Dynamic Path Generation via Load Monitoring with a Force Sensor for Robot Processing Using a Chisel

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Abstract –

A static path, pre-calculated as the tool trajectory, cannot reflect potential changing states during the machining process. Therefore, adjusting to environmental differences between the assumed and actual conditions, such as variations in the physical properties of the material, is not possible. In this study, the path was dynamically changed by monitoring the load applied to the tool during processing. Furthermore, applying our method to processing with a chisel demonstrates that parts can be machined appropriately via dynamic path generation.

Keywords –

Robot processing; Dynamic path; Wood carving; Force sensor

1 Introduction

In architecture, numerically controlled machining is becoming widespread for manufacturing building members. When machining a member, a static machining path, in which the trajectory of the tool tip is calculated in advance, is generally used. The machining path can be obtained by calculating the three-dimensional (3D) shape of the member, and the member can be accurately machined by combining with numerical control machining. However, when using a static path, the state of the workpiece being machined cannot be considered. Proper processing requires processing conditions according to the physical properties of the material; however, there are large variations in the physical properties of workpiece materials, such as wood. If there is a difference between the assumed and the actual physical properties, the pre-set machining conditions may not be appropriate, and machining may ultimately fail.

Among indices used to determine the state of the workpiece during processing, the magnitude of the load/reaction force applied to the tool is one of the better candidates. When an excessive load is observed, it can be inferred that an excessive force is being applied to the tool at that time and assess if it is within the range of appropriate processing conditions.

By using a force sensor, it is possible to measure the magnitude of the load and moment applied to the tool in real time. For example, when the tool overcuts a member, an excessive load is generated between the tool, which tries to follow a predetermined path, and shavings that oppose it. Furthermore, if the cutting amount exceeds the capability of the tool, the load applied to the shavings becomes excessive as the tool advances. If the path can be dynamically controlled while assessing the status during machining via load monitoring, a more appropriate machining can be realized.

In this study, by monitoring the load applied to the tool during processing using a force sensor and considering the logic for dynamic control that reflects the result in the path, we developed a dynamic path generation method. This method was verified via wood carving with a robot using a chisel.

2 Related research

In metal processing, in which the metal is a homogeneous material, there are examples of finishing techniques for the surface of parts, such as deburring and polishing, by robots using force sensors [1][2]. The force sensors are used for monitoring and fine-tuning the pressing force of the tool. In this study, we dynamically changed the path by using a force sensor to monitor the machining status.

There are also examples of using force sensors for wood carving using robots [3][4]. In such examples, to determine the parameters in wood carving, the movement and force during cutting by a human were recorded for machining using a vibration chisel. Furthermore, the machining path was optimized by modeling these data via machine learning. Based on this optimization, a cutting test was performed with a robot equipped with a vibration chisel and the machining parameters were determined. However, they targeted static paths as the processing paths, as opposed to the dynamic paths targeted herein. In this study, we aim to realize processing in response to variations in physical properties and in the processing environment by monitoring the processing status via load monitoring using a force sensor and dynamically changing the processing path.

3 Experimental set-up

The robot used in this experiment is shown in Figure 1, left. The force sensor was attached to the tip of the robot flange (Figure 1, right). This sensor can measure the force in three axes and the moment around those three axes. The measurable range is ± 200 N for force, which is approximately the payload of the robot, and ± 20 Nm for moment. At the time of installation, the coordinate system set on the flange of the robot was aligned with the directions of the force sensor measurement axes, and the normal line of the flange and the Z-axis of the force sensor were aligned.

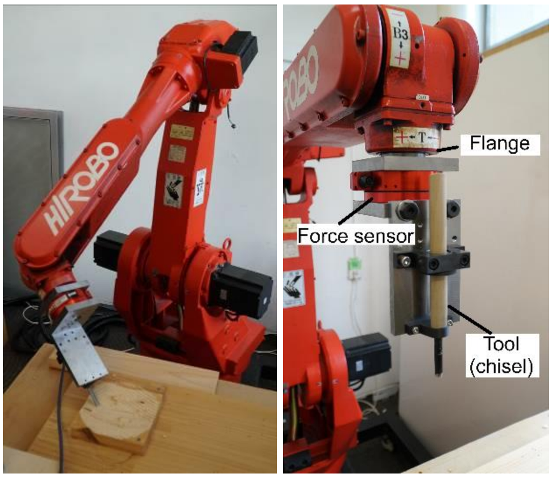

Figure 1. Robot (left) and tool set-up (right) used in this study

The tool held by the robot was a round-edged chisel with a width of 9 mm. A vibration chisel is an alternative tool for carving that can be machined with a relatively low load owning to the vibration of the blade. However, this vibration becomes a noise source for the force sensor measurement, which makes the load monitoring required for dynamic path generation impossible. Therefore, we did not adopt a vibration chisel. Instead, we built an adapter that enabled attaching a hand-held chisel to the robot and installed it at the tip of the force sensor.

