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AXIOMATIC DESIGN OF A BEAM ADJUSTER FOR A LASER MARKER

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ABSTRACT

The usage of a beam scanning type laser marker is rapidly increasing in the field of semiconductor equipment. A device called a "beam adjuster" is employed to adjust the visible diode laser, which points to the marking position for various settings. The device is very sensitive to manufacturing tolerances and assembling conditions. The axiomatic approach is applied to the design of the device. An existing design is analyzed based on the Independence Axiom, but the existing design is discovered to violate the axiom. Two new designs are proposed to satisfy the Independence Axiom. The Information Axiom is utilized to evaluate the designs, and the selected design has minimum information content. The significance of this research is that a full cycle of axiomatic design is applied to a real engineering product.

Keywords : Axiomatic design, Independence Axiom, Information Axiom, Laser marker, Adjuster

1 INTRODUCTION

Recently, concern about conceptual design is increasing in the field of semiconductor equipment. The capability of creating a new design becomes more important than ever before because the engineering environment is rapidly changing. A good design has a large impact in the entire engineering process. The usage of a beam scanning type laser maker is increasing in IC (integrated circuit) marking equipment. A laser marker engraves characters or logos on the surface of an IC. It uses a laser with a moving mirror for marking them in desired positions [Rofinsinar Laser, 2000]. In addition to a main laser, a visible diode laser is used to confirm the position of marking before the real work. If the main laser is utilized from the beginning, the surface can be deteriorated in the adjustment process. Therefore, the visible diode laser is used for the simulation of the adjustment process without ruining the surface. A device called a "beam adjuster" is utilized to adjust the visible diode laser. It determines marking positions for various settings. The device is very sensitive to manufacturing tolerances and assembling conditions [Kim, 1992; Dongyang Semiconductor Equipment 2000]. An axiomatic approach has been applied to the design of the device to overcome this difficulty.

Axiomatic design is one of the useful design methodologies. It consists of two axioms for general design [Suh 1978, 1979, 1990]. The first axiom is the Independence Axiom. It states that the independence of functional requirements (FRs) must always be maintained, where FRs are defined as the minimum set of independent requirements that characterize the design goals [Do and Park, 1996; Lee and Park, 2000; Shin, et al. 2000]. The second axiom is the Information Axiom, and it states that among those designs that satisfy the Independence Axiom, the design with the smallest information content is the best design [Albano, 1993; Frey, 2000; Suh, 2001]. Both axioms are applied in the design process of the beam adjuster. An existing design is analyzed based on the Independence Axiom. The existing design is found to violate the axiom. Two new designs are proposed to satisfy the Independence Axiom. The Information Axiom is utilized to evaluate the proposed designs. One with minimum information content is selected as the final design. The logical process of the design is presented in detail.

2 AXIOMATIC DESIGN

2.1 INTRODUCTION OF AXIOMATIC DESIGN

A design is completed through continuous interactions between the goal set by a designer and the method for attaining the goal. Design is a form of a product or process that can satisfy the functional requirements (FRs) a designer wants. In other words, it is an embodiment process of mapping functional requirements pertaining to a functional domain into design parameters (DPs) pertaining to a physical domain. Mapping is choosing a relevant design parameter, which satisfies a given functional requirement. The mapping process is illustrated in figure 1. A multitude of appropriate designs that satisfy a designer's functional requirements can be derived. The axioms offer design principles that can give the grounds for comparing a design with others or selecting one among many alternatives [Kim, 2001].

According to axiomatic principle, the essence of the design process lies in hierarchies as illustrated in figure 1. Designers begin the design from comprehensive functional requirements. A design can decompose functional requirements into many hierarchies. But the decomposition of functional requirements must be carried out at the same time with the decomposition of design parameters. The zigzagging between functional requirements and design parameters is necessary because the two sets of each level are connected and mutually dependent.

The axiomatic design is a design process for a satisfactory product or design through a systematic method. A satisfactory design can be expressed as one that satisfies all the functional requirements. Therefore, a designer's role is to satisfy the requisites for a design and to define those requisites properly. In axiomatic design, a requisite for an acceptable design is to satisfy functional requirements through proper selection of design parameters. An FR is "the goal to achieve," and a DP is "the means to achieve the goal."

Axiomatic design provides a framework for choosing a good design. The two design axioms are the "tools" that are helpful for the creation of a new design. The first axiom tells us about the selection of a functional requirement. The second axiom shows a quantitative method of judging which design is more desirable. The design axioms are defined as follows:

Axiom 1: The Independence Axiom
Maintain the independence of functional requirements.
Axiom 2: The Information Axiom
Minimize the information content.

