Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 18 (2014) 226 – 231

www.elsevier.com/locate/procedia

International Conference on Manufacture of Lightweight Components – ManuLight2014

# Small Batch Assembly of Space-Frame-Structures with Production Related Deviations of Individual Components

**J. Fleischer[1], G. Lanza[1], M. Otter[1], W. Pangboonyanon[1*]**

[1] Institute of Production Science, Karlsruher Institute of Technology (KIT), Germany

* Corresponding author. Tel.: +49 (0) 721 608 47357; fax: +49 (0) 721 608 44005; *E-mail address*: Woramon.Pangboonyanon@kit.edu

**Abstract**

In this paper an approach for a precise assembly of space-frame-structures is presented, while each of the single components features production-related deviations. The first section shows the results for the compensation of production-related deviations for dimensionally curved profiles in a space-frame-structure. The actual approach deals with the machining of the profile-end segments. Thus, the spatial alignment of the entire profile-contour can be optimized and therefore be adjusted to the theoretical profile-contour. In the second section, a flexible clamping-gripper for the assembly of space-frame-structures is presented. With this gripper, it is possible to handle and clamp different profiles for a certain assembly process.

Peer-review under responsibility of the International Scientific Committee of the “International Conference on Manufacture of Lightweight Components – ManuLight 2014”

*Keywords:* qualitiy, assembly, flexibility

## 1. Introduction

Due to rising energy prices as well as the overall effort to increase energy efficiency, light weight concepts will play a decisive role in the reduction of fuel consumption [1]. Space-frame-structures made by joining aluminum extrusion profiles, which are increasingly used in the automotive and aerospace industries, significantly contribute to weight reduction and therefore to the increase of energy efficiency [2].

Because of the tendency of product customization, which leads to an extended product variety, the production process is more and more shifting towards a small batch production [3]. Within a high product variety, the assembly is still one of the most cost effective operations [4]. Therefore, the individual assembly processes have to be made more flexible and adaptable [3].

The assembly of space-frame-structures in a small batch series is mostly done manually and with the help of cost intensive devices which often make up 10-20 % of the total production cost [5]. The demand for a high reproducibility during the assembly of a space-frame-structure is often impossible to guarantee by a manual process [6]. Therefore, the automated assembly is preferred because of quality and economic aspects [7].

Concerning space-frame-structures, the number of joints should be minimized as they usually represent a mechanical weak spot. Therefore, as well as for economic reasons, the number of profiles used in a space-frame-structure is minimized which increases the geometric complexity of the individual profiles [8-9]. One possibility for the production of complex three-dimensional aluminum profiles is the process “curved profile extrusion” [1], [10].

In general, production processes are subject to variations and can never be considered as perfect [11]. Therefore, certain deviations from the target geometry of the single components may occur when using new and innovative production processes for a small batch production, as the leveling of these processes to increase the stability is not possible, or only in a limited way, due to economic reasons [12]. The quality of the single components is normally very important especially for the assembly of space frame structures in order to guarantee their functional completion and assembly requirement. Hence, the consideration of relevant

Peer-review under responsibility of the International Scientific Committee of the “International Conference on Manufacture of Lightweight Components – ManuLight 2014”
doi:10.1016/j.procir.2014.06.136

existing deviations of each single profile occurring while assembly has to be performed.

Concerning the assembly of space-frame-structures, two main issues arise, as the existing deviations can add up during assembly in such a way, that a “closing” the structure is only possible to a limited extend. If a flexible, automated assembly without specific devices is aspired, it becomes evident that the assembly will not be possible without any measures to increase the accuracy. A manual assembly process performed with specific rigid devices may cause a “forced closing” of the structure, which leads to the insertion of residual stress and therefore to a negative impact on the fatigue strength [12].

Depending on the area of application, approaches to minimize the effects that cause deviations are not sufficient, since due to the processes not all influences can be detected [13]. Given that, as well as the fact that accuracy problems are often not recognized until the components are assembled [14], it becomes evident that advanced measures have to be implemented and the inline-quality control should be conducted in order to ensure an automated and flexible assembly process.

### *1.1. General Approach*

The machining of the end sections of single profiles is a flexible and economical way to compensate production related deviations and therefore to increase the accuracy of a space-frame-structure.

Two different machining possibilities can be executed on a profile. The first option is the shortening of the start- and end-sections of a profile, which represents two translational degrees of freedom. The other possibility is to insert a chamfered edge at the start section of the profile, which allows a spatial rotation of the profile and thus represents the rotational degrees of freedom for a profile. Combined, this is a flexible way for adjusting an actual-profile to a target-profile, which allows a compensation of deviations and therefore, to increase of the accuracy.

Figure 1 illustrates the context schematically, by taking a two-dimensional profile that is fixed to a panel. Compared to the target-profile, the actual-profile shows deviations regarding the length as well as the profile-contour (fig. 1, top). By cutting the beginning and the end of the profile and adjusting an angle at the beginning of the profile, the optimized profile (fig. 1, bottom) can be aligned spatially in a way that the deviation of the end points and the contour can be minimized. Consequently, the profiles can be adapted individually and the accuracy of the space-frame-structure can be increased [9], by applying the following procedural method.

