ALIGNMENT SYSTEM OF PROTON ACCELERATORS FOR CANCER THERAPY

Takashi Kitahara[1], Yasutaka Tagawa[2], Shizuo Imaoka[3], and Yuichi Yamamoto[4]

ABSTRACT

The high accurate alignment system to install proton accelerator is developed. The accelerator has a number of electromagnets, which control the orbit of a proton beam. These electromagnets have to be installed with very high accuracy (design value ±0.1mm) by 3D measurement and position adjustment operations. A laser tracker is used to get the 3D coordinates of the electromagnet. And 10 position adjustment bolts, which are put in a mount of the electromagnet, are used to adjust the position of the electromagnet. However, the conventional method is inefficient and makes it difficult to predict the installation time of an electromagnet, because the 3D measurement and bolt operation are repeated time and time again till the electromagnet is installed to a target position. The alignment system we developed has the laser tracker, dial gages and a control unit. Dial gages are used to measure operational amounts of the position adjustment bolts. The system can calculate the optimum operational amounts of the bolts by obtaining the Jacobean matrix between the operated variables of the bolts and the 3D position changes of the electromagnet. This paper describes an overview of the alignment system, the calculation method of the optimum operational amount of the bolts, and the results of an experimental alignment using a mock-up of the electromagnet.

KEY WORDS

alignment, electromagnet, installing, Jacobean matrix, proton accelerator, 3D measurement

[1] Researcher, Matsudo Research Laboratory, Hitachi Plant Technologies, Ltd., 537 Kami-Hongo, Matsudo-shi, Chiba-ken, 271-0064, Japan, Phone +81 47/361-6122, FAX 47/361-5296, takashi.kitahara.cj@hitachi-pt.com

[2] Professor, Applied Mechanical Engineering Dept., Tokyo University of Agriculture and Technology, 2-24-16 Nakacho, Koganei-shi, Tokyo, 184-0012, Japan, Phone +81 42/388-7091, FAX +81 42/385-7204, tagawa@cc.tuat.ac.jp.

[3] Senior Researcher, Matsudo Research Laboratory, Hitachi Plant Technologies, Ltd., 537 Kami-Hongo, Matsudo-shi, Chiba, 271-0064, Japan, Phone +81 47/361-6122, FAX 47/361-5296, shizuo.imaoka.gc@ hitachi-pt.com

[4] Nuclear Power Plants Construction Project Group, Hitachi Plant Technologies, Ltd., 1-13-2 kita-Otsuka, Toshima-ku, Tokyo, 170-8466, Japan, Phone +81 3/3576-1366, FAX 3/3576-4208, yuichi.yamamoto.du@ hitachi-pt.com

INTRODUCTION

In recent years, cancer therapy using a proton beam is becoming widespread. Protons from hydrogen atoms are converged into a proton beam. And after an accelerator imparts the energy to the beam, it is accurately aimed and irradiated an affected part to destroy cancer cells.

The irradiated proton beam reaches a depth based on the degree of energy imparted to it. X-rays or γ-rays used in conventional radiotherapy gradually lose their energy as they penetrate a body. On the contrary, a proton beam immediately transfers energy before the beam is stopped. If there are cancer cells at that position, the proton beam destroys only the cancer cells with minimal influence on normal cells at other locations and this greatly reduces side effects. Japan and a number of Western countries are planning to introduce many proton beam therapy facilities in the future.

Fig.1 shows a layout of a typical proton beam therapy facility. The facility consists of a proton synchrotron, an accelerator, and irradiation rooms. A proton beam emitted from the proton synchrotron is converged by electromagnets into the circular beam line of the accelerator, accelerated to about 70% the speed of light, and is then sent to the irradiation rooms using directional control. Therefore the electromagnets need to be positioned with accuracy as high as the design value of ±0.1 mm. To realize the installation of electromagnets with high accuracy, the alignment system using 3D measurements and robotic control technology is developed.

