Beam for the Steel Fabrication Industry Robotic Systems

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Abstract –

In this paper, we present a comparison between the older DSTV file format and the newer version of the IFC standard, dedicating special attention of its impact in the robotization of welding and cutting processes in the steel structure fabrication industry. In the last decade, we have seen in this industry a significant increase in the request for automation. These new requirements are imposed by a market focused on the productivity enhancement through automation. Because of this paradigm change, the information structure and workflow provided by the DSTV format needed to be revised, namely the one related with the plan and management of steel fabrication processes. Therefore, with this work we enhance the importance of the increased digitalization of information that the newer version of the IFC standard provide, by showing how this information can be used to develop advanced robotic cells. More in detail, we will focus on the automatic generation of robot welding and cutting trajectories, and in the automatic part assembly planning during components fabrications. Besides these advantages, as this information is normally described having as base a perfect CAD model of the metallic structure, the resultant robot trajectories will have some dimensional error when fitted with the real physical component. Hence, we also present some automatic approaches based on a laser scanner and simple heuristics to overcome this limitations.

Keywords –

BIM; IFC; Robotized Welding and Cutting; Automation; Construction Industry;

1 Introduction

Considering the market globalization and high economic competitiveness environment that is inserted, the Architecture, Engineering, Construction (AEC) industry is facing the mandatory need to reduce project costs, to increase productivity and quality, and be more time efficient. To meet these requirements in the last few years we verified a clear effort for improving the interoperability and easy share of information between all partners and inner processes involved in a building project. Commonly, in these projects, the number of software tools involved (for electronic tendering, invoicing, 3D - design, structural analysis, and others) is very high. These software tools, commonly lack in compatibility of information and file standardization, making this industry dependent on paper-based drawings and documents for project execution, which obviously traduces in loss of time and money, and increases the probability of the occurrence of errors.

These effort lead to the creation of an ISO standard for data modeling - the Industry Foundation Classes (IFC) developed by buildingSMART [1]. Up to recently, the IFC based work flows are more commonly to be seen in the design phase of the building projects, being less available for the fabricators.

1.1 Steel Construction Industry

Considering specific case of the steel fabricators domain, the use of computer-assisted methods is very pronounced, due to the high grade of prefabrication and increasing automation. Nowadays, the steel fabrication industry is demanding the automation of several inherent production processes, as a way to shorten the projects life cycles and reduce the related costs. The market requirements vary from automatic robotic cells for welding and surface treatment and automatic handling [2].

This paradigm change has created new challenges for the information required to plan and manage the steel fabrication process. Lately, the steel fabrication industry was accustomed to the DSTV file format, which filled the gap between the 3D model and the manufacturing (using CNC machines) of each individual steel part. Now, the focus is oriented for the optimization of the assembly phases of the production process, as it is still under automated and represents a very laborious part of the production process.

In here, the DSTV standard was struggling to fulfill the demands, preventing the steel constructing industry from achieving the so desired efficient flow of information, between the design and specification phases and the production process. These limitations led the steel fabrication sector to put pressure for a new file format capable of storing more structured and richer information. For this purpose, the buildingSMART and some of the major companies in the structural steel fabrication industry (FICEP, Steel Projects, Tekla, HGG and others) studied the possibility of extending the Industry Foundation Classes (IFC) standard for the steel fabrication industry needs [3].

In this paper we discuss the introduction of this new file format and the main advantages that it can bring to the industrial process, focusing not only, on the information flow in the fabrication process, but also in the amount of information that IFC can transfer and how this information contributes for process automation.

The paper is organized as follows. In Section 2, we start by presenting an overview of file formats focusing on the advantages of IFC. In Section 3, we present the capabilities provided by the IFC in the fabrication industry, with especial focus on robotized work cells. In Section 4, we present some conclusions and future work.

2 Background

2.1 Product Models for The Steel Fabrication Industry

The steel construction industry has lived for many years using limited file formats to manage the production cycle. Moreover, the need of using individual files from production planning to production has created a very difficult task in the management of shop floor.