4 Dynamic machining path

4.1 Machining path

The path required for machining consists of the trajectory (path), through which the tip of the tool passes during machining, and machining parameters, such as the feed rate and rotation speed of the tool blade. Because the path determines the movement of the tool for processing the member's shape, it is mainly determined based on the 3D shape of the member and limitations regarding the moving direction of the tool.

In this study, machining paths are classified into static and dynamic machining paths. In the former, pre-set paths remain unchanged from start to finish during machining. In the latter, paths change during machining.

The machining parameters may be manually changed by the operator during machining depending on the user interface of the machine. For example, when cutting, it is possible to operate the controller to reduce the feed rate override and increase the rotation speed of the tool blade. Such machining parameters can be easily controlled manually via the user interface; however, it is difficult to change the path manually on the spot because it is calculated based on the 3D shape of the member.

4.2 Dynamic machining path overview

A simple dynamic machining path control involves changing the feed rate according to the load applied to the tool. This method is effective for tools such as circular saws, drills, and end mills, which rotate the blade for machining. If the feed rate is reduced, the amount of cutting per blade of the tool is reduced, and the load on the tool is reduced. Therefore, low-load machining is possible without changing the machining path.

However, in the case of chisels, this method may not be effective. After the tool enters the workpiece, the load continues until the shavings are cut from the workpiece. This tendency does not change even if the feed rate is reduced. In other words, if an excessive load is applied during processing, it is necessary to change the path itself to avoid it. If the machining path is not appropriate, it can lead to tool or machine damage due to overload (Figure 2). Accordingly, if a certain amount of load occurs, such damage can be avoided by changing the path.

In addition, wood, which is often used as a workpiece, has anisotropic physical properties, and when processed along the grain, it may be deeply scraped along the fiber direction.

By monitoring the machining status via load monitoring using a force sensor, it is possible to dynamically change the machining path and perform an appropriate machining.

Figure 2. Excessive workpiece carving with improper machining path

5 Dynamic machining path logic

The process under a load-based dynamic machining path is as follows (Figure 3).

1. Generate the original machining path for machining the member.
2. Command the robot the position and orientation of the tool based on the generated machining path.
3. Monitor the load on the tool during machining with a force sensor.
4. When the load exceeds a set threshold, the machining path is recalculated and registered as the path to be executed next.
5. Repeat steps 2–4 until the original path, that is, processing of the member surface, is completed.

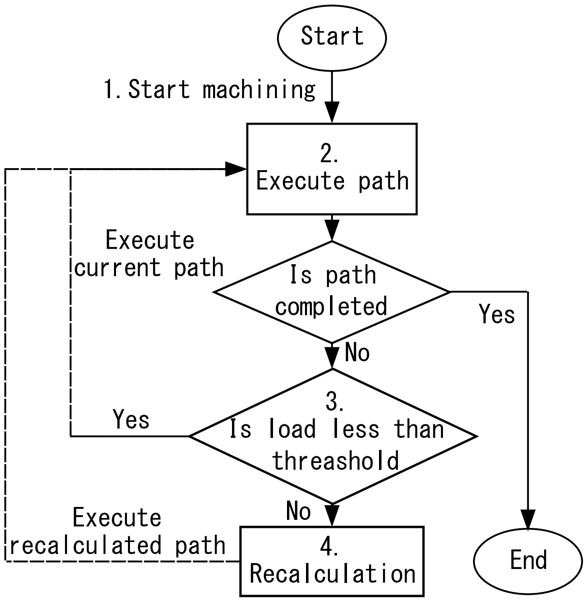

Figure 3. Machining flowchart under a dynamic machining path

In this study, the original machining path in step 1 was calculated based on the 3D shape of the member. The sampling rate of the force sensor was approximately 10 Hz, which is the execution cycle of steps 2–4.

The method of recalculating the machining path in the event of an overload may differ depending on the tool and the way to avoid overload.

For example, the machining with chisel in this experiment produces large shavings that are cut from the workpiece. Therefore, a method of processing a shallow position, that is, a position close to the workpiece surface, can be considered as a method of reducing the load. If the load is heavy, the path is recalculated and executed to handle a certain amount of the shallow part. If the recalculated path is still overloaded, a path to handle the shallower parts is calculated. This time, the depth, the position away from the target path, is managed, and the processing path completed when the original path could be processed without overloading.

If an overload condition occurs during machining, it is necessary to interrupt the machining path and correct the tool trajectory to reduce the load. This is easily realized by going back to the last processed path. The place where the tool passed is already machined and will not interfere with the tool, so it can pass safely.