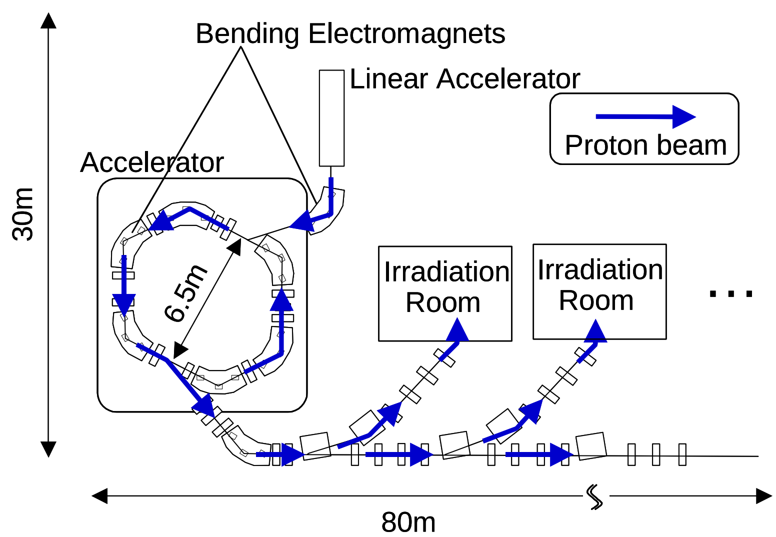


Figure 1: Prton Beam Therapy Facility

2. ELECTROMAGNET ALIGNMENT SYSTEM

2.1 CONFIGURATION OF ALIGNMENT SYSTEM

Fig.2 shows an overview of the electromagnet alignment system. This system has a 3D measuring instrument, dial gages to measure the operational amounts of bolts for position adjustment of the electromagnet, and a control unit to calculate the optimum operational amounts of the bolts. The mock-up of the bending electromagnet in the figure simulates the shape, mass, and the positioning mechanism of an actual electromagnet. Here the bending electromagnet is used to veer the traveling direction of proton beam by the electromagnetic power. On the top surface of the electromagnet, there are three holes to allocate mirror reflectors for 3D measuring instrument. The target position of the electromagnet is given as 3D coordinate values of these mirror reflectors.

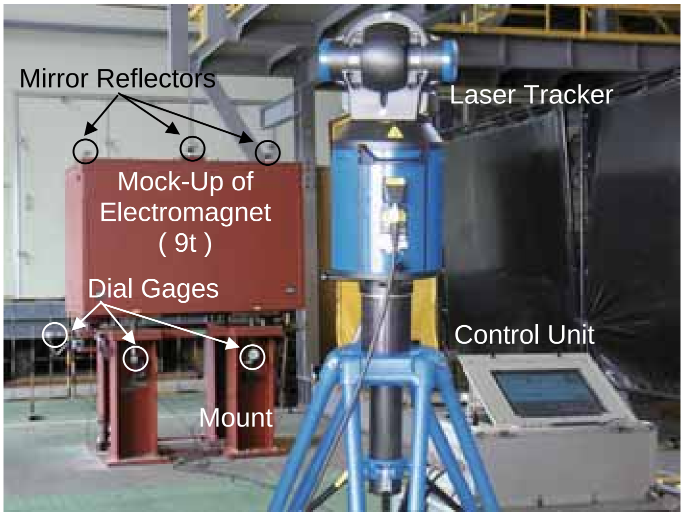


Figure 2: Alignment System

Fig.3 shows details of the vertical and horizontal position adjustment bolts on the electromagnet mount and the dial gages attached to them. There are four adjustment bolts in the vertical direction and six in the horizontal direction for the 6-DOF electromagnet position adjustment.

Vertical bolt (M42)

Horizontal bolts (M24)

Figure 3: Position Adjustment Bolts and Dial Gages attached to them

Fig.4 shows the 3D measurement instrument and mirror reflector for the instrument. For the measurement instrument, a laser tracker is used. The laser tracker is known as a portable high accuracy 3D measurement instrument for industrial use. And it measures 3D coordinates with its laser and angular encoders by following a mirror reflector. Its 3D single point accuracy is ±0.027mm when there is distance of 2m between the instrument and the object.

Laser Tracker   Mirror Reflector

Figure 4: Laser Tracker and Mirror Reflector

2.2 STUDY OF ALIGNMENT TECHNIQUE

The conventional method aligns an electromagnet to a target position by repetition of 3D measurement and position adjustment. However, such repetitive process lead to low efficiency and make it difficult to predict the installation time, because the 3D measurement and bolt operation are repeated time and time again till an electromagnet is installed to a target position. So the total time required for constructing the entire therapy facilities may also be affected. Therefore, we have developed an alignment technique for positioning an electromagnet efficiently onto a target position by obtaining the relationship between the operated variables of the position adjustment bolts and the position changes of the electromagnet.

For the new technique, the gravity point of a triangle formed by the mirror reflectors and 3 rotational axes are defined on the electromagnet. These are shown in **Fig.5**. θz is a rotation around an axis that is at right angle with the triangle, and θy is a rotation around an axis that is set from the gravity point through the reflector **P2**. And the rotational axis of θx is set at right angles with the other axes. So, the manipulation of the vertical adjustment bolts V1 to V4 gives the displacement of gravity point in the z direction and rotations, θx and θy, to the electromagnet. And horizontal manipulation using bolts H1 to H6 also gives the displacements in the x and y directions and θz rotation to the electromagnet.