Over the last years, the DSTV file was the main file format used in the production process, but the limitations in geometrical descriptions of single parts and the need to include additional data e.g. scribing, welding, assembly hierarchy, information (status, scheduling, costs, materials, etc.), opened space for new formats to enter and fulfill this gap. Nevertheless the reasonable success of the CIS/2, the need of a more generic file format representative for all construction chain, from the design to project software's and manufacturing equipment, has created a new demand between all partners that buildingSMART has been able to fulfill with IFC (Industrial Foundation Classes) in BIM (Building Information Modeling).

2.2 Building Information Modeling (BIM)

The Building Information Modeling term was first introduce in 1992 [4] and refers to a building design methodology characterized by the generation and use of coordinated, internally consistent computable information about a building project in design and construction. Building information models are files which reliably represent a building providing support for design, decision making, fabrication, high-quality construction, document production, construction planning, performance predictions, and cost estimates. Up-to-date accessible information gives architects, engineers, builders, and owners a clear overall vision of all their projects, as well as the ability to make informed decisions faster [5]. A growing number of early adopters in public and private sectors, including GSA, Disney, and Intel, are starting to explore BIM and pursue integrated delivery approaches. Their common interest is ownership of facilities that extends beyond construction completion.

2.3 The Industry Foundation Classes (IFC)

The Industry Foundation Classes (IFC) data model is neutral and open file format specification that intends to describe building and construction industry data to allow interoperability between different players in the architecture, engineering and construction industry. It is a platform neutral, open file format specification that is not controlled by a single vendor or group of vendors. It is an object-based file format with a data model developed by buildingSMART (formerly the International Alliance for Interoperability, IAI) and is a commonly used collaboration format in Building information modeling (BIM) based projects [6]. The IFC model specification is open and available. It is registered by ISO and is an official International Standard ISO 16739:2013.

The IFC standard is the key to guarantee that projects developed by different software vendors can be reused consistently. All the major players in the sector and particularly the major CAD vendors have participated, through the buildingSMART alliance, in developing IFC, and therefore there is a wide range of software applications that support this initiative. The IFC main purpose is to provide architects and engineers with the ability to exchange data between CAD tools, cost estimation systems and other construction-related applications. IFC provides a set of definitions for all object element types encountered in the building industry and a text-based structure for storing those definitions in a data file. IFC uses a plain text file, the only truly universal computer data format. Individual CAD developers store data in product-specific binary file format that best suits their system.

2.4 IFC for Fabricators

Concerning the fabrication industry the IFC file format fills an open gap in the exchange of information between the design and project software and the manufacturing equipment. Moreover this new file format present as a solution for some limitations that were impeding the automation of the production process.

The good results and acceptance of this new format (IFC) can be seen in many occasions. Some examples of that is the mapping of others formats, like CIS/2 format that had some reasonable success, to the IFC standards [7], and the improvement of IFC in each new version, already at version four.

3 Robotic Systems for the Steel Fabrication Industry

Nowadays, fabricators are focused on enhancing the production process efficiency and to be less dependent on external means. The use of robots is efficient for that purpose. One example that is commonly seen on shop floors is the welding on jigs, as in this operation the variability of parts is relatively low, and therefore the need to constantly readjust the robotic cell set-up is eliminated.

In the cutting and welding process for steel fabricators, this scenario does not occur, as most of the work requires the use of an external source of information to allow these processes to be automated in a reliable and efficient manner. In the shop floors, even in our days, is normal to see operators introducing the information's by hand. Examples of this scenario can very frequently be seen in the cutting processes, where the use of CNC machines to drill and to perform strait cuts on profiles are based on a paper drawing; or seeing the operators marking/adjusting the points to be cut or weld by a robot directly in the teach-pendant.

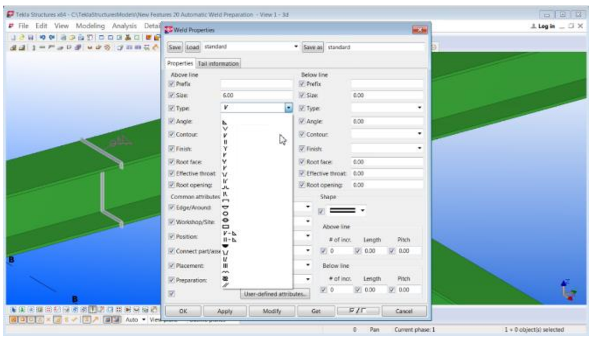

Figure 1. Welding seam definition Tekla

The potential of IFC in generic terms can provide all the information required to full automate the welding and cutting processes. The mesh information of the metallic parts, the assembly hierarchy and the complete specification of welding seams (very recent) in the design and project software (e.g. Tekla, Figure 1) are some of the examples of the advantages that IFC can provided to fulfill the total automation of shop floor work cell's.