In the processing with chisel in this experiment, when the load exceeded the threshold (step 4), the processing was set as follows (Figure 4).

a. Return along the machining path until the load falls below the threshold.
b. Recalculate the machining path. The recalculated path passes through a part shallower than the machining path that was being executed.

The above dynamic machining path logic was implemented as a robot control program. The control program determines the machining status while monitoring the force sensor measurement, and sequentially commands the robot to position and orient the tool according to the above algorithm.

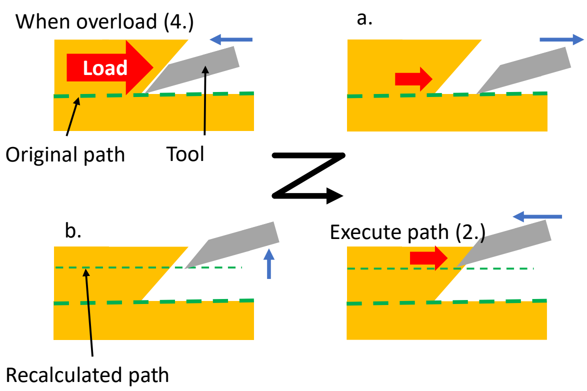

Figure 4. Processing path recalculation for chisel machining

6 Machining experiments

6.1 Load measurement and threshold setting

To set the load threshold value to be referred to in the dynamic machining path, a trial machining was performed with a static path that passes through a certain depth in a straight line. The machining result was observed while recording the load. In the Z-axis (tool-axis) direction of the force sensor, the load due to the weight of the tool acts as tension, and the reaction force from the workpiece acts as compression. From the test processing, we found that if compression is applied up to approximately 60 N in the tool-axis direction, it is a reasonable machining (Figure 5). Conversely, if a larger load is applied, excessive digging (Figure 6, top) or cutting occurs. This force was used as the threshold value for overloading during processing (at step 4).

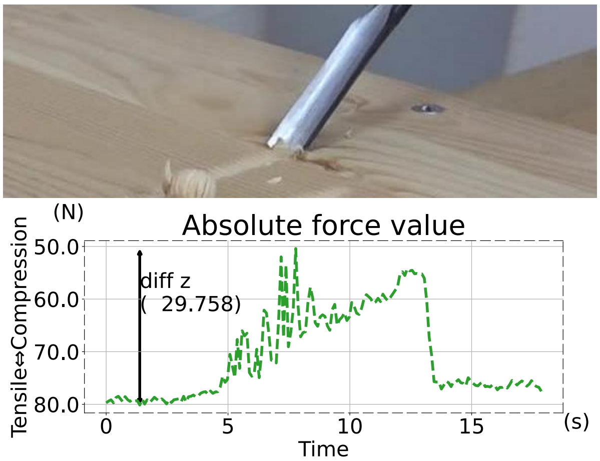

Figure 5. Low-load processing

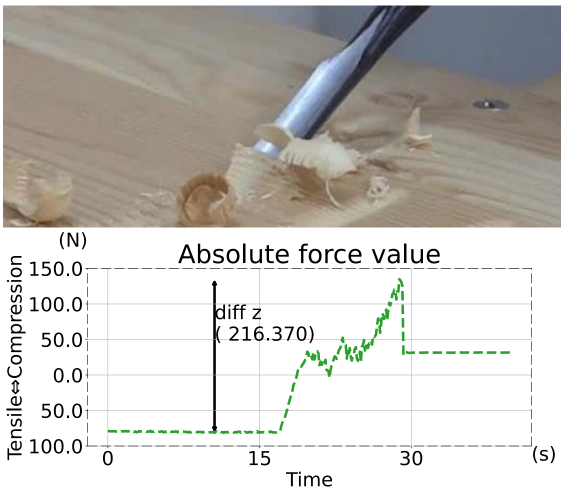

Figure 6. Above-threshold-load processing

6.2 Planar processing

As an experiment using a dynamic machining path, we performed machining on the work surface. The workpiece used was a single-plate laminated material. This processing was performed along the grain of the wood. The processing area was set to 50 x 200 mm, and depth was set to 2 mm. This width range was divided in the width direction by 4.5 mm, which is half the width of the chisel, and linear paths were arranged to form the entire path. Using the logic described in Section 5, in the event of an overload, the path is returned and recalculated so that the next path is 0.2 mm shallower. The processed product is shown in Figure 7. By detecting an overload, to avoid the excessive excavation of the blade that may occur when machining in the grain direction and the machining that results in an excessive amount of cutting that exceeds the capacity of the tool, the path is dynamically changed when the threshold is exceeded. It was confirmed that processing that could not be executed using the original path can be executed using the dynamically changed path.

