Enhancement of Agility in Small-Lot Production Environment Using 3D Printer, Industrial Robot and Machine Vision

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***Abstract* — For the diversification and individuality of customers' requirements, the multi-specification and small batch production is becoming the primary production model. More new technologies are adopted to enhance the intelligence and flexibility in traditional manufacturing environment. However, incompatibility between hardware and software architectures from different vendors, as well as high integration costs, hinder the application of such new technology. A flexible production line prototype is presented with the integration of 3D printer, industrial robot and machine vision. Firstly, a low-cost and open-source 3D printer was fabricated based on the fused deposition modeling technique. Meanwhile, a grasper was designed to automatically remove the printed part from the positioning platform. Secondly, an industrial robot picked the printed part and placed it into the storing box under the guidance of a machine vision camera. The whole system control depended on a programmable logic controller. Finally, an experiment was conducted to verify that this intelligent solution could enable highly flexible work cells and innovative manufacturing processes.**

Keywords - 3D printing; industrial robot;machine vision;intelligent manufacturing

I. INTRODUCTION

Owing to the diversification and individuality of customer satisfaction, the multi-specification and small batch production is increasingly becoming the primary production model. Although a mushrooming number of new technologies can be adopted to enhance the intelligence and flexibility in the traditional manufacturing model, incompatibility between hardware and software architectures from different vendors, as well as high integration costs, hinder the application of many new technology. For most plants, to retrofit the existing traditional manufacturing system is the first step toward the smart factory of the future. In the context of infusing agility into the existing manufacturing system, a great deal of research has been conducted by worldwide researchers. For example, Hu presented an affordable and more convenient way to add robotic devices into existing numerical control machine tools to enhance its intelligence, automation and flexibility [1]. Vinodh and coworkers found that the traditional industries can achieve agility and thereby acquiring global competitiveness through adopting CAD and 3D printer[2]. For small and medium-sized enterprise, Bi and his team underlined the significance of reusing, redesigning, recovering, remanufacturing, recycling and reducing in adopting industrial robots [3]. And their research illustrated that the capabilities and flexibility can be improved greatly by infusing low-cost modules into integrated robotic systems to accommodate specific needs. Navarro-Gonzalez et al. put forward a multimodal assembly controller method to embed and effectively enhance knowledge into industrial robots working in multimodal manufacturing scenarios such as assembly during kitting operations with different shapes and tolerances[4].

Generally for a concrete manufacturing scenario, its agility not only depends on the flexibility of every module, but also depends on the integration and connection of every module. For instance, 3D printing or additive manufacturing can produce incredibly complex products with minimal lead times and without raw material waste. However, to withdraw the printed part from the build platform, to remove the supports and to replace the filament are usually laborious. Additionally, the small and medium-sized enterprise also faces the cost and sustainability problem when considering the increase of intelligence and flexibility. Therefore the design concept and system framework are both playing a pivotal role when we use the 3D printer, industrial robot , machine vision and other enabling technology to enhance the system flexibility .

In this paper, we are interested in building a flexible production line prototype to produce the plastic toys with the integration of 3D printer, industrial robot and machine vision. First, we would mainly discussed the integration and connection strategies of the whole system. Furthermore, the 3D printer made by ourselves based on the open source system would be analyzed from the view of structure design and accuracy calibration.

II. SYSTEM STRUCTURE

As illustrated in Figure 1, the presented flexible system mainly embraced the following components:

A. 3D Printer

This 3D printer is made by ourselves based on the open source system. Its function is to transform 3D models into physical objects that received from the customers via the online tablet. We will discuss its design and accuracy calibration in more detail below.

