Establishment of Body Auto Fitting Model "BAFM" Using "NJ-GPM" At Toyota

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Abstract: The Toyota Production System (TPS) exemplifies Japanese manufacturing. It has been further developed and spread in the form of internationally shared global production systems. The author has proposed the New Japan Global Production Model "NJ-GPM", a system designed to achieve worldwide uniform quality and production at optimal locations – the keys to successful global production at Toyota. Based on NJ-GPM, the author has further established the Body Auto Fitting Model "BAFM". The author has realized innovative unmanning of a fitting line by integrating the technologies utilizing BAFM. The ability to automatically fit and tighten door, hood and luggage compartment panels to the car body was achieved, utilizing robotics, vision systems, bolt tightening and product quality management. This paper shows the development of the highly reliable production system combining the following three items: (1) panel fitting accuracy, (2) automatic bolt tightening, and (3) integration into flexible assembly line at Toyota.

Keywords: NJ-GPM, Body Auto Fitting Model "BAFM", Toyota.

INTRODUCTION

The leading Japanese management technology that has contributed most to worldwide manufacturing from the second half of the 20th century is the Japanese production system. It is typified by the Toyota Production System (TPS) (Ohno, 1977). TPS has been further developed and spread in the form of internationally shared global production systems.

With this in mind, the author has proposed the New Japan Global Production Model "NJ-GPM" to enable the strategic development (Amasaka and Sakai, 2009a, 2011). The aim of this model is to realize a highly reliable production system suitable for global production by reviewing the production process from production planning and preparation through production itself and process management. The newly-created NJ-GPM is fundamental to the strategic development of global production.

Based on the development of NJ-GPM, the author has established the Body Auto Fitting Model "BAFM" and has verified its effectiveness through an example application. Specifically, this study focuses on the fitting line at Toyota by integrating the technologies using BAFM.

BACKGROUND

The Current Condition and Problems of the Conventional Production System

Today's manufacturers in Japan are globally expanding their operations at a full speed to be price competitive and need to establish a new production system to suit their global strategies. Conventionally, well-experienced and highly-skilled trainers go to local production sites and provide local production operators hands-on training one-on-one in order to secure the reliability as same as the domestic plant.

The quality of trainings for production operators greatly rely on personal capabilities of the highly-skilled trainers. Different trainers would give different trainings, which may confuse trainees and result in unevenness in production operators' skill acquisition processes. Production operators in Japan also have experienced the same problems while passing down the Japanese manufacturing technology.

Ideas for Three Important Points for Global Production

The author has proposed that there are three important points to assure high quality and high efficiency, and shorten lead time:

(1) Production equipment using industrial robots

(2) Skilled workers who operate the equipment (production operators)

(3) Production systems including production data systems to activate the equipment and workers

The main factors for global production are to build a linkage among individual processes in production planning, production preparation, actual production and process control, to make those processes as perfect as possible, and to raise reliability in the manufacturing

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technology for global production. (Sakai and Amasaka, 2007b; Sakai and Amasaka, 2007c).

DEVEMOPMENT OF THE NEW GLOBAL PRODUCTION MODEL “NJ-GPM”, STRATEGIC DEVELOPMENT OF ADVANCED TPS

Global production must be developed in such a way as to establish the kind of manufacturing that is required to gain the trust of customers around the world. It must achieve a high level of quality assurance and efficiency and shortening lead times to reinforce the simultaneous achievement of QCD requirements. The vital key to achieving this is the introduction of a production system that incorporates production machinery automated with robots, skilled and experienced workers (production operators) to operate the machinery, and production information to organically combine them (Brooks, 1986; Raibert, 1986).

Having recognized the need for a new production system suitable for global production, the author has created the New Japan Global Production Model “NJ-GPM” to realize the strategic development of the “*Advanced TPS*” (Amasaka and Sakai, 2009a, 2011). This model eradicates ambiguities at each stage of the production process not only from production planning and preparation through production itself and process management, but also between the processes. The purpose is to achieve a highly reliable production system for global production which will improve the reliability of manufacturing through the clarification and complete coordination of these processes.

ESTABLISHMENT OF BODY AUTO FITTING MODEL “BAFM”

The author has established the Body Auto Fitting Model “BAFM” based on the development of NJ-GPM. The aim of BAFM is to realize a highly reliable production system suitable for global production by reviewing the production process from production planning and preparation through production itself and process management.

The missions of BAFM for global production are to (i) solve technical problems in advance in a production planning process by simulating technical problems with computer graphics created in CAE (Computer Aided Engineering), (ii) improve production operators’ skills to operate automated equipment and the manufacturing technology, and (iii) create production data that network and visualize the above objectives by the aid of IT.

To fulfill those missions, one requirement is that production operators must create a combination of processes in process planning and be well-prepared so that they can easily do the processes. Digital engineering will lead to building a linkage among production processes to prevent technical problems including:

(1) Integrity between advanced equipment and its operators’ skills

(2) Integrity between production operators’ skills and their movements

(3) Integrity among facility, its production operators’ skills, and parts

Another requirement is network systems that enable production operators to build the linkage. It is required urgently to build the linkage that disperses and integrates information globally while respecting local independence.

Four Essential Techniques to Build the Linkage among Production Processes in BAFM for Global Production

The idea in Figure **1** to build the linkage among production processes in BAFM for global production consists of the following four essential techniques.

(1) PSCS: Production Support CAE System

(2) PSAS: Production Support Automated System

(3) OTAS: Operator Training Application System

(4) HQAS: High Quality Assurance Production System

To use PSCS and PSAS, it is important to plan precisely from production planning stages and prevent problems by simulating. By reforming production planning, the CAE data simulation will optimize production requirements regarding production lines (logistic and transportation), robots (placing arrangement) and production operators (allocation and workability) for the entire plant. By reforming production preparation, the highly accurate robot production system will replace heavy load processes that are currently done manually by workers.

