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AUTOMATIC PRINT BED LEVELING FOR INDUSTRIAL ROBOT SYSTEMS

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Abstract

Additive manufacturing with 3D-printers enables the creation of any kind of object by printing it layer by layer. However, the object size and complexity that can be reliably produced with standard industrial applications is limited by the 3D-printer's size and degrees of freedom. In contrast, industrial robots typically have larger work envelopes and more degrees of freedom. Combining a robotic system with a 3D-printer increases the possible print area and thus the opportunity to create bigger objects. However, a larger print surface becomes increasingly uneven because of mechanical constraints and deformation caused by heat, reducing the adhesion quality. Adhesion is required to achieve a high product quality, or even a successful print at all. The UAS Technikum Wien Digital Factory robotic printing system consists of an ABB IRB 2400 and a custom-built print bed. This allows the production of objects with a surface area of over 3 m² in a short time span, which allows for faster prototyping durations of different projects. However, the adhesion properties suffer severely. This report describes the implementation and evaluation of an automatic print bed leveling system, as well as the possibility to print on curved surfaces. A grid-based probing approach controlled by using a touch probe sensor with an appropriate mounting and offset calculation was designed to compensate for the disadvantage of the sizable print bed. This results in a higher percentage of even surface area and therefore to an increase in overall adhesion quality. For printing on curved surfaces, it is recommended to further expand the system using a collision check as well as an orientation interpolation.

Keywords: Additive Manufacturing; Auto Bed Leveling; 3D-Printing; Robotic System; Print Bed Leveling

1. **Introduction**

3D-printing or more precisely fused filament fabrication (FDM) has become a regular application in the industry. It is widely used to create different and mostly complex components in one step compared to the numerous steps that occur in conventional manufacturing processes. In order to create such objects, a fine-tuned printing system is needed. One of the most common problems that occur during these prints is the bad adhesion properties between the actual object and the print bed. The reason for this can be many things like temperature differences or bad filament. But most of the time the problem occurs because of a non-constant distance between the extruder and the print bed. This leads to objects warping or sliding around the bed during the print. This effect is even more evident when printing with robotic systems.

The problem with those systems is, that they usually don't level the bed before a print. Because the bed itself isn't perfectly even, the distance between the extruder and the actual bed changes constantly during the print. Even though the differences in distance are minimal, the actual result of the print quality depends highly on a constant distance during the first layer of the print.

The goal of this work is therefore the implementation of an automatic bed leveling system for the current application of the 3D-printing robot system situated in the digital factory of the UAS Technikum Wien. For this purpose, different sensors will be evaluated, compared and finally implemented in a modular bed leveling application that can be used for different robotic systems. Therefore, the current printing process will be expanded with the bed leveling system. More importantly a quality increase of the prints is to be expected. Furthermore, approaches for leveling with the system on curved surfaces are being examined.

Chapter 2 examines the actual problems that occur on the current printing system. In chapter 3, the current state of the art for commercial and robotic leveling systems, including sensors and algorithms, as well as curved surface leveling is examined. Chapter 4 describes the methods used to implement the system, following with chapter 5 where the practical realization will be documented. The subsequent chapter will summaries the results with the conclusion giving a glimpse into the future and ongoing work about this topic.

2. Problem description

3D-printing is becoming a common technology in the industry and for private consumers. The applied technology that is utilized with those commonly used printing machines cannot easily be transferred to a robotic system. This spans from slicing an object with a slicer to converting the result into the actual robotic system. More importantly this applies to functionalities which are normally not used while printing with robotic systems, like using a bed leveling system.

2.1. *Robotic system*

Currently the actual robot system that is used in the Digital Factory of the UAS Technikum Wien for printing large objects consists of an ABB robot system with an appropriate extruder and customized heated print bed. More precisely the robot used is an ABB IRB 2400/16. The maximum weight of this robotic system lies at about 16 kg. One problem that is currently leading to an imprecise operation during printing is caused by the weight of the extruder contraption. The used extruder is called a Noztek Xcalibur and weighs with all the additional parts mounted to it about 20kg. This can lead to limitations [1] of the actual robot system that occur because of this overweight extruder. Another key characteristic of the robot is the position and path accuracy. These two values sit at 0,03 mm for the position and at 0,11 – 0,15 for the path accuracy. It is to mention that those two values are for the repeatability of the robot. Using the robot for points resulting from a sliced object applies the absolute accuracy, which has a value of around 0.3 mm [1]. The reason for the implementation of the bed leveling process is to counteract those limitations created by the robotic system. Above all, this has to be done on the first few layers of the print in order for it to get the best adhesion possible. Of course, it is not possible to fully reduce those limitations with just a bed leveling system, but the implementation will by all means improve the actual result. The current state of the robotic printing station can be seen in Figure 1. The different parts of the system are highlighted respectively.

