

DEVELOPMENT OF SOFTWARE FOR SLICING 3D SHELL-LIKE COMPUTACIONAL MODEL AND FOR OFF-LINE GENERATION ROBOT TRAJECTORY FOR BUILDING METALLIC PARTS BY MEANS OF LAYERED GAS METAL ARC WELDING

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Abstract. This work describes the development of a software capable of generating trajectory points for guiding a welding robot, so that it might reproduce, by depositing weld metal in layers, the geometry of a shell-like object initially represented as a 3D computational model. Such a process is known in the literature as Shaped Metal Deposition (SMD), or Rapid Prototyping (RP) by means of 3D welding, or Solid Free-form Fabrication. The software development included the definition of the strategy for slicing a solid-body, strategies for planning the object's construction process, and assignment of orientation and velocity to a sequence of points through which the robot's end-effector will need to pass in order to physically rebuild the body by depositing the weld metal. The software uses the three-dimensional geometric modelling engine ACIS®, creating a text file with the trajectory points for the offline programming of an ABB IRB2000 AW robot. These points are used by the developed software to create either the deposition process planning in the Karel language, for simulation purposes in Workspace LT®, or the real robot program in the ARLA language (native ABB S3 controller language) for the off-line programming software SportS3®, which is able to compile the program and to upload it to the robot program memory. Some parts were built using the developed process planning strategy in order to demonstrate its effectiveness.

Keywords: Shaped Metal Deposition, Robotic GMAW, Off-line Programming, 3D welding

1. INTRODUCTION

Rapid Prototyping (RP) can be defined as the automatic construction of physical objects by means of layered material deposition based on a computational model, and is an efficient method for the development of new products or in the construction of highly customized objects. In particular, RP methods capable of accurately producing metallic parts are given special attention due to this material's obvious importance to the industry at large.

One such technique is known as 3D Welding or Shaped Metal Deposition (SMD), and consists of using a welding robot to deposit beads of metal along a trajectory that reproduces the geometry of the desired object. The main variables of importance for this process include (Fig. 1): torch motion behavior, wire feed rate, layer height, step height, bead width, among others (Bonaccorso *et al.*, 2011). The correct setting of these variables is of fundamental importance for the successful completion of SMD trials.

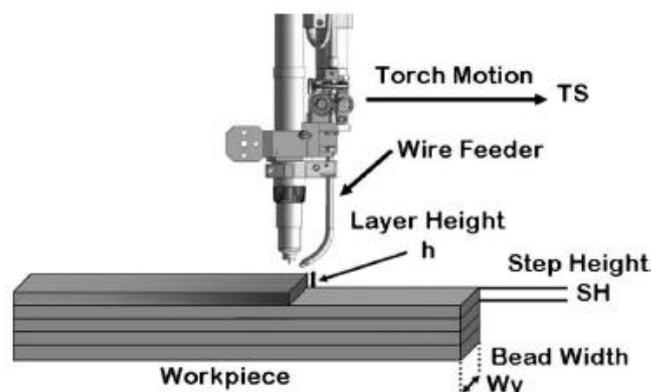


Figure 1. Schematic representation of the SMD process (Bonaccorso *et al.*, 2011)

For the last few decades, SMD has frequently being the target of scientific research given its potential: it can be a flexible and cost-effective alternative to traditional production methods (Escobar-Palafox *et al.*, 2011), promising

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superior reliability for the prototyping of metallic parts when compared to non-metallic RP techniques (Zhang et al., 2002).

The purpose of this paper is to detail the development of a software capable of, based on a 3D computational model, generating a trajectory for the offline programming of an ABB IRB 2000 AW robot so that it may move its welding torch in such a way as to reproduce the desired object by depositing weld, hence turning the welding cell currently being used into a SMD prototyping/fabrication cell. To reach this goal, it is necessary to define the strategy to be used on the slicing of the 3D model, so as to produce a sequence of positions that the robot must pass in order to physically rebuild the body when depositing weld, each point requiring the assignment of the torch's velocity and orientation. Besides, the construction process planning for building the desired object is also of importance, and must consider the possibility of further machining after the deposition is over.

In order to verify the reliability of the trajectory generated, the robot simulation software Workspace LT® has been used to visualize a robot moving through the resulting trajectory for several models.

This work also shows the attempts of performing deposition trials after transferring the trajectory to the IRB 2000, an articulated six degree of freedom industrial robot manipulator. The robot is equipped with a GMAW welding gun. GMAW (Gas Metal Arc Welding) is a fusion welding process that uses an electric arc between a consumable wire electrode and the work piece, applying a shielding gas to protect the resulting weld against contaminants in the air (Bracarense, 2003).

