DEVELOPMENT OF AN AUTOMATED FREEFORM CONSTRUCTION SYSTEM AND ITS CONSTRUCTION MATERIALS

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ABSTRACT

Recently, 3D printing technology in the manufacturing field is in the spotlight. In the construction industry, similar rapid prototyping technology that does not use conventional form can be applied to meet the demand on free formed structure that can provide aesthetic value and functionality. Conventional formwork can increase construction cost and period for various structure with complex shapes while it has numerous advantages such as high strength, convenience, accuracy and good quality of surface roughness. To meet the demand on free formed structure, automated freeform construction systems such as Contour Crafting and Concrete Printing have been developed with active collaboration between university and industry in USA and England. However, details on the system have not been fully released in public, so the possibility of its fusion and spin-off technology cannot be expected. In this paper, cost-effective solution for mechanical and control system for constructing a free curved structure without mold are described. As an appropriate material for the system, fiber reinforced mortar was selected by experiments on compressive strength, setting time and fluidity. After performing G-code simulation, transfer and extrusion experiments with the selected mortar mix were performed and the possibility of the development of automated freeform construction system was demonstrated. Based on this research results, it is required to keep the automated freeform construction system improve and extend it into the new application area in construction industry.

KEYWORDS

Automated Building Construction, Freeform Construction, 3D Printing, Rapid Prototype, Fiber-Reinforced-Mortar

INTRODUCTION

Recently, a lot of researchers in construction area have been studied on the automated building construction system to save time, labor and cost as well as improve safety. Slip-form construction technology that is used in building large towers and bridges is one of the examples that satisfy the above advantages and is widely used in construction field. Automated building construction system such as SMART system utilizes the automated vertical and horizontal transportation system for handling construction materials in building construction with automatic erection mechanism. These kinds of research are continuously developed since 1990s. The demand on free formed structure providing aesthetic value as well as functionality is increasing in construction industry. Even though the conventional construction method using formwork has many advantages, there are limitations in realizing the complicated design in its nature. Also construction of many forms that are used only one-time can increase construction cost and period and raise environmental problems. Therefore, the development of new construction method is required that can fabricate various and complicated form of structure overcoming the limit of the conventional method based on forms. Among the automated freeform construction system, Contour Crafting proposed by Behrokh Koshnevis is the technology that apply the FDM(Fused Deposition Modeling) of rapid prototyping to the construction field in large scale (Khoshnevis et al., 2001). Concrete

Printing was developed at Loughborough University in England to construct the structures of various designs (Lim et al., 2010). They also developed the fiber reinforced mortar as the concrete printing material that has a compressive strength over 100MPa (Le, T. et al; 2011). While the objective of Contour Crafting is mass production, Concrete Printing pursuits small quantity batch production for structures. However, it is hard to know its current problems and possibility of extended research unless we perform real experiment since information and knowhow on its construction material and system are partially released through papers and the real problems are rarely magnified. In addition, the possibility of spin-off technology and its fusion cannot be expected since the research groups are few in number. In this study, the mechanical and control hardware for automated freeform construction system are designed and suitable construction material is selected in the viewpoint of strength, setting time and fluidity. By performing the automated construction experiment, the possibility of realization and current problems are evaluated.

HARDWARE DESIGN OF AUTOMATED FREEFORM CONSTRUCTION SYSTEM

Mechanical System Design

Selection of the gantry type robot enables initial development easy since the intuitive coordinate system can be used and large workspace is obtained. The nozzle for mortar extrusion is connected at the end effecter of Z-axis and its motion is controlled in any direction in X, Y, and Z-axis in Cartesian coordinate as shown in figure 1. The whole system consists of 3-axis linear actuators on the box type support frame. Depending on the suitable requirements for each axis, the type of linear actuator is selected among belt-driven type and ball screw driven type. To meet the speed requirement, additional reduction gear is connected on the brushless DC servo motors. The dimension of usable workspace is 1300mm × 950mm × 800mm. X-axis is most longest axis and the motion along X-axis is driven by two synchronized linear actuators in parallel configuration. If the X-axis is driven by only one actuator, it becomes weak to the moment Mz. Pulley and belt driven type actuator is suitable for the long distance transportation. Since Y-axis has a resistance to moment My and Mx, ball screw type actuator equipped with double LM guide is selected. Z-axis should resist for moment caused by nozzle hose as well as be lightweight. The maximum speed of X and Y-axis is set to 500mm/sec and that of Z-axis is set to 300mm/sec. G-code is the general name of programming language in CNC(Computer Numerical Control) widely used in Computer-Aided Engineering. By considering the convenience in usage and conversion compatibility, G-code is adopted in our research to move the mortar extrusion nozzle in X, Y, and Z-axis. Therefore, once the G-code command file for nozzle movement is given to the main controller, the motion of the gantry robot is generated automatically. Mortar pump used in the system is a mono pump which has electric power of 2.2kW, maximum pressure of 20 bar and maximum extrusion speed of 11L/min.