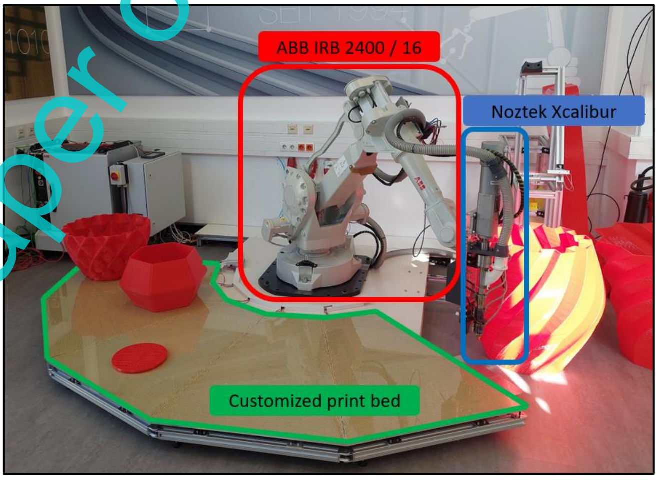

Figure 1. Robotic system used for 3D-printing, positioned in the Digital Factory of the UAS Technikum Wien

2.2. *Print bed and sensor systems*

The robotic system has a customized heated print bed. This print bed consists of two big aluminum plates mounted together in order to form the actual print bed. On top of those plates are mounted heat pads. These are used to raise the bed temperature to about 60 °C during operation, which is the optimal temperature for printing with polylactide (PLA).

The actual surface on which it is printed on is realized with a glass plate on top of the heat pads. Glass usually has a very smooth surface texture, which is actually a good thing for 3D-printing. The main problem that can happen despite the smooth surface, is an actual tilt of the bed. This can occur because of many reasons. One could be an extension of the mounting structure because of the increase of the temperature. Another could be that the actual mounting cannot be done with such high precision, so that no tilt is occurring at all. All these reasons lead to a bad adhesion between the actual print and the surface of the bed. With an appropriate bed leveling system, the tilt can be balanced out using the results of the probe points.

Because the main print surface consists of glass, the sensors that can be used for leveling the bed are very limited. Typically used sensors like inductive ones, which are utilized by many common printers, cannot be applied for this reason. Instead, other solutions need to be considered. Therefore, material independent sensors should be the main focus for realization.

One disadvantage that the material independent sensors provide is, that other sensor types that would be a better use for curved surface leveling, for example laser systems, cannot be applied because they rely on specific materials. Consequently, the sensors used for the planar leveling should also be able to perform curved surface operations.

2.3. *Software implementation*

The robotic system utilized for printing relies on three different programs used to realize the actual print. The first component applied consists of a PC based programmable logic controller used to control external components like the extruder, the material feeding process and the print bed heating process. The second system used is the actual slicer of the 3D-printed parts. For this case the Cura slicer is utilized. One problem that occurs using traditional slicers like Cura slicer is, that there are only two predefined print forms that can be applied. One is a cylindrical shape, the other one is a traditionally used rectangular cuboid. The dispute that occurs is, that the actual print bed is shaped in a special way according to the robot’s workspace. For this matter the rectangular cuboid is utilized in the slicer. The size defined is far bigger than the actual print bed in order to cover it completely. The actual differences in size of the print area and slice area can be seen in Figure 2. Additionally, the position where the height of the glass was teached in the system is visualized. The further away the position of the object is from the work object point, the more severe the error to the real print bed becomes.

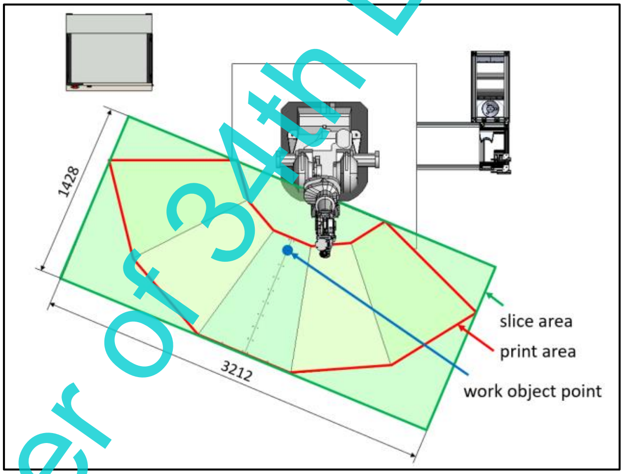

Figure 2. Comparison of print area and slice area (top view of the system)

The actual resulting G-code gets then moved in the correct position using the third software called RoboDK. The problem that results is that the leveling process should only be done on the actual print surface. Therefore, the differences between the rectangular surface and the print area need to be considered.

2.4. *Printing results of the current station*

Although a lot of objects that have already been printed on the newly designed and extended print area turned out to be good results for printing with PLA in this order of magnitude, some shapes tend to create a few problems. The same problems that occur on standard printing machines at a smaller scale, also take place while printing with a robotic system. This is even more apparent, the bigger or longer the actual object is. In order to compare the prints with and without bed leveling, the same object is being examined. For this purpose, a long rectangular like shaped box was printed without the actual leveling applied. The resulting print has severe issues that occurred because of the material cooling down and leading to warping effects. This warping effect even led to a tear in the wall. The reason for this was the movement of the wall during the print resulting in wrong positions for the robot, where the filament was being extruded. The actual print can be seen in Figure 3 which is split into a top and bottom view of the resulting object. The object has a dimension of 145 x 37 x 15 cm.

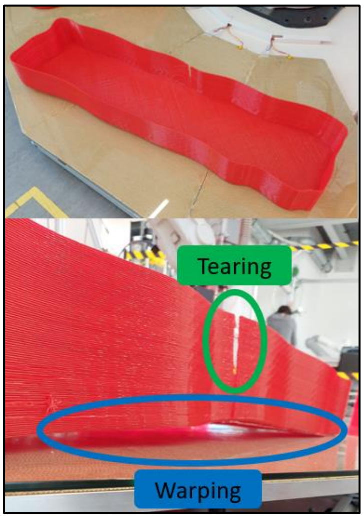

Figure 3. Problems with current printing results on a relatively long object (top: aerial view of object, bottom: warping and tearing of the object)

3. State of the art

Currently mostly all of the commercial 3D-printers available use some sort of leveling system. This leveling of the print bed is either done manually or automatically on more expensive devices [2]. In either way the goal of the leveling process is to keep the nozzle of the extruder at a constant distance to the actual bed [3]. If the nozzle is too high or too low, different results may occur as seen in Figure 4.

