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Development of Machine Vision System and Dimensional Analysis of the Automobile Front-Chassis-Module

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In the present research work, an automated machine vision system and a new algorithm to interpret the inspection data has been developed. In the past, the control of tolerance of front-chassis-module was done manually. In the present work a machine vision system and required algorithm was developed to carryout dimensional evaluation automatically. The present system is used to verify whether the automobile front-chassis-module is within the tolerance limit or not. The directional ability parameters related with front-chassis-module such as camber, caster, toe and king-pin angle are also determined using the present algorithm. The above mentioned parameters are evaluated by the pose of interlinks in the assembly of an automobile front-chassis-module. The location of ball-joint center is important factor to determine these parameters. A method to determine the location of ball-joint center using geometric features is also suggested in this paper. In the present work a 3-D best fitting method is used for determining the relationship between nominal design coordinate system and the corresponding feature coordinate system.

Key Words : Machine Vision, Front-Chassis-Module, Ball-Joint Center, Dimensional Analysis, Least Squares, Best Fitting

1. Introduction

Present day automobile industry is highly competitive due to large number of manufacturers and over production. In order to prevail over competitor's products, the manufactured product must conform to the standards and should have superior quality, performance. Usually an automobile consists of about 20,000 parts systematically assembled and unexpected variability of these parts affects the quality and commercial value of the product. Earlier as the part were inspected using manual methods or semiautomatic methods it was difficult to achieving good tolerance control. Also by using these inspection methods, it is not possible to accurately measure complicated shapes like front-chassis-module. Front-chassis-module affects the directional ability of the automobile which in turn affects driver. Location of king pin and ball-joint center of front-chassis-module is important factor to determine directional ability parameters (Ozdalyan et al., 1998). Recently, Sigvard proposed ideas that contribute to a better chassis design aiming at fulfilling the needs of future cars (Zetterstorm, 2002 ; Lee et al., 2002). To determine assembly pose of sub-frame, inspection of flanges which are in physical contact with automobile body must be done and best-fit between inspection data and design data

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must be carried out.

In recent years, automated part dimensional inspection techniques have been developed to enhance the speed and accuracy of the system compared to traditional dimensional inspection. Popularly used inspection methods using Coordinate Measuring Machines (CMM) are accurate but time consuming in the sense that the system has to obtain data point by point. The vision system based inspection methods are suitable for accurate and fast inspection environment (Sheng et al., 2000). Kondo et al., 1995 proposed a vision system using robot and vision sensor for inspecting the body of an automobile.

A common need in machine vision is to compute the 3-D rigid body transformations that align two sets of points for which correspondence is known (Eggert et al., 1997).

For best-fitting between two coordinates, Arun et al.(1987) and Horn et al.(1987) have presented a solution based on Singular Value Decomposition (SVD) of a covariance matrix of the data. Umeyama (1991) have suggested a solution using Lagrange multiplier based on SVD. Hong-Tzong et al.(1996) suggested a unified least-squares approach to the evaluation of geometric errors using discrete measurement data obtained from CMM. Samuel and Yang (2003) suggested a method based on computational geometry to map the coordinates of design and inspection system. A comparative analysis of popular methods such as SVD, Unit Quaternion (UQ), using Orthonormal Matrices (OM) and Dual Quaternion (DQ), for translation and rotation is carried out. In most cases SVD found to be more stable and accurate in 3-D problems (Eggert et al., 1997). Hence, in the present work the least squares method based on SVD and Lagrange multiplier is used for mapping inspection data and design data obtained from laser vision system for automobile chassis lower arm and sub-frame assembly.

In this research, automated three dimensional machine vision system and dimensional analysis algorithm are developed to inspect sub-frame assembly pose and location of ball-joint center. The machine vision system consists of a vision sensor, a gantry robot and two SCARA robots to inspect front-chassis-module with considering geometric features of sub-frame and ball-joint. By using gantry robot, just one vision sensor is needed to inspect sub-frame. And by using SCARA robot, rotation of ball-joint is inspected. The least squares method based on SVD and Lagrange multiplier is used to determine assembly pose of sub-frame using inspection data and design data. And location of ball-joint center is calculated by using geometric features.