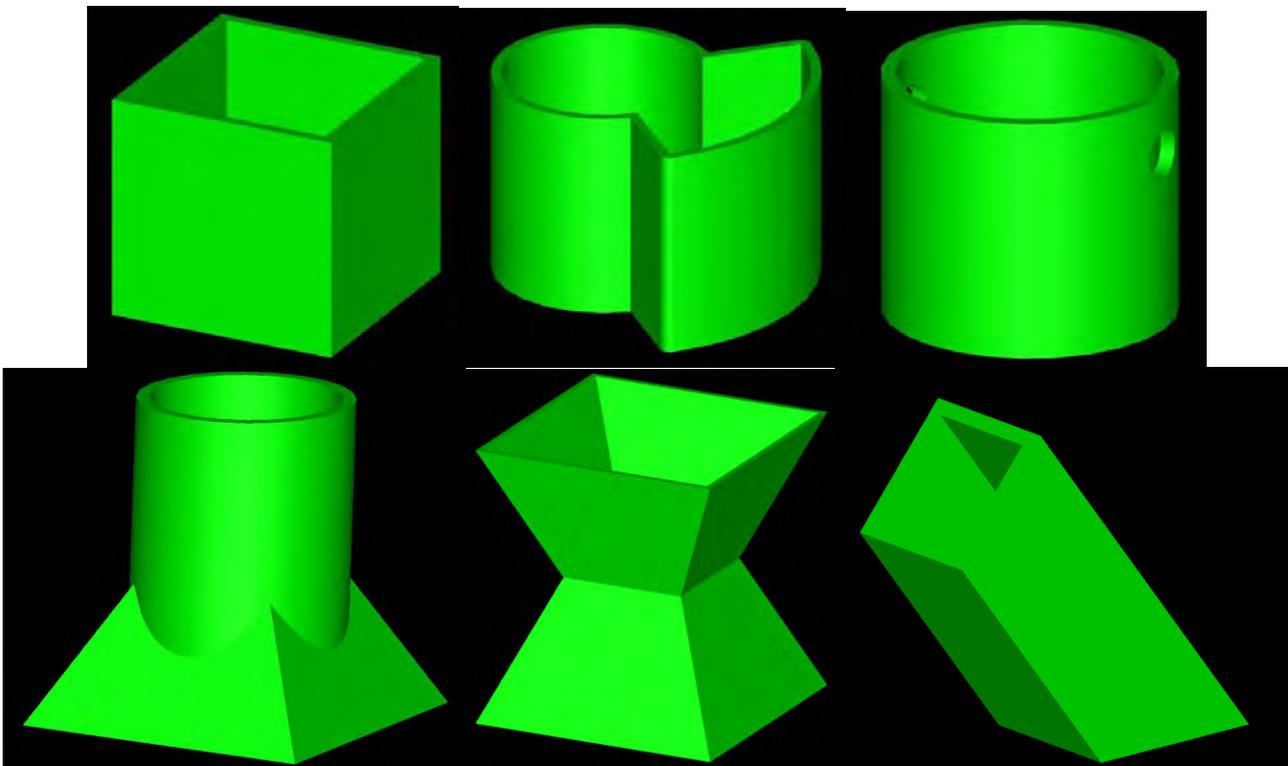


Figure 2. 3D models created for testing purposes

2. SOFTWARE DEVELOPMENT

The software was developed using version R13 of the ACIS® 3D modeling engine, an object oriented platform for modeling solids and geometries developed by Spatial Corp® (ACIS, 2010). In particular, this software was built upon the Scheme ACIS Interface Driver Extension (Scheme AIDE), a demonstration application based on ACIS.

The output of the software is a text file containing the trajectory in an adequate language for the next desired step: either Karel 2, in case the user wishes to simulate the trajectory with the Workspace LT program, or ARLA, the IRB 2000 robot language, if the user intends to perform deposition trials.

In order to adequately test the software under development, several 3D models with different characteristics were created, all of them saved on an ACIS recognizable file format (.sat). Figure 2 shows these models, whose characteristics include the combination of round and linear shapes, a non-vertical axis of growth, or the presence of one or more orifices.

Although a positioning table was not used on this work, the software gives the user the option of considering its presence when slicing the model. For now, the program assumes a positioning table capable of performing any

necessary rotations for building the desired object, with all necessary axis of rotation passing through the center of the table. Future papers may consider adding slicing capabilities with more specific tables.

2.1 Model slicing strategies

Adequate selection of the slicing strategy, that is the procedure for slicing the 3D computational model, is paramount for any RP method, and SMD is not an exception. In particular, the strategy to be used must consider the effects the GMAW process variables and characteristics may cause on the final piece. For this work, two strategies were at first considered: parallel plane slicing, which is commonly used on other RP methods, or spiral planes slicing.

Parallel plane slicing, illustrated in Fig. 3, consists of slicing the model in planes that are always perpendicular to the surface of growth, and material is deposited on the regions of intersection between the slicing planes and the model. This process is repeated for every layer, depositing material on top of the previously deposited layer. Despite being a popular strategy for most RP methods, it has proven inadequate for SMD due to limitations of the welding process, which demand constant movement of the welding gun. Figure 4 shows the ill effects of non-continuous paths: excessive concentration of heat and weld material on the region of discontinuity of the path.