The two axioms present the most fundamental means needed to choose the best design.

For a design to be acceptable, the design must satisfy the first axiom. A design matrix is defined to pursue the relationship between FRs and DPs as following:

$$\mathbf{FR} = \mathbf{A}\ \mathbf{DP} \tag{1}$$

where **FR** is a vector for functional requirements, **DP** is a vector for design parameters and **A** is a design matrix. If we have three FRs and DPs, equation (1) can be shown as following:

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \end{Bmatrix} = \begin{bmatrix} X & O & O \\ O & X & O \\ O & O & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \end{Bmatrix} \tag{2}$$

where X means a relation exists and O means there is no relation. The components in the design matrix can be expressed by constants or equations instead of X and O.

When the Independence Axiom is satisfied, the design matrix takes the form of a diagonal matrix or a triangular matrix. A diagonal matrix in equation (2) represents a perfectly uncoupled design and is the most desirable form. In this case, just one DP affects each FR because a modification on each DP has influence only on the corresponding FR. A triangular matrix represents a decoupled design. This form of design is also a proper design, but the DPs need to be rearranged in a specific order so as to satisfy the FRs. On the other hand, an uncoupled design does not require a specific order. The third form of a design is a coupled design. This type of design is undesirable because when a DP is modified, multiple FRs are changed. There is no effective solution for undesirable change on the FRs.

The Information Axiom is related to the complexity of a design, and implies that the simpler design is the better one. In the Information Axiom, the DPs are selected according to information content. The information content is defined by the probability of success to satisfy corresponding FRs. For example, the information content for the i-th functional requirement is defined as:

$$I_i = \log_2 \frac{1}{p} \tag{3}$$

where p is the probability of success for the i-th functional requirement with the design parameters. The total information content is the summation of the information quantities. When multiple solutions satisfy the Independence Axiom, the Information Axiom can be well exploited. A solution with minimum information is selected as following:

$$I_{\min} = \min \sum_{i=1}^{n} I_i \tag{4}$$

2.2 FLOW OF AXIOMATIC DESIGN

It is noted that the Independence Axiom should be firstly applied. Sometimes, it is not easy to find a single solution which satisfies the Independence Axiom. If only one solution is found, it is the final solution. However, the general utilization of axiomatic design is illustrated in figure 2. At first, various design solutions are investigated to satisfy the Independence Axiom. If multiple solutions are identified, the Information Axiom is utilized. The information content is evaluation index. The one with minimum information is selected as the final solution.

3 THE BEAM ADJUSTER FOR THE LASER MARKER

3.1 THE LASER MARKER AND THE BEAM ADJUSTER

A marking process resides in the back end assembly line for a semiconductor. The character logo and the device number are usually engraved. Among various marking equipment, the beam-scanning YAG laser marking is widely used. It is used with a laser beam and the direction of the beam is controlled by a reflecting mirror. The YAG laser is a solid-state laser using crystal of yttrium, aluminum and garnet. The laser marker consists of a beam generating part and a scanning head as illustrated in figure 3 [Lee Laser Inc., 1996; Rofinsinar Laser, 2000]. In the beam generator, the laser beam is produced and reflected by the mirrors as illustrated in figure 4. One laser beam is divided into two beams by an optical device. The optical device is a mirror which reflects 50 % of a beam and passes the rest. It is illustrated in figure 4. It is efficient in that two semiconductors are marked with one generator. This type is called a dual laser marker and is widely used in the field of semiconductor surface marking [Walter, 1999].

In the scanning head, there are other mirrors controlled by high-speed motors. The fixed beam from the beam generator can be re-directed by these mirrors to mark certain logos. If the beam direction is determined by the beam generator, the mirrors and motors in the scanning head make the detailed marks and the motors are controlled by a computer program. Before the real marking process is conducted, many test processes are needed for trial-and-error. If we use the YAG laser in this process, the surfaces of semiconductors are damaged. Therefore, a simulation with low-cost is carried out by a diode laser. The diode laser sheds a weak light beam and the simulation can be easily carried out. The result of the marking process is visible due to the high-speed motors. The process is as follows:

1. Test plates are placed at the marking positions in figure 4. The YAG laser is turned on. The mirrors in the beam generator are positioned to make the beam go through the scanning head and mark points on the plates. The points are starting points of the marking process and illustrated as hollow points as illustrated in figure 5.
2. The YAG laser is turned off. The diode laser is turned on. The solid points in figure 5(a) would be the final destinations of the diode laser.
3. The adjuster of the diode laser is utilized to make two identical points as illustrated in figure 5(b). If the two points accord, the angles and the final destinations from YAG and diode lasers are considered identical. Now, we are sure that the two lasers have the same routes.
4. The marking is simulated with the diode laser. That is, the motors in the scanning head are simulated by a computer program. The program is the one specifically developed for the marking process. As mentioned earlier, the marking result is visible.
5. If the results are validated, the test is terminated.