For OTAS and HQAS, it is inevitable to improve, visualize and systemize workers’ skills in production processes. For those purposes above, skill-mastering

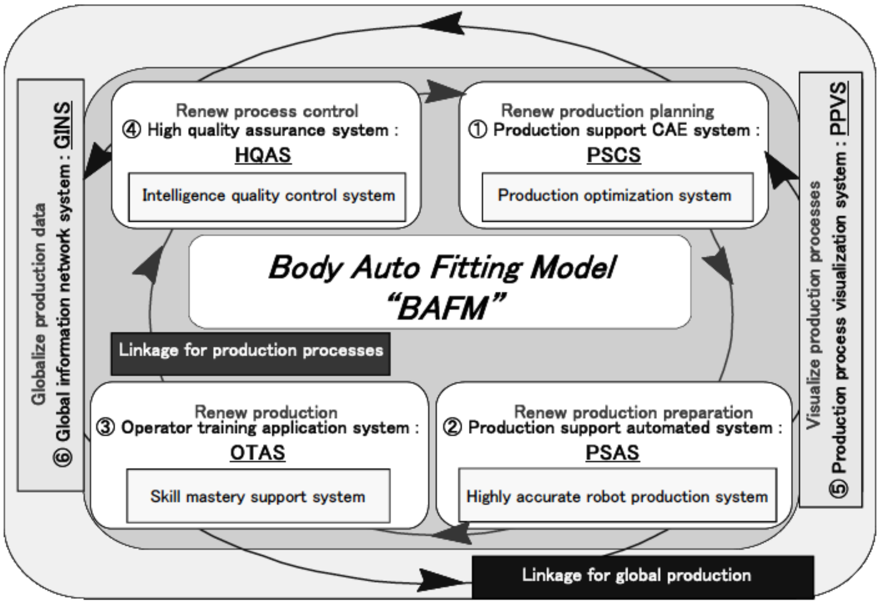


Figure 1: Outline of the Body Auto Fitting Model "BAFM".

support systems will improve and judge workers' skills and place workers in the most appropriate positions in production processes. In process control, intelligent quality control systems will use IT control charts based on statistics and assure process capacity (Cp) and machine capacity (Cm).

It is vital to reform these stages in production planning, production preparation, mass production and process control.

In this paper, the author verifies the effectiveness of highly reliable robot production system for PSAS using the development of BAFM in order to secure the stable reliability in the earlier stage.

Two Essential Techniques to Build the Linkage to Globally Develop BAFM

The following two systems will support building the linkage to globally develop BAFM among production operators.

To use PPVS (Production Process Visualization System), and GINS (Global Information Network System), in Figure **1**, the additional, following two systems are required.

(5) Systems to visualize production processes in planning, preparation and process control and gain better results of QCD activities

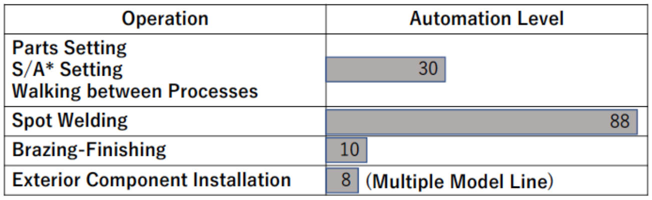
(6) Servers and client systems to use production data globally

All of these above will implement BAFM for global production to immediately establish the manufacturing technology that assures high quality and high reliability (Amasaka and Sakai, 1996, 1998, 2009b: Sakai and Amasaka, 2007a).

EMPLOYING THE FITTING LINE UTILIZING BAFM AT TOYOTA

Necessity of the Fitting and Tightening Automation

Considering the decreasing and aging population of youth in the future society, the need for reduced manpower is heightening greatly. Now, in the body assembly plants, automation such as spot welding is almost completed. The work contents in the body assembly plants and the present state of automation, and the construction of the body are shown in Figure **2**.



Operation	Automation Level
Parts Setting S/A* Setting Walking between Processes	30
Spot Welding	88
Brazing-Finishing	10
Exterior Component Installation	8 (Multiple Model Line)

Figure 2: Operations in body assembly plant and level of automation. (prior to new system) *S/A: sub-assembly.

On the other hands, automation of setting, fitting and tightening of door, hood and luggage compartment panels requiring highly skilled operators' intuition is the next important step in complete automation of the body shop as shown in Figure **3.** Furthermore, in the overseas body assembly plant, the quality problem has occurred every time the operator has fired.

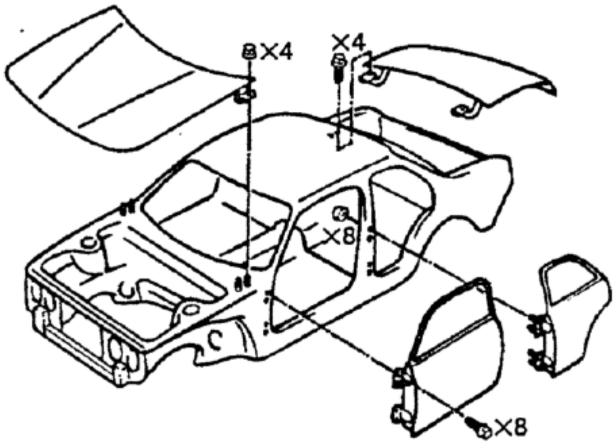


Figure 3: Schematic of exterior component installation.

Therefore, the author has realized innovative unmanning of the fitting line by integrating each technology utilizing BAFM. The ability to automatically fit and tighten door, hood and luggage compartment panels to the car body, such as robotics technology (Sakai and Amasaka, 2007a, 2007c), vision systems, automatic bolt tightening and product quality management, was achieved. This paper shows the development of the highly reliable production system combining the following three items: (1) panel fitting accuracy, (2) automatic bolt tightening, and (3) integration into flexible assembly line at Toyota (Sakai and Yasumatsu, 1993; Sakai, Yasumatsu and Matsuo, 1993).

Development Requirements

First, development requirements were determined, and the technical problems were clarified.

