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A Multi-Component Automated Laser-Origami System for Cyber-Manufacturing

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Abstract. Cyber-manufacturing systems can be enhanced by an integrated network architecture that is easily configurable, reliable, and scalable. We consider a cyber-physical system for use in an origami-type laser-based custom manufacturing machine employing folding and cutting of sheet material to manufacture 3D objects. We have developed such a system for use in a laser-based autonomous custom manufacturing machine equipped with real-time sensing and control. The basic elements in the architecture are built around the laser processing machine. They include a sensing system to estimate the state of the workpiece, a control system determining control inputs for a laser system based on the estimated data and user's job requests, a robotic arm manipulating the workpiece in the work space, and middleware, named Etherware, supporting the communication among the systems. We demonstrate automated 3D laser cutting and bending to fabricate a 3D product as an experimental result.

1. Introduction

Advanced technologies have led to many innovations in the manufacturing industry such as productivity enhancement by automation technology, facility enlargement by information communication technology, and quality improvement and product diversity by manufacturing process technology [1][2][3]. Employing their innovations, the manufacturing industry is proceeding towards producing customized and high quality products at low costs.

3D printing technology is emerging to lead the manufacturing industry. However, additive-type 3D printing has some shortcomings like long process times, unhealthy powder additives, and limit to product sizes. In order to resolve these issues, a laser origami technology has been introduced [4]**.** It rapidly manufactures customized 3D creatures by using a laser to cut, bend or fold sheet material. However, manually operated bending processes require a human operator to perform and monitor the whole process. As the switching between cutting and bending processes is performed by a human operator, he or she can be exposed to hazards caused by the laser. Moreover, it takes significant amount of time to find the proper intensity of a laser beam and feed rate of a laser head by trial and error. Also, the experience level of the operator can affect the quality of the product due to poor intensity and feed rate. It can be difficult to guarantee the quality of the product with manually bending.

On the contrary, the proposed feedback-based automatic laser fabricating system can not only assure the safety of a human operator, but it can also reliably repeatedly reproduce high-quality products.

Even more, considering the scalability of the automatic system, massive and customized production with high-quality is enabled.

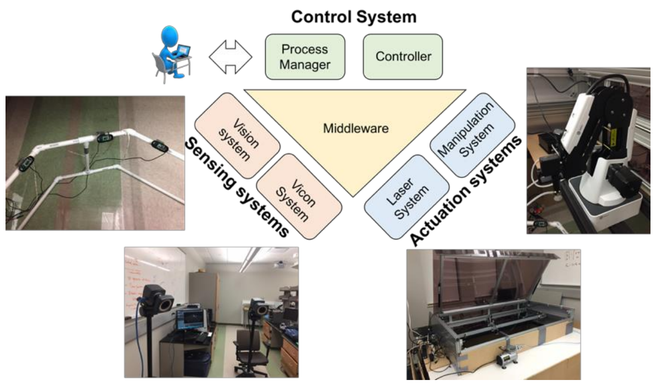


Figure 1. The overview of an automated laser origami system based on middleware.

We propose an automated laser origami system for cyber manufacturing. Figure 1 shows the overview of an automated laser origami system based on middleware. A sensing system with cameras monitors the status of the manufacturing process and a control system controls the feed rate of a laser head, the intensity of a laser beam and the position of a robotic arm based on the feedback information from the sensing system to operate cutting and bending processes, automatically. Middleware enables laser, sensing and control systems, which are connected over a network, to communicate with one another by sending and receiving messages. It can also support component-based development which offers simple quick deployment, easy extension, and maintenance. We validate the proposed system by experimenting with laser cutting and bending in a real laser origami system.

