

AXIOMATIC DESIGN METHOD APPLIED TO A PARALLELOGRAM MICROMACHINE FOR LOW COST MICROMECHANICS

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INTRODUCTION

This paper describes the experience of the Laboratory of Micromechanics and Mechatronics (LMM) at Center of Applied Sciences and Technological Development (CCADET) at National Autonomous University of Mexico (UNAM), using simple mechanisms and high level control systems to develop low cost micromechanical systems. To date, this group has developed three prototypes of micromachine tools, some models of manipulators and several versions of stepping motors for its automation. The main idea to develop low cost micromechanical systems consists of decreasing the size of the designs tested at human scale by means of generational way [1]. The first generation has overall sizes around 200mm, the second generation has overall sizes around 100mm; following this way some generations after, the n-generation could have overall sizes around some millimeters. The authors are currently working in the second generation of micromachine tools.

Using parallelograms and levers, as Richard Feynman proposed [2], the authors of this article developed a micromachine tool with resolution of 600 nm. This resolution is the same for the three translational axes and every single axis is able to move along 20 mm. Applying this low cost developed-mechanisms, the movements in each axis has a semicircular trajectory, this kind of motion requires advanced control techniques to convert it in lineal movements. Due to the goal that the authors are looking for a proper design to scale in future generations of micromachines, it is necessary to analyze and to conclude the advantages and disadvantages of the proposed design. This machine has the same setup of stepping motor, gear train, feed screw, lever, and parallelogram for every axis. The employed configuration allowed the authors to simplify the manufacture process and reduce the number of pieces required for assembly. An advantage of this design consists in the

capability to place all the actuators and gear train elements far from the final motion elements, reducing the inertia problems. It is important to mention like this mechanisms are not convenient to apply at human scale because it would result in a machine with huge components.

In order to optimize the elements associated with the motion of the micromachine, the analysis of the design by means of an axiomatic design method is presented. The results will allow the authors to improve the original version of the micromachine and to propose a better design to minimize the control requirements. The first axiom is used to know the interdependence of every function and its vulnerability in the conceptualization process, while the second axiom is used to know the operational vulnerabilities of the design. The use of the axiomatic design method results leads to some recommendations which will be considered for the design of future generations of low cost micromachine tools.

ANALYSIS

As the authors presented in [3], the lever method is a good choice to reduce problems related with backlash, but for the development of low cost micromechanics it is necessary to take care of the manufacturing process. Based on this idea, the authors analyzed two different possibilities to obtain high resolution motion while keeping the estimated low cost of around 110usd. The first alternative consists in the use of common round bars guides and carriages, figure 1. The second alternative consists in the use of the levers and parallelogram described above.

The figure 2 shows the micromachine described above, the second alternative. The points marked as B are levers, the points marked as P are parallelograms, the trajectories marked as

IM are input motion and finally the trajectories marked as OM are output motion.

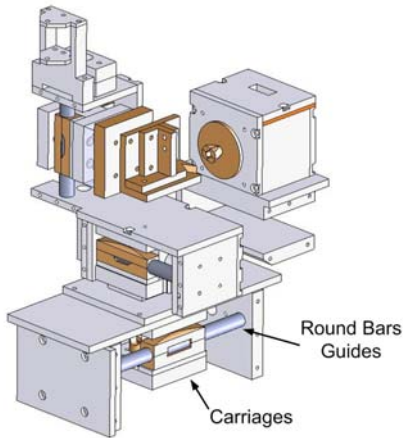


Figure 1. Micromachine based on round bars guides and carriages

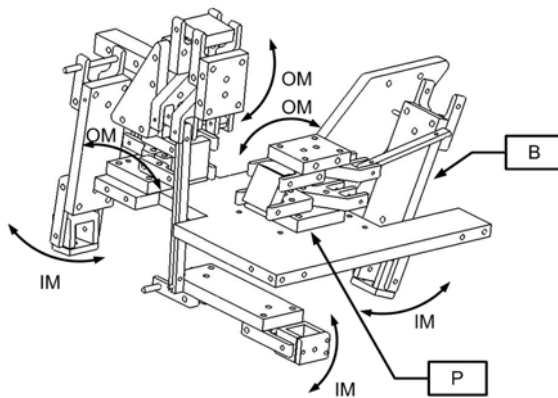


Figure 2. Micromachine based on Levers and Parallelograms.

First of all, the authors obtain and separate the main requirements to develop a micromachine tool. These requirements are:

- three dimensional motions
- independent motions
- high resolution motion and
- facility of manufacture

The independence axiom

This axiom consists in the searching process of a matrix which relates the functional FR requirements -minimum set of independent requirements that completely fulfill the design objective- to the design DP parameters -physical solutions- [4].

$$\{FR\}_{m \times 1} = [A]_{m \times p} \cdot \{DP\}_{p \times 1} \quad (1)$$

This axiom is not fulfilled until the resultant matrix [A] is a diagonal matrix (uncoupled design) or a triangle matrix (decoupled design). These kinds of matrices allow us to keep control of the variables involved in the solution process of the design. For the case of study, which is a micro machining center, the FRs are:

$$\{FR\} = \begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{Bmatrix} \quad (2)$$

where FR_1 is the requirement of three dimensional motions, FR_2 is related to independent motions, FR_3 is related to the high resolution motion and FR_4 is the parameter which determines how easy the manufacture will be. For this last requirement we apply selection criteria on the base of the equipment installed in the LMM.