(1) Fitting Quality Requirements

In order to secure the accuracy of the construction, it is important to control the clearance and the level difference in order to realize the flush feeling of the outer skin design. Recently, its requirement has become severe. Therefore, the requirement for the fitting quality variation was made to be more severe set at 3σ: ±1.0mm (compared with the conventional : 3σ: ±1.5mm) as shown in Figure **4**.

(2) Equipment Requirements (Tightening Element Technologies)

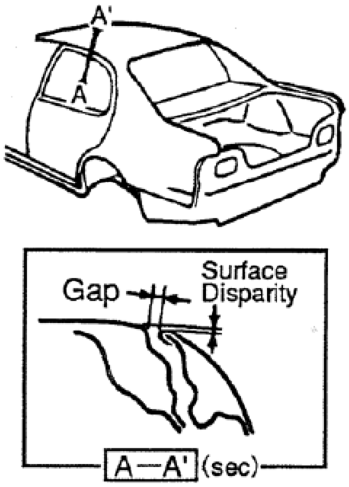


Figure 4: Quality requirements for fitting.

As the most important elemental technology in the building equipment, it is the elemental technology of feeding and tightening of bolts and nuts. In order to realize the target 95% of the line operation rate, the tightening reliability (success rate per one piece) 99.99% is necessary, but the tightening reliability 99.99% security was made to be a development requirement, because it is low as about 99% until now.

(3) System Requirements

As a system requirement of the production line, not only pursuit of the flexibility but also assurance of the line reliability, layout with high space efficiency, and rationalization of the system control were made to be requirements.

Technological Issues to be Achieved

Next, technical problems for achieving the above requirements are shown in Table **1**, and the following solved methods are described.

APPLICATION EXAMPLES

In this section, the author (Amasaka and Sakai, 2009a) illustrates example application "body auto fitting system" of Toyota's pioneering technology using application examples of the BAFM, which has contributed to the advancement of management technology at Toyota.

A) Fitting Accuracy- [A-1]: Setting the fitting quality standards

Determination of standards for fitting in luggage compartment panel and doors is described.

Table 1: Technical Goals in Development of Automated Body Fitting Line

	Requirement	Technical Goals
Ⓐ Fitting Accuracy	3σ:±1．0mm (Variation in Gap and Surface Disparity)	[A-1] ・Setting the Fitting Quality Standards [A-2] ・Selecting the Fitting Adjustment Method [A-3] ・Establishing the Means of Measuring the Fitting Position
Ⓑ Equipment	Tightening Success Rate: ９９．９９％	[B-1] ・Analysis of Tightening Mechanisms [B-2] ・Study of Bolt and Nut Designs [B-3] ・Defining the Equipment Specifications

(1) Luggage compartment panel

The luggage compartment panel (hereafter luggage) is built into an opening composed of left and right side member panels, an upper back panel, and a lower back panel. However, the shape of the opening is not necessarily constant, back and forth, but has a slight dimensional error in the left and right is the actual situation. In order to precisely fit the luggage in the opening, the gap between the side member panel and the luggage (s_1~s_4) and surface disparity (d_1~d_4) were measured three-dimensionally by a sensor provided to the robot to set the luggage, and the "gap is evenly distributed to the right and left, and the level difference is corrected to the target value" s1=s2, s3=s4 and d1=d2, d3=d4=d' as the basic idea. This is shown in Figure **5**.

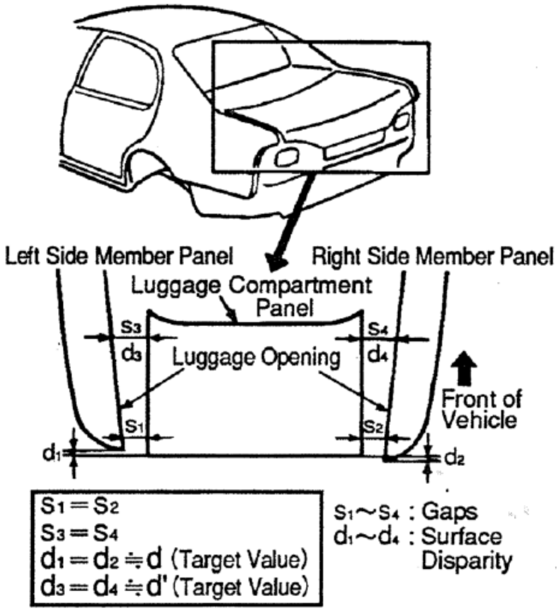


Figure 5: Luggage fitting standards.

(2) Doors

To determine the orientation of the body, initially the measurement datum was taken from an underbody panel. This was because the underbody pallet carries the white body and an underbody panel was assumed to be “held” in the most accurate position.

These measurements led to a deviation of σ=0.1~0.4mm in relation to the door opening. However, if two holes on the side member panel are used as the datum, the dimensional deviation is σ=0.1~0.2mm for the door opening as shown in Figure **6**.

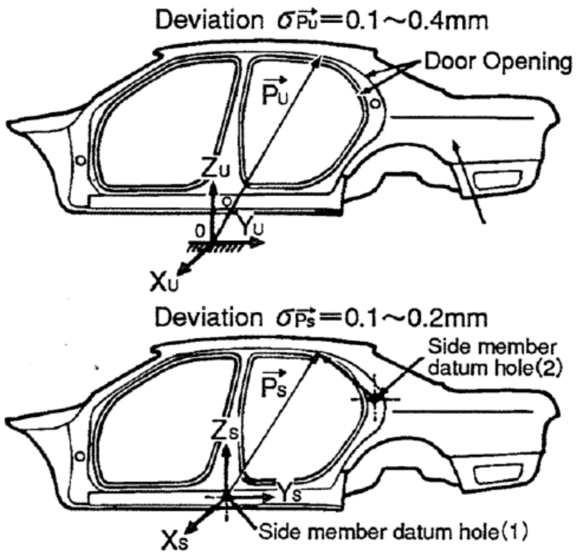


Figure 6: Standards for door fitting.