3.1 IFC Parser

The IFC Parser is not an easy task to accomplish. The buildingSMART [1] organization provides all the tools and information required to do it. But the complex definition of the elements, the hierarchy and the relation of each other inside the file make this a complex task (Figure 2).

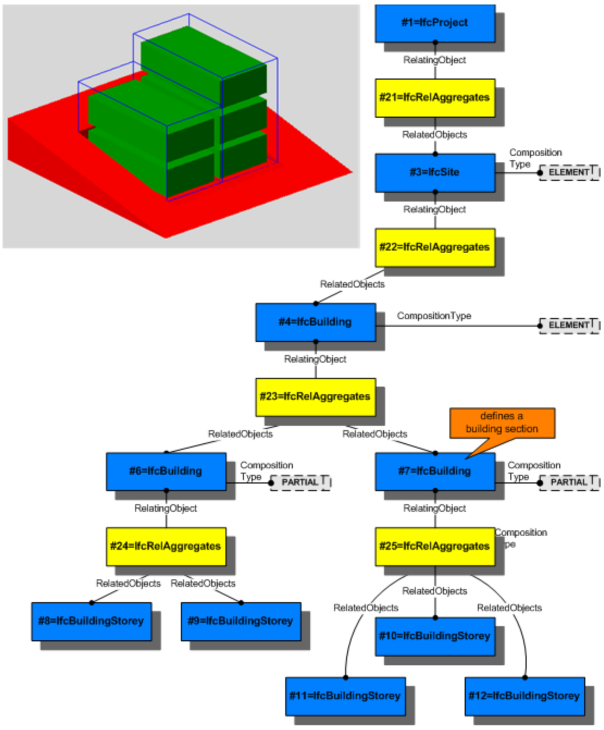

Figure 2. IFC spatial structure element [1]

In these days there is extensive offer of alternatives, free or commercial parsers like the OpenBIM [8] or some of the toolboxes of parsers that can be found on buildingSMART website or IFCWiki [9] for example.

3.2 Process Automation - Robot Automatic Trajectory Generation based on IFC

The quality of trajectories that are generated on-line is always related with the amount of information available. The dependency on the quality of path generation and process information give more strength on the use of IFC files.

Looking inside the IFC structure, and focusing in the benefits for steel structure fabrication domain, we are able to identify some important key points:

- The ability of providing multiple profiles in the same file, Figure 3., allows to reduce the amount of files required to pass to the shop floor for production and makes it easier to track the project information and planning.

- Definition of profile representation as is, using mesh geometry, give more advantage to the process and take the need of future task.
- Hierarchization of the structure, where it is detailed the information of the parts assembly order.
- More recently, the possibility to introduce welding information. This is a huge step for the automation of this specific production process (visible on Figure 4. in red).

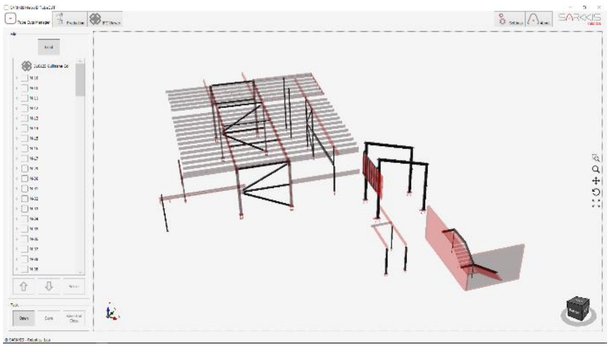

Figure 3. IFC parser with multiple profiles

The generation of trajectories using this kind of information are more profitable for the process. Despite the possible drawback on some points, like the size of IFC files, or mesh triangulation definition, this can always be overcome with some algorithms to provided fastest and accurate results. Furthermore, the gains obtained by working with the object that is pretended in the end and the parametrization of the process, like welding preparation, make the IFC files more profitable for all the automation process.

