Automation and Robotics in Construction XI
D.A. Chamberlain (Editor)




# Automatic Laser-Controlled Erection Management System for High-rise Buildings

Tadashi Kanzaki, Koichi Nakano, and Michio Matsumoto

Taisei Corporation
1-25-1, Nishi-Shinjuku, Shinjuku-ku, Tokyo 16306, Japan

**Abstract**

Various new construction techniques, such as the multi-layer, block, unit, and lift-up methods, have recently been introduced for the construction of high-rise buildings. The aim of bringing in these new methods is labor-saving and reducing the construction period, and the trend is likely to continue in the future. Little progress, however, has been made in the techniques used to measure the position of structural steel members during construction, and surveying is still carried out manually.

## 1. INTRODUCTION

To meet the need for improvement, the system described in this paper has been developed to replace manual positioning of steel members during plumbing and straightening with an automatic method. When compared with conventional measuring methods, the system offers faster and more accurate surveying and has a significant effect on labor reduction.

This system has been developed as a part of the T-UP construction method, which was used in construction of the Yokohama Building for Mitsubishi Heavy Industries, Ltd. After full verification of its measurement accuracy, measuring speed, and operability

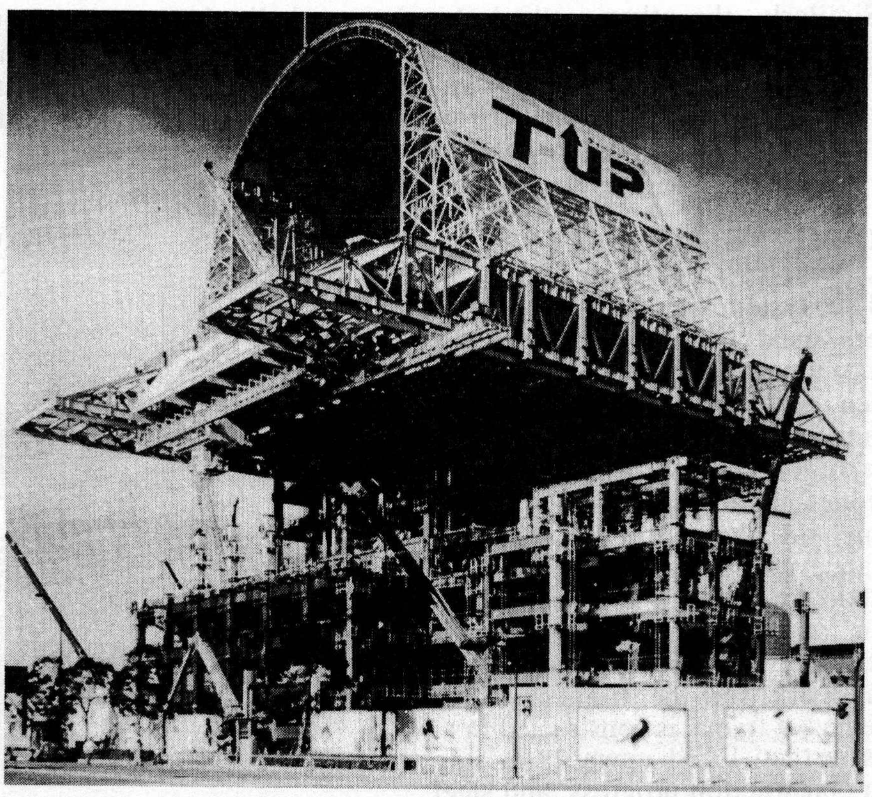


Photo 1 Yokohama Building under construction

in field experiments, the system has now been put into practical use. An outline of the system is given below, along with the results of field experiments.

## 2. CONVENTIONAL MEASURING METHODS

Conventional methods of taking measurements during building construction can be classified roughly into two types: those in which reference points are shifted upwards as building progresses and those in which steel structures are placed on each floor. With the former methods, surveyors move the reference point up one floor at a time using plumb lines or optical instruments in step with construction progress. When plumbing and orienting steel members, surveying is usually done manually using tape measures, levels, and transits. (See Photo 2.) There are several drawbacks to this method, however: long plumbing rules are required to cover greater vertical distances, and measurements using optical instruments are limited to four or five floors because of limitations in the view through a telescope. Measurement errors are apt to accumulate as the instrument is moved higher and higher in the building.

