Stereolithography, a Rapid Prototyping Technique for Orebody Modeling and Mine Design

(Accepted for publication in Proceedings for Annual CIM Conference & Exhibition Mining, Minerals and Society – A Future In Balance – Vancouver 2002)

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Abstract

Stereolithography is a well known rapid prototyping technique in the manufacturing sector. Essentially it is a three dimensional printing process that produces plastic prototype parts from standard CAD files. At present, Canadian mining companies are not fully aware of the potential of Rapid Prototyping Techniques (RPTs) for their production and mine design systems. Mining engineers and geologists attempt to visualize and understand the characteristics and layouts of orebodies on computer models and in cases where it is decided to develop physical models, the process is time consuming based on simplified constructions. Rapid prototyping techniques (RPTs) such as stereolithography can facilitate engineers and geologists to quickly and with satisfactory accuracy to visualize sections of orebodies and evaluate alternative ore extraction techniques using 3D solid models.

The research discussed in this paper is carried out by the Laurentian University Mining Automation Laboratory (LUMAL) in collaboration with the Department of Mines Research of Inco Limited and the Integrated Manufacturing Technologies Institute (IMTI) of the National Research Council of Canada. The main objective with this research is to evaluate the applicability of state-of-the-art RPTs (e.g. stereolithography) to underground hard rock mining systems. RPTs can play a significant role in accelerating the design and development process of mining systems.

1. Introduction to Stereolithography

Rapid prototyping is a term describing a series of techniques used to create solid models based on computer drawings. Rapid prototyping is widely used in the manufacturing industry mainly due to the quick turn-over and low cost compared to other modeling techniques. Stereolithography (STL) is a well known Rapid Prototyping Technique (RPT) that is capable of producing a physical three dimensional object from a Computer Aided Design (CAD) file (Bakerjian and Mitchell, 1999). Stereolithography allows anyone with CAD skills to create models that can be processed, revised, and reprocessed in a matter of hours. This is a vast improvement over some traditional modeling techniques (carving, molding, etc.) that require specialized skills and often weeks of labour with little or no flexibility in the process. Figure 1 shows an SLA 7000 stereolithography printing workstation (3D Systems Inc., 1989).

Figure 1 - SLA 7000 Stereolithography Machine

A stereolithography machine uses a computer controlled laser to cure a photosensitive resin layer by layer. By exposing thin layers of resin to the laser and moving the model vertically within the resin tank, a full model is constructed in a layered fashion in a few hours depending on the capabilities of the printing machine. The process allows for the rapid creation of small scale three dimensional (3-D) plastic models that can be utilized for conceptualization, test-fitting of parts, and for display purposes. There are many levels of finishing available depending on accuracy and finishing quality (e.g. well sanded, smoothed, painted etc). There are different formulas available for the photosensitive polymers, and with heat curing, the resin can achieve extremely high strength. As a validation tool, stereolithography is invaluable allowing components to be verified early in the design phase. This allows changes to be made in the validation stage rather than having a potentially costly redesign later in the project.

2. The STL Process

The STL process begins as a 3-D computer model. This model can be developed in a variety of modeling programs as the STL format support has become a common feature in most new releases of CAD software such as AutoCAD and Mechanical Desktop, Pro Engineer, and many others (3D Systems Inc. 1989), (Jacobs 1995). Most software packages capable of creating 3-D solid models can ultimately be used to create stereolithography models, but may require transfer to another program that supports STL. For this project a combination of software packages was used. For the initial orebody model files, Datamine Version 5 was used (Datamine Canada, 2002). Datamine is a mine planning software tool used by Inco Ltd., this project's industrial partner. For file transfer and additional design functionality, AutoCAD 2000i was used (AutoDesk Inc., 2002). Finally for the final export to an STL compatible format, Rhino 3-D version 2.0 was adopted (Robert McNeel & Associates, 2002).

The STL machine consists of two main parts, one is a computer controlled laser and the other is a platform that is raised and lowered within the confines of a vat of photosensitive resin. When a valid 3-D solid computer model is created it can be inputted into the workstation that controls the machine. The software of the machine then breaks down the solid model into a series of vertical layers and adds support structures to support portions of the model as it is constructed to prevent sagging (these are later removed). The model starts with the platform in the upper most position. The laser is then traced across the resin in a pattern that matches the bottom most layer of the computer model. In this way a very thin layer of the photosensitive resin is exposed to the laser and will correspondingly harden in that shape. When a layer is completely exposed, the platform drops by the thickness of a layer (approximately 0.02mm) and the process is repeated until the entire model has been created.

The thickness of each layer can vary depending on the required model's resolution but usually ranges from 0.0254 mm to 0.127 mm with a vertical tolerance of 0.001 mm. Current large format printing machines such as the SLA 7000 made by 3-D Systems can create a model up to 508 mm x 508 mm x 584 mm in size. The laser is capable of printing with more than one resolution (controlled by changing the diameter of the laser) depending on the requirements of the model. A high resolution laser spot will have a diameter of 0.23 mm and a large spot (for quicker results) has a diameter of 0.838 mm. The drawing speed of these machines varies depending on the size of the laser spot. With a small laser the maximum drawing speed is 2.54 m/sec and a large laser is capable of drawing at 9.52 m/sec. Each layer will become a slice of the physical model and a precision elevator platform is used to lower the model into the vat of resin as each layer is completed.