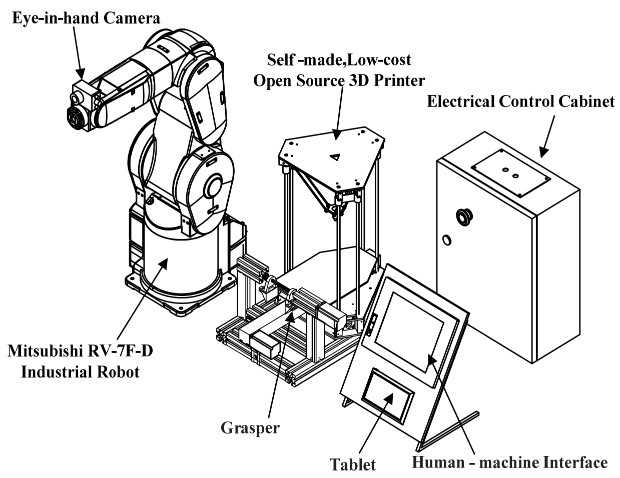

Figure 1. System configuration

B. Grasper

Once the digital model is printed over, the movable build plate will move back from the 3D printer and stop when reaching the target position against the limit witches. Then the grasper starts to close up and withdraw the part from the build plate. For a better view, Figure 2 gives the detail structure of the movable build plate and the grasper. The movable build plate is fixed on a linear slide module that is positioned by the QD77MS motion module from Japan Mitsubishi Electric Corporation. The grasper is actually improved through a two way automatic slide table which is also controlled by the QD77MS motion module.

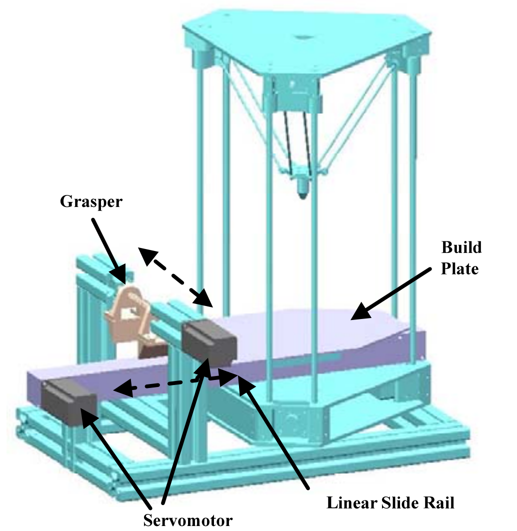

Figure 2. Specific view of movable build plate and grasper

C. Industrial robot

The six DOF articulated robot would pick the part and place it into the storing box under the guidance of an eye-in-hand camera. The model of the industrial robot used is RV-7V-D series from Japan Mitsubishi Electric Corporation. And the machine vision type is ISM1403-01 of COGNEX In-Sight series.

D. Control system

The integrated control of the whole system is achieved through the programmable logic controller (PLC). And the human-machine interface uses the touch screen operation.

III. SYSTEM ESTABLISHMENT

As mentioned above, the intelligence and agility or flexibility of a manufacturing scenario not only depend on the flexibility of every module, but also fall on the integration and connection of every module. Next we discussed the integration and connection strategies of the whole system. Figure 3 has given the basic connection and correlation among subsystems. Since the PLC, touch screen, motion module, servo drive, servomotor and industrial robot are selected from Mitsubishi Electric Corporation, they naturally have good compatibility and easy communication interfaces. Therefore, we mainly described the servo positioning system configuration, as well as the communication between the CONGEX camera and the Q series PLC.

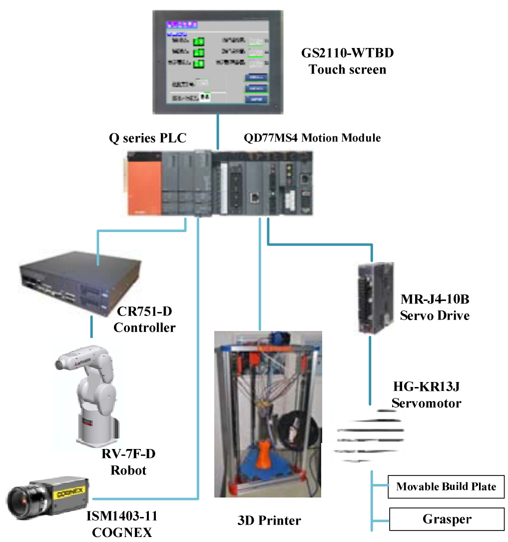

Figure 3. Connection and correlation among subsystems

A. Servo positioning

"Positioning" refers to moving a moving body, such as a component or tool, at an expected speed, and accurately stopping it at the designated position. As mentioned, the grasper and the movable build platform are controlled using

