Application of Laser-Based 3D Imaging to Steel Construction

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Abstract: The ability to automatically recognize, locate and track structural steel components during production, fabrication, and erection in real-time using laser-based 3D imaging technologies has the potential to provide a notable improvement in the productivity of the steel industry. This paper provides a review of current practices in the U.S. steel construction industry and presents potential insertion points for 3D imaging technologies. A brief review of the National Institute of Standards and Technology (NIST) research towards construction object recognition and automated steel construction is included.

Keywords: 3D imaging systems, construction automation, laser scanning, steel construction, object recognition.

1 INTRODUCTION[1]

The Construction Metrology and Automation Group (CMAG) at NIST is conducting research to support the stated need of the American Institute of Steel Construction (AISC) for a 25 % reduction in the time required from design to erection of steel frame structures. At the 2002 Automated Steel Construction workshop co-sponsored by NIST and AISC, steel construction experts were tasked with identifying the challenges facing the industry and potential technologies that could be used or developed to meet those challenges [1].

In reviewing the listed challenges and technologies, it was apparent that the ability to identify and locate steel members and subassembly components would be an enabling capability for the steel construction industry. Unlike the high volume, low variability production lines commonly associated with highly automated manufacturing, steel fabrication can be characterized as low volume and high variability. Even in fabrication shops that have dedicated Computer Numerical Control (CNC) equipment to manufacture required subassembly components (e.g., beam drill lines, plate punching and thermal cutting stations, etc.), the final assembly of those components is primarily a human endeavor. Automated welding, a mainstay in the automobile industry, is not typically used in steel fabrication. Steel erection on the job site is likewise a labor-intensive process.

One CMAG research area involves identifying, locating, and tracking known construction objects to facilitate machine guidance applications, where 'known' implies the perception system is seeded with identification data regarding the targeted object. The test application for this research is structural steel assembly in the Automated Construction Testbed using high resolution laser-based 3D imaging systems[2] for determining general locations of target objects and high frame-rate range cameras on RoboCrane for close-in control and docking.

The targeted objects will be structural steel components with the identification data derived from product model data, such as the CIMsteel Integration Standards Release 2 (CIS/2) [2], for the specific pieces.

This report primarily provides background information related to current practices in the U.S. steel construction industry for the purpose of introducing researchers to potential insertion points for laser-based 3D imaging and object recognition. Section 2 provides an introduction to the structural steel industry including a review of current practices in steel production, fabrication and erection. Section 3 describes potential impact areas for laser-based 3D imaging and object recognition in steel construction. Section 4 provides a brief overview of NIST research in these areas.

2 CURRENT PRACTICES – STEEL PRODUCTION, FABRICATION AND ERECTION

2.1 A Brief History

In looking at the history of construction, the prevalent use of structural steel is a relatively new phenomenon. Schulitz et al. [3] define the periods for use of iron and steel in load-bearing construction as follows: the use of cast iron (1780 - 1850), the use of wrought iron (1850 - 1900), and the use of steel (1900 - present). Misa [4] provides a thorough summary of the development of the steel industry in the United States, and is the primary source for the broad overview which follows. The documentary "American Steel: Built to Last" [5] was also informative.

Until the late 1800's, steel was difficult to produce, required extensive manual labor, and was therefore too expensive for use as a common construction material. In 1856, Sir Henry Bessemer introduced the Bessemer converter, which enabled the first low-cost, mass

[1] Any mention of commercial companies, products or services within this report is for information only; it does not imply recommendation or endorsement by NIST.

[2] In this paper the terminology "laser-based 3D imaging system" is used to describe the class of active emission optical range image sensors which are commonly known in the construction industry as laser scanners and in the defense research community as LADARs. 3D Imaging System is used in order to be consistent with the newly formed ASTM standards committee (E57) on these instruments.

production of steel. The first Bessemer process mill in the U.S. was constructed in 1864, and ten more were added in the ensuing decade. The rapid rise of the steelmaking industry was spurred by the railroad industry, which needed steel production capacity to meet both its extraordinary growth in the late 1800's as well as to replace miles of poorly performing iron rails already installed. A turning point occurred in 1877, when the use of steel in railway construction exceeded that of iron.