Figure 1 – 3-axis Gantry Robot for Automated Freeform Construction System

Control System Design

General-purpose 3-axis controllers which support G-Code are high in cost as well as lack of applicability with general sensors and actuators and flexibility in control method. However, by adopting the distributed control system that is recently used as a multi-axis robot solution, cost reduction, flexibility, extendibility, and reliability can be achieved. Embedded PC with PC/104 interface works as a main computer sending the position command to the sub-controllers via CAN(Controller Area Network) communication(Kim et al; 2008). CAN communication, a widely used communication protocol of high reliability, enables configuration of effective communication network among main controller and low-level servo controllers only with 2 communication lines. Reference position trajectory generated in the system is transferred to servo motor controller via CAN communication and each servo motor controller is designed to trace the trajectory. Figure 2 depicts designed embedded PC with PC/10 interface and low-level controllers. In order to secure safety of LM guide linked to actuator of each axis, proximity sensors are installed which alarm when LM guide is close to proximity sensors in certain extent so that LM guide can stop moving.

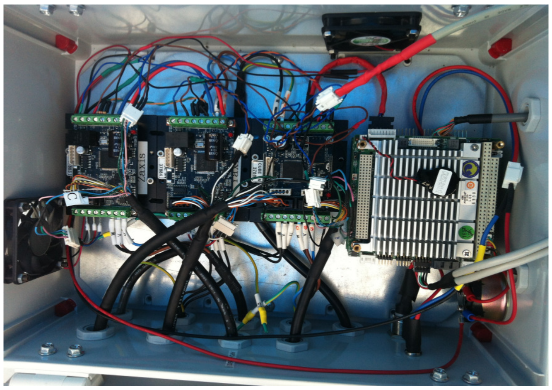

Figure 2 – Low-level controllers and PC/104 Embedded PC

G-code interpreter algorithm is programmed and installed in the main PC which interprets the G-code command text, calculates the position trajectory in maximum 500Hz and sends the commands to sub controller in real-time. Drawings which determine the trajectory of the nozzle are firstly designed in CAD program and then they can be transformed to G-code by using CAM(Computer Aided Manufacturing) programs. By this process, G-code text command can operate the 3-axis gantry robot automatically. In addition, trajectory simulation programs in MATLAB and main controller are prepared to check the position trajectory and to avoid the malfunction of the system. Figure 3 represents the control system architecture.

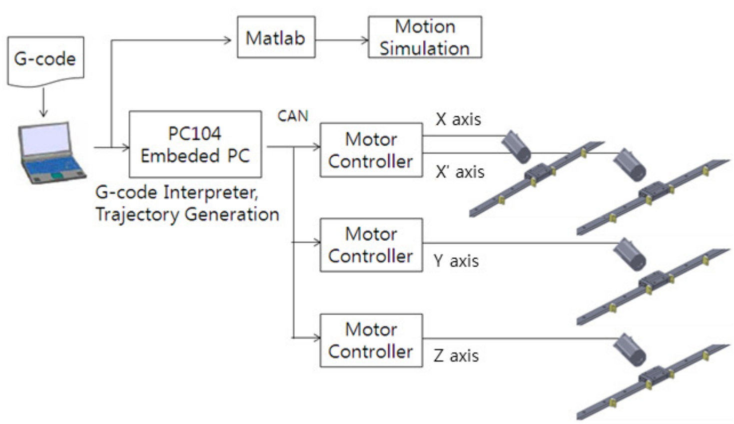

Figure 3 – Control system architecture

CONSTRUCTION MATERIAL FOR AUTOMATED FREEFORM CONSTRUCTION SYSTEM

Our automated freeform construction system extrudes mortar mixture through a nozzle part and builds up the structure layer by layer. Here, the mortar mixture proportion design that enables extrusion and deposition is important. By evaluating the physical properties such as compressive strength, setting time and fluidity, the ternary blended fiber reinforced mortar mixture is designed

In mixture proportion design, type I ordinary portland cement, fly ash, blast furnace slag and silica fume are considered. In addition, polysaccharide type thickening agent, styren-acrylic polymer resin and polycarbonate type water reducing agent are used for improving the performance and nylon fiber of 3mm length is used to control crack. As a fine aggregate, the silica sand range in diameter from 0.28 mm to 0.6mm and 0.1 mm to 0.28 mm are used. The compressive strength and setting time are measured by changing the water-to-binder ratio, the kinds of admixture, and replacement ratio of admixture. Mixture proportion design is performed with the experiment factors and level in Table 1.