2. Related works

Balkcom et al. [6] extended some well-known necessary conditions for origami patterns to be flat-foldable, such as Kawasaki's theorem, Maekawa's theorem, and Meguro's theorem, for automatic planning and folding manipulation, and presented the world's first origami folding robot through a video. However, all processing was open-loop so that the number of foldings was limited due to the accumulated errors in the frictional insertion of the paper into the slot and in the positioning and grasping of the paper. Namiki and Yokosawa [7] achieved a feedback-based robotic origami folding in a real system. They extracted dynamic motion primitives from a valley folding process and experimentally demonstrated valley folds twice in a row in real time by using 3D visual and force-torque information and a physical simulation model. On the other hand, there was still a limit to the kind of a material that could be only a flexible sheet, like a paper. Tanaka et al. [8] analyzed the difficulty of the origami folding tasks by decomposing them into subtasks, and defined the levels of difficulty for each subtask. Based on observation of manipulation by humans, they designed a four-fingered origami folding robot and achieved folding of the Tadpole. However, their system was able to manipulate only a material similar to paper, and required online teaching by humans (i.e., semi-automatic) to generate the trajectories of the hands to fold a paper. Mueller et al. [4][5] suggested a prototyping system which could manufacture a 3D object by using a regular laser cutter. A laser was defocused to heat a desired region on the surface of a workpiece until it was bent or stretched to produce a 3D object. They proposed three design elements by using LaserOrigami and presented various 3D creations such as a card holder, a suspender, and a pen holder, which were manufactured by LaserOrigami without manual assembly. However, the open-loop process required an operator to supervise the bending process to achieve the desired angles.

3. Etherware

Conventional manufacturing machines have usually been operated and monitored by onsite supervisors and there have been difficulties in changing or expanding their system configurations. On the other hand, middleware offers extensibility and remote controllability to cyber manufacturing. Customized cyber-manufacturing needs heterogeneous manufacturing machines to cater to the convenience and requirements of customers. Component-based middleware enables the management of various kinds of devices which allows dynamic system configuration. Employing a remote control, supervisors do not need to stand by machines to manage and monitor them. They can operate the whole system with graphical user interfaces in real time based on the streams of sensing information and control commands over a network.

We have implemented the system over Etherware which is a middleware developed in our prior work [10]. Etherware has been developed to support a rapid, reliable and evolvable application development. Figure 2 describes the architecture of Etherware.

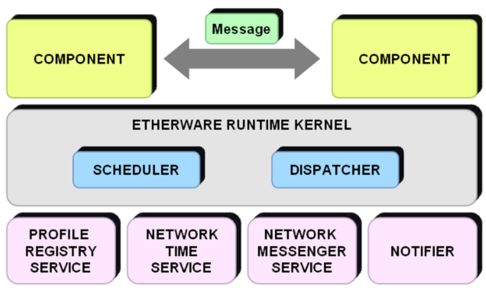


Figure 2. The architecture of Etherware.

The kernel of Etherware is designed with micro-kernel architecture which consists of a scheduler and a dispatcher. A scheduler manages messages requested by components and a dispatcher executes the messages transferred by the scheduler. There are three Etherware services: Profile Registry Service (PRS), Network Time Service (NTS), and Network Messenger Service (NMS), which provide communication networking among components. PRS allows semantic naming of components. One component can send a message to another component with the profile name of the destination component instead of its IP address. NTS deals with the clock differences among different computing devices to synchronize their events. It calculates the time offsets of the computers and translates the timestamp of the received message into local time. NMS manages the network connectivity among computers and handles message delivery over the network. It uses an XML format to transfer messages so that a developer can easily define type and contents of a message to be sent.

4. Middleware-based system integration

Current machine tool monitoring technologies are mostly limited to using static or well-accessed wireless sensors. Recent advances in mobile communications and computer vision algorithms offer a radically new approach for real-time process control and quality assurance. We have built a multi-component manufacturing system centered around a laser processing machine. The network architecture for the manufacturing system offers considerable advantages for custom manufacturing systems. For the system integration, Etherware was used to implement the networking among the individual system components. The middleware enables control over a communication network and computations can be carried out elsewhere in the cloud with seamless migration.

Figure 3 shows the feedback-based laser origami system. All systems are connected over Ethernet and communicate with each other by Etherware which supports message-based communication. The kernel of Etherware, which is run in each computer, executes components, and the profile registry service of Etherware provides a semantic naming service with the profile table mapping IP addresses of computers and IDs of components which are assigned by the kernel to the profile names of components. For example, a Vision Sensor component can send a message containing the bending angle to a Controller component by using only its name 'Controller', instead of the IP address of the computer which the component is running on. Networking among the system components enables the scalability of the system, Etherware supports component-based application developments and facilitates not only the development of the individual system components, but also system integration, management, and maintenance.