The use of cast iron for columns and wrought iron for beams and trusses in construction was not uncommon, and iron had been used for railway bridges and elevated trains for many years. The Bessemer process enabled mass-produced, economical steel, but it was soon realized that product quality was difficult to control and it was, therefore, not suitable for producing structural-quality steel. The regenerative open hearth system – invented in Britain by Siemens in 1861 – provided a way to mass produce higher quality steel and allowed for the reuse of scrap material. Hearth linings yielding a chemically basic process also removed phosphorous impurities, resulting in a less brittle steel and enabling better use of North American ore.

In the U.S., the change to the predominant use of steel instead of iron for structural shapes took place in the period between 1885 and 1895. The commercial construction boom in Chicago in the late 1800's, the development of Chicago-style steel skeleton construction, and the introduction of the elevator by the Otis Elevator Company sparked the extraordinary rise of steel construction. A similar change took place in New York with the introduction of the New York-style steel cage construction.

2.2 Steel Production

In 2004 the U.S. produced approximately 98.9 million metric tons of steel which represents slightly less than 10 % of the world production totals. (The U.S. is the third leading producer behind China and Japan, and is a net importer of steel). World-wide, approximately 63 % of the steel produced uses the basic oxygen furnace process, with the electric-arc furnace (EAF) process second at approximately 34 %. In the U.S. more than half of the steel produced is from EAFs [6]. All wide-flange structural steel produced in the U.S. is created using the EAF process [7].

During the NIST/AISC workshop, it was noted that tighter manufacturing tolerances for steel production would reduce the amount of tolerance required for the connectors during erection and plumbing of the structure. These tighter tolerances would enable improved fabrication and more importantly, more rapid assembly in the field.

The following description of steel production describes the EAF process used by one manufacturer. Although this section describes only one EAF implementation, the generalized description is representative of most structural steel production practices in the U.S. [3]

Structural steel in the U.S. is made almost exclusively from recycled material. This material includes industrial and post-consumer scrap as well as alternate iron units such as pig iron and mill returns. Each general category of scrap iron has different material qualities and associated costs. A batch of refined steel, or 'heat', is produced by blending these various types of scrap to optimize material composition and costs.

The scrap is loaded into a 6.7 m (22 ft) diameter, 3-phase EAF which can hold 122 metric tons (135 short tons) of liquid metal. Current is applied through three 0.61 m (24 in) graphite electrodes at 30 kA to 47 kA per phase at an operating voltage of 760 VAC to 1350 VAC. The EAF can melt a heat in approximately 45 minutes. The process is controlled by a computer-based arc regulation system.

Once the required temperature and carbon levels are reached in the EAF, a heat - 109 metric tons to 113 metric tons (120 tons to 125 tons) - is transferred to one of two Ladle Metallurgy Furnaces (LMF) using a 3.5 m (11.5 ft) diameter ladle. In the LMF, current is applied through three 0.48 m (18 in) diameter electrodes at 20 kA to 23 kA per phase at an operating voltage of 250 VAC to 370 VAC. Similar to the EAFs, the LMFs use a computer-controlled regulation system. During processing at the LMF, alloys and slag formers are delivered to effect the proper chemical composition. Steel chemistry analysis is conducted within the LMF control station using spectrometers, thermocouples, and dissolved oxygen probes.

When the steel reaches the proper chemistry composition, it is cast into preliminary shapes (known as blooms and beam blanks[4]) using continuous casters. The ladles are positioned above a refractory-lined basin on top of the caster known as the tundish. Molten steel is transferred from the ladle to the tundish through a hydraulically-controlled slide gate, the position of which is controlled by tundish load weight.