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the QD77MS motion module . QD77MS module performs positioning according to the user-set positioning data, which is a set of information comprised of the control strategies (position control, speed control, speed-position switching control), positioning address, operation pattern, and so on. The QD77MS can achieve complicated positioning control when it reads in various signals, parameters and data and is controlled with the PLC CPU. Parameters and positioning data for the QD77MS can be set using GX Works2 software. Moreover, using the test function of GX Works2,we also can check the wiring status and the availability of the predetermined parameters and positioning data by performing trial operation before creating a program for positioning control. The control monitor function of GX Works2 allows user to debug programs efficiently. The servo parameters can be set easily by using the GX Works2 in combination with the MR Configurator2. Meanwhile, the QD77MS can be directly connected to the Mitsubishi servo amplifiers of MR-J4-B series using the SSCNETIII cable (optical communication). Because the high speed synchronous network by SSCNETIII is used to connect the QD77MS and the servo amplifier, or servo amplifiers, saving wiring can be realized [5]. By the use of SSCNET, influence of electromagnetic noise and others from servo amplifier, etc. are diminished. In addition, the servo parameters can be set on the QD77MS side to write or read them to/from the servo amplifier using the SSCNET communication.

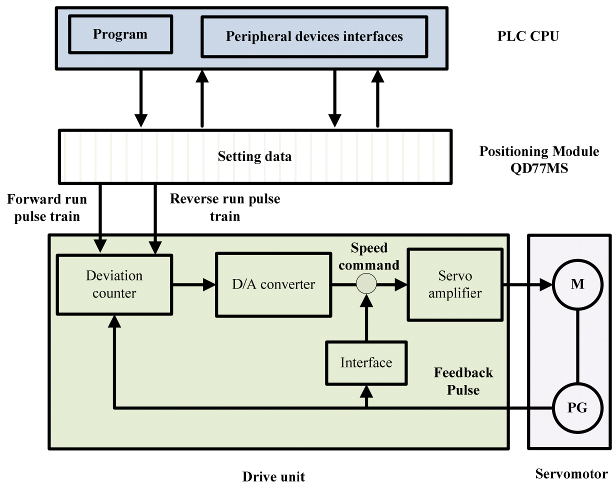

Figure 4. Outline of the positioning operation of QD77MS

As illustrated in Figure 4, QD77MS module controls the position with the "total number of pulses in a pulse train", and the speed with the "pulse train frequency". The above "total number of pulses in a pulse train" is an element required for movement distance control, but when carrying out positioning control or speed control, the speed must also be controlled. This "speed" is controlled by the "pulse train frequency". Therefore, when a movement amount per pulse is given, the overall movement amount can be determined by the number of pulses in the pulse train. The pulse frequency, on the other hand, determines the motor rotation speed (feed speed).

B. Connection between vision system and PLC

The COGNEX vision system can be connected directly on the Ethernet port on the Q-series PLC using Ethernet based on the seamless message protocol (SLMP) or MELSEC communication (MC) protocol[6]. Thereby, the SLMP/MC protocol communication enables COGNEX vision system to communicate directly with Mitsubishi PLCs without requiring ladder logic. COGNEX vision can read and write many different data types via SLMP/MC protocol, including tool results, data strings and tolerances. The following diagram (Figure 5) illustrates the communication method between In-Sight and Q-Series PLCs using MC Protocol. The initial communication request when In-Sight is put online, the In-Sight vision reads message when a trigger occurs, and the In-Sight vision writes message after the inspection is complete.