The two datum holes are measured via CCD cameras attached to the door panel jig. The jig is in turn attached to the robot via a tool changer and two-dimensional measurements are then possible through coordinate conversion algorithms.

A) Fitting Accuracy- [A-2]: Selecting the fitting adjustment method (gap, surface disparity and datum hole measurement)

(1) Measurement system adopted

The measurement of the gaps and surface disparity between the luggage compartment panel and the opening essentially requires three-dimensional measurement (Aloimonos, 1988: Higuchi, Ozeki and Yamamoto, 1992: Tsukada, Higuchi, Ozeki and Yamamoto,1993)

While there are several methods of three-dimensional measurement such as holography and interference fringe pattern analysis, this paper adopts a method of triangulation in which a measuring device is simple and considered to be the most practical. This is to expose the laser slit light to the measurement site, and to catch the reflected light by the CCD camera. And, as a two-dimensional sensor for measuring a built-in hole of a door, this paper adopts a system to recognize a contour of an object (circle) by capturing a shade image by a CCD camera and binarizing, and to determine its center of gravity position. The digitized data was then used to calculate the object centered as shown in Figure **7**.

(2) Preliminary examination (results of trial) and problems

Luggage compartment panel:

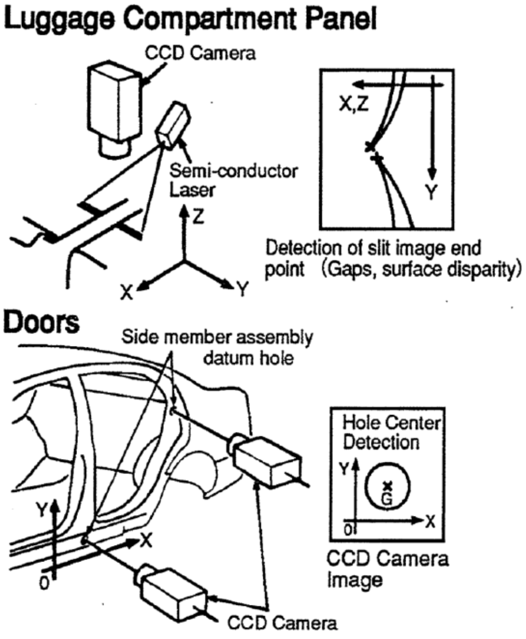
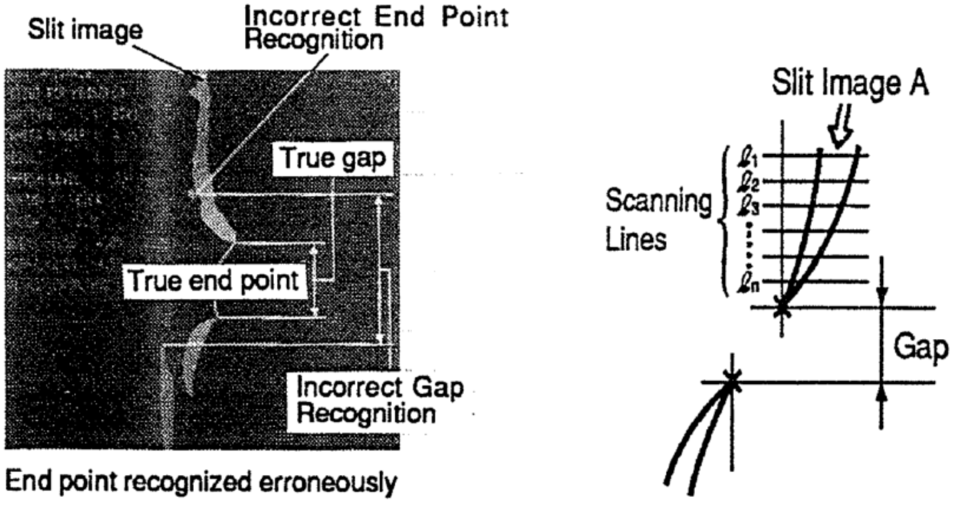


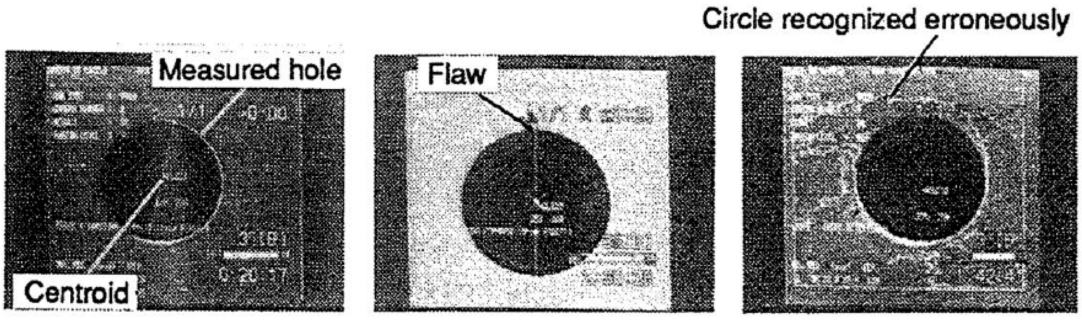
Figure 7: Outline of measurement system.

The result of preliminary measurement of the gap and level difference is shown in Photo 1, but the end point deviated from the end point to be originally detected is mistakenly recognized. It is considered probable that the logic of scanning the image scan line l_1 as shown in Figure **8** and recognizing the position where the slit image disappears as an end point erroneously recognized the change in the minute gloss of the body.



(**1**) Photo1: Measurement of gap and surface disparity (**2**) End point detection logic

Figure 8: Measurement system for luggage compartment panel and doors.



i) Normally detection ii) Presence of Flow iii) Blurred Image

Figure 9: Measurement with two-dimensional CCD camera (Photo 2).