The steel then flows into the mold through a straight-bore entry shroud. Liquid flow rate and the bloom/beam blank withdrawal rates are computer-controlled to maintain a constant liquid steel head within the vertically-oriented mold. In the mold, the outer edges of the steel solidify leaving a molten center. This casting is continuously withdrawn from the bottom of the mold and water spray on the continuous caster is used to remove heat and solidify the steel. Mechanical restraints known as 'segments' support the casting as it moves through the machine, and prevent the cast from bulging as it further

[3] The principal sources of information for this section included a thorough site tour conducted by Mr. Douglas Rees-Evans, and the presentation "A New Mill for the Production of Long Rails," available from Mr. Rees-Evans. See also [8] and [9].

[4] Blooms have a rectangular cross-section. Beam blanks have an 'I-beam' cross section. Different molds for creating different sized blooms and beam blanks are used depending upon the actual structural shape under production.

cools. The mold and the containment segments are curved, allowing the casting to transition from vertical to horizontal orientation. At the exit of the machine, the combination withdrawal / straightening pinch rolls control the rate of casting and flatten the casting from the curved shape. Once straightened, the blooms/beam blanks are cut to the desired length and either allowed to cool and stored or sent directly to the reheat furnace.

Prior to sending the blooms/beam blanks through the rolling mill, they are first reheated in the Reheat Furnace, where they are discharged at a nominal temperature of 1232 °C (2250 °F). The furnace is capable of handling either 272 metric tons (300 tons) per hour (hot-charged) or 181 metric tons (200 tons) per hour (cold-charged). Following the reheat furnace, the blooms/beam blanks pass through a water jet descaler.

The blooms/beam blanks are then rolled into a rough shape in the reversible breakdown mill. Computer-controlled side rails align the bloom into the proper pass position on the breakdown rolls. Once the piece has been plastically deformed into the rough shape, it is sent next to the combination mill which includes a universal rougher, an edger, and a universal finishing stand. A series of passes through the combination mill produce the desired shape and the piece is then sent to the cooling bed.

Following cooling, the product is straightened using horizontal rotary straighteners, cut to length, and stored for customer shipment.

2.3 Steel Fabrication

The process of turning the standard structural shapes produced by the mill into members ready for assembly on a job site is known as fabrication. The fabrication process includes the handling of stock members, cutting stock members to size, punching and drilling for connections, preparing the connections, and shop painting or finishing as required [10]. The finished steel member is a combination of stock structural shapes with plates and angles bolted or welded to the main member as described in the approved shop drawings.

Shop drawings are produced during the detailing process, which begins once the contract documents for a construction project (which uses structural steel) are approved. The contract documents define the responsibilities between the parties involved in fabricating and erecting the structural steel, and normally include the design drawings, the specifications, and the contract [11]. The detailer works from the more general steel design drawings and produces the 'detailed' shop drawings (e.g., connection details), erection drawings, and anchor rod placement diagrams. The shop, erection, and anchor rod drawings together are known as the detailing package. Historically, the detailers started their work using paper drawings provided by the structural engineer and re-entered the design data into their shop's detailing package. With the advent of CIS/2 as a standard product model for interoperability between design, analysis and detailing software packages for the steel industry, this information is increasingly being transferred among parties electronically.

Fabrication starts when the architect (or designee) approves the shop drawings. Of note, steel shapes and other materials are typically ordered ahead of approval of the shop drawings to ensure timely delivery from the mill (or service center if used).

Steel fabrication companies in the U.S. can be loosely characterized as either 'bolted' shops or 'welded' shops. In the former, a CNC drill line is used to create the necessary hole patterns to attach clip angles and plates using bolted fasteners. In shops lacking a dedicated CNC beam drill line, the subassembly components are primarily attached by welding. There is no specific structural advantage in either case, as long as quality control standards in locating and attaching the sub-components on the main piece are maintained.