It can take from 2 to 12 hours to complete a model depending on the size of the model and the capabilities of the machine. Post processing of the model is often required in order to give it a finished surface as well as removing any of the temporary supports that were added in the pre-processing phase. The model is then cured in an oven to increase the strength of the resin.
The STL process has many advantages over other modeling techniques:

- It can accommodate any geometric shape and is not limited to the exterior contours,
- It is accurate enough to act as a test-fitting phase when dealing with small parts,
- Once the file is prepared, little human intervention is required,
- The final model can be sanded and painted to any finish for display purposes,
- When the parts are heat cured they are very strong.

The disadvantages of this process are:

- Parts are currently limited to 508 mm x 508 mm x 584 mm in size but there are methods of creating "Lego" style end pieces to stitch together more than one model,
- Parts must be properly supported during the creation phase and temporary supports are often required to hold pieces of the model in place until it is finished,

- The photopolymer used in the process is expensive.
- Parts must be cured to increase their strength and prevent sagging.

Compared to other modeling techniques, stereolithography provides the fastest setup and model creation with the least amount of post processing and user intervention.

3. Research Approach

Overall, the aim of this research is to explore the potential and limitations of stereolithography to orebody modeling in underground hard rock mining. For achieving good accuracy and high realism in the production process of 3D solid mine models, a methodology will be developed. Furthermore, software connectivity between existing mine planning software and a stereolithography machine will be investigated and defined. For testing and experimentation purposes, an already available computer model of one of Inco's orebodies will be used (the 175 orebody). In more detail, the approach to implement the proposed research will involve the following steps:

1. *Determine the applicability of stereolithography to orebody modeling and mine design in underground hard rock mining*
   The potential and limitations of stereolithography are examined to determine the final output and any issues that might arise limiting the success.

2. *Develop a methodology to model orebody's sections in a CAD environment in such a manner that it will be possible to produce accurate and realistic 3-D solid models on a stereolithography machine*
   The characteristics of an orebody in conjunction with the applied ore extraction method define the layout and the access to the orebody. Different ore extraction techniques produce different layouts and access requirements to an orebody or section of it. Current mine planning software do not offer an export option to a stereolithography machine. As a result, it is necessary to determine the capabilities of the software and define a course of action to meet the STL requirements. Most modeling packages include support for the STL format; however mining software is not among these packages. As a result, it was necessary to investigate the process by which a model could be transferred out of Datamine and into a software package that does support the STL format. It was found that a combination of software packages gave the most efficient means of completing the work. Using Datamine, AutoCAD and Rhino 3-D, the orebody model could successfully be transferred from its original format, to a format compatible with stereolithography.

3. *Test the methodology on an existing orebody*
   Following Inco's recommendation, the 175 orebody was used as a basis for the design of the models. From the 175 orebody computer files, three models were created that show a sub-level caving extraction, a vertical retreat mining (VRM) extraction, and a model that shows the orebody and existing development.

   - Sub-Level Caving is a method of ore extraction that uses multiple mining levels and allows material above the ore to collapse as the ore is drawn off. When the grade of the ore drops to a minimum level, extraction stops and the next level below is blasted and the cycle repeats. This method requires a large amount of development.
   - VRM mining is based on crater blasting theory to remove thin ore layers vertically from a top horizon. The ore is then extracted from a lower horizon. The advantage of VRM is the reduced development required since levels often can be in excess of 60 meters apart.

4. *Evaluation*
   One of the three models created will be processed with the STL printer. The physical model will be evaluated for accuracy and appearance and recommendations made for future applications. At the time of submission of this paper, the physical stereolithography model was not ready.

4. Applicability of Stereolithography to Orebody Modeling

At present and to the best knowledge of the authors, application of stereolithography in the mining industry is not common. This is mainly due to the cost associated with the purchase of stereolithography machines as well as the lack of support for the STL format by commercially available mine planning software. During the past decade in Canada, new technologies have demonstrated the possibility to tele-operate mobile mining equipment from surface and achieve a comprehensive automated information flow (Vagenas et al., 1996). These breakthroughs facilitate lean mining which aims to minimize throughput time, stockpiles, wastage, rework and improve workers' safety. A prerequisite for lean mining is the ability to rapidly make decisions and deploy machines, as well as to selectively extract ore (Vagenas et al., 1995). It becomes apparent that the design process of a mine is now even more critical and the ability to rapidly identify design alternatives and evaluate them is a key factor for achieving lean mining. In this context, RPTs can play a significant role in the design process of mining systems. For instance, stereolithography can aid engineers and geologists in quick and effective visualization of orebody sections and evaluate alternative ore extraction techniques using 3-D solid models.