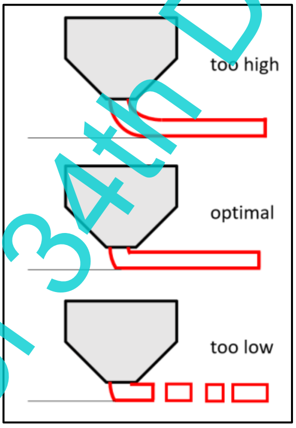

Figure 4. Extruder nozzle distance to print bed (modified adopted from: [3])

3.1. *Leveling processes and applied sensors*

The manual leveling process on commercial 3D-printers is usually done using a sheet of paper. This paper is placed beneath the extruder and the actual print bed. The position between the nozzle and the bed is then reduced to a point where the paper is moving with a little bit of resistance from the pressure that occurs. This is usually the optimal distance between the nozzle and the print bed. This position is then saved and done on the next point [2]. Usually this is done on the four ends of the print bed. This manual process needs to be done every time a new print is about to be started. Due to the manual process a lot of errors can occur which leads to an imprecise method of leveling the print bed [4].

In case of an automatic print bed leveling system, a sensor is used to measure the exact distance to the print bed at a specific point [5]. There are many different sensors that can be used for this specific task. The most common sensor types are infrared, ultrasonic or proximity sensors like capacitive or inductive types. Even load or force sensitive resistor (FSR) sensors can be used for leveling a print bed [3]. Additionally, switch sensors can be applied which need to be set in front of the extruder to sense the bed and need to be removed afterwards in order to print properly. Inductive, infrared or capacitive sensors can only be used on specific bed materials. Ultrasonic and switch sensors can basically be used on any print bed surface. Furthermore, each sensor type has different results in precision which leads to a distinct quality of the actual print. Hence each sensor has its advantages and disadvantages for each application [4]. Most common 3D-printers use metal sheets as print beds. This leads to preferable thermal properties and to the use of inductive sensors for the print bed leveling process. Big brands like for example Prusa use inductive sensors for their leveling process. Their specific inductive sensors, called PINDA, are commonly used in the 3D-printing market. The use of inductive sensors combines the advantage of precision and range. Therefore, the sensors can be positioned behind the extruder leading to no complications during the print [6].

3.2. *Algorithms used for leveling print beds*

Either manual or automatic print bed leveling processes rely on different algorithms which are applied to level the actual bed. The most basic algorithm typically used by common 3D-printers is a three-point leveling system. As the name applies, three different points are probed on the print bed. Thee points lead to a plane in a 3D space which can be further analyzed. This is necessary in order to get a rotational matrix which tries to describe the actual tilt of the bed as precise as possible [5].

Another typical algorithm is the planar grid approach. Hereby a grid is set up across the whole bed. The actual crossing points of the lines from the grid are the probe points for the algorithm. With the different probe points in place, a linear relation between the actual points can be achieved. This leads to more precise values depending on how fine the grid is set up [5].

A more precise application that is typically used for leveling the actual print bed is a bilinear approach. This approach is basically the same as the planar grid, but the relation between the different probe points is bilinear in this case. The precision is higher as compared to a planar approach. Hence the calculation amount of the resulting mesh is higher [5].

The goal of the algorithms is to keep the nozzle at a constant distance to the bed. If the bed has a tilted surface, then a normal print without leveling would lead to a too small distance on one side and a too large distance on the other side. The auto bed leveling algorithm changes the z-axis value of the extruder according to the position it is currently at. An example of some layers with and without leveling can be seen in Figure 5 [7].

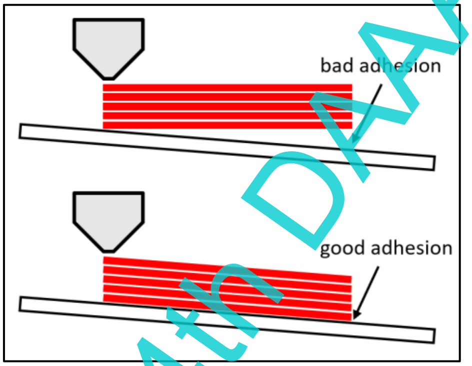

Figure 5. Print with no bed leveling (top) and with bed leveling (bottom) (modified adopted from: [7])