In a welded shop, the job of locating the sub-components correctly is done by the 'fitter'. This role is one of the most critical jobs in the fabrication process. Subassembly component locations are measured and marked, and then the piece is temporarily held by tack-welding until the final weld is done (Fig. 1). This process is known as fitup and layout. Fitting errors are the most common and are usually not discovered until the piece is in the field. The placement of pieces during fitting is one of the biggest areas for improvement. Not only are these processes prone to measurement errors, but sometimes the pieces themselves are unwieldy, (e.g., fitting a column to a base plate), and are difficult to hold in the correct location during welding. It was also noted that an improved shop inspection system would not only improve shop quality control but also reduce time-consuming field inspection. As with steel production, better fabrication processes would also reduce the tolerance requirements in the connector, and ultimately produce more rapid field assembly.

Whether the fabrication shop is a 'welded' or 'bolted' shop, the side of the connection to be completed in the field (the field connection) is usually a bolted connection due to the difficulties imposed by field welding.

Figure 1. Component tack-welded in place. Note Fitter's locating marks.

The surface of the steel member is then prepared and painted as required. Each member is also provided with a unique identifier known as a piece mark. This piece mark is cross-referenced on the shop and erection drawings. Different fabricators have different systems for creating and applying piece marks. The AISC standard piece mark consists of drawing number followed by the piece type followed by the piece number on the sheet. The left end of the piece as it appears on the detail drawing is most typically the end of the piece on which the mark appears.

Once the steel members meet final quality inspections, they are either stored in the shop's laydown area or directly loaded on trailers for shipment to the erection site. Shipment strategies are defined by the erection sequence, the number of erection crews on the site, availability of site storage, and other factors. A rule of thumb used by one fabricator/erector is that a crew can erect approximately 54 metric tons (60 tons) - roughly 90 pieces - in one day. This load would be transferred on 2 to 3 flatbed trucks. These loads are typically assembled based on transportation efficiency as opposed to site delivery (unloading) efficiency.

2.4 Steel Erection

The steel erector is responsible for an erection plan which specifies standard practices and in particular outlines the safety measures to be employed. An outline of these standard practices is available in the AISC Certified Steel Erector Audit Checklist [12]. The steel erector is ready to commence the field assembly of the steel structure when the erection drawings are approved, the foundation is set, the anchor rod positions are verified, and erectable steel[5] is on site. The AISC Audit Checklist also provides guidelines related to anchor rods. Steel erection should commence only after receiving notification that the foundation has sufficiently cured and that any modification of the anchor rods have been approved by the Engineer of Record. An erector should also have a record of the anchor rod survey. On numerous occasions (during NIST workshops, site visits, etc.) it has been reported that improper anchor rod locations are one of the primary causes of assembly setbacks during steel erection (fabrication errors were noted as the greatest cause for problems).

The unloading, or *shake-out*, of each truck load - approximately 18 metric tons (20 tons) - takes about one hour. For higher productivity, a dedicated shake-out crew can be assigned to provide steel for multiple erection crews. Delays caused by a failure to find the next required piece of steel on the job site have been reported as another source of on-site problems. For smaller projects or where there is insufficient laydown area for the steel, lifts may take place directly from the fabricator's delivery truck.

The delivery sequencing is based on a lift list generated by the erector. The actual day-to-day lift sequence is then decided in the field by an experienced foreman based on the predetermined lift plan and modified as required due to site contingencies.

A team of ironworkers – normally five – comprise the raising gang. Two members climb the steel to grab the pieces lifted by the crane, guide them into place, and make the initial connections (Fig. 2). These workers are known as connectors, and generally have the most difficult (and hazardous) role in the steel erection process. Two ground personnel assist the crane operator in moving the steel to the connectors. The hook-on man places the choker on the next lift and the tag-line man uses a tag-line to help guide the steel to the connectors. The foreman, or pusher, gives overall directions and decides which pieces are to be erected next in the sequence. A bolting-up gang follows the raising gang to permanently install the bolts after the frame is plumbed [13].