Introducing the gravity point and rotational axes make it possible to describe the relationship between the operated variable of each bolt and the position changes of the electromagnet by a Jacobean matrix. In generally, a Jacobean matrix is used to express the relationship between the hand displacement of a multi-joint arm robot and the rotational angle of each joint.

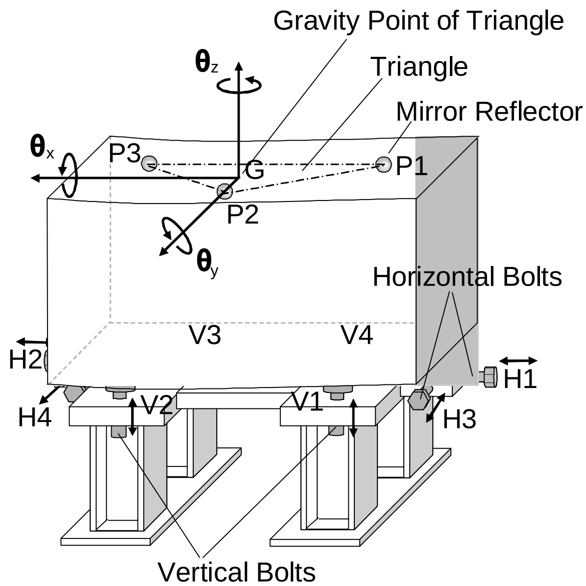


Figure 5: Gravity Point of Triangle and 3 rotatianal axes on Electromagnet

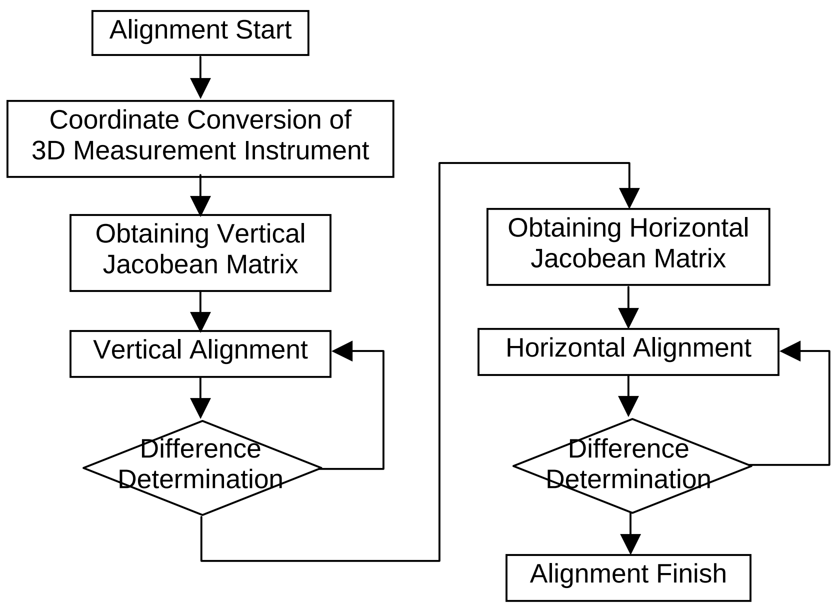
Using the horizontal alignment as an example, the definition and obtaining method of the Jacobean matrix are explained next. If the position changes of the electromagnet are dx, dy, and dθz when the horizontal bolts H1 to H4 are fed slightly by dLi (i = 1 to 4), the relationship of equation 1 becomes true. Here, the first term on the left is the Jacobean matrix. This matrix indicates the position change of the electromagnet when each bolt is fed 1mm. When this Jacobean matrix is $\boldsymbol{J}$, the pseudo-inverse matrix $\boldsymbol{J}^{+}$ changes equation 1 to equation 2. Equation 2 enables the calculation of the operational amounts of bolts, dLi (i = 1 to 4), to change the magnet position by dx, dy, and dθz. In other words, if the difference between the current position and the target position of the electromagnet is expressed by dx, dy, and dθz, the operational amount of each bolt necessary for positioning can be calculated. The above method is for horizontal alignment. However, the vertical Jacobean matrix can also be obtained by operating bolts (V1 - V4) in the same way.