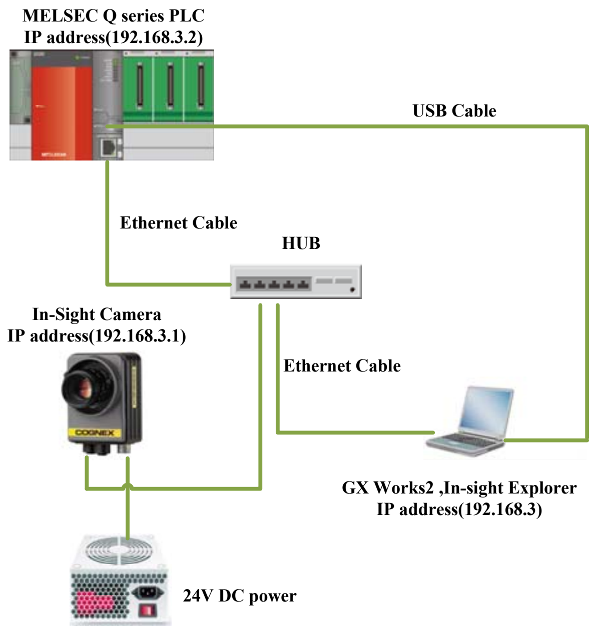

Figure 5. Connection configuration for the vision system

IV. 3D OPEN-SOURCE PRINTER

Now there are several ways to melt or soften material to produce the layers and then print the final object, such as selective laser sintering (SLS) ,fused deposition modeling (FDM) , stereolithography (SLA) and so on. The technology used by most 3D printers to date, especially hobbyist and consumer-oriented models, is FDM, a special application of plastic extrusion. The main advantages of this technology for industrial machines include: a good variety of materials available, easy material change, low maintenance costs, quick production of thin parts, a tolerance equal to ±0.1 mm overall, no need for supervision, no toxic materials, very compact size and low temperature operation. There are many types of small scale 3D printers, the RepRap, the Fab@home and Ultimaker are open source projects, which were started at universities and have a large open source community supporting their development.

In our project, we built a Rostock 3D printer which has a Delta configuration rather than the more common Cartesian coordinate system used by most other RepRap's printer. The main difference with a Delta based system is that motion on the vertical Z axis is achieved by driving all three positional motors together, this is due to the fact they are in a triangular configuration. It's a very efficient and compact positioning system using only three motors, all able to be driven at high speed by belts.

Although the open source online community has provided a set of solutions to build a low-cost printer, there are still two core problems remaining to be settled by hobbyist. Firstly, in order to properly use the delta mechanism, we need a clearly-defined relationship between the positions of the three carriages on their vertical slides and the location of the nozzle from which material is extruded. This problem can be addressed through the inverse kinematics. Secondly, we are greatly concerned with the geometrical accuracy of the final object . On the one hand, inverse kinematics can be utilized to determine the positioning accuracy at the best and worst case scenarios. On the other hand, dimension error of every part, feed fluctuation and calibration also would impact on the geometrical accuracy of the final object. Therefore, we should analysis the method to evaluate the performance of the self-made 3D printer.

A. Build volume analysis

For delta 3D printers, the inverse kinematics are extremely important. 3D printing requires that the extruder nozzle be located at the correct point in space at all times. Because the end effector position is prescribed by the slicer software, we must convert this into positions for the carriages. In other words, the inverse kinematics solution can be used to discern whether any region in space can be reached by the print head. Therefore, it can be used to analytically compute the build volume of the printer and, by extension, the final dimensions of the assembly.

For the purpose of inverse kinematics, we firstly simplify the actual structures into the diagram of Figure 6, where offsets due to joints, print head geometry, and carriage size have been eliminated[7]. In the Figure 6, Le denotes the effective length of the rods, and Re is the effective radius of the circle that the three columns stand on. It is not necessary to include calculations for all three sides of the mechanism, since the equations are identical except for the column angle φ. We denote the origin by $\mathbf{O}$ at the center of the bottom platform and the rod's endpoints by points **A** and **B** ,where **A** is on the carriage and **B** is on the nozzle tip.

If the height of a carriage is given by $\mathbf{z}$, then its position, relative to its lowest position, is given by ($\mathrm{Re}\,\mathbf{cos}\varphi$, $\mathrm{Re}\,\mathbf{sin}\varphi$, $\mathbf{z}$).We can then define the vectors

$$\mathbf{r_{OA}} = \mathrm{Re}\,\mathbf{cos}\varphi\mathbf{i} + \mathbf{Re}\,\mathbf{sin}\varphi\mathbf{j} + \mathbf{zk} \quad (1)$$