Doors:

Result of a test operation with the two-dimensional sensor is shown in Figure **9**. Photo 2 shows i) indicates a normal case, ii) the case of detecting a flaw, the measurement accuracy is lowered because the position of the center of gravity of the hole produces an error with respect to the center and iii) a measurement failure and the measurement system stops.

The prototype measurement system described above was improved by introducing the following ideas.

Luggage compartment panel:

(a) Development of Noise Detection Software

Doors:

(a) Statistical processing of image recognition data

(b) Development of Center Detection Logic for Incomplete Circles

(3) Problem solutions

The following description uses the two-dimensional hole recognition sensor as an example.

(a) The selected method quantitatively represents the characteristic properties $f(\mu, \sigma)$ of the image. These characteristic properties are then statistically confirmed using a pattern recognition process that utilizes 18 typical patterns stored in a database as shown in Figure **10**.

The logic was developed by first assuming the image pattern which corresponds to$\mu+n\sigma$ is image A' and the pattern which corresponds to$\mu - n\sigma$ is image A'' with regards to one characteristic property $f(\mu, \sigma)$ (where$\mu$is the mean value of the characteristic property, $\sigma$is the deviation, and threshold level is set at $\mu \pm n\sigma$). These two images are then used to determine a characteristic property C which is determined by $\mu - n\sigma < C < \mu + n\sigma$ which then denotes a particular pattern A.

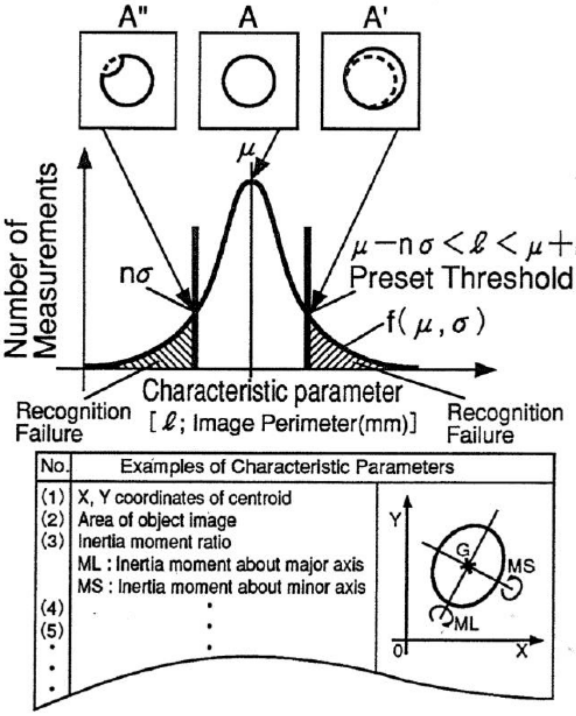


Figure 10: Statistical processing of image recognition data.

(b) Accurate hole location by the algorithm described in (a) may be adversely effected by minute impurities such as changes in the surface gloss, existence of flaws or deformations around the hole. To compensate for such effects, we developed the following detection algorithm. Centered G of the image is first determined as shown in Figure **11**.

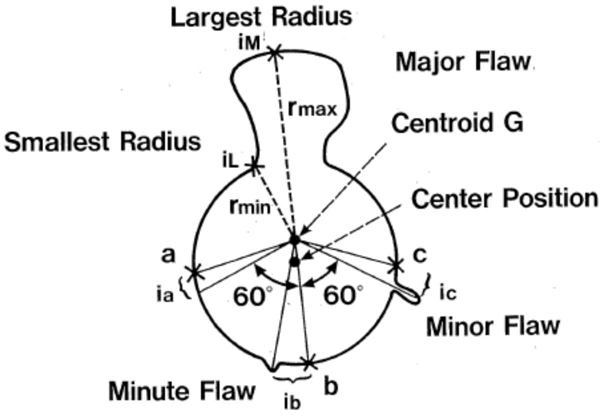


Figure 11: Hole center detection.

Then distances r= $\overline{Gi_n}$ (from G to the point i_n), which divide the perimeter into n equal parts, are checked to determine three points corresponding to the value of r which most frequently appears, denoted by i_a, i_b and i_c. The center of a circle defined by these three points is determined to be the true center of the hole. This algorithm is shown in Figure **12**.

Through both the statistical processing and the software improvements, both 100% recognition success rate and detection accuracy within 0.1mm were achieved.

A) Fitting Accuracy- [A-3]: Establishing the means of measuring the fitting position

A robot with coordinate conversion function capability was chosen to be utilized by the fitting system. As the robot “fits” the panels to their respective openings, the fitting position was corrected by using coordinate data obtained from the sensors mounted on the robot hand. The algorithm selected to determine **F**, the coordinate conversion technique for the luggage compartment panel, will be described below.

Gap measurement is denoted by S_i, surface disparity by d_i (i=1~4) and the position vector matrix of the hand coordinate viewed from the base coordinate of the robot by $\tilde{M}$. The target values of S_i and d_i are defined as S_{io} and d_{io} respectively, while $\mathbf{g}_i(S_{io}, d_{io})$ are the ideal functions. Let positions on the side member be $\vec{p}_{bi}$ (i=1~4) and the positions on luggage side be $\vec{p}_{l_i}$ (i=1~4). Allowing $\Delta\tilde{M}$ represents the displacement of the robot, the least squares method can be applied to approach S_{io} and d_{io} as close as possible. $\Delta\tilde{M}$ can then be obtained by solving the following equation (1):

$$\frac{\partial \|\tilde{M}\cdot\Delta\tilde{M}\cdot\vec{p}_{li}-\vec{p}_{bi}-g_i(S_{io},d_{io})\|}{\partial_{aj}}=0 \quad (1)$$

where a_j(j=1,2,3…6) are elements of $\Delta\tilde{M}$ and || || indicates the absolute function.