Many problems occur in the adjuster of the diode laser. Currently, screws are used in the adjustment. Since tolerances and human errors are involved, it takes quite a long time and precise adjustment is difficult to obtain.

3.2 Axiomatic evaluation of an existing design

Since the laser marking machine is already commercialized, there is an existing design for the diode beam adjuster. Therefore, it is necessary to define the functional requirements and corresponding design parameters to evaluate the existing device. The relationship between the FRs and DPs can be expressed by a design matrix. The FRs of the existing device is defined as follows:

FR1: Align the vertical position of the diode laser beam.
FR2: Align the vertical angle of the diode laser beam.
FR3: Align the horizontal position of the diode laser beam.
FR4: Align the horizontal angle of the diode laser beam.
FR5: Fix the beam alignment.

Figure 6 illustrates each functional requirement. The two-beams from YAG and diode lasers should be properly accorded. Firstly, the horizontal and vertical destinations of the diode laser should be the same as those of the YAG laser (FR1, FR3). Secondly, the angles of the beams must be the same (FR2, FR4). Figure 7 illustrates the existing product. DPs corresponding to FRs are defined as follows:

DP1 : Vertically moving component
DP2 : Supporting block
DP3 : Fixing screw

The design matrix is defined as following:

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \\ FR4 \\ FR5 \end{Bmatrix} = \begin{bmatrix} X & O & O \\ X & O & O \\ O & X & O \\ O & X & O \\ O & O & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \end{Bmatrix} \quad (5)$$

The design in Equation (6) is a coupled design because the number of DPs is less than the number of FRs. When we move the solid points in figure 5(a) (DP1), the vertical angle also varies because FR1 and FR2 are coupled by DP1. In a similar manner, when we move the horizontal position (DP2) the aligned angle can vary. If a design is coupled in the way of Equation (5), it can be decoupled by adding new DPs to make the numbers of FRs and DPs equal to each other.

4 DEVELOPMENT OF NEW BEAM ADJUSTER USING AXIOMATIC DESIGN

4.1 New design using the Independence Axiom

Because the existing design does not satisfy the Independence Axiom, a new design is searched with new design parameters as illustrated in figure 2. By separating the coupled terms, Equation (5) can be decomposed as follows:

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X \\ X \end{bmatrix} \{DP1\} \quad (6)$$

$$\begin{Bmatrix} FR3 \\ FR4 \end{Bmatrix} = \begin{bmatrix} X \\ X \end{bmatrix} \{DP3\} \quad (7)$$

$$FR5 = [X]\ DP5 \quad (8)$$

where DP3 in Equation (7) is equivalent to DP2 in equation (5) and DP5 in equation (8) is equivalent to DP3 in equation (5).
From equation (6), it is required that one DP be added. Two designs are created as illustrated in Figs. 8-9. In figure 8, DP1 and DP2 are holes. Screws are inserted in the holes and the positions of the holes can be changed by the movement of the screws and fixed by the fastening function of the screws. A designer can determine FR1 by DP1. FR2 can be determined by DP2. The design matrix is defined as following:

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X & O \\ X & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix} \quad (9)$$

The design in equation (9) is a decoupled design. Therefore, it satisfies the Independence Axiom. The second design is illustrated in figure 9. The functions of the DPs are similar to those of figure 8. The movement is carried out by the rotation of the screws instead of the translation in figure 8. Therefore, the design matrix is defined in figure 9 and it also satisfies the Independence Axiom.