$$\begin{pmatrix} \frac{\Delta x}{\Delta L_1} & \frac{\Delta x}{\Delta L_2} & \frac{\Delta x}{\Delta L_3} & \frac{\Delta x}{\Delta L_4} \\ \frac{\Delta y}{\Delta L_1} & \frac{\Delta y}{\Delta L_2} & \frac{\Delta y}{\Delta L_3} & \frac{\Delta y}{\Delta L_4} \\ \frac{\Delta \theta z}{\Delta L_1} & \frac{\Delta \theta z}{\Delta L_2} & \frac{\Delta \theta z}{\Delta L_3} & \frac{\Delta \theta z}{\Delta L_4} \end{pmatrix} \begin{pmatrix} dL_1 \\ dL_2 \\ dL_3 \\ dL_4 \end{pmatrix} = \begin{pmatrix} dx \\ dy \\ d\theta x \end{pmatrix} \quad (1)$$

$$\begin{pmatrix} dL_1 \\ dL_2 \\ dL_3 \\ dL_4 \end{pmatrix} = \boldsymbol{J}^{+} \begin{pmatrix} dx \\ dy \\ d\theta x \end{pmatrix} \quad (2)$$

2.3 PROCEDURE OF VERIFICATION EXPERIMENT

We verified the developed alignment algorithm by using the mock-up of the electromagnet. **Fig.6** shows the flow chart of an alignment operation. At the beginning, it is necessary to obtain the conversion matrix from the coordinate values of the 3D measurement instrument into the standard coordinate system values of the therapy facility, since the target position values of electromagnets are specified on the standard coordinate system. On the walls and floor surfaces of the therapy facility, there are many benchmarks, which have strictly accurate coordinate values. So, measuring at least 3 of these benchmarks makes it possible to obtain the conversion matrix.



Figue 6: Flow Chart of Alignment

After the coordinate conversion, obtaining the Jacobean matrix for vertical alignment is executed. The operation sequence is as follows:

- Set dial gages to the each vertical adjustment bolt.
- Measure the position of 3 mirror reflectors on the electromagnet by the laser tracker.
- Feed one of Verticale adjustment bolts using a wrench.
- Measure the operated variable of the bolt by the dialgage.
- Measure the position of the mirror reflectors again.
- Slacken the bolt by the feeding amount.
- Repeat these operation on the each vertical adjustment bolt.

When the Jacobean matrix is obtained, the vertical alignment is executed and repeated until z-coordinate value of the gravity point and 2 rotational angles, θx and θy, of the triangle are fit into the target values. **Fig.8** shows the vertical alignment screen of the control unit. At the lower left of the screen, the 3D measurement values of reflectors and the current position of the triangle formed by reflectors are displayed. And at the upper right of screen, there are display windows for dial gages. The Jacobean matrix obtained by previous procedure does not be shown in this screen, but it can be confirmed by another screen. At the lower right of the screen, there are windows to indicate the target position of the triangle. These values are calculated automatically by reading a csv file, which has information about the target position of mirror reflectors. In the same area, there are windows for indicating the operational amount of each vertical position adjustment bolt calculated by the equation 2. Workers only have to operate bolts in accordance with this information.

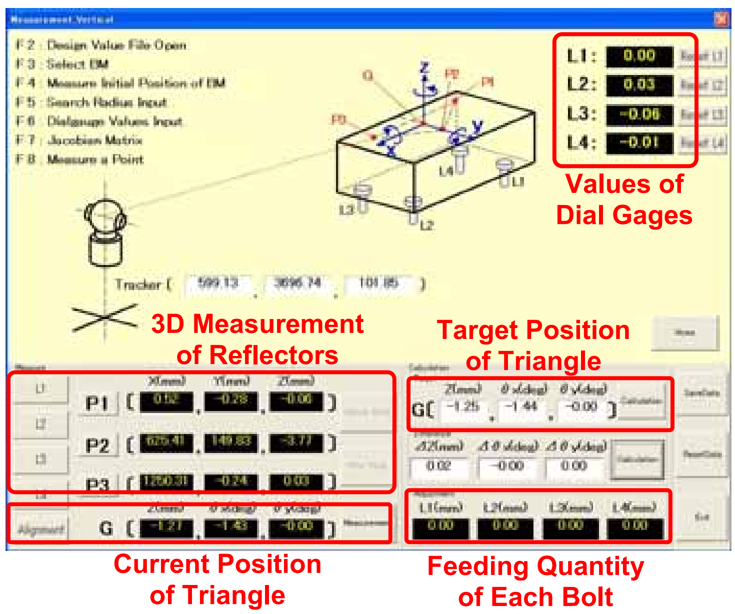


Figure 8: Horizontal Alignment Screen

After the vertical alignment, the horizontal alignment is performed and repeated until x and y-coordinate values of the gravity point and the rotational angle θz of the triangle are fit into the target values. After a series of these operations, the coordinate values of 3 mirror reflectors will fit precisely into those of the target values.