Photo 2 Plumbing and positioning of steel members by conventional methods

Similarly, the other methods have several disadvantages: positioning takes a lot of manpower, surveyors must take safety precautions when using rulers and rod scales on the top of steel members, and there is no way of checking the movement of structural members other than the one being aligned at the particular time. In addition, wind-induced swaying and vibration needs to be taken into consideration when surveying.

## 3. OUTLINE OF SYSTEM

### 3.1. System configuration

The system consists of vertical lasers used to transfer reference points upwards and a laser scanner which measures the position of steel members during the erection process. (See Figure 1.) Vertical lasers are stationed at the four corners of a steel frame on the ground called an advance core. In the construction method to which this technique has been applied, called the T-UP method, the structural steel framework for the highest floor, called a hat frame, is constructed first. This is then lifted upwards in step with construction progress, and steel structural members are erected under a temporary roof. The laser scanner was mounted centrally on the under-

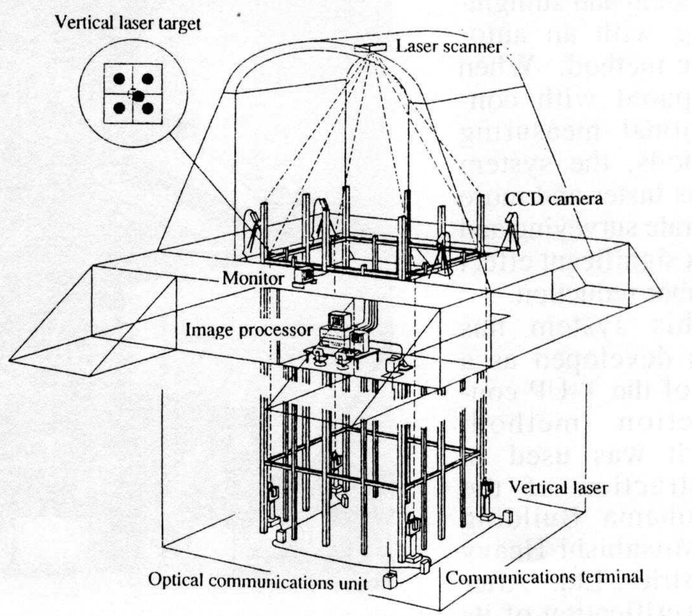


Figure 1 Configuration of automated laser-controlled erection management system

side of the temporary roof, allowing it to scan downward onto steel members being moved into place.

To allow information provided by the lasers and scanner to be utilized in steel erection work in real time, computers and monitors were installed in an instrumentation room within the hat frame. A TV was also placed at the steel erection level, allowing workers to monitor the position of steel components. The four vertical lasers, the laser scanner, and the various computers are linked in a network to facilitate data exchange.

### 3.2. Principle of operation

Each vertical laser, stationed at one of four reference points on the ground, radiates a beam upwards with a vertical accuracy of about four seconds of arc. The beams form red laser spots on translucent target sheets at four points on the hat frame. These red laser spots act as reference points for the scanner. The scanner first measures its own position using these spots, then measures the position of the steel column head. This measurement procedure is described below.

(1) Computing the position of the laser scanner itself

In general, the coordinates of a point can be calculated from at least three sights of points with known coordinates. Say A1, A2, and A3 are these three known points, and A0 the point with unknown coordinates (X0, Y0, Z0), as shown in Figure 2. If the included angles, $\alpha 1$, $\alpha 2$, and $\alpha 3$, can be determined, the coordinates of point A0 can be calculated as follows.

The lengths of segments, S1, S2, and S3 are obtained by solving the following equations:

$$S2^2 + S3^2 + 2 \cdot S2 \cdot S3 \cdot \cos\alpha 1 = l1^2$$

$$S3^2 + S1^2 + 2 \cdot S3 \cdot S1 \cdot \cos\alpha 2 = l2^2$$

$$S1^2 + S2^2 + 2 \cdot S1 \cdot S2 \cdot \cos\alpha 3 = l3^2$$

where $\alpha 1$, $\alpha 2$, $\alpha 3$, l1, l2, and l3 are known. Substituting the lengths of segments S1, S2, and S3 from the above equations and the coordinates of the known points into the equations below and solving them simultaneously gives the coordinates of point A0.

