Development of a Robotic Structural Steel Cutting System

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Abstract. Curved buildings and structures are getting popular and digital fabrication of the structural steels has been successfully tried in several ways. This study presents a development of a robotic system cutting structural steels and marking texts on the steels using digital information of shapes. A configuration of the overall system is explained based on functional decomposition of conventional cutting systems. The cutting system consists of a robotic system and a handling system, and the main functions of the cutting system are classified as translation, orientation, alignment, and cutting. A digital model of the system was created and tested in a robot simulation system. A robot tool-path generation system was also developed. The tool-path generation system uses the DSTV file, an industry standard for the shape of a structural steel, to generate robot job files. This study also provides robot workspaces in which the cutting tool can safely access and cut the workpieces. The proposed system was tested for cutting structural steels clamped in front of the robot. The results show that the generated tool-paths are valid in cutting the structural steel and the possibility of an overall robotic system for cutting structural steels.

1. Introduction
This study presents a development of a robotic structural steel cutting system. The cutting system consists of a robotic system and a handling system. The robotic system cuts structural steel beams and marks text on the steel beams using digital files that include the final shape of the structural steel. The handling system feeds, aligns and clamps structural steel beams allowing the robotic system to cut the beams accurately. This study describes the conceptual design and the development of the structural steel cutting system.

Standard structural steel as shown in Figure 1 should be cut and fabricated for use in the construction of buildings, bridges and other large structures. Curved buildings or structures make it more difficult to fabricate the steel beams because curved structures include angled and curved steel frames made of a variety of shapes as shown in Figure 2. These days with the help of Building Information Modeling (BIM) technology, the curved steel frames are designed as digital models, and the digital models include all the information of the structural steel. Using the digital models, robotic systems can accurately and quickly fabricate the various shapes of structural steel at low cost.

2. Background
The shape, size, mechanical property, etc. of common structural steels are regulated by standards in most countries [1]. Typical shapes of standard structural steel are shown in Figure 1 and they are usually 4 to 12 meters long and 100 to 600 millimeters wide. The most popular one is an H-beam (or
I-beam) with an H-shaped cross-section. Therefore, this study mainly uses the H-beams as examples although it focuses on all types of structural beams. The structural steels with various shapes as shown in Figure 2 are made by cutting and joining standard structural steels. Cutting structural steels to length has usually done with band saws, and drills and mills have been used to make holes and slots on the steel beams. For cutting curved ends and irregular openings of the steel, Computer Numerical Control (CNC) machines with a cutting torch are typically used [2]. A CNC machine moves a torch head in accordance with programmed cutting instructions. Oxy-fuel, laser and plasma torches are common technologies for cutting the steel beams [3].

As the digital design technology such as BIM is developed, automated structural steel cutting systems are becoming common. PythonX [4] and KraneDonk [5] are the representative robotic solutions for cutting and welding structural steel. They are all good solutions, but no detail technologies have been published. This study describes the functional requirements, and presents an approach of development of the robotic system for cutting structural steel.

Curved buildings and structures are getting popular. The percentage of curved buildings designed by world’s 5 largest architecture firms increased to 25% in 2010 [6]. Mun et al. researched the applications of digital fabrication and described a CNC system to fabricate irregular steel workpiece for the curved buildings [7]. Using the CNC system, the welded structural steel could be precisely assembled at construction site.

There have been several studies on robotic cutting system in ship building industry [8, 9]. One of the studies have explained a method to define the working envelop of an articulated robot for H-beam cutting and presented a verification method using a robot simulation system.

Recently most of curved structure designs are performed digitally [10]. For the digitally designed structural steel, robotic cutting system is necessary and possible. This study explains the functions of the robotic structural cutting system and presents a new robotic cutting system.

3. Overall Function of Structural Steel Cutting System

In order to identify overall function, the authors have analyzed traditional operations and existing systems for the fabrication of the structural steel. Functional decomposition technique [11] have been used for conceptual design of the system. The proposed structural steel cutting system has four sub-functions; cutting, translation, orientation, and alignment.
The cutting function is the most basic function of the system, which cuts a steel beam into two parts along a contour or makes holes in the steel. The function is accomplished by a cutting tool or torch, which is the end effector of a robot. The cutting tool can be an oxy-fuel, laser, or plasma torch [3, 12, 13]. The presented system employs a plasma torch which makes a clean cut section at a low cost. The translation function provides linear movement in length direction. As shown in Figure 1 standard structural steels are long. The longest one is 12m in length and the popular one is 10m. The translation function can be achieved by two ways; moving the robot with a cutting tool and moving the structural steel. The proposed system uses a roller conveyor to move the structural steel.