3.3. *Printing with robotic systems*

Robotic systems are currently commonly used to act as a complete 3D-printer. Typically, 3D-printers use control units which generate the motion of the printer based on a G-code file. This G-code is generated by slicing the desired object using a so-called slicer-software. Robotic systems usually cannot use G-code information in order to move the robot directly [8]. To convert the G-code into an actual robot motion, different software options are currently applied. Big robot companies like ABB and KUKA created their own software which enables this sort of application. ABB enabled 3D-printing in their robot programming software called Robot Studio [9]. KUKA integrated their own slicer and use KUKA.CNC in order to generate the robot motion [10]. Additionally, KUKA implemented a software application called KUKA.TouchSense, which can be used to compensate irregularities on an actual workpiece. This application was created for arc welding but can actually be used for any application that requires a constant distance to a specific surface, like 3D-printing. For that purpose, a wide array of sensors can be applied to measure the distance to the object [11]. A more common used method for 3D-printing with robotic systems is the software called RoboDK. With this software it is possible to use a vast variety of robots to accomplish a 3D-printing operation. The objects can directly be sliced using an in-built slicer. Additionally, custom python scripts and plugins can be used to perform different movements based just on code ([8], [12]). In the implementations used by ABB and RoboDK, an in-built bed level system is not available. Therefore, these solutions rely on a print surface implemented using a CAD file of the print bed in the software ([9], [12]). Applying the solution offered by KUKA, an actual print bed leveling process can be achieved, using the additional application typically used for arc welding ([10], [11]).

3.4. *Projection algorithms for curved surfaces*

Additive manufacturing processes typically use planar slicers in order to slice the printed object in layers with a specific height. Therefore, a flat plane is used, where the object is placed and sliced [13]. Some advanced slicer algorithms even try to create different planes for different parts of the object as a means to reduce stair effects and support material during the printing process [14]. However, intending to print on a curved surface, the planar result needs to be projected using some sort of algorithm. This can either be done using just a projection or a lossless projection. Using just a projection, the actual plane gets distorted resulting in a warped object. Applying a more complex lossless projection, the result on the curved surface will resemble the actual object more precisely, with some errors still available. In an effort to achieve such a projection, the curved planes, or more precisely the triangles of the STL file, are converted into a 2D plane. Basically, the surface of the object gets unfolded. The actual print can then be projected on the 2D surface. Because of the resulting transformation matrix from the unfold process, the plane with the print can be transformed back to the actual curved surface, resulting in a lossless projection [15]. The actual process of this projection algorithms can be seen in Figure 6.

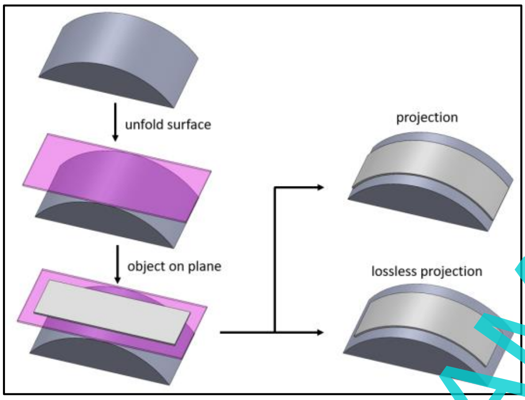

Figure 6. Projection of a 2D object on a curved surface using normal projection and lossless projection (modified adopted from: [15])

With the usage of a projection algorithm, it is basically possible to project 2D data onto a 3D surface. The result of a sliced object are hundreds of planes stacked on top of each other. Therefore, a projection of those planes is theoretically possible. Any kind of 2D plane can be projected on a curved structure [16], which includes grid planes for leveling as well. In this case a 2D leveling grid plane algorithm could be projected on a curved object, leading to a leveling process for that kind of surfaces. The plane sliced object could then be adapted to the curved surface using the leveling results.

4. Materials and methods

In order to achieve a print bed leveling on such a scale, different methods need to be addressed. These include the specification of an appropriate sensing device, programing of the logic that can be executed on the robot and finally the adjustment of the G-code with the leveling result. Additionally, methods need to be examined in order to apply a print leveling on a curved surface.

4.1. Evaluation of applied sensors

To appropriately measure the distance to the print bed, a sensor has to be found, which enables this kind of application. Because the applied surface area of the print bed is a glass plane, the sensor selection is limited. Commonly used sensors like inductive types cannot be utilized in this situation. Therefore, other categories need to be examined. The two main sensors that come in mind when sensing glass are touch probes and ultrasonic sound devices. In both cases the accuracy of those sensors is a main criterion for the evaluation. As mentioned by [1] the absolute position accuracy of the ABB IRB 2400/16 lies at around 0,3 mm, while the repeatability has a value of 0,03 mm. In order to get reliable results with the sensor, an accuracy of lower than this amount would be perfect for the application.

Ultrasonic sound sensors tend to have a quite unprecise accuracy most of the time. However, there are still products available, which have a precision in those small ranges required. The UM18 series of SICK has accuracy levels in a range that is still acceptable for the leveling application. For this case the UM18-2 Pro version was selected to be further examined. With a defined precision of about 0.069 mm, the sensor is just a little bit over the repeatability accuracy of the robot, which is acceptable in this case [17].

Furthermore, a touch probe sensor can be utilized to sense the glass plane. Commercial printers without a bed leveling sensor can often be enhanced with such a probe sensor in order to achieve an auto bed leveling result. In this case the probe sensor from ANTCLABS called BLTouch was chosen for further examination. This simple sensor can reach a precision of around 0.01 mm [18]. In this case the accuracy is way better compared to the ABB IRB 2400/16.

In order to compare the two sensors and find out which of the two is more reliable for the operation, a small 3D-printed measuring station was used. In this station, the ultrasonic and probe sensor were installed and teached on a fixed distance. After that, a wall was slowly moved towards the sensor leading to an activation of the digital output. Subsequently the distance was measured and repeated numerous times. Using a normal distribution, the results were visualized and compared. The actual diagram can be seen in Figure 7. As expected, the touch probe provides the better reliability compared to the ultrasonic sensor on a fixed distance. Even though, the ultrasonic sensor has the advantage of sensing the bed at a safe distance, a more reliable and precise sensor is a more important factor in this case.