Table 1 –Experiment factor and level

	Experiment Factor		Experiment Level
Series I	W/B(%)	2	35%, 40%
Series II	Fly Ash (%)	2	0, C×30%
	Blast furnace slag (%)	2	0, C×30%
	Silica fume(%)	2	0, C×10%
Series III	Thickening agent (%)	2	0, B×0.1%
	Polymer resin(%)	2	0, B×0.1%
Experiment	Fresh Mortar	2	Mortar flow test Gillmore needle test
	Stiffen Mortar	1	Compressive strength test

(1) C: Cement, W:Water, Binder = Cement + Fly ash(Blast Furnace Slag) + Silica Fume

Figure 4 shows the compressive strength for different mixtures and W/B ratios. Left figure shows the test results for the mortar mixed with fly ash while the right represents the results for the mortar mixed with blast furnace slag. The test results show that the strength of the mortar mixed with fly ash is higher than that mixed with blast furnace slag. Additional admixture, 10% of silica fume, increases long-term compressive strength in the experiment. Both early and long-term strength of W/B ratio of 35% is higher than that of 45%. The difference of long-term strength is bigger than that of early strength.

Among the mixtures, mortar mixed with 30% of fly ash and 10% of silica fume with 35% of W/B ratio (35FA30SF10) shows the fastest setting time, where initial set is 60 min and final set is 185 min. If W/B ratio is increased into 40% from this mixture proportion, initial set is retarded 5 to 10 min and final set is retarded 20 min. If blast furnace slag is mixed instead of fly ash, average initial set is retarded 28min, and final set is retarded 20 min. When silica fume is additionally mixed, initial set is shorten by 20min and final set is shorten by 15 min in the experiment. So, the mixture 35FA30SF10 is selected as a suitable mixture proportion since it has the most highest compression strength and shortest setting time. The fluidity is evaluated when the thickening agent and polymer resin (0.1% of binder weight) are added on the mixture 35FA30SF10. The mortar flow measured by ASTM C 1437 standard shows that addition of 0.1% of thickening agent and polymer resin decreased the original flow value from 201 mm to 182mm. Polymer resin does not have a great effect on the fluidity and it is required to achieve adhesive strength and maintain the shape of extruded mortar.

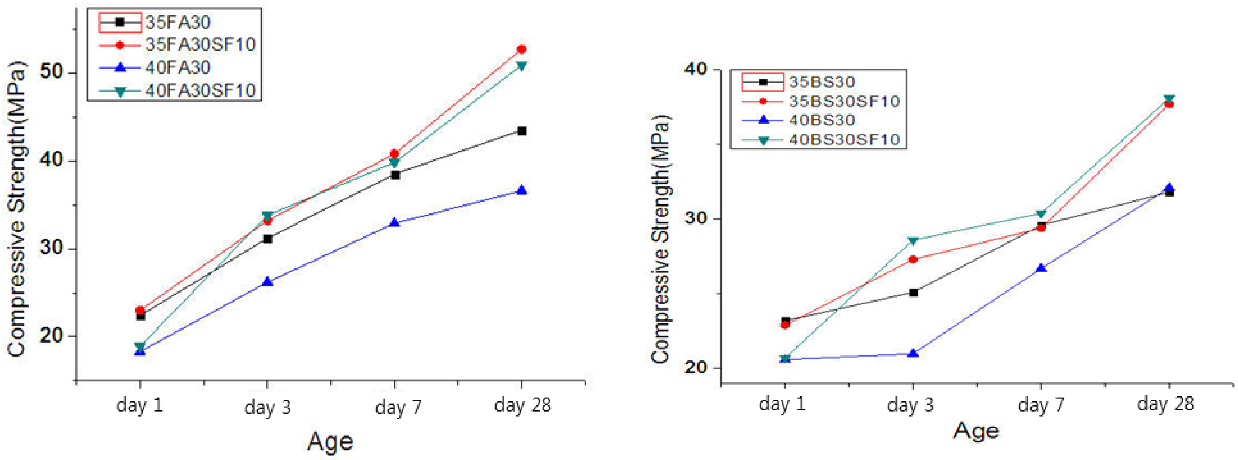

Figure 4 – Compression test results for mortar with different admixtures and W/B ratio