2. Vision System and Inspection of Front-Chassis-Module

Vision sensor is composed LED, a slit beam laser and a CCD camera as shown in Fig. 1. Shape of flange and the upper surface of king-pin is a circle. In order to inspect these surfaces, the camera is rotated about the laser axis. To make inspection cheaper and faster, only three points on the surface are inspected and not all data points as done during scanning. By using

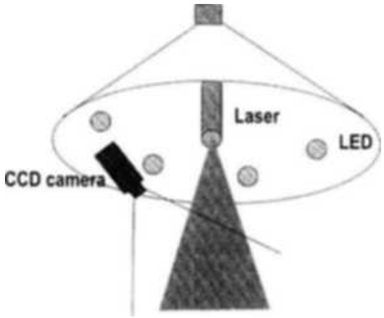


Fig. 1 Components of s vision sensor

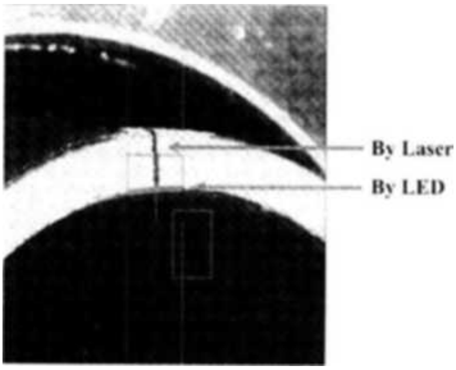


Fig. 2 Display taken by laser and LED at the flange

LED, it takes outline of flange and king-pin's upper plane and obtains a point of intersection with laser as shown in Fig. 2. It uses the principle of optical triangulation as shown in Fig. 3.

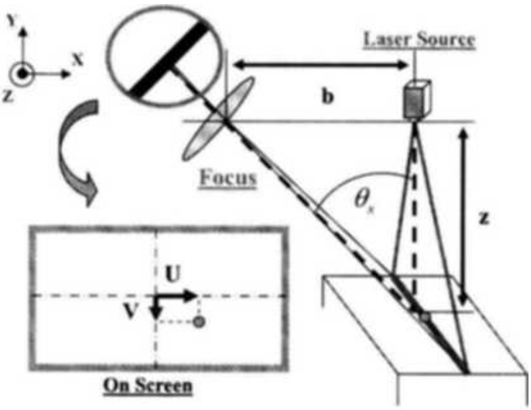
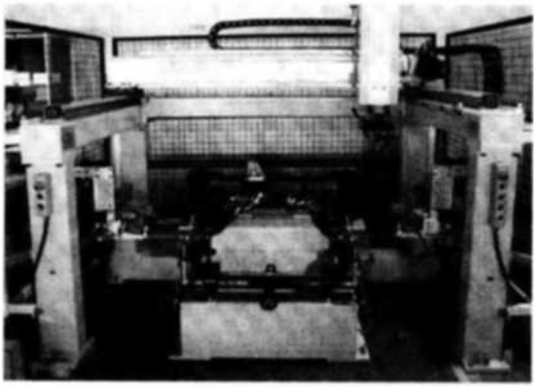
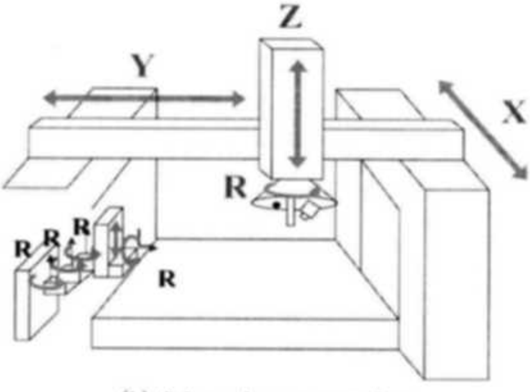


Fig. 3 Optical triangulation



(a) Total system



(b) Schematic representation

Fig. 4 Machine vision system

Total system is consisting of Gantry robot, Selective Compliance Articulated Robot Arm (SCARA) robot and Vision sensor. Gantry robot is composed of three linear guides and one rotating axis. SCARA robot is composed of 1 linear guide and 4 rotating axis. The size of Total system is 2200×4200×2400 mm and the components of total system are shown in Fig. 4.