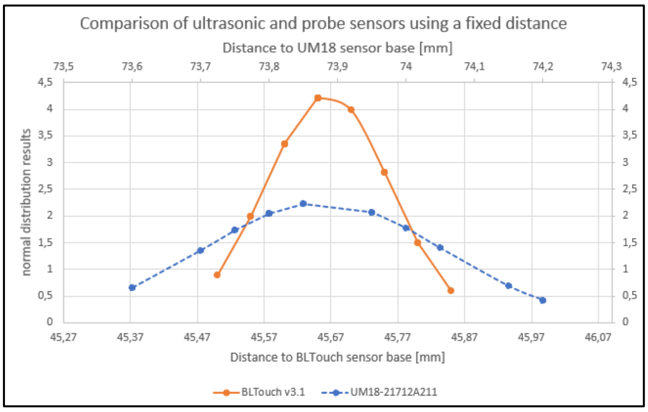

Figure 7. Comparison of ultrasonic and probe sensors using a normal distribution

4.2. *Probing algorithm*

To properly achieve an automatic bed leveling process, an algorithm needs to be realized. As mentioned before, the print bed isn’t shaped like a commercial printing area. Therefore, a simple level algorithm cannot be applied in this case. Hence the actual print area needs to be separated in smaller sections, on which the leveling can be achieved normally. In order to achieve that, a grid, the size of the slicer volume, needs to be pictured on the current print bed. This results in a lot of probe points depending on the fineness of the grid. However, some of the probe results are not on the actual print bed and need to be marked as invalid in this case. The remaining cross sections are therefore valid probe points and can be used for the actual leveling algorithm. Because the probing of such a huge grid will take quite a long time, the grid fineness needs to be a variable factor in order to reduce it. A finer grid will lead to a lot of points being measured using the robot. The bigger the grid distance becomes, the fewer points need to be probed, but the actual result will not be as precise. The basic concept of the probing algorithm with the specified grid can be seen in Figure 8. It is also visible that an additional reference point needs to be set up in order to calculate the x and y positions of each probe point on the print bed.

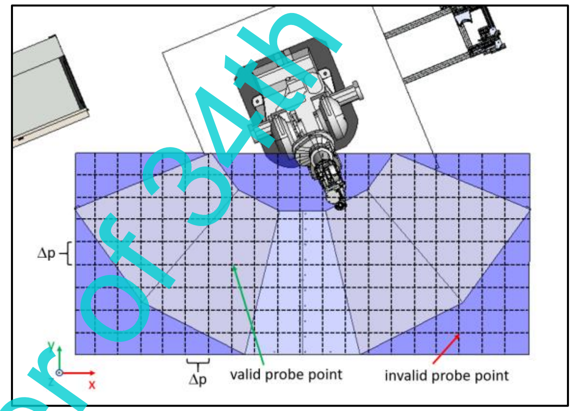

Figure 8. Probing grid algorithm concept

4.3. *Adjustment of the G-code*

The result of the probing algorithm should be a lot of points with different z-values according to the sensor readings. Those results need then be applied on the actual G-code itself. Because each G-code line is a target for the robot to reach, those targets can then be adjusted according to the leveling results. As mentioned, a grid gets projected above the print area. Each G-code target will sit somewhere in a square that results from the projection of the gird. Therefore, a bilinear approach [5] can be applied to edit the z-value of the appropriate G-code target. This approach needs to be repeated for every target that exists in the converted G-code. The result will be a leveled object on the print surface.

4.4. *Leveling on a curved surface*

Leveling 3D sliced objects onto a curved surface requires some additional problems that need to be solved. According to Guo et al. [15] any 3D surface can be flattened into a 2D plane. This approach then needs to be applied on the surface on which it is going to be printed on. Furthermore, the normal bed leveling algorithm needs to be expanded to handle curved surfaces. What this means is, that the different probe points which result on the flattened surface need to be projected back to the surface of the object as described by Luo & Tseng [16]. After that the probing needs to be achieved with the appropriate orientation of the nozzle resulting from the curvature. The position of the extruder and in this case also from the sensor needs to be orientated accordingly in order to not scratch or even destroy the surface or object. After that, the G-code, which was sliced on a plane, needs to be adapted with the new z-values resulting from the curved surface leveling. Each point between the projected grid points needs to be interpolated not just for the z-value but also for the orientation between the four neighboring grid points. Therefore, the grid on a curved object needs to be as fine as possible to reduce orientation errors. This complex procedure then needs to be programed and executed using RoboDK, which itself creates a whole new number of problems, resulting from the application programing interface (API) limitations.

5. Practical realization

The actual implementation of the leveling process requires different tasks to be solved. Those include mounting options, sensor readings, the RoboDK API implementation as well as handling the actual robot movements without damaging the surface of the print area. Additionally, the results of the leveling process need to be implemented in the current operation of the 3D-printing station without changing the procedure.