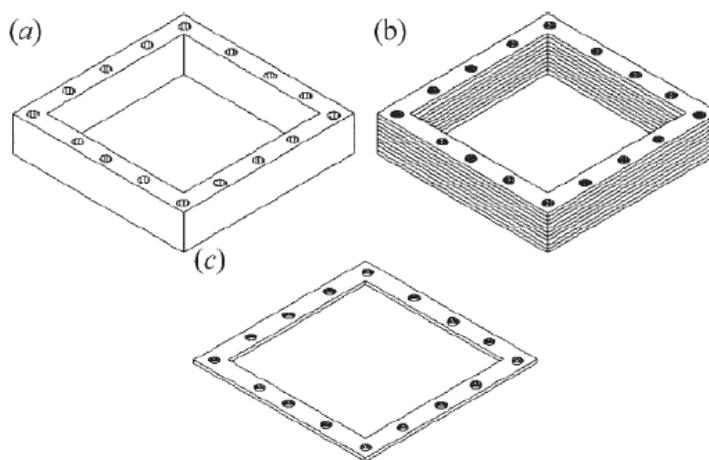


Figure 3. Example of a 3D model sliced in parallel planes: (a) original model; (b) post-slicing model; (c) single layer of the sliced model (Cao and Miyamoto, 2003)

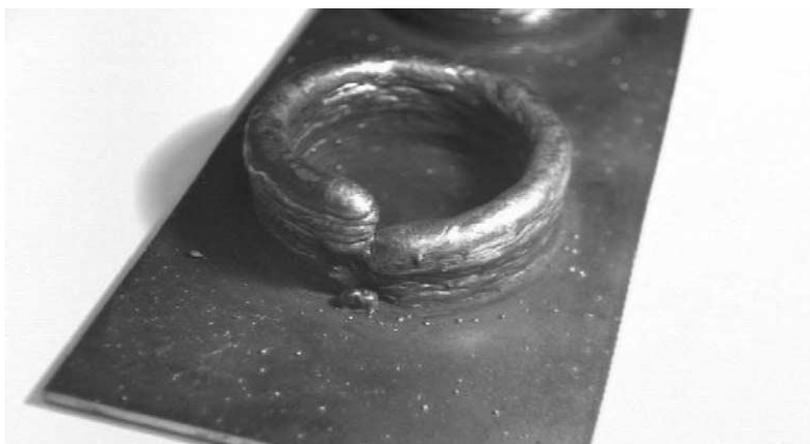


Figure 4. Result of a deposition trial using parallel plane slicing with a non-continuous path for the welding gun (Zhang et al., 2002)

To avoid these issues, one may use spiral planes slicing, which consists of using rays parallel to planes perpendicular to the axis of growth of the model (Fig 5 - left). By incrementing the height and angle of each ray, the intersections of the rays with the model form the desired trajectory.

Although generally superior to the previous strategy, spiral planes slicing introduces problems of its own. As illustrated by Fig. 5 (right), models with a relatively distant bulge may lose trajectory accuracy. This problem is worsened if the bulge grows in the same direction of the rays.

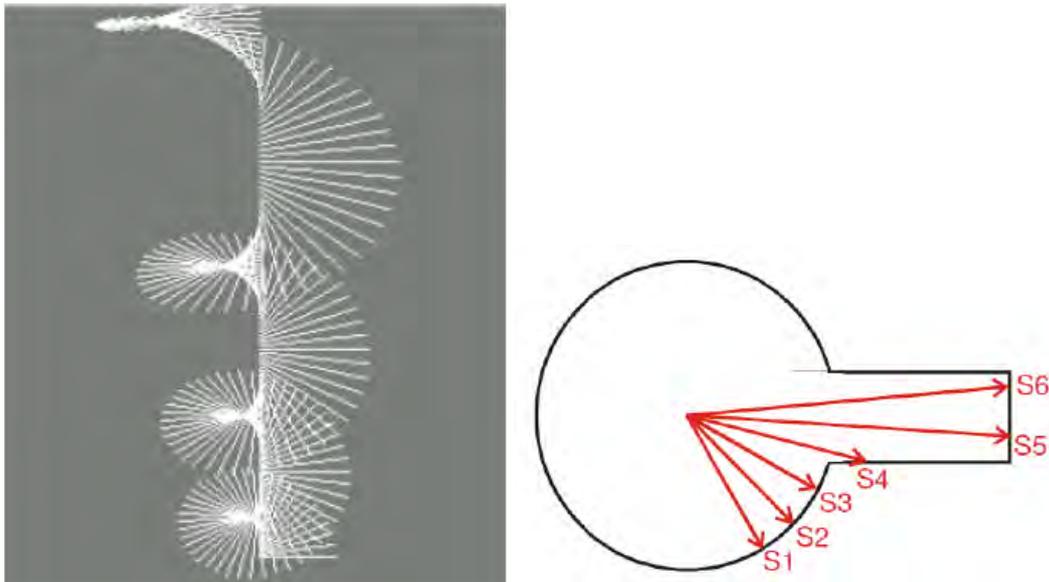


Figure 5. View of a group of rays for spiral planes slicing (left) and superior view of a model with a long bulge (right), showing the resulting trajectory obtained from using rays (Silveira, 2003)