The front-chassis-module consists of sub-frame, front-lower-arm and corner-module as shown in Fig. 5. The position of the king-pin and ball-joint as shown in Fig. 6, which is located at the end of front-lower-arm is important as it influences the directional ability of the automobile. By the assembly pose of sub-frame on automobile's body and the behavior of ball-joint on both front-lower-arms, directional ability is determined. The design gives the information about the center point of the four flanges of sub-frame. But it is impossible to measure the center point directly as it doesn't located on product.

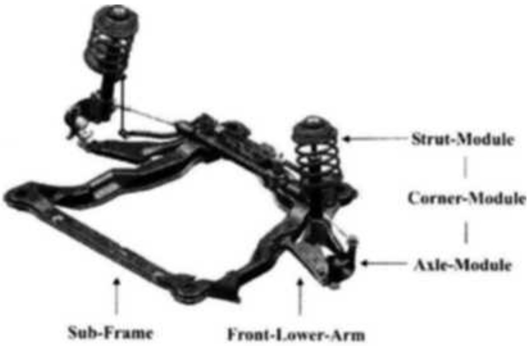


Fig. 5 Front-Chassis-Module

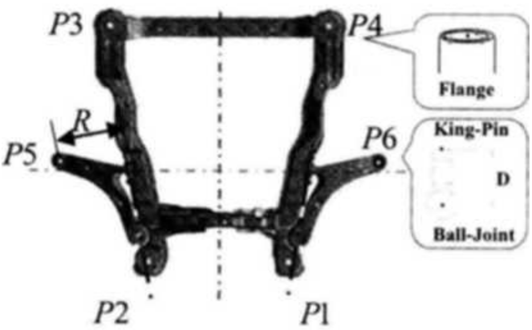


Fig. 6 Sub-frame and front-lower-arm

Hence three points on the flange are inspected to make a circle and obtain center of circle. The definition of circle and method to obtain circle by using three points are shown in Eq. (1) and Fig. 7.

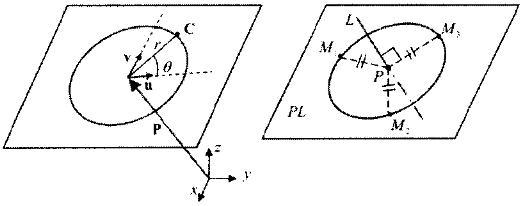
$$\begin{aligned} &C(\mathbf{P}, \mathbf{u}, \mathbf{v}, r, \theta) \\ &=\mathbf{P}+r(\mathbf{u}\cos\theta+\mathbf{v}\sin\theta) \end{aligned} \tag{1}$$

Also, to obtain center of ball-joint located at the bottom of the king-pin, it inspect three points of king-pin's upper plane. To express rotation behavior mathematically, it use circle in three dimension and inspect three poses (upper, middle, lower) to obtain rotating circle as shown in Fig. 8. Because ball-joint center is located at the bottom as shown in Fig. 6, it is impossible to inspect ball-joint directly because there are manufacturing errors and ball-joint is capped by some material. However, it is possible to obtain the center of the ball-joint as explained below. The line which is perpendicular to plane made by three points and go pass center point of king-pin's upper circle is determined. The king-pin is positioned at two poses as shown in Fig. 9 and obtaining a point of intersection of two lines. In this case, king-pin offset distance is distance from center point of king-pin's upper circle to ball-joint center.