$$\mathbf{r_{OB}} = X\mathbf{i} + Y\mathbf{j} + Z\mathbf{k} \quad (2)$$

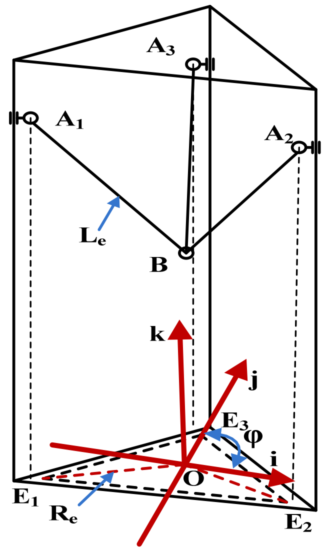

Figure 6. A visual representation of inverse kinematics

where $\mathbf{i}$, $\mathbf{j}$, and $\mathbf{k}$ are unit vectors in the 1, 2 and 3 directions, respectively. Subtracting $\mathbf{r_{OA}}$ from $\mathbf{r_{OB}}$ yields the following vector representing the vector $\mathbf{AB}$:

$$\mathbf{r_{AB}} = (X - \mathrm{Re}\,\mathbf{cos}\varphi)\mathbf{i} + (Y - \mathbf{Re}\,\mathbf{sin}\varphi)\mathbf{j} + (\mathbf{Z - z})\mathbf{k} \quad (3)$$

Since the rod's length is constant, computing the magnitude of this vector gives the equation:

$$\mathbf{L_e^2} = (X - \mathrm{Re}\,\mathbf{cos}\varphi)^2 + (Y - \mathbf{Re}\,\mathbf{sin}\varphi)^2 + (\mathbf{Z - z})^\mathbf{2} \quad (4)$$

The carriage positions must therefore lie on a sphere originating at the print head's position. The inverse kinematics solution can be easily obtained from Equation (4). Solving this equation for the carriage height z , we obtain

$$\mathbf{z} = \mathbf{Z} \pm \sqrt{\mathbf{L_e^2} - (X - \mathrm{Re}\,\mathbf{cos}\varphi)^2 - (Y - \mathbf{Re}\,\mathbf{sin}\varphi)^2} \quad (5)$$

There are thus two possible positions of each carriage for any given print head position. This makes sense because a vertical line (the column) should intersect a sphere in two places (or none). One solution corresponds to the case in which the carriage is above the print head, and for the other solution the carriage is below the print head. Our design places the carriages above the print head, so we choose the greater solution.

Furthermore, these inverse kinematic equations, combined with other geometric constraints, can be used to calculate the exact build volume attainable by the printer. It must also be true that the carriages do not exceed their maximum travel in either direction. The constraints for the bottom and top of a carriage are,

$$0 \le \mathbf{z} \le \mathbf{H_{max}} \quad (6)$$

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Next, the rods must point in toward the center of the mechanism so that they do not crash into the carriages. More specifically, the vector $\mathbf{r_{AB}}$ defined in Equation (3) must not have a component in the direction away from the 3 axis. This condition is enforced by defining a vector normal to the face of the carriage and computing its dot product with $\mathbf{r_{AB}}$:

$$\mathbf{r_{AB}} \cdot (-\cos\varphi\mathbf{i} - \sin\varphi\mathbf{j}) \geq 0 \tag{7}$$

Finally, we intend to impose an angular constraint on the rods so that they do not become too close to the horizontal. Here we use θ_m to denote the minimum angle between rods and horizontal. This is a safety measure that will be implemented in the control system of the printer. This angle is implemented as follows:

$$\mathbf{r_{AB}} \cdot \mathbf{k} \geq \mathbf{L_e} \sin\theta_m \tag{8}$$

All of the above equations were implemented in a MATLAB script, which is input an end effector position and outputs linear slide positions. As shown in Figure 7 , the script generates plot of the build volume by sampling points in and around the build volume and plotting points that satisfy the requirements in Equation (5) through Equation (8), which was used to iteratively size parts and satisfy the build volume requirements. The columns' positions and geometries are plotted for reference.