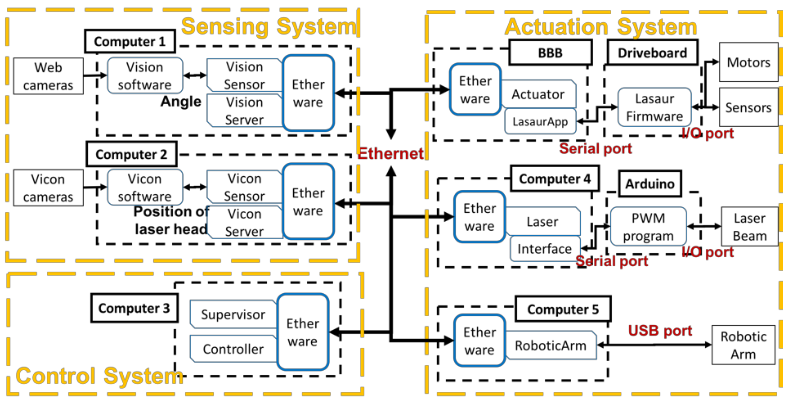


Figure 3. The system configuration of the automatic laser origami control system based on middleware.

The proposed automatic manufacturing system consists of three subsystems: a sensing system, a control system, and an actuation system. The sensing system observes the status of the process and provides observed information to a control system. For the sensing system, we have used two individual vision systems consisting of a multi-camera vision system which finds the bending angle of the workpiece during the bending procedure, and a Vicon system which finds the position and velocity of the laser head. Vision and Vicon sensor components obtain observation data from image processing programs, and Server components deliver them to a Controller component.

The control system has a supervisor as a high-level process manager and a bending controller. The supervisor receives the list of tasks from an operator and sends each task to a bending controller or an actuator system. With the exception of bending tasks all tasks such as cutting tasks or motion tasks of a robotic arm are executed by the actuator system directly because they do not need any feedback. When the current task is a bending task, it is executed by a bending controller. Once the bending controller receives the desired angle, it determines Gcode-type commands describing the intensity of the laser beam, and the feed rate of the laser head, based on the feedback from the sensing system, and sends them to the actuator system.

The actuator system plays the role of moving the laser head, regulating the intensity of the laser beam and manipulating the robotic arm. It executes the sequence of gcodes received from the high-level process manager and the bending controller to manufacture a 3D product from a sheet material by cut-bend-fold operations.

5. Feedback control scheme for laser bending

A feedback-based laser bending control system has shortened manufacturing lead time. Since manual operation for laser bending uses constant intensity of laser beam and feed rate of laser head throughout the whole bending process, it demands much trial and error to find the best heating policy manually. Especially, in the case of the changes of some parameters such as kind of work sheet or length of a bending line, a new heating policy will need to be found by trial and error. Feedback-based control system automatically deals with those issues. Based on the latest observation data, a control policy determines control inputs such as the feed rate of laser head and intensity of laser beam every control period, so that it not only accomplishes fast bending, but also prevents overheating which can degrade the quality of the bending process.

For laser bending, the feedback system controls the feed rate of the laser head and the intensity of the laser beam. A PID controller determines control inputs based on the desired angle from a supervisor component and the previous bending angle from the sensing system.

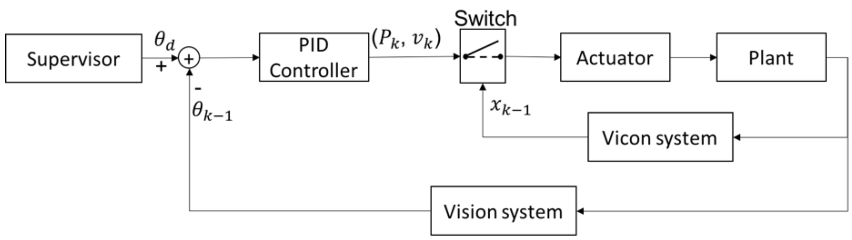


Figure 4. The control scheme for laser bending.

Figure 4 shows the control scheme with a PID controller for laser bending, where θ_d is the desired bending angle, θ_{k-1} is an observed bending angle at time $k-1$, and P_k and v_k are the intensity of a laser beam and the feed rate of a laser head, respectively, at time k. Let $e_{k-1} = \theta_d - \theta_{k-1}$ denote the error of the bending angle at time $k-1$. The PID controller for calculating the desired derivative of the intensity of the laser beam ΔP_k is designed as

$$\Delta P_k = k_{P_P} \cdot e_{k-1} + k_{I_P} \cdot \sum_{i=0}^{k-1} e_i \cdot dt_i \quad + k_{D_P} \cdot \left(\frac{e_{k-1} - e_{k-2}}{dt_{k-1}}\right) - P_{k-1}, \tag{1}$$