For these reasons, a variation of the parallel planes strategy has been used for this work. It consists of performing the slicing on parallel planes, but maintaining a continuous movement of the robotic arm. Instead of moving through the perimeter of the intersection between slicing plane and solid to later repeat the process on top of the previous layer, a continuous trajectory is interpolated based on the intersection of two adjacent slicing planes. The trajectory initiates on the lower plane, rising and eventually reaching the upper layer. Figure 6 illustrates the procedure for a shell-like cylinder model. The process then repeats itself, now with a new upper layer and the previous upper layer being used as the lower one.

It can be seen that the adopted strategy avoids the problems of the ones previously discussed, apparently introducing no failings of its own (with the exception of the naturally superior computational cost).

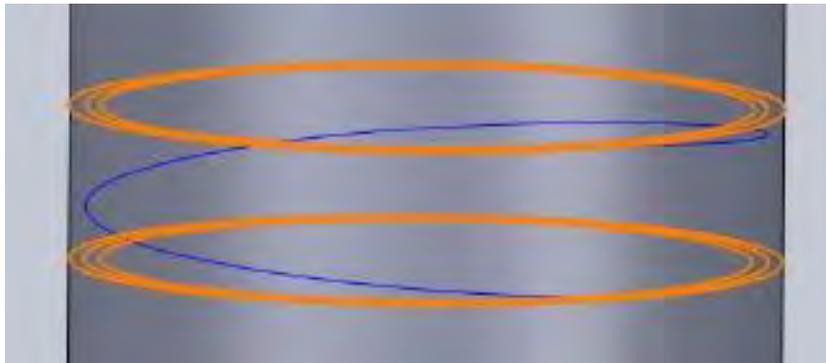


Figure 6. Example illustrating the slicing cycle. The distance between slicing planes is deliberately large for ease of visualization

2.2 Object's construction process strategy

Due to the nature of the welding process, some models cannot be completely built by means of SMD, as for example models with orifices: their complete construction would demand the deposition of weld on places without support for it, and it would be necessary to consider the altering of the 3D model or the execution of some post-deposition machining job.

It was then decided that for models with orifices, the software should ignore the presence of said orifices, creating a trajectory as if they did not exist, so that adequate machining could be performed after the deposition.

Furthermore, since the desired object's finishing quality is out of the scope of this work (as long as the geometry is correctly built), it must also be considered that a finishing machining is necessary to obtain the proper final piece.

3. WORKSPACE LT SIMULATION ENVIRONMENT

The third-party software Workspace LT, from WAT Solutions, is a sophisticated simulation system developed for educational purposes. It combines CAD and simulation properties to allow the creation of robotic workcell modules where the user can evaluate data such as performance, range and collision detection (WorkspaceLT, 2013).

In this paper, Workspace LT has been used to simulate the robot moving through the trajectory generated by the developed slicing software, and the goal here is to confirm if such trajectory truly reproduces the geometry of the desired model. To perform said verifications, a simulated environment was built (Fig. 7) consisting of a IRB 2000 robot equipped with a GMAW welding torch, and a simple block representing the worktable where the solid would be deposited.

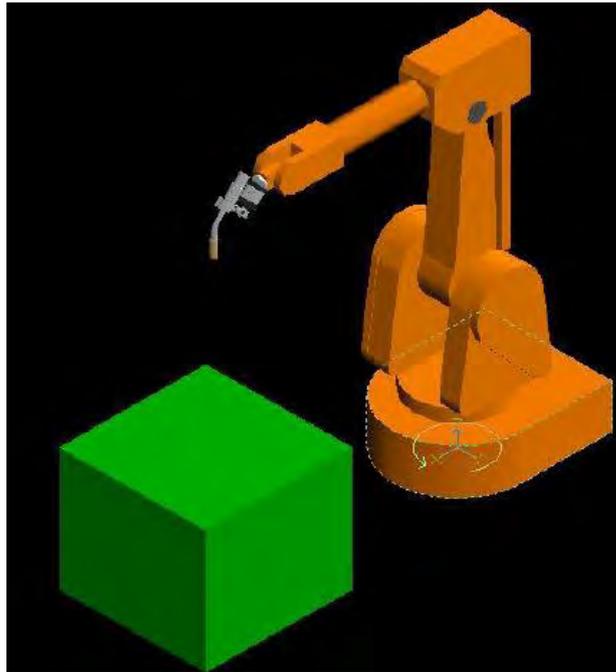


Figure 7. Welding cell developed on Workspace LT to simulate deposition trials

4. ROBOT AND WELDING POWER SOURCE COMMUNICATION

Upon the user's choice, the developed software produces a text file with the trajectory written in ARLA, the IRB 2000 robot programming language. This file contains not only the positions for the robot, but all initial configurations needed for proper operation, such as: coordinate reference frame, welding gun orientation and position related to the robot's final link (TCP), velocity of movement, and controller outputs for welding power source control.