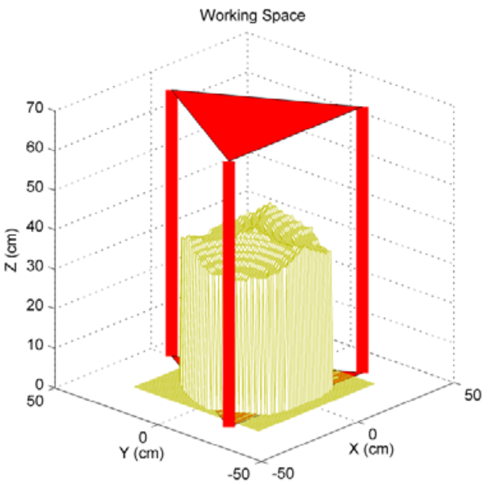

Figure 7. Build volume analysis

When analyzing the working space from a top-down view, it can be seen that the working space is roughly triangular, however the accuracy drops toward the vertices of the triangles, so our working space will remain circular so as to maintain accuracy. The best case scenario for positioning accuracy occurs at the center of the robot's working area due to the inclination of the arms resulting in a smaller lateral displacement per unit vertical displacement at the actuators.

B. Geometrical accuracy evaluation

With regard to the performance of 3D printed objects, dimensional accuracy and material properties are two most important issues. Desktop 3D printers typically use acrylonitrile butadiene styrene (ABS) or polylactic acid (PLA) thermoplastics feedstock. The study of Tymrak, et al.[8] indicated that the 3D printed components from open-source 3D printers are comparable in tensile strength and elastic modulus to the parts printed on commercial 3-D printing systems.

As to dimensional tolerances, Sanchez et al. proposed an experimental protocol of geometrical performance evaluation[9]. There are two goals in the deployment of their methodology. The first is to evaluate of a DIY 3D printer in terms of dimensional accuracy and reproducibility through statistical analysis of the set of manufactured samples. This quantitative qualification will make it possible to establish a characterization of machine performance, in terms of four types of dimensional accuracy: XY-Plane, Z-Axis, circular features and thin walls. Once the degree of reproducibility of the machine is verified, the second goal is to find the parameters of the 3D printer machine, among the parameters tested, that give the lowest dimensional accuracy discrepancies possible for the fabrication of a benchmarking model. Using the proposed protocol by Sanchez et al. [9] and Galantucci et al. [10], we found that the International Standard Tolerance Grade of our 3D printer is situated between IT14 and IT16.

V. SYSTEM PROTOTYPE

As shown in Figure 8, we built the system prototype in laboratory environment. Operation results showed that the prototype system had favorable flexibility with the integration of 3D printer, industrial robot and machine vision. Undoubtedly, this work was just verified only in laboratory environment. However, the complexity of technology integration is enough to induce industrial application. In particular, due to this work, we won the third prize of the national undergraduate electrical and automatic contest in August 2015 in Nanjing of China.

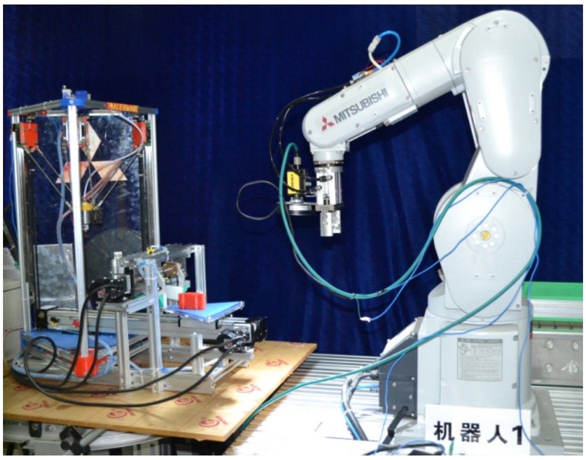

Figure 8. System prototype

Obviously, this system prototype had many aspects that can be improved. For instance, the process lacked inspection of the 3D printed component. Actually, this work can be done by the vision system.

VI. CONCLUSIONS

In the present work, we mainly discussed a flexible production line prototype to create the plastic toys with the integration of 3D printer, industrial robot and machine vision. Operation results showed the prototype system had favorable flexibility: fabrication using 3D printing, unloading by grasper, storing by industrial robot and machine vision. In particular, the build volume analysis of the open source Delta printer was performed based on the inverse kinematics as well as structural constraints. Further research is required to completely build a more flexible and intelligent fabrication system..

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