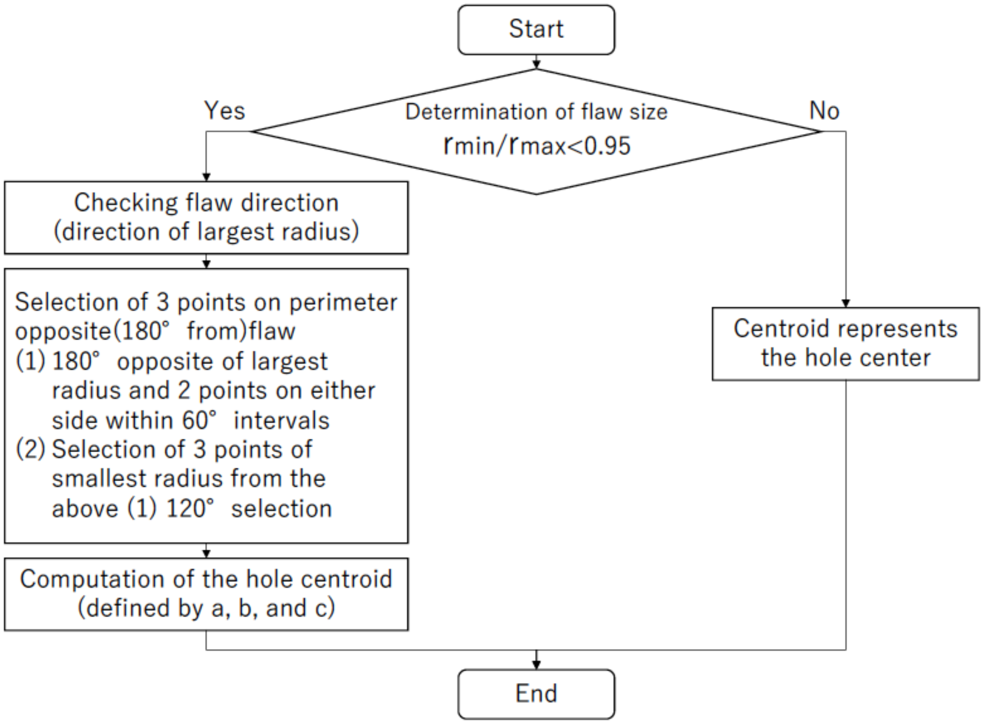


Figure 12: Algorithm.

Defining $\tilde{M}_0 * \Delta\tilde{M} \equiv \mathbf{F}$, determines the algorithm which determines the optimum gaps and surface disparities at each location, as shown in Figure **13**.

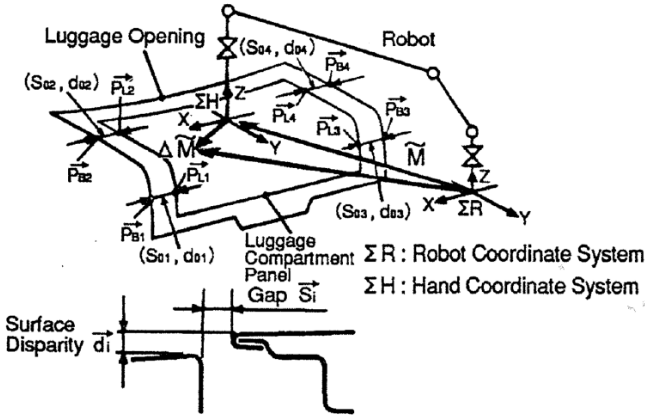


Figure 13: Coordinate conversion algorithm.

B) Equipment requirements to overcome technical hurdles – [B-2]: Study of bolt and nut designs (bolt type review)

Especially for the bolt type review, bolt designs were studied because of its significant influence on the reliability of tightening. Flat tip, round tip and self locating tip bolt types were studied with regards to the allowance for approach misalignment of bolt β and the bolt inclination allowance α, as shown in Figure **14**. This study revealed that the round tipped bolt and the best tightening reliability.

B) Equipment requirements to overcome technical hurdles - [B-2]: Bolt position measurement study (rear door application)

When viewing a bolt, an incorrect object may be mistaken as the intended object due to the presence of multiple candidates. To eliminate such mistakes, a program was developed which chooses among multiple candidates an object which has the characteristic properties closest to those of the intended object, as shown in Figure **15**. With this program, we achieved 100% success rate in the bolt recognition, compared to 70% in the trial operation. Images from the bolt

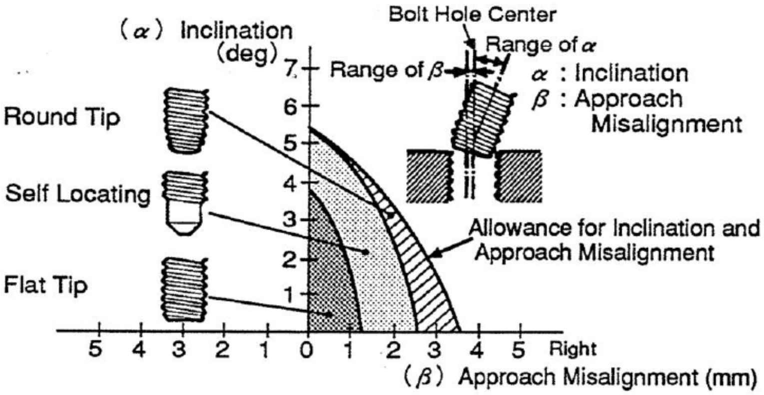
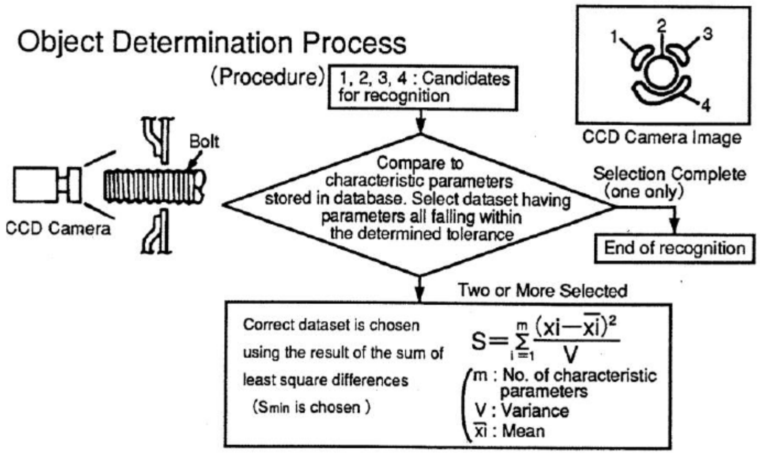
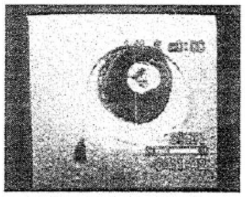
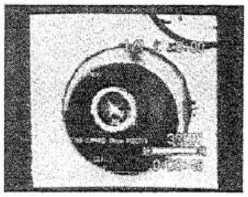