In the same manner, equation (7) can be modified to satisfy the Independence Axiom. figure 10 illustrates the final design via the extension of the idea in figure 9. For the FRs in Section 3.2, DPs are defined as follows:

DP1 : Upper low screw
DP2 : Upper front screw
DP3 : Rear side screw
DP4 : Front side screw
DP5 : Fixing screw

The design matrix is defined as a decoupled one as following:

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \\ FR4 \\ FR5 \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O \\ X & X & O & O & O \\ O & O & X & O & O \\ O & O & X & X & O \\ O & O & O & O & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \\ DP4 \\ DP5 \end{Bmatrix} \quad (10)$$

If we replace DPs in figure 10 with those in figure 8, then all the movements are carried out by translations. Therefore, we have two designs. The one has the concept in figure 8 and the other has the concept in figure 9. As mentioned earlier, the Information Axiom can be utilized a superior design. Thus, if we evaluate the designs of Figs. 8-9 in the context of the Information Axiom, we can determine the final design.

4.2 SELECTION OF A BEAM ADJUSTER USING THE INFORMATION AXIOM

The Information Axiom is utilized to select the best design out of multiple designs which satisfy the Independence Axiom. The probability of success is considered as the information content. The relations between FRs and DPs should be expressed by explicit functions to evaluate the information content. The two designs in figure 8-9 are compared for the information content. In this section, real values in a design are utilized.

When DP1 in figure 8 moves, the vertical position moves by the same distance. Thus, the following function relation is defined as following:

$$FR1 = DP1 \quad \text{(for the design in figure 8)} \quad (11)$$

Designs developed here are supposed to be employed in an existing machine. Considering the environmental and geometrical aspects of a certain existing design, the following relation is approximately defined:

$$FR2 = -4DP1 + 4DP2 \quad \text{(for the design in figure 8)} \quad (12)$$

In the design of figure 9, the moving distance is indirectly made by the rotation of the screw. The translation and rotation have the following relationship:

$$2\,\pi\, r \tan\theta = p \quad (13)$$

where r is the radius of the screw, p is the pitch of the screw and θ is the screw angle. The pitch p also means the translating distance made by a unit rotation. The radius r is set to 1.5 mm and p is set to 1mm. The slope has the following relationship:

$$\tan\theta = 1/3\pi \cong 0.106 \quad (14)$$

Therefore, the following design matrices is defined for both designs:

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} 1 & O \\ -4 & 4 \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix} \quad \text{(for the design in figure 9)} \quad (15)$$

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \frac{1}{3\pi} \begin{bmatrix} 1 & O \\ -4 & 4 \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix} \text{(for the design in figure 9)} \quad (16)$$

Figure 11 illustrates the graphical views of FR1 of both designs. It shows that the slope of design 1 is stiffer.

Equation (3) is utilized to calculate the probability of success. The probability of success p is the integration of the joint distribution function [Albano and Suh, 1993; Frey, 2000]. The target value (τFR) is set to 0, the tolerance $\delta FR1$ to 0.2 and $\delta FR2$ to 0.3 as following:

$$\begin{Bmatrix} \tau FR1 \pm \delta FR1 \\ \tau FR2 \pm \delta FR2 \end{Bmatrix} = \begin{Bmatrix} 0 \pm 0.2 \\ 0 \pm 0.3 \end{Bmatrix} \quad (17)$$

The design parameter is adjusted by the human hand around the target value. The tolerance is set to 1mm. If we assume that each parameter is independent and has continuous uniform distribution, the design parameter is expressed as following:

$$\begin{Bmatrix} \tau DP1 \pm \delta DP1 \\ \tau DP2 \pm \delta DP2 \end{Bmatrix} = \begin{Bmatrix} 0 \pm 1 \\ 0 \pm 1 \end{Bmatrix} \quad (18)$$

Using the unit step function U, the probability distribution function for the design parameter is as following [Yu and Jang, 1985]:

$$p(DP1) = \frac{1}{2\delta DP1}\{U[DP1 - (\tau DP1 + \delta DP1)] - U[DP1 - (\tau DP1 - \delta DP1)]\} \quad (19)$$

The joint distribution function for DPs is calculated by the multiplication of two distribution functions, and the joint distribution function for FRs is calculated by Jacobian transformation as following [Mood, 1963]:

$$f(FR1, FR2) = \frac{1}{2}[U(FR1-1) - U(FR1+1)] \times \frac{1}{2}\left[U\left(\frac{1}{4}FR2 + FR1 - 1\right) - U\left(\frac{1}{4}FR2 + FR1 + 1\right)\right] \times \frac{1}{4} \quad (20)$$

The integration of equation (20) is the information content as following:

$$\int_{-0.2}^{0.2}\int_{-0.3}^{0.3} f(FR1, FR2)\ dFR2\, dFR1 = 0.015 \quad (21)$$

When we substitute equation (20) into equation (21), the probability of success is 1.5% and information content is 6.059 for the design in figure 8. In the design of figure 9, the probability of success is 58.2% and information content is 0.782. Therefore, the design in figure 9 is superior. The same idea can be applied to FR3 and FR4. Therefore, the design in figure 10 is the final design because it is the extension of the design in figure 9. It is noted that the design in figure 9 has less slope, that is, it is a flexible design. It is well known that a flexible design leads to a robust design [Suh, 2001]. This case study shows that the design with less information makes a flexible and robust design.