Communication with the robot is performed using the SportS3 third-party software package, created by PPM AS® and intended to increase safety and ease of use for the rather obsolete ABB S3 robotic systems. It permits textual off-line programming and control of multiple robots from a single interface (SportS3, 2013). The trajectory text file must be manually imported to this software, so that the code may be compiled and uploaded to the robot.

For control of the welding power source, the Fronius ROB5000® interface has been used. Connecting the S3 controller's outputs to this interface, commands for activation of the welding gun can be embedded into the ARLA code, while welding process variables such as wire feed speed and applied voltage are manually controlled through the power source's LCD console.

5. RESULTS AND DISCUSSIONS

The software described in this paper possesses a simplistic user interface, but permits viewing both the 3D model and the generated trajectory for its construction by SMD. Figure 8 displays the interface console, while Figure 9 shows the user's view of a certain 3D model and the generated trajectory for that particular model. In both cases the user can manipulate the image (zoom in or out, and change the viewing angle) with the mouse.

The acquired trajectory is displayed as a continuous red line throughout the model's geometry (Fig. 9). If the user chooses to consider a positioning table, the original slicing planes (whose perpendicular direction follows the model's axis of growth) are displayed as yellow lines.

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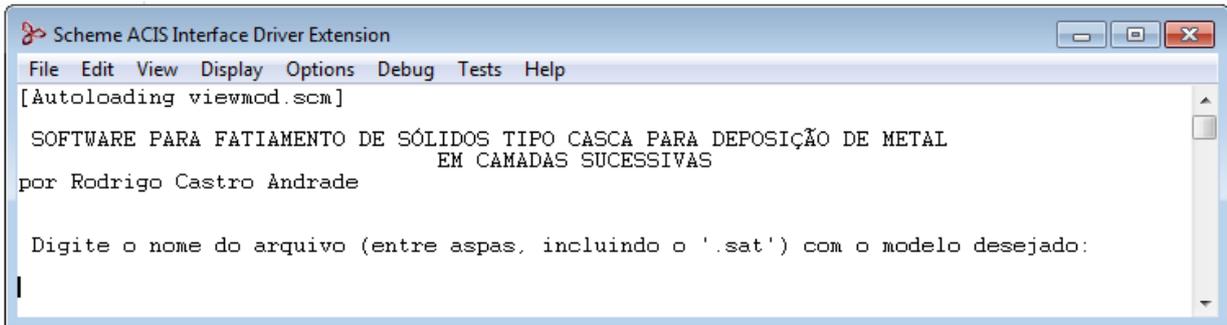


Figure 8. Software's interface console

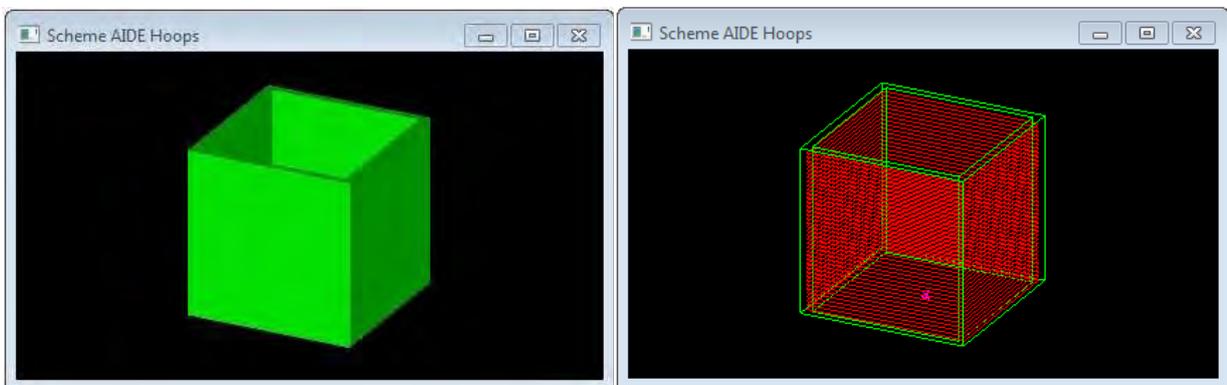


Figure 9. Windows displaying the desired 3D model for slicing (left) and the acquired trajectory, drawn as a continuous red line, to build the model (right)

After the user enters the desired model, the software requests the distance between slicing planes, then proceeds to the slicing process and generation of the trajectory, which for now is maintained as an internal list of positions. The user then chooses the destination for the trajectory, and the software finalizes its operation by writing the trajectory on a text file with the adequate programming language (Karel 2 for simulation on Workspace LT, or ARLA for off-line programming of the robot).

5.1 Generated trajectories for the proposed computacional models

All models presented on Fig. 2 have been successfully processed by the slicing software, with results available on Fig 10. Different distances between slicing planes have been used, as can be noticed by the meshes' varying densities.