where k_{P_P}, k_{I_P} and k_{D_P} are the proportional, integral and derivative gains, respectively. The intensity of the laser beam at time k is determined as

$$P_k = \begin{cases} P_{k-1} + P_{step}, & if\ \Delta P_k > P_{step} \\ P_{k-1} + P_{step}, & if\ \Delta P_k < 0 \\ P_{k-1}, & otherwise \end{cases}, \tag{2}$$

where P_{step} is the step size for increasing or decreasing the intensity of the laser power. In order to design a controller for the feed rate of the laser head, let $\dot{e}_{k-1} = (e_{k-1} - e_{k-2})/dt_{k-1}$ denote the derivative of the error of the bending angle. The derivative portion of the controller for calculating a desired derivative feed rate is designed as

$$\Delta v_k = k_{d_v} \cdot (\dot{e}_{k-1}) + v_{base} - v_{k-1}, \tag{3}$$

where k_{d_v} is a derivative gain and v_{base} is the minimum feed rate. The feed rate of the laser head at time k is determined as

$$\mathrm{v}_k = \begin{cases} v_{k-1} + v_{step}, & if\ \Delta v_k > v_{step} \\ v_{k-1} + v_{step}, & if\ \Delta v_k < 0 \\ v_{k-1}, & otherwise \end{cases}, \tag{4}$$

where v_{step} is the step size for increasing or decreasing the feed rate of the laser head. The control inputs P_k and v_k are delivered to an actuator component every control interval. The control interval is determined as

$$dt_k = \frac{2 \cdot L_{bending}}{v_{k-1}}, \tag{5}$$

where v_{k-1} is the previous feed rate of the laser head and $L_{bending}$ is the length of a bending line. This means that the control interval is varying during bending control process. When the previous feed rate of the laser head is slow, the current control interval is long. Conversely, a fast previous feed rate makes the control interval short. A flexible interval enables the control decision timing to adapt to the status of the bending. For example, when the angular velocity of bending is zero, the bending line is heated up radically with slow feed rates of the laser head. When the unfixed segment of the part starts falling down, the bending angle is controlled more frequently with fast feed rate of the laser head. This allows achievement of more precise bending, even mid-air stopping at 60 degrees.
The switch obtains the position data of the laser head from a Vicon system to check if the back and forth movement of the laser head is completed. When the laser head returns back to the starting position, the next control input is delivered to the actuator. According to the actuator's output signals, the laser system bends the material by the movement of the laser head and the heat from the laser beam. When the bending angle reaches the desired angle, the bending process is terminated.

6. Experiment

The experiment of evaluation validates the performance of the proposed feedback-based control system for cyber-manufacturing. Existing laser bending processes require an operator to manually repeat the sending commands to heat the bending line or stop the bending process while monitoring the status of the bending angle. This has several inherent issues such as the separation of the bending process from cutting processes, the possibility of overheating caused by human errors, the dependency of the process performance on the skill level of the operator, and repeated trial and error experimentation to obtain better performance. On the other hand, the proposed feedback-based control system eliminates the need for an operator to carry out the repetitive tasks. Moreover, it results in uniform and proper heating, and minimizes the deformation of the bending line by controlling the heat output of the laser and the velocity of the laser head in real time. It results in high performance and quality of the bending process. The performance of the proposed system is compared with that of a manually bending system.

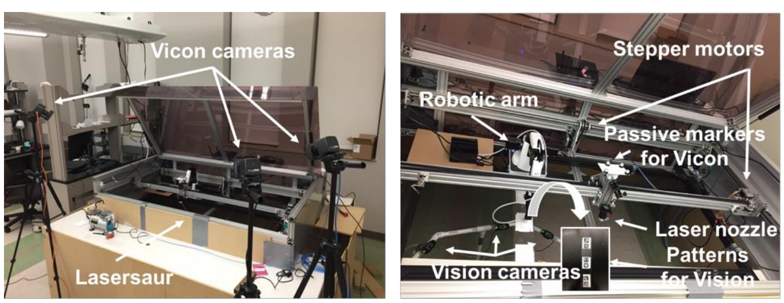
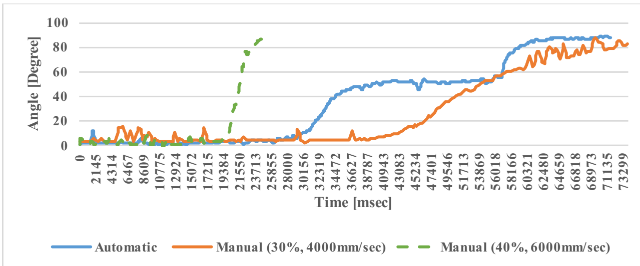


