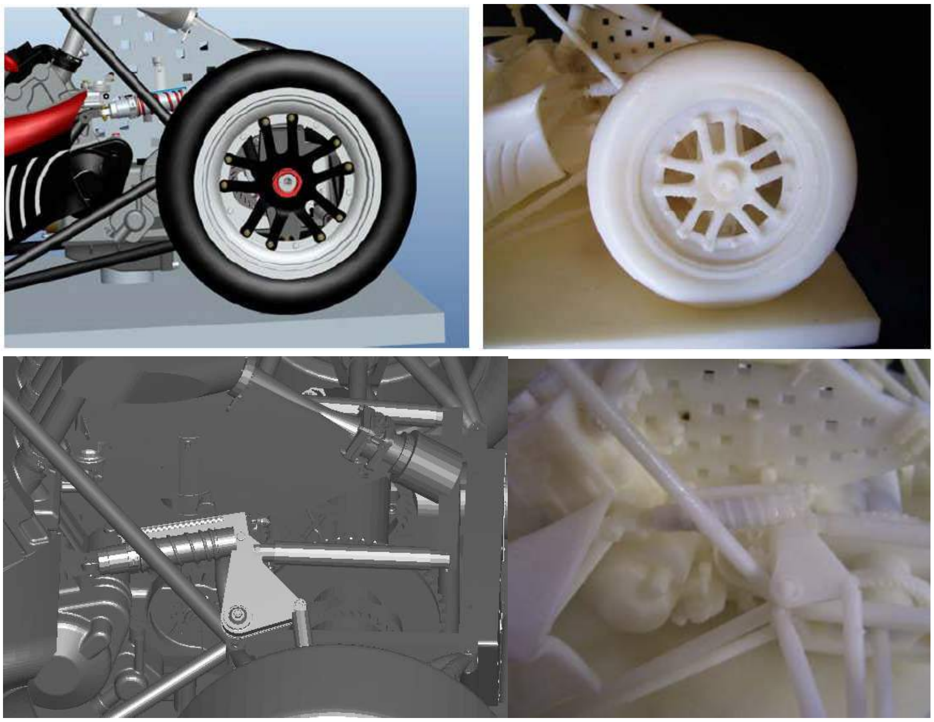

Fig. 15: Closer looks at the CAD and physical models: (a) CAD of wheel center, (b) Printed wheel center, (c) CAD of rear shock, and (d) Printed rear shock.

A few closer looks to the physical models shown in Figure 15, comparing with their respective CAD portion, demonstrate that the physical models represent the CAD model with an excellent fidelity. The wheel center is shown in Figure 15a, both in the modified CAD model, and the final product as printed. The spokes have been thickened in order to improve the structural integrity of the printed model. In Figure 15b, the modified shock can be seen along with the quality of the printed model. The spring on the shock can be clearly seen on the prototype.

5 CONCLUSIONS AND FUTURE WORK

The feasibility of fabricating scaled complex assemblies of thousands parts using RP has been investigated. Issues encountered in both software and physical prototypes have been identified and a systematic approach was proposed to address them. The proposed approach has been applied to the entire race car model, single cylinder engine model, and the HMMWV parts. The proposed method has been shown to work well. However, more work must be done to further improve the proposed approach. The work involves printing the same models on other RP systems in order to investigate potential process or proprietary software related issues, as well as to provide a good comparison between the capabilities of the machines. In addition, it is desired to use other RP systems, such as Sinterstation and ZPrinter650, for improving the model strength and printing color parts, respectively.

REFERENCES

[1] Jacobs, P. F.: StereoLithography and Other RP&M Technologies, ASME Press, 1994.
[2] Jingbin, H.; Liang, F.; Zhigen, D.: Research on generating similar-shaped assembly features for model partitioning, Proc. Mechanical and Electrical Technology (ICMET), 2010, 439-443.
[3] Medellin, H.; Lim, T.; Corney, J.; Ritchie, J. M.; Davies, J. B. C.: Automatic Subdivision and Refinement of Large Components for Rapid Prototyping Production, Journal of Computing and Information Science in Engineering, 7(3), 2007, 249-258.
[4] Kim, G. D.: A benchmark study on rapid prototyping processes and machines: quantitative comparisons of mechanical properties, accuracy, roughness, speed, and material cost, Journal of Engineering Manufacture, 222(2), 2008, 201-215.
[5] http://www.3dsystems.com/products/sls/sinterstation_hiq/index.asp
[6] http://www.dimensionprinting.com/3d-printers/3d-printing-main.aspx
[7] Hartman, J.; Wernecke, J.: The VRML 2.0 Handbook: Building Moving Worlds on the Web, Addison-Wesley. ISBN 0-201-47944-3, 1996.
[8] http://www.zcorp.com/en/Products/3D-Printers/spage.aspx
[9] Aptek Laboratories, Inc., http://www.apteklabs.com/
[10] www.ambroid.com
[11] http://www.3dvision.com/wordpress/index.php/2009/04/08/explaining-catalyst-ex-build-properties/
[12] http://www.zcorp.com/en/Products/3D-Software/ZEdit-Pro/spage.aspx
[13] www.synergeering.com/ebm.php
[14] www.solidica.com
[15] http://www.zcorp.com/en/Products/3D-Printers/ZPrinter-650/spage.aspx
[16] http://dimensionsca.com/
[17] http://www.ultrasonicleaners.com/default.php
[18] http://advancedrp.com/store/index.php?main_page=product_info&cPath=4&products_id=4
[19] http://www.students.sae.org/competitions/formulaseries