5.1. Sensor mounting and output reading

The BLTouch sensor consists of a base body and a pin that gets extracted to a probe position. If the pin gets pushed in, the sensor outputs a signal. The actual length of the pushed pin is 6.6 mm [18]. Therefore, the sensor needs to be mounted in such a position in which it can detect the surface before the nozzle touches the glass and retract behind the nozzle in order to not disturb the actual printing process. Because the maximum reach of the probing pin is such a small length, the mounting needs to be very precise. Additionally, the pin needs to be pushed in approximately 1 mm to send the signal. According to ANTCLABS [18] the sensor needs to be placed at around 2.3 to 4.3 mm behind the nozzle to achieve good results and not disturb the printing operation. Therefore, a mounting plate was constructed which can be fixed onto the Noztek Xcalibur assembly. The actual mounting solution can be seen in Figure 9. It is also important to mention, that the touch distance and actual trigger distance are marked with planes. The green one marks the distance at which the probe pin touches the glass, the red one marks the actual triggering distance of the sensor.

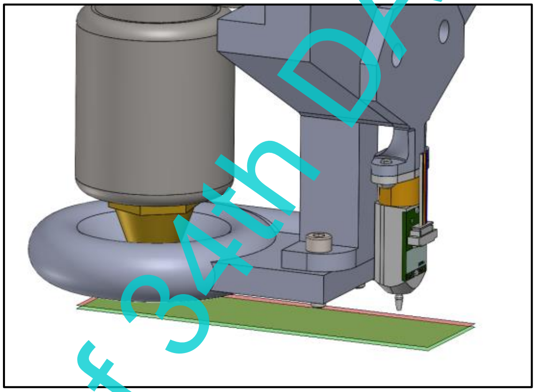

Figure 9. Mounting point on the Noztek Xcalibur extruder using a 3D-printed plate

To get the real z-value from the sensor, a small calculation of the resulting offsets needs to be applied. To better understand the mounting procedure, a graphical interpretation can be seen in Figure 10. Because the print bed surface isn't positioned perfectly even, it may occur that the teached in z-value of the bed is higher or lower than expected. Therefore, the subtraction of those offset measurements has to be done in order to receive the real z-value of the print bed at any given probe point.

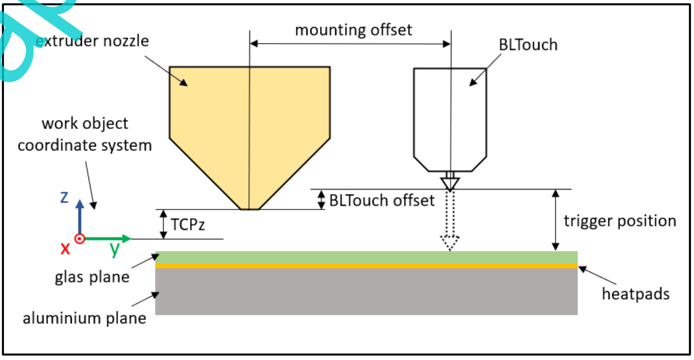

Figure 10. Interpretation for the different offsets occurring with the mounting of the sensor

To actually receive the signal from the BLTouch, an Arduino board needs to be set up appropriately. Therefore, a small script was implemented, which sends a serial command when the sensor activates via USB to the Laptop on which

RoboDK is running. The actual instruction to push the pin down and up again is achieved via PWM signals. Additionally, the script pulls the pin up as soon as the sensor triggers.

5.2. *RoboDK API implementation*

The actual leveling algorithm was implemented using the RoboDK C++ API. For that, the plugin which is already used for printing was utilized as a base for the implementation. The leveling process was programed in such a way, that the current plugin is not affected, if no leveling is applied. Therefore, an additional section was created in the interface for the user. The user has a few parameters which can be changed to perform the leveling process. These include setting the grid distance in mm as well as an offset to the border of the print surface. This is necessary because with a specific grid distance value it is possible to exactly place a probe point on the corner of the print bed, which would lead to bad results at that position. For this case, a fixed offset is already present, but can be changed according to the user.

With the parameters set, the actual leveling algorithm is set in motion. This is done using the "Calculate Leveling Mesh" button. On pressing the button, the leveling routine is called. The sequence starts with the mesh being created. Therefore, the grid distance is applied. With the mesh created, the actual probe points get calculated, depending on the offset defined. After that the leveling program gets created. This includes every probe point target on the print bed with the appropriate orientation to the robot as well as the offsets to the sensor and position on the surface of the bed. An example of the result visible in RoboDK can be seen in Figure 11.

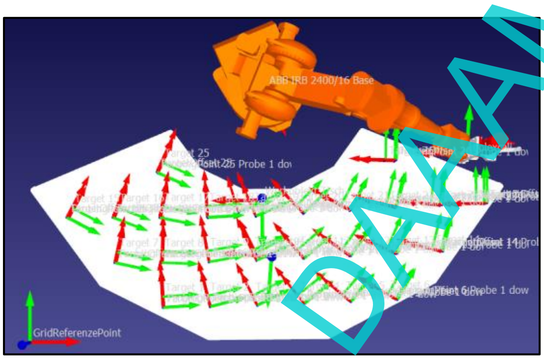

Figure 11. Top view of RoboDK with the resulting probe points of the leveling algorithm using a grid distance of 300 mm with an offset of 100 mm

One disadvantage that is present when using the RoboDK's C++ API is, that code can only be executed once and not during the whole operation of a task. If the function, which is executed on the press, doesn't finish, or stays in an infinite loop, RoboDK will be unresponsive or even crash. Therefore, a solution has to be found, in order to read sensor inputs during the operation of the robot. For this case, RoboDK supports python scripts [12]. Python scripts can be executed via the button press and can run during the operation of the actual leveling program. As soon as the leveling begins, a custom python script is launched where a connection to the sensor is being established. If the sensor detects the ground while probing, the current tool center point (TCP) value is used for further calculations. One constraint that occurred during the implementation on the robot was, that the TCP value cannot be read during the operation of the robot. This is because of the RoboDK communication socket only supporting one connection to the robot at a time. In order to overcome this problem, the simulation of RoboDK was used. TCP values can be accessed via the simulation even if the robot is currently executing a task. As a means to reduce simulation and physical TCP errors, the simulation was synchronized with the robot motion before each probing point. Therefore, the task was stopped before the next probe point, the simulation was synchronized with the real robot and after that, the task was continued. This results in the python script to receive the values from the simulation during the operation of the actual task being executed on the robot.