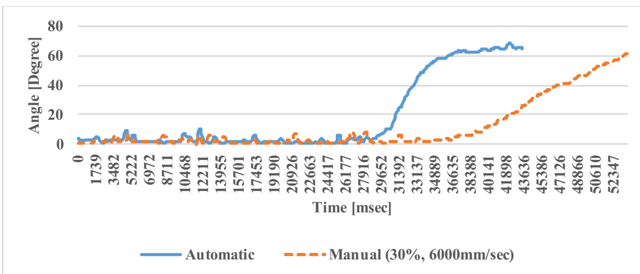
Figure 5. The overview of the experimental testbed.

6.1 Testbed

The figure 5 shows a feedback-based laser origami control system which controls a laser system to manufacture a 3D product by cut-bend-fold operations with a sheet material. The cyber-manufacturing system consists of a vision system estimating the state of the workpiece, a Vicon system observing the position and velocity of a laser head, a control system determining Gcode-type control inputs to a laser system based on the estimated data and user’s job requests, a robotic arm manipulating the workpiece, and a laser system processing the workpiece with an incremental forming tool and a laser source.



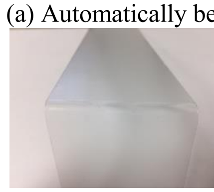
(a) 90 degree bending



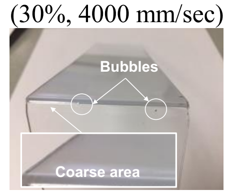
(b) 60 degree bending

Figure 6. The comparison of the performances of automatic bending and manual bending from the viewpoint of completion time.

(a) Automatically bent



(b) Manually bent (30%, 4000 mm/sec)



(c) Manually bent (40%, 6000 mm/sec)

Figure 7. The comparison of the performances of automatic bending and manual bending from the viewpoint of quality of bending.

The laser system is Lasersaur [11]. Its maximum laser power is 120W. It has two stepper motors to move a laser head with the maximum speed 6000 mm/min on the work area 1220 x 610 mm. The resolution of the movement of a laser head is less than 0.1 mm.
The robotic arm is Dobot magician [12]. It has 4 degrees of freedom. It can move the end effector along the x, y and z axes in the work area which have dimensions, 340 x 300 x 400 mm, and rotate up to 270 degrees. The payload is 500 grams.
A multi-camera vision system uses three web cameras whose resolution is 640 by 480 pixels. The cameras detect two dimensional barcode pattern patches which are attached on the surface of the workpiece. The vision program calculates the angle between the two planes, defined by the patterns, every 150 milliseconds. Moreover, we used three Vicon cameras, which are LED cameras, to detect the shape of a group of small balls on the top of the laser head every 100 milliseconds. The information is used for the control system to determine when the control commands should be executed because of the varying control period during the bending procedure.

6.2 Automatic cutting and bending

We experimentally demonstrate that the proposed system noticeably improves the performance of the process and the quality of the product. Figure 6 and figure 7 compare the performances of those manually bent versus those automatically bent, with respect to completion time and quality of bending. Figure 6 describes the graphs of the bending angles according to time. The dimension of work piece used in the experiment was 355 x 70 x 1 mm. The length of the bending line was 100 mm, which was longer than the width of the work piece to avoid overheating at both end sides by laser. The focal distance from the laser nozzle to the work piece for bending was 150 mm. For the manual bending, we used two pairs of static intensities of the laser beam and feed rates of the laser head because the nonlinearity and uncertainty of the bending model make it very hard to find the optimal combination of various intensities and feed rates manually. They are 30% with 4000 mm/sec, and 40% with 6000 mm/sec. For the automatic bending, the parameters of the PID controller were tuned by trial and error due to the nonlinearity of the system model. The gains of the PID controller for controlling laser intensity, k_{P_P}, k_{I_P} and k_{D_P} are 0.1, 10 and 0.002, respectively. The step size of increasing or decreasing the laser intensity, P_{step} is 10%. For controlling the velocity of the laser head, the derivative gain, k_{d_v} the minimum feed rate, v_{base} and the step size of the feed rate, v_{step} are set as 2000, 3000 and 1000, respectively.