5.2 Simulations on Workspace LT

With the exception of the inclined model, the proposed models on Fig. 2 were processed by the slicing software for simulation of the acquired trajectory on the Workspace LT environment. Figure 11 shows the simulated workcell during the process of construction of two separate models. In order to easily notice if the model's geometry has been correctly built, the simulation software was configured to display a yellow line at the end of the welding gun when it is activated, thus showing its welding path.

Figure 12 shows the simulations results, where once again several distances between slicing planes were used, as can be noticed by the meshes' varying densities.

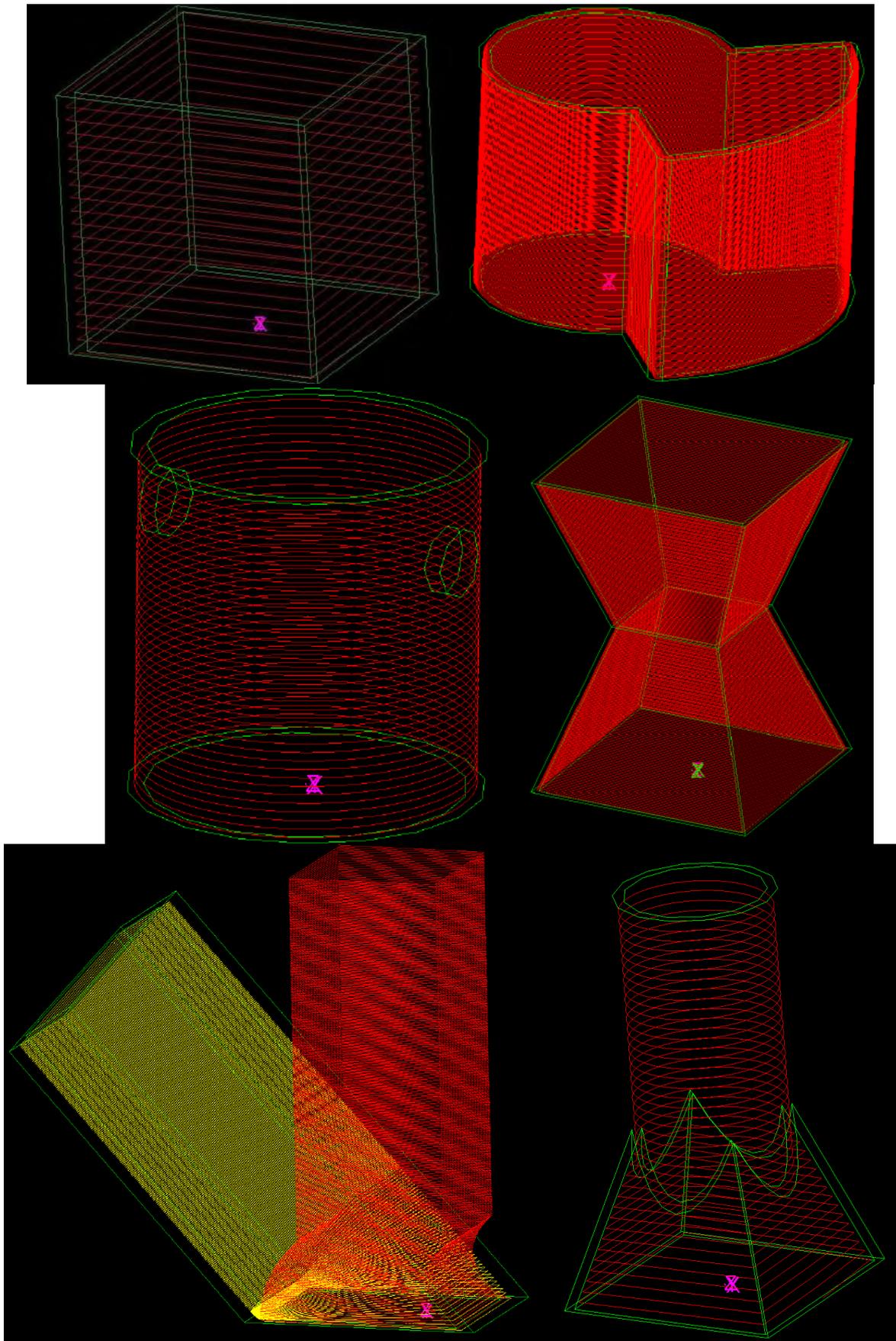


Figure 10. Result of the slicing for the proposed models, with the trajectory drawn in red. For the inclined model, the yellow lines indicated the original slicing planes (for use with a positioning table)