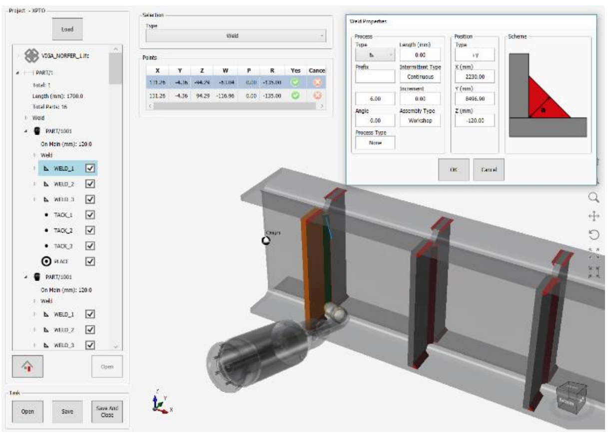

Figure 4. Developed software for robot automatic trajectory generation based on IFC

4 Handling Real Parts Inaccuracies

The work on steel metal structures is a very inaccurate procedure due the tolerances and weight of parts involved. Additionally, the placement of the metallic structure in the workstation is usually performed manually using an overhead crane. These specificities are not in accordance with the requirements for the operation to be carried out automatically by an industrial robot. Thus, it is necessary to provide the industrial robot perception skills appropriate for localizing the steel metal structures and at the same time extract its dimensions. This will allow the estimation of the position and orientation, and the extraction of the real dimensions of the profiles with high precision, allowing the adaptation of the robot trajectories. For this purpose, we propose the use of one of the two following solutions: the use of a laser dot or a 2D laser scanner.

4.1.1 Laser Dot

Laser dot is more common to see in automated work cells, mostly because of the low computational requirements of the algorithms involved. For example, using a smooth algorithm that make uses of some key points from the parts it is possible to find the relation coefficient between the theoretical and the real size of a metallic structure. In Figure 5. it is presented an example of the type of measures that can be made to estimate the position of the beam and validate its dimensions. In the case illustrated, this operation is performed before the assembly of a part to be welded.

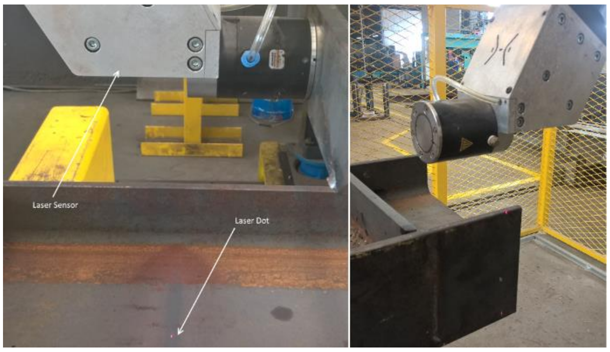

Figure 5. Example of the measurement of some key points for the validation of the beam dimensions and position estimation for execution of an assembly operation

Moreover, the calibration of this sensor as a tool in robot structure is simplified, comparatively to the 2D laser scanner, that will be presented in the following section.

4.1.2 2D Laser Scanner

On the other hand, the solution based on the laser scanner as the potential to be more time efficient, as in one scan, we can retrieve much more and richer information about the metallic structure. Such sensors are nowadays frequently used in industrial equipment's for carrying out measurements without contact. Because of their high accuracy, they are also considered as a rapid 3D modeling technique.

Laser Scanner Calibration on the Robot Tool Center Point: One of the first problem associated with the use of this type of sensor in the robot structure is its calibration. For this purpose a sphere base methodology can be used [10,11]. It consists in two different steps:

1. In the first step is where we compute the rotation matrix R_s between robot *tool0* and laser scanner.
2. Then, in the second step, we compute the translation vector $t_s$using the previously computed R_s matrix.