Figure 2. Using a spud wrench to align holes during initial assembly. (*Source: AISC*)

In general, the erection sequence is to first lift and bolt the columns in place, and then fill in the main girders. The beams are then placed between the girders. Each steel member is first connected using two initial bolts. Temporary bracing is also installed as required to provide structural support during assembly. Depending upon many factors (e.g., crane location and availability, site access, coordination with other trades, etc.) the building may be erected in sections, with the steel frame for one section almost complete prior to starting another section. When three floors are raised the structure is plumbed and the first two floors are permanently bolted prior to installing the fourth floor. The third floor is left loose to allow for some compliance when attaching the next floor. An alternative approach is to plumb after two floors and then permanently bolt and install decking on the first floor. As each floor is added, the structure is plumbed and bolted, leaving only the top floor loose for compliance. Every other floor can be decked after plumbing and bolting to satisfy some of the fall protection requirements.

Of note, this discussion describes the erection of a relatively simple structure with purely orthogonal columns, girders and beams and no welded field connections. Complicated structures, such as the Disney Concert Hall

[5] The term "erectable steel" means the correct steel (per the sequence diagram), properly fabricated, delivered and located on the site.

and the Denver Art Museum are not represented in this generalized discussion. However, this description is applicable to the majority of steel buildings erected in the U.S.

3 3D IMAGING IMPACT AREAS IN STEEL CONSTRUCTION

Initial work on the use of laser-based 3D imaging systems for tracking construction progress is provided in [14]. Reed [15] discussed the use of the CIS/2 data product model for automating erection and survey of structural steelwork. Foundational work on formalizing processes for construction quality control and defect detection (including anchor rod location) using 3D imaging and other advanced sensing systems is provided by Akinci et al. [16]. The use of 3D imaging for site status monitoring was discussed by Shih [17].

The following sections present potential scenarios of how laser-based 3D imaging and object recognition could improve the steel construction process. The basis for these scenarios are numerous discussions with steel construction experts and brainstorming sessions with researchers and industry experts such as those that occurred during the NIST/AISC Automated Steel Construction workshop [1]. The scenarios are presented without any specific description of how they will be implemented, whether the means exist to implement them, or whether prior research in these areas is applicable. Cost and potential return on investment are likewise not considered.

3.1 Steel Production

Roller Verification and Monitoring: During the hot-rolling process, the roller is continuously imaged and checked against its design specifications for out-of-tolerance wear. The process is halted and the roller(s) are replaced prior to producing out-of-tolerance steel shapes.

Shape Straightening: Structural steel shapes are imaged in transit prior to entering the straightener. The straightening process is dynamically changed depending upon the actual requirements of the piece.

Shape Tolerance Verification: Steel is imaged again after final straightening and cutting to length to verify conformance to the tight tolerances required for automated construction. An electronic geometric model of the as-produced shape is generated and stored along with the material genealogy information. Steel fabricators and service centers can access the mill's data and track available inventory and/or status of pre-ordered pieces.

3.2 Steel Fabrication

Receipt Inspection: Shapes are scanned as they are unloaded into the storage area. Scan data is compared to the electronic manifest for piece verification and checked for tolerance compliance.

Fitup and Layout: Fabrication starts by loading a "shop transport" (e.g., rail car, air bearing 'sled', etc.) with the main shape and subcomponents. A radio frequency identification (RFID) tag on the main shape is updated with the CIS/2 descriptor and control number of the piece being constructed. The transport moves to the fitup and layout station, where subcomponents are selected, positioned, and held in place with robotic manipulators while a robotic welder performs the initial tack weld. Guidance for the fitup and layout process is provided by 3D imaging sensors, using fitup data provided from the CIS/2 file on the RFID tag.

Final Welding: Following fitup and layout, final welding is performed using a robotic welder at a follow-on station. Welding instructions are extracted from the CIS/2 data and seams are identified using 3D imaging. Welding is adaptively controlled along the seams using 3D imaging.

Final Inspection: The piece is imaged prior to surface preparation and painting to verify compliance with intended design. Deviations are noted by comparing the CIS/2-described geometry against the imaged piece.