2.4 RESULT OF VERIFICATION EXPERIMENT

Table 1 gives the result of an alignment with the mock-up of the electromagnet. As **Table 1** shows, there are certain quantities of differences between target values and those of before alignment. And some of them ware around 3mm. However, after alignment, all the differences are less than 0.1mm. In this case, the vertical alignment was repeated 3 times and after that, the horizontal alignment was repeated 2 times. It took about 50 minutes to align the electromagnet. On the contrary, it will take a few hours with the conventional way.

Table 1: Position Changes of the mirror reflector **P1,P2** and **P3**

	P1 (mm)			P2 (mm)			P3 (mm)		
	x	y	z	x	y	Z	x	y	z
Target Position	0.00	0.00	0.00	605.69	349.62	0.00	1212.07	0.00	0.00
Before Alignment (Difference)	-2.78 (-2.78)	0.78 (+0.78)	-1.89 (-1.89)	602.97 (-2.47)	350.32 (+0.70)	-0.43 (-0.43)	1209.28 (-2.79)	0.57 (+0.57)	1.59 (+1.59)
After Alignment (Difference)	-0.04 (-0.04)	-0.06 (-0.06)	-0.04 (-0.04)	605.66 (-0.03)	349.60 (-0.02)	-0.03 (-0.03)	1212.02 (-0.05)	-0.04 (-0.04)	-0.03 (-0.03)

Then, **Table 2** and **Table 3** show the results of each direction alignment. In the vertical alignment (**Table 2**), the target values of θx and θy were set to 0°. Also, in the z-axis direction, an adjustment of 0.24 mm was attempted. After the third alignment, the electromagnet was almost horizontal and its difference in the z-axis direction was ±0.1 mm or less. **Table 3** shows the results of the horizontal alignment. It was determined that the electromagnet be moved 1.58 mm in the x-axis direction and -0.36 mm in the y-axis direction, and the target value of θz was set to 0.01°. Similar to the result of the vertical alignment, the electromagnet was positioned successfully to the target position when the alignment is repeated 2 times. The results of this experiment clearly proved that the calculation method of the optimum operational amounts of the position adjustment bolts by Jacobean matrix is an effective means of aligning an electromagnet efficiently with high accuracy.

Table 2: Result of Vertical Alignment

	z (mm)	θx (deg.)	θy (deg.)
Target Value	0.00	0.00	0.00
Before Alignment	-0.24	-0.05	-0.16
1st. Alignment	-0.14	0.00	-0.04
2nd. Alignment	-0.02	0.00	-0.01
3rd. Alignment	0.01	0.00	0.00

Table 3: Result of Horizontal Alignment

	x (mm)	y (mm)	θz (deg.)
Target Value	605.92	116.54	0.00
Before Alignment (Difference)	606.34 (+1.58)	116.18 (-0.36)	0.01 (+0.01)
1st. Alignment (Difference)	606.17 (+0.25)	116.25 (-0.29)	-0.04 (-0.04)
2nd. Alignment (Difference)	605.88 (-0.04)	116.50 (-0.04)	0.00 (0.00)

3. CONCLUSIONS

This paper describes an overview of the electromagnet alignment system for the accelerator of the cancer therapy facility, the calculation method of the optimum operational amount of the position adjustment bolts, and the results of an experimental alignment using a mock-up of the electromagnet. The conclusions are as follows:

- The gravity point of the triangle formed by 3 mirror reflectors and 3 rotatinal axes were introduced on the electromagnet to clarify the current positon of the electromagnet.
- The Jacobean matrix for the relationship between the position changes of the electromagnet and the operated variables of the position adjustment bolts was used to calculate the optimum operatinal amounts of the bolts to align the electromagnet to the target position.
- In the result of veryfication experiment, the mock-up of the electromagnet is installed to the target position by 3 times vertical alignment and 2 times horizontal alignment. It took about 50minitus, which was clearly faseter than the conventional way, and Advantageous effect of the alignment system was shown.

REFERENCES

Uchiyama, K., “Super Survey”, Nihon Rikou Shuppan Kai Co., Ltd., Tokyo, Japan, p.91, (1994)

Umegaki, K., Hiramoto, K., Kosugi, N., Moriyama, K., Akiyama, H., Kakiuchi, S. “Development of an Advanced Proton Beam Therapy System for Cancere Treatment” The Hitachi Hyoron, Hitachi Co., Ltd., Tokyo, Japan, Vol.85, No.9, p.606, (1985).

Wakamatsu, K., Tamura, K. (editor), “The Automatic Control of Robots”, The Society of Instrument and Control Engineers, Tokyo, Japan, p.27, (1985)