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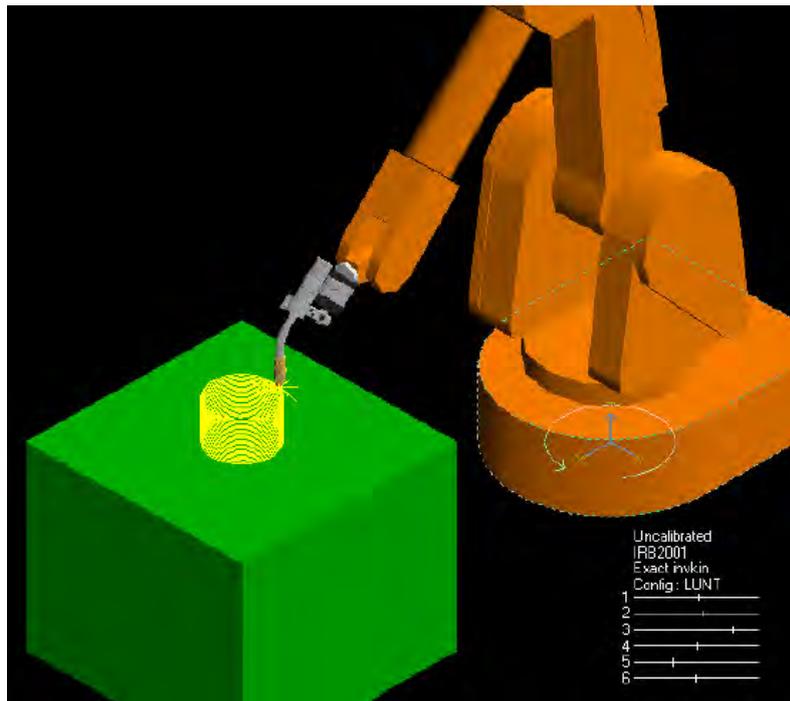


Figure 11. Trajectory, in yellow, of the welding gun's tip while active, on the simulation environment built for the WorkspaceLT software

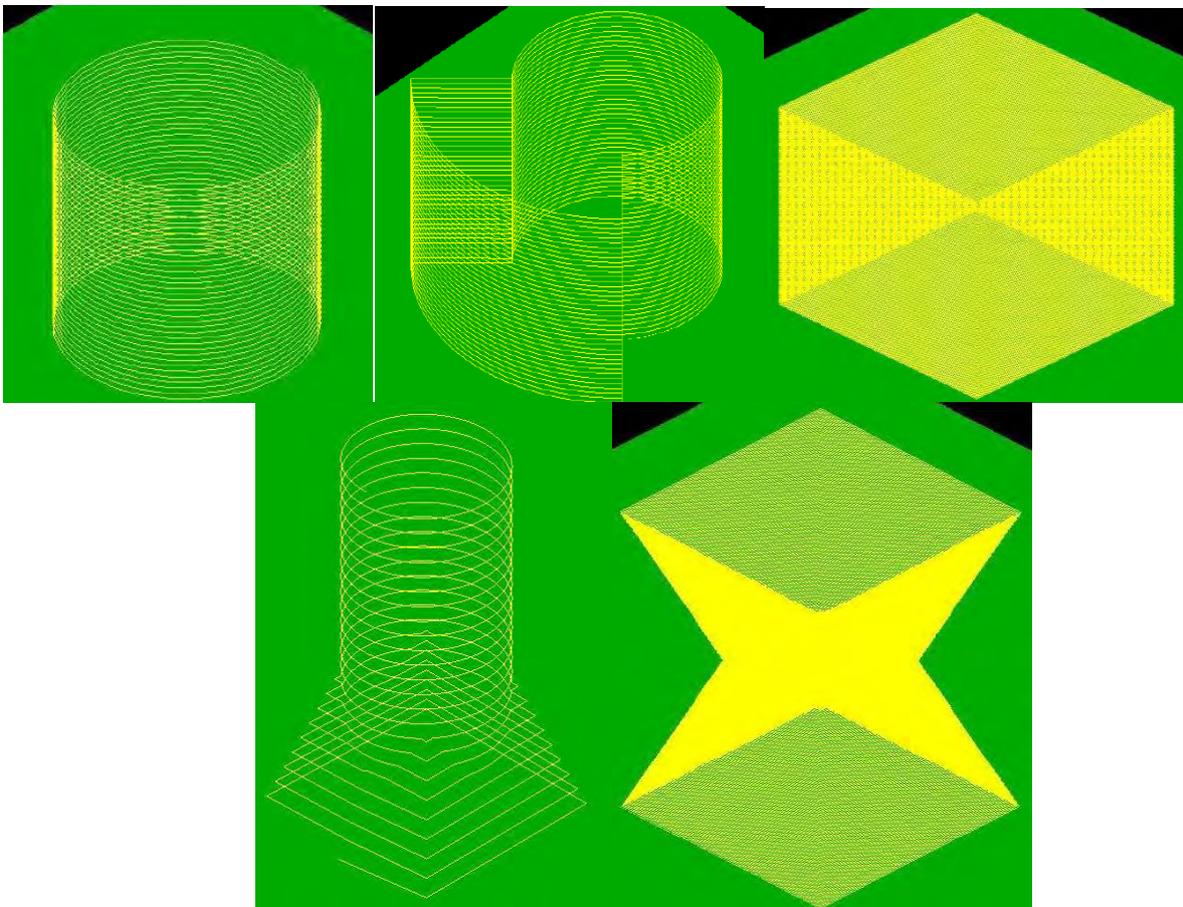


Figure 12. Result of the simulation for the trajectories produced for each of the proposed models

5.3 Deposition trials

The deposition trials consisted of two auxiliary trials, followed by the primary one. It was decided to perform these auxiliary depositions in order to ascertain reasonable values for the GMAW process variables to be used on the primary trial, as well as a proper value for slicing planes distance. The determination of the best values for these parameters, while fundamental to the process, lie outside the scope of this paper.