To grasp the directional ability, it needs to obtain information about a rotating circle of front-lower-arm and it is solved by calculation of rotating circle of front-lower-arm.

It is possible to know rotating radius and rotating axis by check circle which composed by three points at three positions-upper, middle and lower as mentioned earlier. To compare obtained rotating circle of front-lower-arm with designed data, z value of design data is fixed and calculate point on obtained circle at given z value. The result can be obtained as given Eq. (2) and by using Eq. (1), the ball-joint center's coordinate are obtained by using result angle of Eq. (2).

$$\begin{aligned} &z_0=P_z+r\times\cos\theta\times u_z+r+\sin\theta\times v_z \\ &\theta=\sin^{-1}\frac{z_0-P_z}{r\sqrt{u_z^2+v_z^2}}-\sin^{-1}\frac{ru_z}{r\sqrt{u_z^2+v_z^2}} \end{aligned} \tag{2}$$



(a) Definition of circle on 3-D (b) Calculation of a circle from 3 points

Fig. 7 Geometry of circle

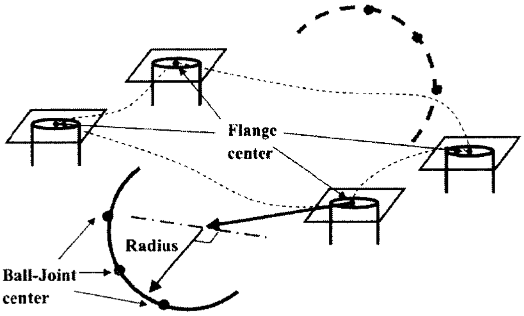


Fig. 8 Rotating circle of the Front-Lower-Arm

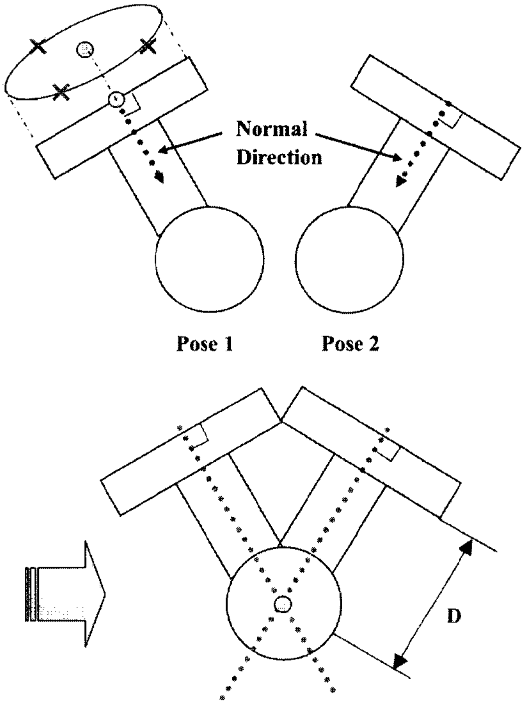


Fig. 9 Method to find King-pin-offset distance

3. Best Fitting of Sub-Frame

Transformation of inspected data is need because when inspection is being done, there are many kinds of error. So there is problem to convert inspection data to design data by using of matching standard points and pose. It is a non-linear optimization problem for best-fitting to match inspection data and design data. In this research, center points of four flanges are used to determine assembly pose of sub-frame as shown in Fig. 10. To obtain solution for this problem, least square method is used by Singular Value Decomposition (SVD) for fast calculation without iterations (Arun et al., 1987; Horn, 1987).