5 CONCLUSION

The Independence Axiom is utilized to obtain good design candidates. If multiple design candidates are found, the Information Axiom is used to select the best design. This is a full cycle of the axiomatic approach. However, the full cycle is rarely applied. It is because multiple solutions may not be found or the information contents are not appropriately defined. The full cycle is executed for the design of a beam adjuster in a laser marking machine. At first, two design candidates are found to satisfy the Independence Axiom. The design solutions are evaluated by the comparison of the information contents. The final design selected has less information content and is also robust. Many researches have shown that robust design generates less information. In the future, this relationship should be systematically investigated.

6 ACKNOWLEDGMENTS

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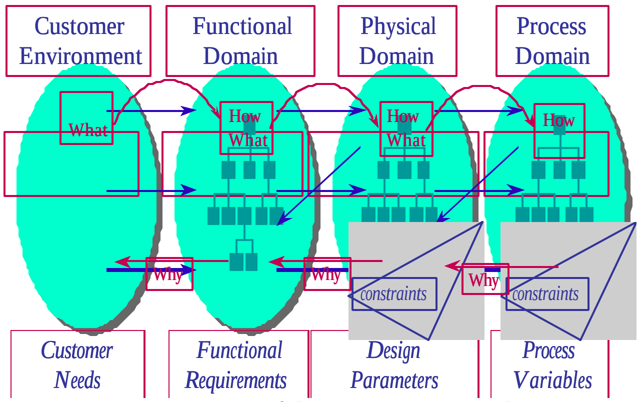