Table 1 shows the values for the process parameters (wire feed rate and welding voltage) for the auxiliary depositions, which were manually changed (through the welding power source's console) during the trials in order to maintain stable welding.

Table 1. Controllable welding variables used on the auxiliary deposition trials

| Moment of the Deposition | Wire feed rate (m/min) | | Electric voltage (V) | |
|--------------------------|------------------------|-------------------|----------------------|-------------------|
| | Auxiliary trial 1 | Auxiliary trial 2 | Auxiliary trial 1 | Auxiliary trial 2 |
| Start | 6 | 5 | 19 | 18 |
| End | 5,5 | 2,5 | 14,6 | 15,5 |

Both auxiliary depositions were carried out using distance between slicing planes of 1mm, with the robot arm moving at 10 mm/s. Figures 13 and 14 exhibit the results for auxiliary trials numbered 1 and 2, respectively. Both trials were interrupted when the distance between the welding gun's tip and the deposited weld (stand-off) decreased excessively, from which was concluded that the primary deposition would require a larger distance between slicing planes (since the robot's vertical velocity was inferior to the weld's growth rate).



Figure 13. Views of the resulting deposited solid of auxiliary deposition trial 1, shortly after deposition (top) and after cleaning (bottom)

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Figure 14. Views of the resulting deposited solid of auxiliary deposition trial 2, shortly after deposition

Aiding in the determination of adequate process parameters, these auxiliary depositions were also useful in revealing an unexpected and yet reasonable issue that occurred: due to the long periods of time involved on SMD construction, an excessive amount of spatter accumulated on the welding gun's gas nozzle, up to a point where it almost blocked the shielding gas flow. To remediate this situation, the developed software was altered to include periodic stops for gas nozzle cleaning.

By comparing the vertical movement of the robot with height measurements on the piece built at auxiliary trial 2 (Fig. 14), a slicing planes distance of 1,6 mm was calculated as adequate to be used on the main deposition. Table 2 displays the controllable process parameters used on three different stages of this final trial, with the robot's welding gun moving at a constant speed of 12 mm/s. Gas nozzle cleaning stops were performed every ten minutes of welding.

Table 2. Controllable welding parameters used on the auxiliary deposition trials

| Moment of the Deposition | Wire feed rate (m/min) | Electric voltage (V) |
|------------------------------|------------------------|----------------------|
| Start | 3,5 | 15,8 |
| Throughout stable deposition | 4 | 16 |
| End | 3 | 15 |

Figures 15 and 16 exhibit the resulting piece, prior and after a post-deposition cleaning, respectively. Notable difficulty to achieve stable welding occurred at the beginning of the process, eventually being reached (stable deposition on Table 2).

Cleaning stops performed adequately while their duration were short. Upon the first lengthy cleaning stop, welding stability was lost (possibly due to the cooling of the deposited weld) and was no longer recovered. Figures 15 and 16 clearly show the part of the object built after the loss of stability. The deposition was eventually interrupted due to the

excessive instability of the process, which caused an increase of the gap between the welding torch and the deposited weld.



Figure 15. Deposited solid resulting of the primary deposition trial, before cleaning



Figure 16. Deposited solid resulting of the primary deposition trial, after cleaning

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6. CONCLUSIONS

This paper described the development of a software capable of generating trajectory points for guiding an ABB IRB 2000 welding robot in order to perform the rapid prototyping of shell-like objects by means of Shaped Metal Deposition. Receiving user information such as the desired model to be built and the distance between slicing planes to be used, the developed software produces a text file either with a program to be transferred to the robot (in ARLA programming language) or a program to be used on a Workspace LT simulation environment (in Karel 2 language), in both cases displaying the generated trajectory the robot's end-effector should follow.

Several simple shell-like models were created in order to verify the produced trajectory, which were visually accurate. Simulations on Workspace LT also confirmed that the trajectory successfully reproduced the models' geometries.

A few depositions trials were performed and also confirmed the accurate reproduction of the geometries. Auxiliary trials were executed in order to ascertain proper welding parameters and slicing planes distances to be later used, also revealing the need for periodic interruptions for nozzle cleaning.

The main conclusion from these trials was the great difficulty to maintain stable welding through the manual control of the welding parameters, possibly indicating the need of a control system capable of altering welding and robot parameters in order to successfully build an usable component.

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8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.

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