EXPERIMENTAL RESULTS AND DISCUSSION

Before operating the automated freeform construction system, G-code simulation is performed using MATLAB and the program in main controller to confirm the nozzle trajectory and prevent the malfunction of system. The nozzle size is selected by considering the aggregate and fiber size of mortar mixture and 15mm of diameter is selected in our experiment. Figure 5 shows the experimental result of building spiral structure using developed system and construction material. The figure shows that mortar is extruded along spiral trajectory and it preserved the shape after extrusion.

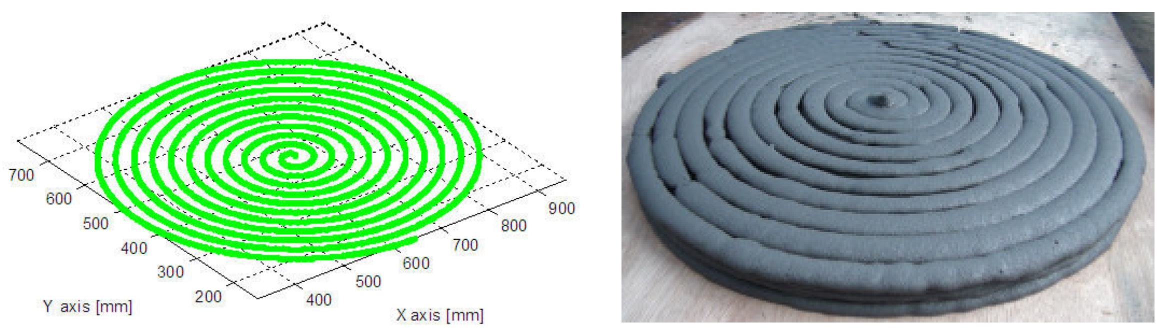

Figure 5 –Spiral structure construction using automated freeform construction system

Thickening agent improves workability and helps preserving the extruded shape by increasing the viscosity. However, caution is needed since the high viscous material can cause the problem in pumping the mortar. Addition of resin is also needed to increase the adhesive strength and maintain the shape.

In the first trial of experiment, the volume of mortar was not extruded precisely because of the flow resistance caused by long distance hose from mixing pump to extrusion nozzle. For precise mortar extrusion, upstream flow path against the gravity should be avoided and pressure drop in coupler and reducer connector should be minimized in the design. When the nozzle speed does not accord with the extrusion speed, the line of mortar becomes disconnected or the extruded line of mortar cannot maintain correct path. So, the calibration of matching the extrusion speed of mortar and the transportation speed of nozzle is required to maintain the shape along transportation path. To extrude the mortar precisely, the improvement of the pumping system such as a feedback using pressure or flow measurement will be required. Pre-processing such as preparing the materials or mixing need to be coordinated with the extrusion process and it should be also automated to minimize the operator intervention. Research on pre-mixed mortar for this purpose can reduce the pre-processing time. Post-processing such as washing nozzle, pipe and pump takes long time and maintenance for each element are required.

CONCLUSIONS

As an initial stage of feasibility study for automated freeform construction system, design elements related with prototype development are described. 3-axis gantry type robot mechanism and a distributed control system is designed pursuing cost reduction, flexibility, extendibility, and reliability. As an operating program, G-code interpreter program in the main controller and simulation programs are successfully developed. To design the mortar mixture suitable for automated freeform construction system, measurement of compressive strength, setting time and flow test are performed by changing the water-to-binder ratio, the kinds of admixture, and replacement ratio of admixture. Mortar mixed with 30% of fly ash and 10% of silica fume with 35% of W/B ratio (35FA30SF10) shows the maximum compressive strength as well as the fastest setting time suitable for automated freeform construction. In addition, fiber and thickening agent are added for adhesive strength and maintenance of shape. The experiment of building spiral structure using the developed system and construction material verifies the possibility of freeform construction and the current problems and future works are discussed. If additional research and modification is continued based on the feasibility study results, it can be utilized as an elementary technology for automated freeform construction system. This automated freeform construction system is expected to improve future construction industry with various applications such as construction of diverse atypical structures, unmanned construction in hazardous location and development of remote concrete repair robots.

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