Figure 14: Bolt design influences.





Before Improvement



After Improvement

(Photo 3. Bolt recognition)

Figure15: Bolt recognition program.

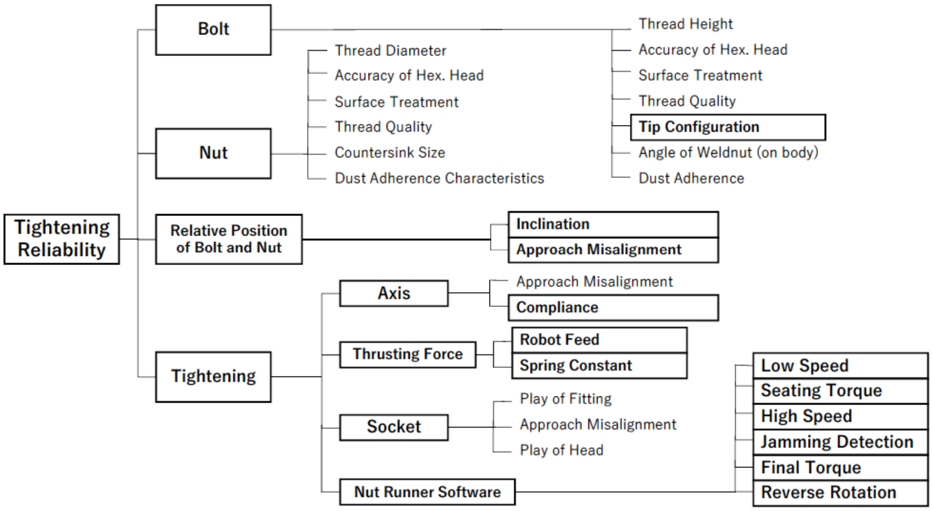


Figure 16: Tightening reliability cause and effect diagram.

recognizing sequence with and without the program are shown in Photo 3.

B) Equipment requirements to overcome technical hurdles – [B-3]: Defining the equipment specifications

Characteristic factors which have influence on the reliability of bolt tightening are shown in Figure **16**. Those having significant effects are enclosed in boxes for emphasis. The major factor related to tightening was determined to be thrust force, thus experiments were concentrated in this area.

Conventionally, since the pressing force depended only on the spring, it was excessive at the early stage of tightening. Therefore, the pressing force could be made constant by synchronizing the robot position according to the tightening (Brady, 1989: Brady, Hollerbach, Johnson, Perez and Mason,1983: Lopes, Connell, Dario, Murphy, Bonasso, Nilsson and Brooks, 2001), as shown in Figure **17**-**18**.

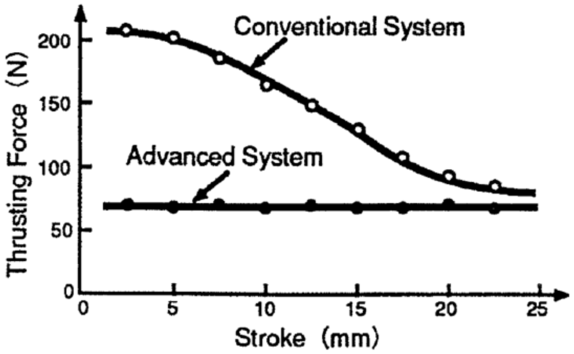


Figure 17: Trust force control.

Engineering Aspects of System Requirements - Development of Floor Space-efficient System Based on Review of the Transfer Equipment and Installation Equipment (robots)

The explanation in this system will be limited to the subject of floor space efficiency.

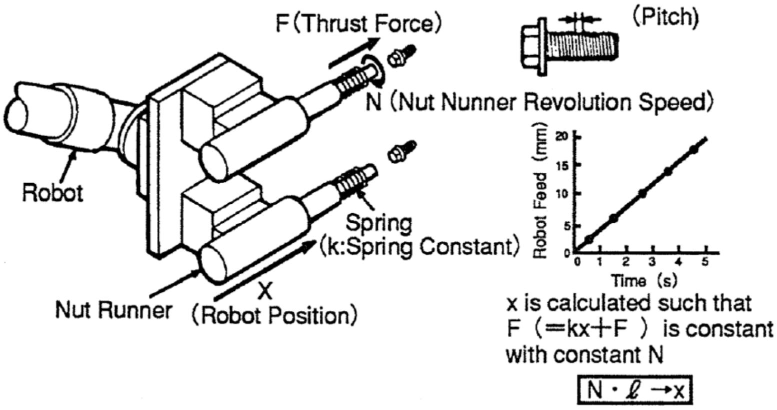


Figure 18: Trust force control method.

Conventional robots use a simple moving parallel link mechanism, so that the work area is set at a position offset from the installation position of the robot. This forces the assembly line to require an undesirably large floor space.

The author has reviewed the arm mechanism of the robot and employed a fixed parallel link mechanism which enabled the robot envelope to include an area very near the robot body (Brady and Paul, 1984: Craig, Khatib and Perez, 1989: Khatib and Perez, 1992: Brooks, 2008), as shown in Figure **19**. The effect of floor space reduction achieved with this type of robot is shown in Figure **20**.