Equation of m_i, inspected data of sub-frame, and d_i, data on CAD drawing, are represented as given below,

$$\mathbf{d}_i=R\mathbf{m}_i+\mathbf{T}+\varepsilon_i \tag{3}$$

$$\bar{\mathbf{d}}=\frac{1}{4}\sum_{i=1}^{4}\mathbf{d}_i \quad \mathbf{d}_{Ci}=\mathbf{d}_i-\bar{\mathbf{d}}$$
$$\bar{\mathbf{m}}=\frac{1}{4}\sum_{i=1}^{4}\mathbf{m}_i \quad \mathbf{m}_{Ci}=\mathbf{m}_i-\bar{\mathbf{m}} \tag{4}$$

Set $\hat{R}$, $\hat{T}$ are the rotation and translation matrices for inspection point to transform it into data set of design point having least square error. A rotation transformation matrix must be an orthogonal matrix. And best-fitting method between inspection data and design data is a non-linear optimization problem having constraint as given below.

minimize

$$e^2(\hat{R},\hat{\mathbf{T}})=\sum_{i=1}^{4}\|\mathbf{d}_i-(\hat{R}\mathbf{m}_i+\hat{\mathbf{T}})\|^2 \tag{5}$$

suject to $\|\hat{R}\|=1$

$\hat{R}^T\hat{R}=1$

To solve Eq. (5), first, center of two data sets must be same (Eggert et al., 1997) and the object function is written as Eq. (6).

$$\begin{aligned} e^2(R)&=\sum_{i=1}^{4}\|\mathbf{d}_{Ci}-\hat{R}\mathbf{m}_{Ci}\|^2\\ &=\sum_{i=1}^{4}(\mathbf{d}_{Ci}^T\mathbf{d}_{Ci}+\mathbf{m}_{Ci}^T\mathbf{m}_{Ci}-2\mathbf{d}_{Ci}^T\hat{R}\mathbf{m}_{Ci})\end{aligned} \tag{6}$$

It is possible to obtain the smallest value if last term of Eq. (6) become greatest and it is same problem as determining greatest of trace of correlation matrix as Eq. (7).

$$H=\sum_{i=1}^{4}\mathbf{m}_{Ci}\mathbf{d}_{Ci}^T \tag{7}$$

Correlation matrix can be singular value decomposition as Eq. (8).

$$H=USV^T \tag{8}$$

To maximize last term of Eq. (6) or trace, rotating matrix is given as $\hat{R}=VU^T$. But if data are distorted greatly or data exist near some plane, there maybe is reflection so it is suggested as Eq. (9) (Arun et al., 1987).

$$\hat{R}=U\begin{bmatrix}1 & & 0\\ & \ddots & \\ 0 & & \det(UV^T)\end{bmatrix}V^T \tag{9}$$

$\hat{T}$ which satisfy constraint is vector which arrange inspected data set's center to designed data set's center as shown in Eq. (10).

$$\hat{T}=\bar{\mathbf{d}}-\hat{R}\bar{\mathbf{m}} \tag{10}$$

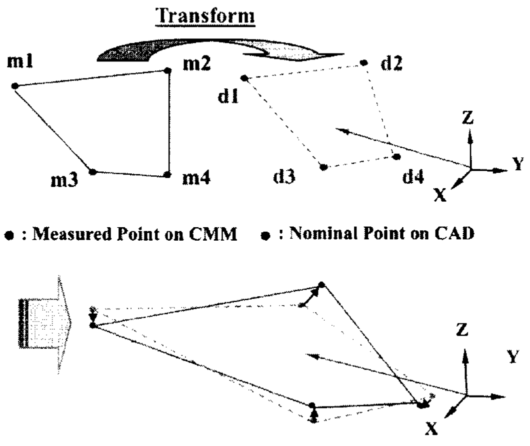


Fig. 10 Best-fitting for a sub-frame

4. Experiment

By using center of four flanges, simulation for best fitting of three dimensions is done. During simulation of required points on the sub-frame as shown in Fig. 2 and Table 1, a random 1000 data

Table 1 CAD specification of each points and radius (unit : mm)

	x	y	z
P1	438	318	−3
P2	438	−318	−3
P3	−622	−494	93
P4	−622	494	93
P5	−15.3	−723.9	−70.6
P6	−15.3	723.9	−70.6
R	308.727		