(1) Calibration of the Rotation Matrix $\boldsymbol{R_s}$: The position of the sphere center in robot coordinates can be described as:

$$x_b = \begin{bmatrix} R_0 & t_0 \\ 0 & 1 \end{bmatrix} . \begin{bmatrix} R_s & t_s \\ 0 & 1 \end{bmatrix} . \begin{bmatrix} X_L \\ 1 \end{bmatrix} \tag{1}$$

, where R_0 and t_0 represent the orientation and position of *tool0* of the industrial robot, R_s and t_s represent the orientation and position of the laser scanner relatively to *tool0*, x_b represent the sphere center position in robot base coordinate system, and X_L the position of the sphere center in the laser coordinate system .

Therefore, and considering two different line scans of the sphere it is possible to write:

$$x_{b_1} = \begin{bmatrix} R_{0_1} & t_{0_1} \\ 0 & 1 \end{bmatrix} . \begin{bmatrix} R_s & t_s \\ 0 & 1 \end{bmatrix} . \begin{bmatrix} X_{L_1} \\ 1 \end{bmatrix} \tag{2}$$

$$x_{b_2} = \begin{bmatrix} R_{0_2} & t_{0_2} \\ 0 & 1 \end{bmatrix} . \begin{bmatrix} R_s & t_s \\ 0 & 1 \end{bmatrix} . \begin{bmatrix} X_{L_2} \\ 1 \end{bmatrix} \tag{3}$$

If both scans are extracted with *tool0* in the same orientation, this means $R_{0_1} = R_{0_2}$, the above system of equations can be rewritten as follows:

$$x_{b_1} - x_{b_2} = R_0 R_s (X_{L_1} - X_{L_2}) + (t_{0_1} - t_{0_2}) \tag{4}$$

As the sphere is fixed in the same position:

$$0 = R_0 R_s (X_{L_1} - X_{L_2}) + (t_{0_1} - t_{0_2}) \tag{5}$$

By extracting different pairs of scans, each with different *tool0* orientation, it becomes possible to use a minimization algorithm, for instance Levenberg-Marquardt minimization method, to compute the value of R_s.

(2) Calibration of the translation vector $\boldsymbol{t_s}$: According to equation 1, the following one is got for a fixed point in the robot coordinate frame:

$$x_b = R_0 R_s X_L + R_0 t_s + t_0 \tag{6}$$

Keeping the robot orientation unchanged to scan a sphere surface, and whatever t_s is, the reconstructed result will always be a sphere. Letting $t_s = 0$ and fit the scanned and reconstructed results x_b, the center of the virtual sphere, x_B in robot base coordinate frame can be computed. The relation between x_B and the real sphere center is given by:

$$x_v = x_B + R_0 t_s \tag{7}$$

By scanning, the sphere with the robot with different orientations, many groups of x_B and R_0 are collected. Solving equation 6, using a minimization algorithm the value for t_s can be estimated.

Having the laser calibrated in the robot structure, we can now use it to estimate and validate the metallic structure dimensions and estimate its position.

The presented calibration methodology was tested in 14 trials with the objective to analyze the repeatability of the calibration procedure.

Table 1. Results for R_s – Euler Angles in Radians

	R_x	R_y	R_z
Standard deviation	0.0011	0.0004	0.0007
Min	1.5659	-0.0005	2.1048
max	1.5695	0.0009	2.1074

Table 2. Results for t_s – Translation vector in mm

	R_x	R_y	R_z
Standard deviation	0.02	0.07	0.01
Min	51.58	25.18	168.96
max	51.64	25.35	169.00

Analyzing Tables 1 and 2 it is possible to see that the calibration procedure presents good repeatability shown by the standard deviation values both for the rotation and translation vectors.

Computing the metallic structure position and dimensions validation: Having the laser calibrated on the robot structure is now possible to make measurements with the objective to validate the dimensions of the metallic structure as well as estimate its position. In here two approaches, or a combination of both, can be used. The first one, is everything similar to the one presented for the laser dot, and is illustrated in Figure 6. Although this similarity, by using this type of sensor the speed of the operation is significantly increased, as the field of view of this sensor is considerably larger.