The potential of rapid prototyping techniques for use in mining is extensive. For an orebody model, it gives a very accurate geometric representation. It can also be used for the planning of development work as was done in this project. Geological features such as faults and dikes can be added to the model increasing the awareness and understanding of these features on the overall mine plan. As a visualization tool for presentations, it can have a very profound impact. RPT's can also be applied to the manufacturing aspect of mining allowing for scale models of machinery to be created as design tools or for marketing purposes.

In mining, orebody modeling is carried out using software packages such as Datamine. These software are customized for the mining industry and can convert drill core data into an orebody outline. The software is then used to add the required development to the orebody using a CAD style interface. Most mining software is compatible with AutoCAD's DXF, a popular CAD format, as well as many other file formats for different purposes. Inco Ltd. supplied the Datamine computer files of the 175 orebody that were to be used in this project.

This project was carried out by the Laurentian University Mining Automation Laboratory (LUMAL) in conjunction with the Department of Mines Research of Inco Ltd. and under the support of the Materials and Manufacturing of Ontario (MMO). The stereolithography machine used in this project was provided by the Integrated Manufacturing Technologies Institute (IMTI) of the National Research Council (NRC) of Canada in London, Ontario.

5. Creation of a Stereolithography File

In order to evaluate the requirements of the stereolithography format, it was first necessary to determine what the Datamine files provided as a starting point. The supplied files included an orebody outline at different grades as well as files for the development stage in the mine.

One of the critical steps involved the transfer of information into and out of the various software used. The Datamine software does not include any support for the STL format and so it was required to export it to another software package that does support the STL format. For connectivity, AutoCAD was adopted. AutoCAD does fully support the STL format but there is limited flexibility in AutoCAD to work with solid models. The solid modeling functionality in AutoCAD mainly relates to a series of standard shapes (box, sphere, cylinder, cone, wedge, and torus) that can be manipulated through Boolean operations and extrusions/rotations to create complex solids. However, the extreme geometry and size of our model made the use of Boolean commands a rather tedious task. As a result, in order to work with the STL file format, a third software package was introduced. Rhino 3-D is specifically designed for 3-D modeling and its solid modeling support is very flexible. It also fully supports the STL file format making it a good choice.

In more detail, Datamine data is exported in DXF format to AutoCAD. AutoCAD is used to draw and make general modifications to the model. The model is imported back into Datamine for verification and the addition of drift cross sections. The model is then exported back to AutoCAD in DXF format and verified.

Finally the model is imported into Rhino 3-D as a DXF file and saved as a "3DM" file, which is Rhino's proprietary 3-D file format. Rhino is then used to merge the development drawings and the orebody drawings as they are exported from Datamine separately. Rhino can then save the file in the proper STL format which can be imported to the stereolithography printing machine.

In this project, three models were created to demonstrate the capabilities of stereolithography. The first model was based solely on the existing development drawings and orebody outline. The other two models were intended to demonstrate the possibilities that stereolithography presented from a mine design perspective. By displaying the same orebody with different development stages, it is possible to offer a true sense of how the mine would look rather than depending on an interpretation of a flat computer view. To this end, two mining methods that require very different development were chosen for the second and third models; sub-level caving and vertical retreat mining. Figure 2 shows an example of Inco's 175 orebody with a VRM development sequence in a rendered STL format after processing through Datamine, AutoCAD, and Rhino 3-D.

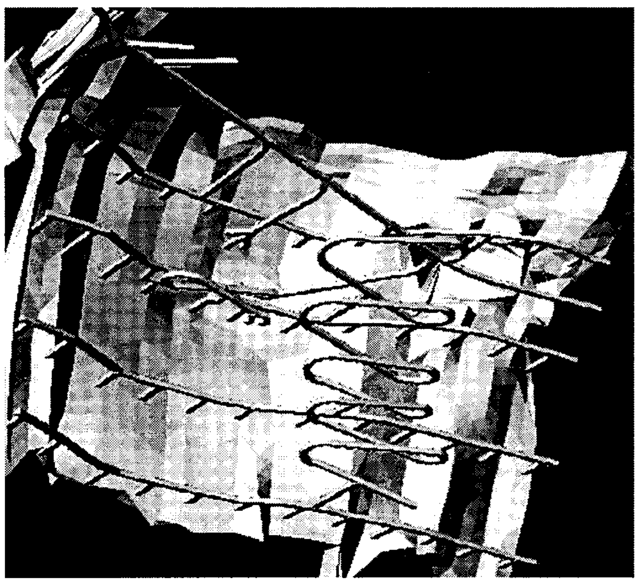

Figure 2 - Rendered STL Output of a VRM Sequence (Rhino 3-D)

6. Final Comments

Each of the three models created is intended to demonstrate the possibilities that stereolithography can offer to mine planning. This Rapid Prototyping Technique (RPT) can assist mining engineers in visualizing sections of mines or orebodies and in communicating the decisions made by the engineers to the working force in a practical and user friendly approach.

Overall, RPTs can contribute to our mining industry in a cost effective and time saving manner and become as successful as they are currently considered by the manufacturing sector.

Acknowledgements

The authors would like to thank Materials and Manufacturing of Ontario (MMO) and Inco Limited for their support of this research work.

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