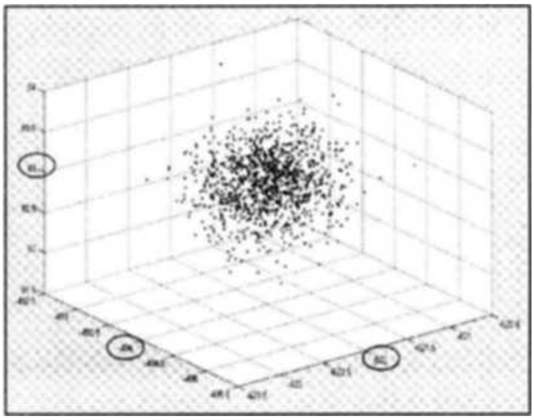


Fig. 11 Initial random data around P1

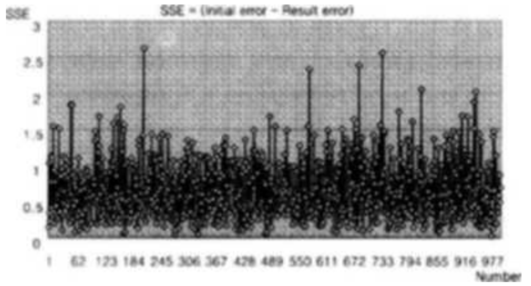


Fig. 12 SSE difference between initial and transformed data

Table 2 Experimental results (unit : mm)

		Specification	Measurement (Final result)	Dimensional Error
P1	x	438	437.293	−0.707
	y	318	318.572	0.572
	z	−3	−2.987	0.013
P2	x	438	437.768	−0.232
	y	−318	−318.715	−0.715
	z	−3	−2.928	0.072
P3	x	622	−621.531	0.469
	y	−494	−492.928	1.072
	z	93	92.925	−0.075
P4	x	−622	−621.530	0.470
	y	494	493.070	−.930
	z	93	92.990	−0.010
P5	x	−15.3	−15.292	0.008
	y	−723.9	−724.508	−0.608
	z	−70.6	−70.600	0.000
P6	x	−15.3	−15.990	−0.690
	y	723.9	723.882	−0.018
	z	−70.6	−70.600	0.000
Left	R	308.727	308.611	−0.116
Right	R	308.727	306.054	−2.673

sets are generated. The data is generated using gauss distribution with 3σ as 1 for each point and Fig. 11 shows random data of P1. To obtain best fitting solution, least square method using SVD and Sum of Squared Error (SSE) is used. Figure 12 shows the difference between SSE of before and SSE of after transformation. It shows that by transforming, there is an improvement of 0.6717 on the average. As the designed value of right and left front-lower-arm king-pin are on rotating circle with z value as −70.6, it calculated coordinate value when z value is −70.6 by using Eq. (2). And also it compared radius of rotating circle. This radius means the rotating length of front-lower-arm.

The result of transformed data of each inspection data by using developed machine vision system is given in Table 2. The table shows the value of average of twenty data sets and the coordinate error of each point. Inspection error is obtained by taking several data sets to get good precision and the standard deviation of each point is under 1.0E-04.

5. Conclusions

In this research, a machine vision system to inspect sub-frame and front-lower-arm of front-chassis-module which affect the directional ability of an automobile is presented. And geometrical analysis algorithms are also discussed in this paper. The present system enables automated inspection of the front-chassis-module, which was previously inspected manually. To match inspection data to design data, least square best-fit method is used. It is significant to note that the best-fit is used for sub-frame first time. By suggesting pose and location of front-chassis-module mathematically, it is possible to calculate the alignment factor numerically and it becomes the basis to estimate quality of dimensional and geometrical tolerance. Before the assembly of automobile is completed, the pose and location of sub-frame can be calculated and hence, the quality can be checked and it gives better profits to company by decreasing inferior goods and waste. The algorithm presented in this paper can be extended to other automobile parts, which otherwise will be inspected using manual methods.

Acknowledgment

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