The second approach is based on the extracting the complete/partial 3D model of the metallic structure. One disadvantage of these approach is the need to create movement (movement of the sensor or movement of the object) in order to extract the 3D model of the object of interest. As the laser is attached to the TCP of the industrial robot, it makes sense to maintain the metallic structure stationary, and the required motion to be executed by the industrial robot. To allow a trajectory with 6 DoF the synchronization between each laser profile and the position information of the laser in the robot reference frame is a critical factor. As a result, with this type of approach is normally associated a reduced speed of the industrial robot, so to minimize possible synchronization delays.

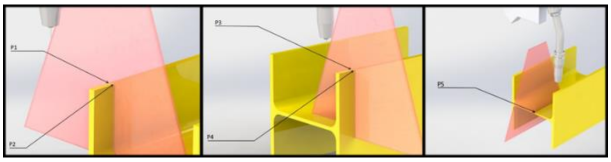

Figure 6. Laser scanner for industrial application – validation of the beam dimensions

In Figure 7. is presented the result of an accumulated 2D laser scan performed using the referred approach. As is is possible to see we were able to extract the 3D model of a metallic structure. The max overlapping error of the scans is about 2 mm. This error also gives us a quality measurement of the laser calibration in the robot TCP.

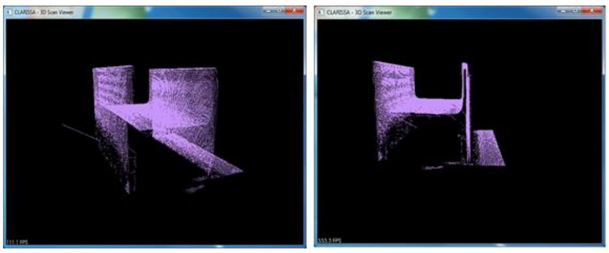

Figure 7. Result of an accumulated scan executed by the industrial robot.

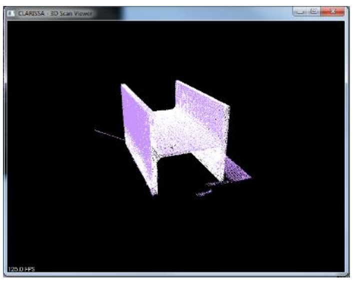

Figure 8. Metal steel structure registration - CAD (white) vs Point Cloud (purple).

Using now some template matching approach, as Iterative closest Point [12], it is possible to fit the CAD model of the metallic structure with the 3D model to estimate its position, please refer to Figure 8..

Also, the beam dimension can easily be extracted from this 3D model. This information can then be used for the adaptation of the robot trajectory that was initially programed based on the IFC information.

5 Conclusions

In this article was demonstrated the advantages that IFC files can bring to the steel fabrication industry. Key points like profile representation, hierarchization of the structure, or even welding information were presented as gains to the process. The IFC files prove to be beneficial in all the chain of construction, from the design to the assembly, that is a big contribution for all and visible on the growing use in industry.

Also in this article, we have demonstrated how the IFC richer information can be used to develop advanced robotic cells, more specifically welding and cutting cells for the steel structure fabrication industry. Features like the ability to provide multiple profiles in the same file, the definition of the profiles as is, and more recently the possibility of introducing welding information, allows the automatic trajectory generation of robot programs.

Despite the ability of the generation of the robot program in an automated way based only in the IFC file information, the dimensional inaccuracies of the real steel structures dimensions makes these programs very difficult to be valid. Therefore, we also propose in this paper some heuristics based on a laser sensor to estimate the real dimensions of the steel structure as well as its position, so the robot program can be adjusted. Despite the advantages of the IFC file format, there still exist some barriers delaying its widespread in industry. Namely, the translation process of BIM to IFC, that some available software’s already support; and the IFC import and execution features of most steel fabrication machines that are currently installed in the fabricators shop-floor and only support the old DSTV file format.

6 Future Work

As future work, we propose to continue to explore the use of the IFC file format to automate the steel fabrication process, focusing this time only in the assembly and welding of metallic structures. Normally, this shop floor operation is associated to heavy parts, which for this reason can not be handle by middle-class industrial robots. Hence, we will explore the possibility of building a human-robot collaboration cell, having as pillars the information provided by the IFC files and some augmented reality approaches to support the operator to insert manually the parts in the correct position into the primary steel structure placed at the industrial robot workstation.

Acknowledgments

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