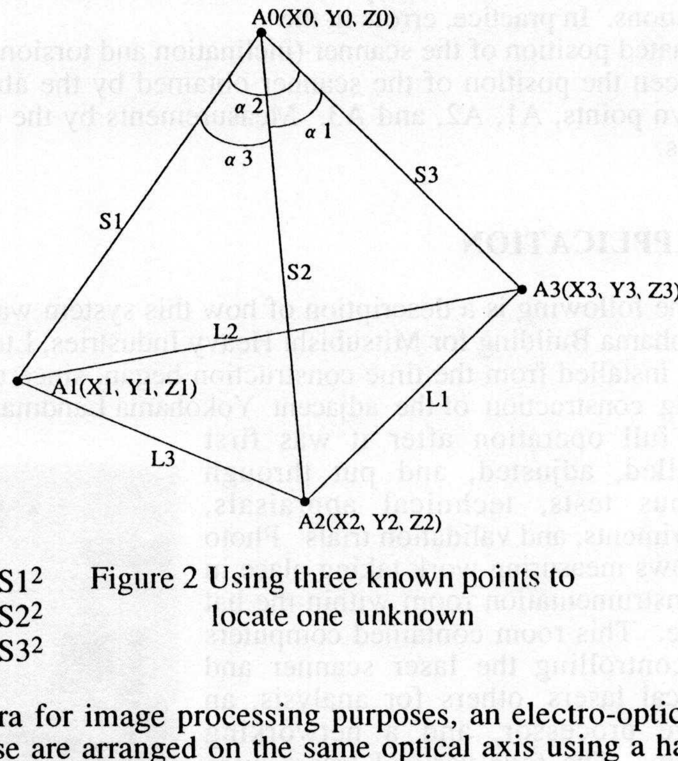


Figure 2 Using three known points to locate one unknown

$$(X1-X0)^2 + (Y1-Y0)^2 + (Z1-Z0)^2 = S1^2$$
$$(X2-X0)^2 + (Y2-Y0)^2 + (Z2-Z0)^2 = S2^2$$
$$(X3-X0)^2 + (Y3-Y0)^2 + (Z3-Z0)^2 = S3^2$$

The scanner contains a CCD camera for image processing purposes, an electro-optical distance meter, and a laser tube. These are arranged on the same optical axis using a half mirror. The optical axis can be oriented using two rotating mirrors, allowing it to scan a range of about $2\pi/3$ steradianswith an accuracy of four seconds using a high-resolution laser encoder. The built-in CCD camera and image processor guide one of the laser spots to the center of the image, and at the moment it comes into alignment, the included angle is calculated from the two angles of the mirrors. Since with four laser spots there are four possible combinations of three spots, the average of the four combinations is used to locate the scanner. Additionally, the position of the scanner can be obtained by measuring the lengths of segments S1, S2, and S3 directly, using the built-in electro-optical distance meter.

(2) Computing the position of a steel column head

Figure 3 illustrates how the position of a steel column center (center of a column head ) is measured using the scanner. Point A0, the scanner position, is found as described above. The three-dimensional location of the column head can be calculated if its distance from point A0, L, the horizontal angle from the collimation line, $\alpha$, and the vertical angle, $\beta$, are measured.

Both the horizontal angle with respect to an encoder reference bearing, $\alpha$, and the vertical angle, $\beta$, can be obtained by the method described above using the rotating mirrors. However, the scanner is not always exactly at its design point because of sway and vibrations. In practice, errors in the estimated position of the scanner (inclination and torsion) are calculated from the relationship between the position of the scanner obtained by the above-mentioned calculations and the known points, A1, A2, and A3. Measurements by the encoder are then corrected for these errors.