In figure 6(a), when we used the pair of 40% and 6000 mm/sec, the bending angle, shown by the big dotted line, dramatically reached the desired degree with 8 back and forth laser heatings. However, figure 7(c) shows that radical heating by the strong laser beam degraded the quality of the bent surface by causing some bubbles and coarse area. Likewise, although figure 7(b) shows that the manual bending with 30% intensity and 4000 mm/sec feed rate achieved high quality of bending surface, its completion time for bending was too long, which is indicated by the small dotted line shown in figure 6(a), with 20 back and forth laser heatings. Otherwise, the automatic bending, shown by the solid line in figure 6(a), accomplished an earlier completion time than manual bending with 30% and 4000 mm/sec as well as better quality of bending than manual bending with 40% and 6000 mm/sec in figure 7(a).

The high performance of the automatic bending is also shown in figure 6(b). Without a rotation machine, in order to reach a mid-air angle which is not 90 degrees, an operator needs to keep the checking current bending angle and stop the back and forth heating as quickly as possible when the current bending angle is near the desired angle. If the feed rate is set fast to minimize the response time, it also causes a delay of completion time. Figure 6(b) shows that the completion time of the automatic bending is much faster than one of manual bending with 30% and 6000 mm/sec, to reach 60 degrees.

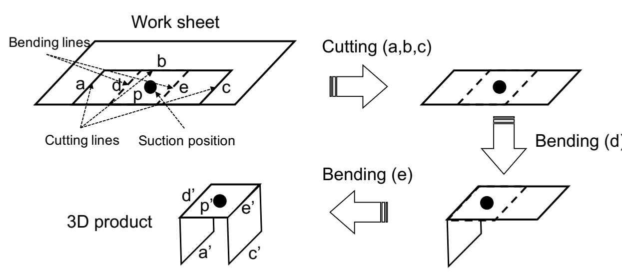


Figure 8. The procedure for 3 cutting and 2 bending processes.

We also demonstrate that the proposed automatic laser manufacturing system performs cut-bend operations effectively. An operator mounts a work sheet on the robotic arm and executes the gcode file which includes cutting and bending tasks. The system automatically manages and controls the whole process to fabricate a 3D-shaped creature. We used an acrylic sheet whose size is 355 x 279 x 1 mm. Figure 8 shows the entire procedure of cutting and bending.

An automatic laser fabricating system makes a simple 3D creation by performing 3 cutting and 2 bending processes. In figure 8 (a), 'p' is the holding position of the robotic arm, 'a', 'b' and 'c' are lines for cutting, and 'd' and 'e' for bending. At first, a laser system cuts the three cutting lines and then, bends along the two bending lines. For cutting, the robotic arm lifts the acrylic sheet up to the focal length of cutting. After cutting the three lines, the outer piece of the sheet is removed. As the bending process requires a long focal length of the laser to melt the bending line, the robotic arm lowers the sheet from the laser nozzle. The desired bending angle is 90 degrees for the both bending processes. During the bending process, a control system controls the bending angle to reach the desired value by sending control inputs such as the intensity of the laser beam and the feed rate of the laser head in real time. When the temperature of the heated region is high enough to melt the workpiece, the unattached portion of the workpiece is pulled downward by gravity, and multiple cameras measure the angle of the falling part and send the information to the control system as feedback. After the first bending process, the robotic arm rotates the workpiece to place the other side in the bending position. Once all cutting and bending processes are completed, we obtain the 3D product as in the Figure 8. The automatic two-sided bending experiment can be seen in [13].

7. Conclusion

We have proposed a feedback-based laser origami control system for cyber-manufacturing. We have established a sensing system and a control system around a laser system to operate the laser cutting and bending processes automatically to make 3D objects. We also integrated the robotic arm with a laser control system to switch between cutting and bending processes automatically due to their different focal distances. We experimentally demonstrate that our proposed automatic laser system successfully produces a 3D creation by cut-bend operations with short processing time and high quality of bending. Future work will include the anticipatory control based on the bending model to obtain fast and accurate bending control. We plan to design a laser bending model for an acrylic sheet by referring the analytic model, which one of the laser-bending literatures suggested to predict bending angle based on the knowledge about the thermo-mechanical process of laser bending [9]. Also, the temperature information around the area heated by a laser will be used to build a bending model to predict the future states of the bending angle. The anticipatory control is expected to reduce not only the lag effect of initial heating up, but also the inertia effect of final cooling down.

8. References

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