It is easy to notice that the last requirement can not be evaluated by means of the first axiom, because the independence axiom relates functional requirements to design parameters, and it is not possible to relate different values to every alternative. This could be solved by means of the second axiom, therefore:

$$\{FR\} = \begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} \quad (3)$$

And the design parameters are:

$$DP = \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \quad (4)$$

Where DP_1 is related to three axes of motion, DP_2 is related to the system of parallelograms, and DP_3 is related to the system of levers. By substituting FR and DP in equation (1) as follows

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \quad (5)$$

It seems like the FR_2 is not related to DP_2 , which results in a coupled design, and does not fulfill the independence axiom. However, the FR_2 could be fulfilled by the DP_2 when the control process is considered; which means that by using algorithms it is possible to convert complex motions (semicircular) into linear ones. Taking this into account the equation (5) is:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \quad (6)$$

The information axiom

For this axiom the information is defined as a measure of complexity and is related to the probability of certain events occurring when information is supplied. Once different alternatives have solved the objective of a design, it is possible to apply this axiom to find the solution which best fulfill the problem [4]. The parameter information (I) is defined as:

$$I = \ln\left(\frac{SR}{CR}\right) \quad (7)$$

Where SR is the system range -the values which every alternative could take- and CR is the common range -the range which intersects the SR and the design requirement (DR)-. Based on the second axiom, it is possible to analyze the FR_2 , parallelograms and the control system, as well as the FR_4 , facility of manufacture (FOM).

For the FR_2 it is necessary to compare different requirements of the control system with different alternatives of mechanism. If we compare the control system of a mechanism which moves linearly with the control system of a parallelogram, we could find that they are not too different from each other, and at present, the microcontrollers have enough power of processing to complete the task promptly.

By defining as solution the capability of both, the linear motion and parallelogram system, to solve direct and inverse tasks, we could be able to execute the second axiom. Figure 3 shows a diagram of the CR, SR, and DR. Using equation 7, and defining DR as the sum of points, one per task, both systems obtain an I value equal zero.

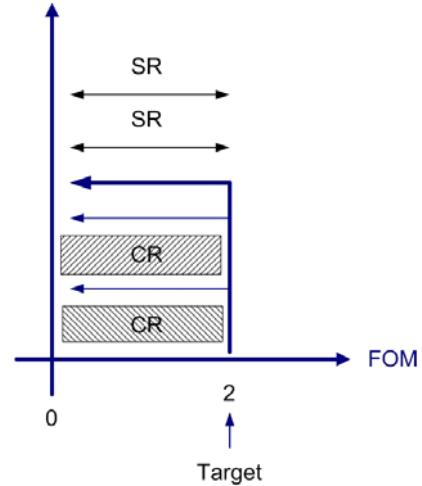


Figure 3. Graphical representation of the FR_2

$$I_{linear} = \ln\left(\frac{SR}{CR}\right) = \ln\left(\frac{2}{2}\right) = 0 \quad (8)$$

$$I_{levers} = \ln\left(\frac{SR}{CR}\right) = \ln\left(\frac{2}{2}\right) = 0 \quad (9)$$

For the FR_4 , it is necessary to consider the range values which define the LOM concept. For the authors, these values are defined as the time required for fully manufacture and assembly time in units of 1 hour (TMA), the number of pieces (NP) and the number of different pieces (NDP). Every single parameter related to the FOM factor of previous designs.

$$LOM = TMA + NP + NDP \quad (10)$$

The first prototype of the micromachine tool [5] requires 20 hours for every axis, 11 pieces of which 9 are different. This results in 40 FOMs.

For the parallelograms and levers micromachine tool [6], it is possible to identify 10 hours for every single axis, 19 pieces of which 8 are different. This results in 37 FOMs.

The graphic representation of this axiom is showed in figure 4. Observe the target for the parameter FOM is located in 37 FOMs, which is the maximum time estimated to manufacture one axis.

This graph shows the values of CR and SR. Applying the equation number 7, we obtain:

$$I_{linear} = \ln\left(\frac{40}{37}\right) = 0.078 \quad (11)$$

$$I_{levers} = \ln\left(\frac{37}{37}\right) = 0 \quad (12)$$

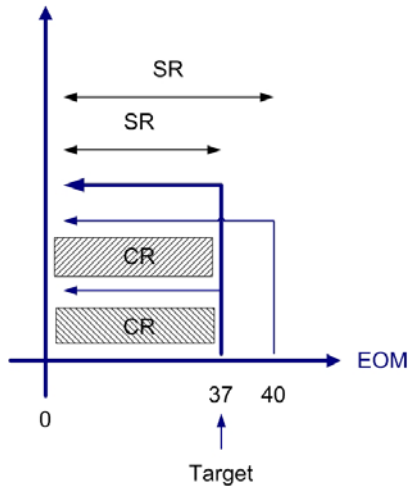


Figure 4. Graphical representation of the FR_4

By adding up of I values for linear design and for levers design, we find:

$$\sum I_{linear} = 0 + 0.078 \quad (13)$$

$$\sum I_{levers} = 0 + 0 \quad (14)$$

As showed in equations 13 and 14, the second prototype (parallelograms and levers) has a better probability of success with the proposed target. This means that the minimum information axiom is fulfilled.

RESULTS

The results presented in equations 6, 13 and 14, shown the following conclusions:

- The proposed design based on parallelograms and levers fulfills the first and the second axiom.
- The proposed design can be improved by means of the control system and the time required for manufacture.
- Using preliminary results, this micromachine tool is able to move with a resolution of $0.6\mu\text{m}$

CONCLUSIONS

The axiomatic design method is a powerful tool in the engineering design. The advantages of

using this tool lie in the minimum correction stages posterior to the conceptual design. This paper describes the application of the axiomatic design method in two different prototypes of micromachine tool developed in the laboratory of Micromechanics and Mecahtronics, CCADET, UNAM. The results confirm the viability of using parallelograms and levers as a motion mechanism to obtain a low cost and high resolution micromachine tool.

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