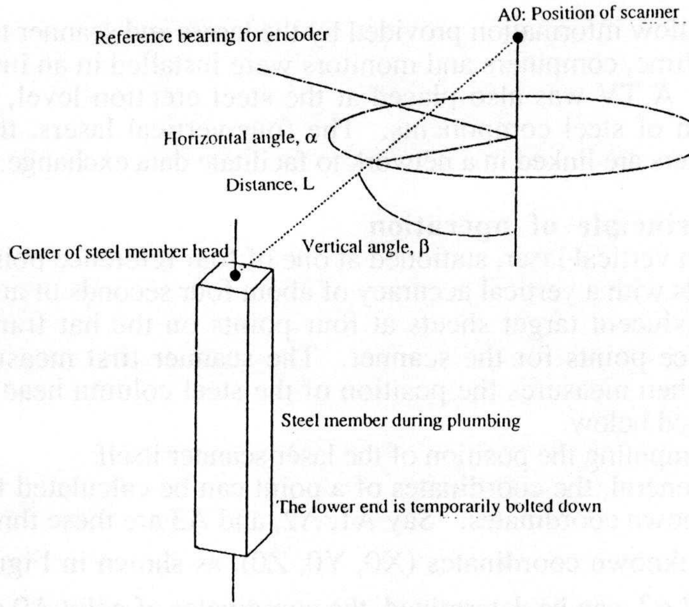


Figure 3 Computing the position of a steel column head

## 4. APPLICATION

The following is a description of how this system was applied during construction of the Yokohama Building for Mitsubishi Heavy Industries, Ltd. (See Photo 1.) The vertical lasers were installed from the time construction began, since their utility had already been proven during construction of the adjacent Yokohama Landmark Tower. The scanner was brought into full operation after it was first installed, adjusted, and put through various tests, technical appraisals, experiments, and validation trials. Photo 3 shows measuring work taking place in the instrumentation room within the hat frame. This room contained computers for controlling the laser scanner and vertical lasers, others for analysis, an image processor, and a networking system. The four vertical lasers were instructed under remote control to illuminate the target sheets on the hat frame. The required data were input from the CCD camera in the scanner, and the scanner itself was also remote-controlled for the collection of image and angle data. The collected data were processed and analyzed using computers and the image


Photo 3 Measurement work in the instrumentation room

processor, and the results were displayed on monitors. Instructions were transferred to these various units through the network.

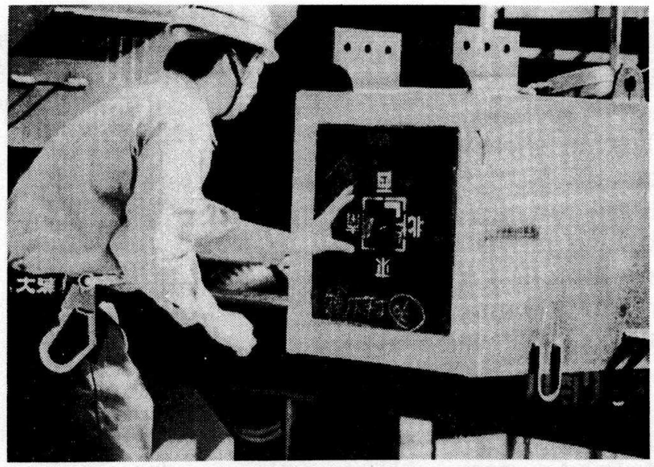

Photo 4 Laser reflection sheet attached to steel column head

Photo 4 shows a laser reflection sheet attached to a steel column head before lifting. The steel member is lifted and moved to an upper floor. The laser tube in the scanner emits a beam towards the steel column, and at the same time its image is captured by the CCD camera; this allows measurement of the position of the steel column head.

This building was constructed using an advance-core construction method, and the 22 steel columns of the core were measured by the scanner; however, the steel columns around the core were not measured. Since the beam has a certain divergence, the CCD camera was able to capture a reflection even if a steel column was not precisely at its design center. The beam width was adjusted to about 30 cm near the head of the steel member. Although the entire reflection sheet was illuminated, the image processor was able to isolate the center of gravity of the image, thus yielding an accurate measure of the deviation from the design center.

Photo 5 shows how a deviation from the design center is displayed on the screen. The data displayed here is for 34th-floor steel columns during straightening. Deviations were some tens of millimeters immediately after plumbing, and they were displayed in real-time on the screen as straightening work proceeded. Workers could monitor progress on a TV on the erection floor while work was under way. Furthermore, since monitoring of movements of steel columns other than those being straightened was possible, make-up time was minimized.

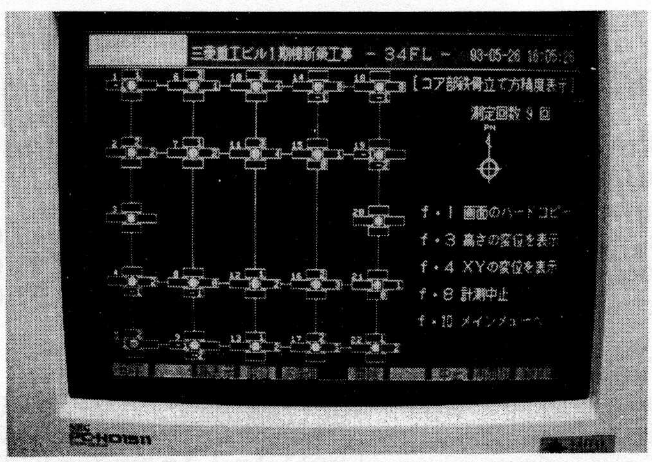


Photo 5 Deviations from design centers displayed on screen

## 5. EXPERIMENTAL RESULTS

To minimize measurement errors due to sway and vibrations, the system was designed to simultaneously measure the position of a steel member while checking its own position against the reference points. To allow a wide area to be scanned, rotating mirrors are used to move the optical axis of the scanner and CCD camera with a response of about 0.8 second. To exclude potential errors during high-speed swaying motion, moving averages were calculated and displayed, although measurements were in fact unaffected by the intensity of sway. Figure 4 shows a typical screen display for steel members under straightening. Workers worked to straighten the steel members and position them within allowable limits while monitoring this output.