The orientation function makes the cutting tool to access the workpiece surface for cutting in the good posture without any collision, and enables possible kinematics and trajectories of the robot. Figure 3 shows the tool orientations for an H-beam. The bottom and top side flanges of the H-beam are accessed from outside, and the front and back side webs should be accessed from both sides; upside and downside. Rotating the structural steel is an alternative of the orientation function. Otherwise dexterity of robot hands in all direction of the steel is necessary. Due to the heavy weight of the structural steel, large expensive mechanical structures are required to rotate the steel. The proposed system utilizes the dexterity of the robot.

In an automated system the geometry of the workpiece should be same with the geometry of digital model, because the cutting tools move along the programmed paths which are computed based on the digital model. Real structural steels are made with tolerances and have warpages, and the geometry can be different from the digital shape. Therefore the distortion of the steel should be straighten physically. Otherwise, the tool paths, digital information, should be adjusted for the actual shape. The alignment makes the geometry of the digital model and the actual workpiece the same. Typically the alignment is accomplished by two methods. Jig and fixtures are used for straightening overall shape of the steel, and an adaptive tool height control system is used to keep a constant distance between the nozzle of cutting torch and the workpiece surface. The proposed system adopts both methods.

![Figure 3. Tool orientations for an H-beam](image)

4. Tool-path Generation System

Robot tool-paths are generated from a digital model of steel beams saved in the DSTV file format. DSTV format is the industrial standard defined by the German Steel Construction Association (Deutsche Stahlbau-Verband) [14]. A DSTV file is a text file in ASCII format, and is designed for the CNC machining. The overall procedure of the tool-path generation system is shown in Figure 4.

At first the shape of an initial steel beam is identified from the given DSTV file, which supports 8 different types of structural steel. The target shape is then extracted. By comparing the two shapes, initial shape and target shape, initial cutting or marking paths can be calculated. Figure 5 shows the initial steel beam as a wire-frame model and the final target shape as a shaded model. The paths that collide with the workpiece must be recomputed, and the presented system uses two strategies. At first it tries to avoid collision by tilting the tool. When the tilt angle exceeds a specified value, it retracts the
tool in surface normal direction. Final tool paths are computed by adding approach and retract paths, and linking separated paths at different locations. Finally the final tool-paths are saved as a job file that operates a robot.

The proposed tool-path generation system has developed and tested through real cutting. The tool-paths were operated by a Yaskawa MA1440 robot [15] with a plasma torch, and collisions were successfully avoided. The results of a test cut are shown in Figure 6.

![Diagram](image)

**Figure 4.** Overall procedure of tool-path generation system

![Example of cut shape](image)

**Figure 5.** Example of a cut shape and tool-paths

5. Digital model of structural steel cutting system

To validate the proposed overall system a digital model was created as shown in Figure 7 and the overall system was tested in a robot simulation system, RoboDK [16]. The system consists of a Yaskawa MA1440 robot with a plasma torch and a roller conveyor with a jig and fixture system. In the digital simulation system, the overall system runs successfully for all test examples without collision.

In the system the work envelope of a robot is important, because the steel workpiece moves only linear by the roller conveyor and the tool of a robot has to orient all direction. If the work envelope is defined incorrectly, the tool-paths of the robot make collisions with workpiece or robot itself. Otherwise, the tool-paths can be impossible positions for the robot. As shown in Figure 8, the authors have found
workspace envelops of four sides; front, back, top, and bottom side of structural steels. In the figure the bottom workspace is two-dimensional because the bottom side of any steel is always aligned at a specific location in the proposed system. The other sides have three-dimensional workspaces because of their different locations and heights depending on the steel. The workspaces allow the robot to cut most standard steel beams. Due to the size of the robot, Yaskawa MA1440, small workspaces are available in the bottom and back sides. Therefore linear translations using the conveyor system are necessary operations for cutting or marking long shapes in the proposed system.

![Figure 6. Results of a test cut](image1)

![Figure 7. Digital model of the proposed cutting system](image2)

![Figure 8. Robot workspaces for cutting four directions](image3)
6. Conclusion
In this study the authors have designed a new robotic structural steel cutting system. The overall system has been modeled as a digital model and verified in a robot simulation system. The results show that the possibility of the proposed system.
Tool-path generation system in the cutting system has been developed and tested in which the geometry information of a DSTV file is converted to a robot job file. The actual cutting test shows that the tool-paths generated by the system can be used to cut structural steel.
The authors have tested only cutting the structural steel clamped in front of the robot. It will be difficult to precisely align the coordinates between a robot and a workpiece which is on a conveyor and moves. It will be also difficult to synchronize the control of the conveyor with the robot dynamically.

Acknowledgments
This paper is supported by the R&D project of the “Innovative Design Advanced Manpower Training Program” of the Ministry of Commerce, Industry and Energy.

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