5.3. *Applying leveling results*

With the leveling results in place, it is possible to apply them to the actual G-code targets. If the user ticks the leveling checkbox, each target gets examined during the path planning algorithm for the robot. If the target is positioned between four neighboring points, a bilinear interpolation of the z-values is performed. This is done for every target resulting from the G-code. If the user positions the object way outside of the grid area, but still on the print bed, different edge cases are applied. Those basically include the outside area of each side from the grid. On such a case, the remaining points that are not in the grid get generated with a z-value of zero. Therefore, an interpolation to the teached in zero level is applied outside of the probe point area. This results in similar results as printing without the leveling in process.

6. Results

Following the implementation of the bed leveling system, different results can be examined. These include the deformation of the actual print bed, the appliance of the leveling results to the G-code and even the quality increase of the resulting objects printed with the system.

6.1. Print bed leveling results

Applying the implemented auto bed leveling system onto the real print bed, results in the actual deformation of the bed. Depending on the user defined values set in the interface, different results with an appropriate fineness are achieved. Even though a higher fineness results in a better leveled bed, the overall unevenness of the print bed is evident in every result. To better visualize the actual deformation, a leveling process was done using a grid distance of 150 mm which is a small step compared to the whole print bed. The results of the actual bed can be seen in Figure 12. As seen in the resulting bed structure, an offset range of about 3 mm occurs from the lowest to the highest point. It is also clearly visible that the area where the print bed was teached in, in this case the middle section of the bed, results in a negative value to the actual position. This behavior occurs because the teaching of the bed cannot be done perfectly by a manual approach. The further the probe points are away from the teached zero point, the more severe the unevenness becomes. Printing an object on the far side of the print bed to the left or right without using the leveling system would result in the nozzle touching or even damaging the glass. Printing in those areas would result in severe failures of the object at those areas. A proper fist layer adhesion in those areas would not be possible using a non-leveled bed.

Comparing a finer grid to a rougher probing setup shows that the overall unevenness is the same. Even though fewer probe points were applied, the interpolation allows to adjust the areas where no probing was done at all. The rougher the user defined grid is, the faster the actual algorithm is executed. The resulting grid with a grid distance of 300 mm can also be seen in Figure 12.

The same result can be seen on an even rougher grid setup, where the offset was set at about 450 mm. The result can be seen in Figure 12. This process took about 13 min to finish on the actual robot.

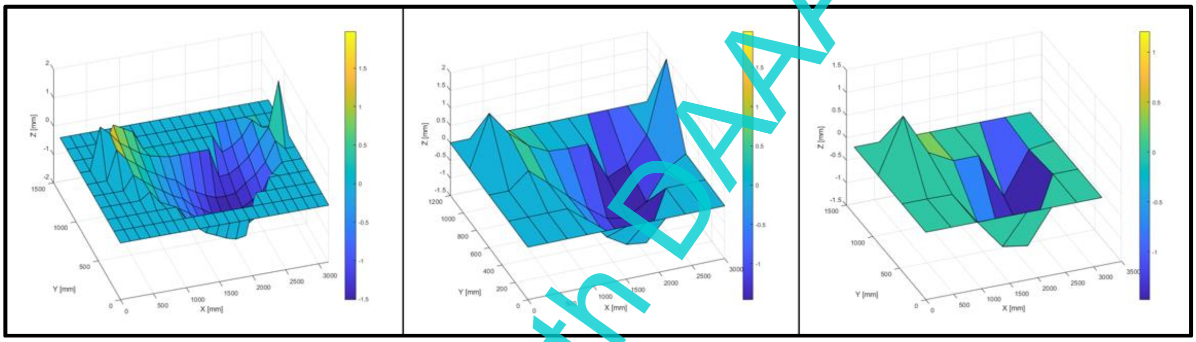

Figure 12. Bed leveling results, 150 mm grid distance (left), 300 mm grid distance (middle), 450 mm grid distance (right)

Even though a finer grid setup takes longer to execute than a rougher one, probed grids can always be used as many times as needed and don't need to be redone every time before the print. However, executing a probe setup after a specific time, for example when the temperature in the room heats up during summer, will result in more precise values than using a few month-old results.

6.2. G-code results

If the user decides to apply the latest bed leveling results onto the G-code, the interpolation process begins on pressing the calculate path button. Even though the interpolation is done using a lot of coordinate system transformations, the actual time difference is not relevant. A geometry with a high number of G-code lines was used to measure the differences. Calculating the robot motion without using the bed leveling results in a time of 19 minutes and 41 seconds. Applying the same procedure but using the leveling system with integrated interpolation results in a time consumption of 20 minutes and 3 seconds. The overall random-access memory (RAM) usage was the same for both procedures. It is to mention that simple structures with less G-code lines take just a few minutes to complete.