Guidance of Piece Transport Mechanism: The fabrication sled uses 3D imaging systems for collision avoidance/safety systems. Alignment of the sled to the various workstations is accomplished using laser guidance systems.

3.3 Steel Erection

Anchor Rod Verification/Real-time Monitoring: During the foundation pour, 3D imaging systems are continuously monitoring the anchor rod locations (or targets affixed to the anchor rods) to verify compliance with the building model. Once cured, the anchor rod locations are imaged to capture the existing as-built conditions, and passed to the steel erector for verification against the detailed steel model.

Crane Mobility Sensor: The crane hook (or equivalent automated gripper mechanism) is equipped with a 3D imaging sensor which provides the operator with 'at-the-hook' situational awareness and collision avoidance feedback. Large scale pick-and-place operations, including docking shapes during the erection sequence, are also guided by the sensor and aided by construction object recognition/tracking algorithms.

Verifying Daily Status: Periodic expected gains are extracted from the Building Information Model (BIM) and compared to 3D images for schedule tracking and as-built verification. Overall site status (e.g. temporary equipment locations, hazards, laydown status) is captured in 3D and provided to supervisors to maintain overall situational awareness.

Verifying Plumbness: Scans of the structural steel are taken during erection to either verify or guide plumbing the structure.

Capturing Existing Conditions of Steel Frame for Subsequent Trades: Once the steel erection is complete, the structure is imaged to verify compliance to the geometric design model. The actual geometry of the structure is captured and used to check the trades' designed installations. Potential clashes are discovered prior to installation through 3D clash detection. (Note: This is currently done during design with teams who are using 3D models. The difference is the feedback of existing conditions following steel erection to verify the design data).

4 3D IMAGING IN THE NIST AUTOMATED CONSTRUCTION TESTBED

CMAG has ongoing research in the application of laser-based 3D imaging technologies in construction. Previous work has primarily focused on laser scanning for applications such as terrain characterization, earthmoving analysis, and targeted object localization. Current work includes the development of standard test methods for the performance evaluation of 3D imaging systems [18] and implementation of these systems for construction object recognition and tracking, site monitoring, and collision avoidance/docking guidance.

4.1 Construction Object Recognition and Pose Estimation from High Resolution Scanning

NIST researchers recently completed an initial study of construction object (structural steel) recognition from high resolution 3D laser scan data [19]. The objectives of this study were to segment potential objects from a point cloud, identify the target object from a set of known objects, and to develop an algorithm to determine the pose of that target object. Two approaches (binning and triangulated irregular networks (TIN)) for segmenting potential objects of interest were employed. Once potential objects of interest were segmented from the rest of the range image, bounding boxes were used to identify which of the objects were potential target objects. If the bounding box fit the segmented points, the point data associated with the target object data set was then analyzed using the method of principal axes to determine the object pose. Variable factors in the study included point density, object size, and the rotation of the object relative to the scan direction.

4.2 Crane Collision Avoidance and Docking

In a related effort, CMAG researchers are investigating the use of high frame-rate (approximately 30 Hz) low-resolution (160 pixels x 124 pixels) 3D optical range cameras for obstacle avoidance and docking guidance on the NIST RoboCrane. The docking guidance will employ continuous tracking of recognized target steel beams in the range image data for real-time feedback to the robotic crane controller.

5 SUMMARY

3D imaging systems are an enabling technology for automating numerous aspects of structural steel production, fabrication and erection. The general categories of application include manufacturing process control, quality assurance, site status monitoring and as-built verification. For steel production, applications include the ability to monitor roller tolerance, shape straightening, and to verify final shape geometric specifications. Steel fabrication could benefit from receipt inspection of shapes, automation of fitup, layout, and welding, and quality assurance of finished pieces. Finally, 3D imaging system applications in structural steel erection include anchor rod verification, crane collision avoidance, productivity analysis, quality assurance, structure plumbness verification, and as-built documentation for follow-on trades.

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