Figure 8 shows a linear path movement during machining. The top and middle graphs show the position of the tool in processing and depth direction, respectively, and the bottom graph shows the load measured by the force sensor over time. The threshold is shown by the solid red line in Figure 8, bottom, and the areas where excessive load occurs are shown as horizontal shaded strips. If an excessive load is applied, it will return by a certain amount in the direction opposite to the direction of travel along the path (such as the arrow in Figure 8, top), and the overload is repeatedly, the path will be recalculated to process the shallower position (Figure 8, middle). This operation is repeated until the processing of the original path is completed. Throughout the planar processing, the path was recalculated approximately 360 times.

Figure 7. Planar processing result

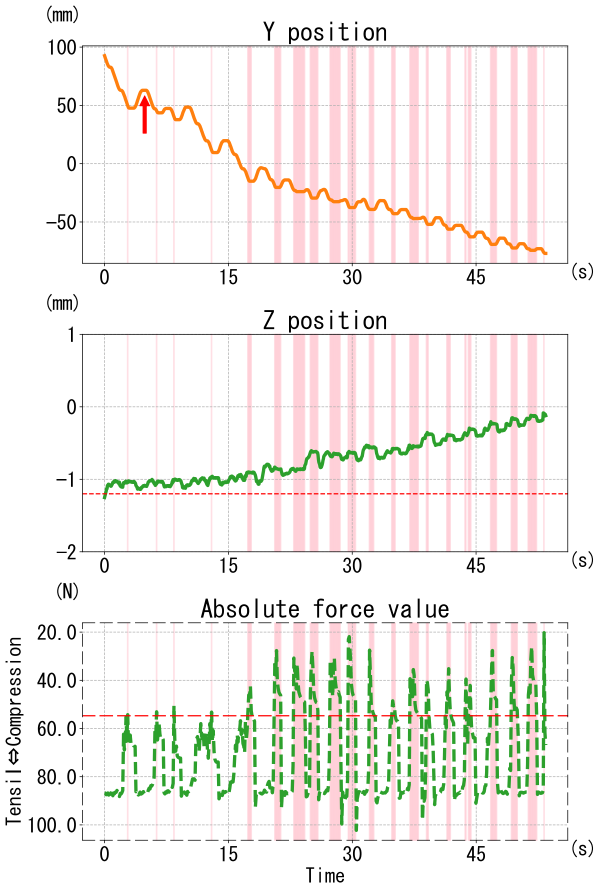

Figure 8. Tool movement under load. Top: tool position in the path direction; Middle: tool position in the depth direction; Bottom: sensor load in the Z-axis direction.

6.3 Bowl-shaped processing

Next, we conducted an experiment to process a bowl-shaped work surface. The work had a spherical dent with a diameter of approximately 120 mm and a depth of 8 mm, which was carved radially along the surface. In this experiment, lime wood was used. Considering the movable range of the robot, the path was divided into four, and the processing was performed while rearranging the workpieces. The calculated path moves the tool along the surface of the finished bowl. By monitoring the load and performing the machining while dynamically changing the path during overload, it was confirmed that machining can be performed without excessive cutting. The processed product is shown in Figure 9. The part orthogonal to the grain of the wood is slightly roughened, but it is generally well processed.

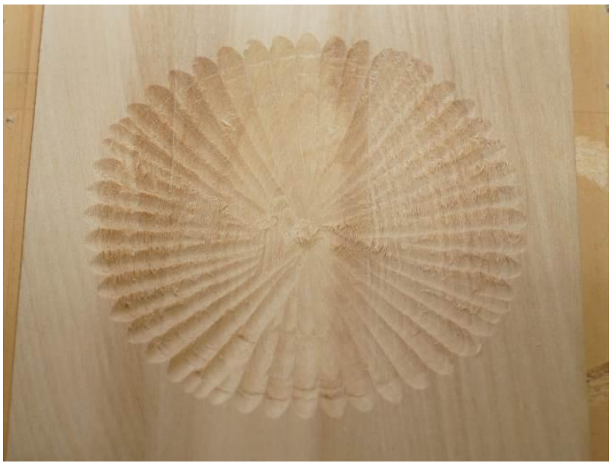

Figure 9. Bowl-shaped processing result

7 Conclusion

In this study, processing was performed using a chisel with a dynamic machining path. It was confirmed that the machining environment can be grasped via load monitoring using a force sensor, and that appropriate machining can be performed by dynamically changing the path. Furthermore, as a countermeasure against overload, we adopted a method in which the path is changed shallowly to reduce the load. However, it is also possible to change the posture of the tool according to the magnitude of the load.

It was also found that even a tool used by humans, not a blade dedicated to a processing machine, can be used by a robot with dynamic control. Because the cutting marks of the blade may be evaluated as a unique texture, we would like to expand the range of applicable blade types in future work.

Acknowledgment

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