Figure 1. Concept of domain, mapping and spaces

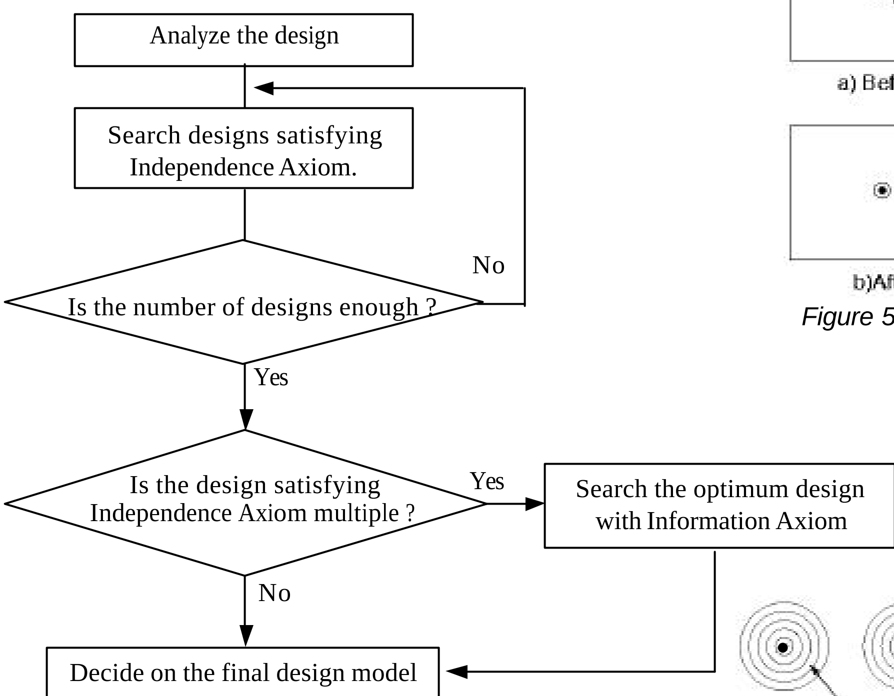

Figure 2. Flow chart of axiomatic design

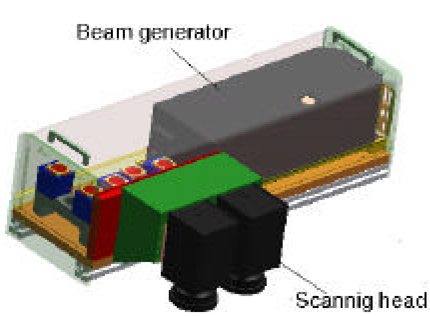

Figure 3. Beam scanning type laser marker

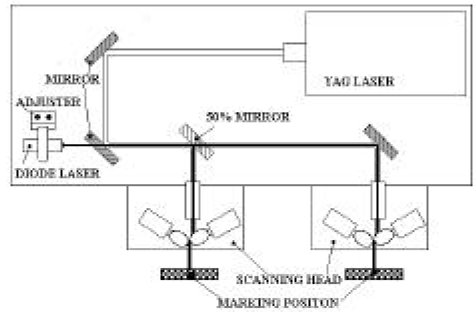

Figure 4. The component layout of a laser

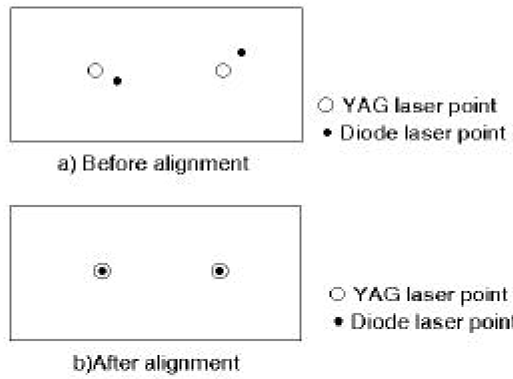

Figure 5. The alignment of a diode laser

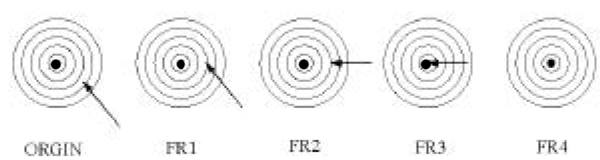

Figure 6. Illustration for functional requirement

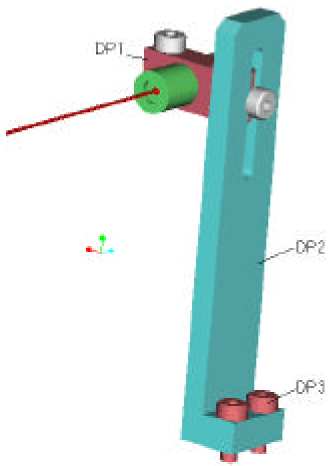

Figure 7. Beam adjuster and DPs

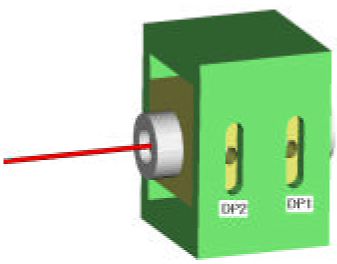

Figure 8. New design model #1

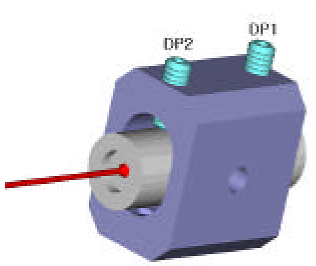

Figure 9. New design model #2

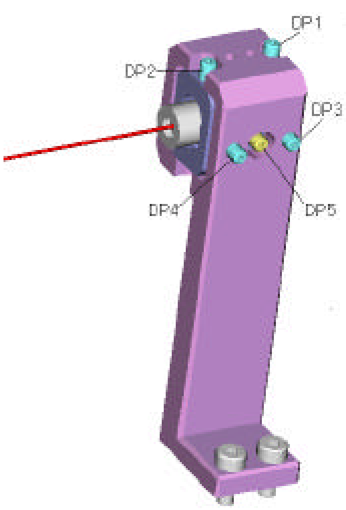

Figure 10. Expanded new design

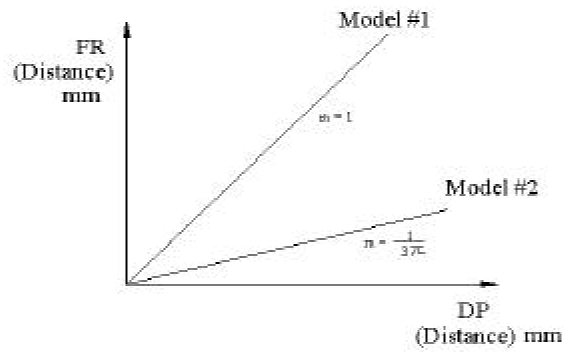

Figure 11. Distance of FR as the adjusting distance of DP