In order to see the results in the simulation itself, arbitrary numbers were written into the leveling results. Those numbers were set at high values to see the G-code bend around the different probe points. In reality, those numbers are so small that there is no difference visible in the actual simulation representation. Examining the simulation results with the respective real values however shows that even small probing results adjust the G-code. The arbitrary G-code manipulation with the self-defined values can be seen in Figure 13. In this case a simple circle structure was used to show the results. The curvature resulting from the interpolation of the different probe points is clearly visible.

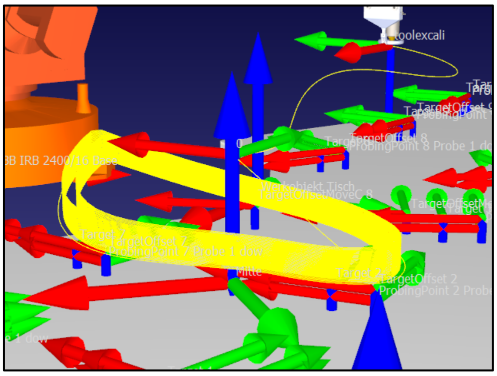

Figure 13. Applying arbitrary probe results to the G-code in the simulation

6.3. Printing results using the bed leveling system

Printing with the enabled leveling system allows the extruder to keep an almost constant distance to the actual bed. The extruded material can therefore stick better to the glass surface. Without the bed leveling system active, the extruder drops the material onto the surface without applying pressure, resulting in grooves between the lines. In order to visualize this effect, a hexagonal object was printed on the same spot with and without the system active. The results can be seen in Figure 14. The grooves or ripples occurring because of the high distance between the nozzle and the bed can be clearly seen. Keeping a constant distance with the leveling system, almost removes those ripples entirely. This in contrast increases the area of the object touching the bed resulting in a better adhesion property.

Figure 14. Surface between object and print bed (top: with bed leveling system, bottom: without bed leveling system)

Furthermore, using the standard extruder settings and applying the leveling systems, results in too much material being extruded. This is because of the height difference that occurs during the operation without the leveling in place. The station was optimized to perform well without the leveling system and is therefore extruding more material than actually needed. Printing with a leveled object results in the material being expanded and pushed away from the extruder. Hence the rotational speed of the extruder needs to be set to an appropriate amount. Figure 15 shows the difference between some extruder properties applied during printing. Using the normal value of 57 1/min results in ripples on the surface of the object. These ripples can be 1 – 2 mm high, which reduces the quality of the print. Printing with almost half the speed of about 30 1/min results in a much smoother surface, without losing the actual stiffness of the object. This is because the extruder keeps the optimal distance to the surface, resulting in less material needed, compared to a higher gap. Different rotational speeds were tested ranging from 15 – 30 1/min.

Figure 15. Print quality with different extruder rotational speeds (from left to right: 1: 57 1/min [standard speed], 2: 30 1/min, 3: 20 1/min, 4: 15 1/min)

Additionally, the lines which follow the first layers were examined using two different rotational speed values. As in Figure 16 depicted, printing with 15 1/min leads to the lines not sticking to each other whereas 25 1/min shows better results in this regard.

Figure 16. Printing lines difference (left: 15 1/min, right: 25 1/min)

As examined from the printing tests, using 30 1/min results in an almost optimal printing quality and adhesion characteristic. Reducing the parameter allows for less ripples in the first layers but reduces the line thickness in the following ones. Printing with less than 15 1/min using the bed leveling system would result in too little material being extruded during the process. However, using the system requires overall less material in order to gain an almost equal result.

Additionally, it has been examined that the layer height of a non-leveled print results at about 2 mm but should actually be 1.5 mm. This again is because of the gap between the extruder and the actual surface of the object. Comparing the layer height to a leveled object shows that they are at a constant 1.5 mm height throughout the object as it should be.

7. Conclusion and outlook

The implemented auto bed leveling system visualizes the uneven behavior of the customized print bed used in the Digital Factory of the UAS Technikum Wien. It allows the user to take advantage of the whole area which the bed provides, without sacrificing print quality because of deformations resulting from mechanical and thermal expansion properties. The resulting probe values clearly show the high amount of deformation happening at the sides of the print bed. Without a leveling system in place, printing in those areas would result in an unsuccessful print or even worse, to a damage on the glass on top of the actual bed.

Printing with the system active has shown that the actual surface area between the object and the print bed increases. Therefore, a stronger adhesion between the print bed and the object can occur. Using the system allows the extruder to keep an almost constant distance to the print bed. Because of this, the actual amount of material that was used without the system needed to be reduced drastically in order to achieve optimal results. Hence a material decrease of about 40 % was possible without sacrificing in print quality.

Applying the leveling approach on curved surfaces would result in a similar approach. The leveling needs to be adjusted according to the actual tilt of the probe point on the curved object. Planar sliced objects can then be projected via the resulting mesh on the actual object itself. In order to achieve the required adhesion properties on an actual object, a leveling system is unavoidable.

Even though the applied bed leveling system works for the defined print bed, applying it to curved objects still requires a lot of work to solve occurring problems. Additionally, ways to implement non-planar printing could be examined in future work. Furthermore, optimizations for different parameters like robot speed and extruder rotation could be examined resulting in an optimal operation during the print. The combination of a bed leveling system for plane and curved surfaces, as well as non-planar approaches during the print would result in a highly flexible station to create different kinds of objects for various applications.

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