RESULTS

This system was integrated in to the body assembly line located in the domestic plant. Conventional robot control method had been the fixed point control, such as handling, spot-welding and arc-brazing. On the other hand, this new one was the actual manufacturing point control, which the robot was synchronized with the tightening progress. Remarkable improvements were achieved in this line, such as the 95% line operation rate, as shown in Figure **21** and approximately 10.6 persons/line of labor saving, as shown in Table **2**. These results were made possible by achieving the target reliability of bolt tightening (99.99%) and the target fitting accuracy (3σ:±1.0mm).

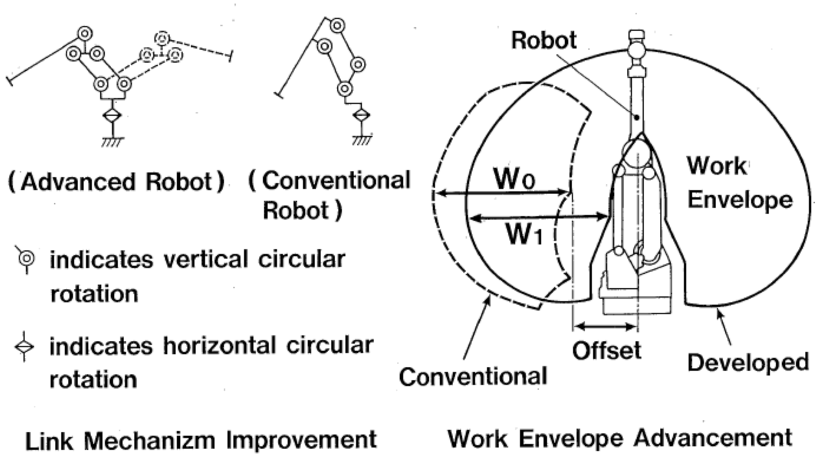


Figure 19: Advanced robot illustration.

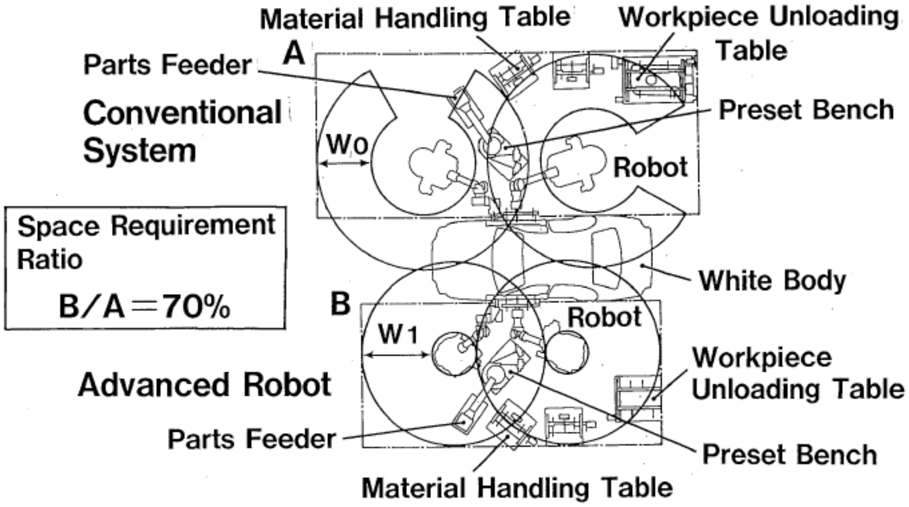
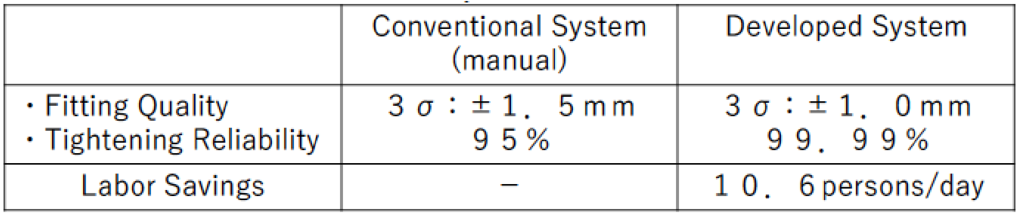


Figure 20: Effect of floor space reduction.

Table 2: System Evaluation



	Conventional System (manual)	Developed System
・Fitting Quality ・Tightening Reliability	３σ：±１．５ｍｍ ９５％	３σ：±１．０ｍｍ ９９．９９％
Labor Savings	－	１０．６persons/day

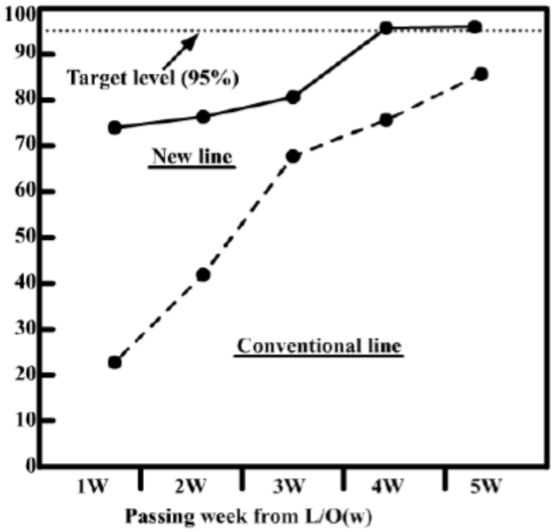


Figure 21: Transition of availability after startup of the line.

CONCLUSION

Complete manpower saving of the installation work which eliminates the need for correction man-hours in the post-process was realized by the development of the plan, correction, and tightening technique described in this paper.

In this study, the author has established the Body Auto Fitting Model “BAFM” using NJ-GPM, and its effectiveness has been verified at Toyota. In the near future, it would be deployed on the occasion of refreshment of overseas plants as well as domestic plants.

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