To check the relative accuracy of the system, a reflection sheet was moved stepwise by amounts ranging from 100 to 500 mm, measuring the movement with a steel rule. The difference between measurements using the system and readings with the steel rule was less than ±1 mm. Figure 5 shows such measurements taken when the position of the reflection sheet on the head of No. 3 steel column on the 32nd floor was moved in the same direction by 100 mm and 200 mm. This test acts as a check of the mechanical behavior of the system, and similar results were obtained for all members. Accordingly, we judge that the optical strain error introduced by the relationship between the two rotating mirrors and CCD camera optical axis were negligible.

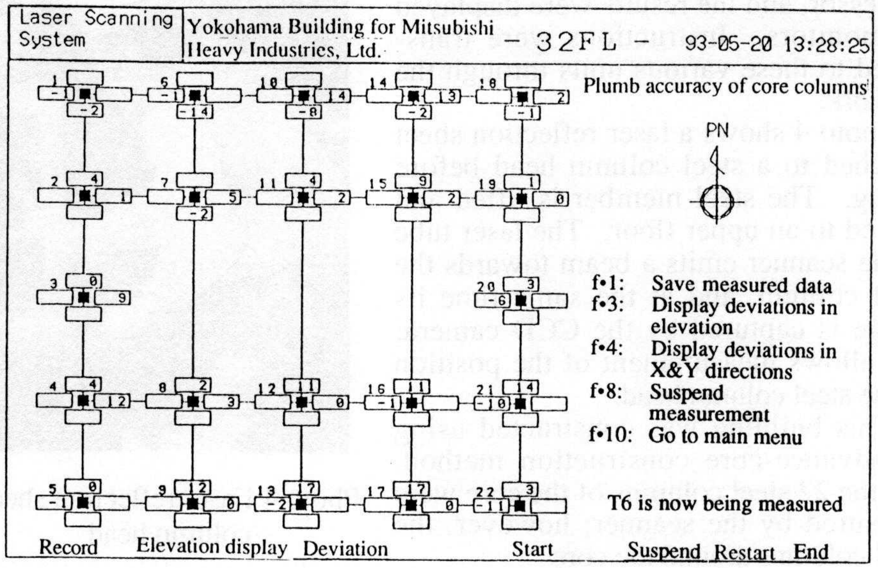


Figure 4 Typical output for steel members being straightened

## CONCLUSIONS

Field tests proved that this system is very helpful in improving efficiency and saving manpower during steel erection work. We expect to apply the system to further building construction projects and collect more data with the aim of improving measurement accuracy. One possible future development is to apply the system to conventional construction using tower cranes. For this purpose, the scanner will have to be improved to enable it to measure objects in a moving, rotating, swaying, and vibrating environment. Other issues for future study are as follows.

- Improving the scanning speed
- Widening the measurable angle
- Improving the accuracy of the encoder's angle-measuring function

The system has so far been used mainly for the measurement of steel column position. Another possible use is in an automatic steel positioning system linked with a control unit. We plan to proceed with further development of the system and investigate these various possibilities.

| | |
|---|---|
| No13 X=-2 Y=4 Z=3 93-05-20 18:15:03<br>No13 X=-2 Y=4 Z=3 93-05-20 18:15:05<br>No13 X=-2 Y=4 Z=3 93-05-20 18:15:08 | Present position |
| No13 X=-2 Y=104 Z=3 93-05-20 18:23:49<br>No13 X=-2 Y=103 Z=3 93-05-20 18:23:52<br>No13 X=-2 Y=104 Z=3 93-05-20 18:23:55 | Position after moving 100 mm in the Y-direction |
| No13 X=-2 Y=203 Z=3 93-05-20 18:29:11<br>No13 X=-2 Y=204 Z=3 93-05-20 18:29:14<br>No13 X=-2 Y=204 Z=3 93-05-20 18:29:17 | Position after moving 200 mm in the Y-direction |

Figure 5 Measuring the position of a reflection sheet after movement