The measurement data of the actual-contour is available for all profiles which are assembled into a space-frame-structure. With this data, the mathematical modeling can be performed. With the help of a virtual assembly, all deviations regarding the length as well as the contour can be analyzed. This allows the determination of all errors that occur when “closing” the space-frame-structure. These errors are subsequently minimized by an optimization with respect to basic and boundary conditions. The processing parameters are calculated in a last step.

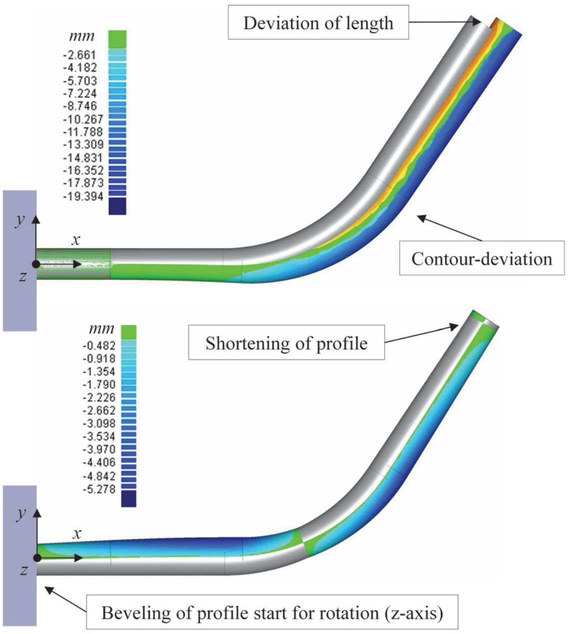

Fig. 1. Compensation of contour deviations in any of spatial directions by machining profile end segments

The mathematical modeling as well as the methodical is already shown extensively in [9] and [12]. For this reason, the next paragraph will focus directly on the results regarding the demonstration structure used in the Transregio10, a German-collaborative research center on behalf of the German Research Foundation (DFG) [9].

## 2. Results for the compensation of deviations

Figure 2 shows the virtual assembly of the demonstration structure for the Collaborative Research Centre Transregio 10. The structure contains twenty profiles and eight joining elements. All profiles were manufactured by using “curved profile extrusion” and measured after the production process. The joining elements are always considered to be perfect, as they are manufactured with a high accuracy. Therefore, the theoretical contour of the joining elements is used in the virtual assembly.

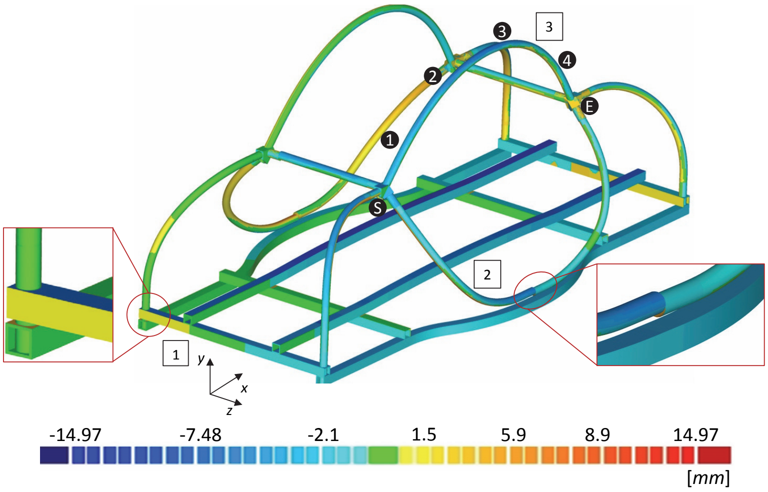

Fig. 2. Virtual assembly of demonstration structure before optimization; the critical positions regarding added deviations by closing the structure (in circles) and the added deviations (in squares) (rearrange fig.2)

All profiles of the demonstration structure shown in Figure 2 feature deviations regarding their contour and length. In general, the deviations of the single profiles resulting from the comparison of their theoretical-actual-contour recline around *1* to *3.5 mm* regarding length and contour accuracy. Caused by an addition of these single errors, maximum deviations up to *15 mm* arise (see fig. 2). Because of these added deviations, problems in "closing" the structure, or sub-parts of the structure, arise at different positions, which are emphasized in the red boxes in figure 2. The deviations of the end points for profile 1 to 3 are shown in table 1.

Table 1: Deviations of end points in [*mm*]

| Profile | x-deviation | y-deviation | z-deviation | res. deviation |
|---|---|---|---|---|
| 1 | 0.983 | 8,379 | 1,138 | 8,513 |
| 2 | 0,167 | 6,589 | 1,465 | 6,752 |
| 3 | 1,434 | 9,259 | 2,563 | 9,714 |

Besides the deviations of the end-points of a structure, it is also important to ensure a high accuracy of the whole structure. On profile 3, four additional contour-points are shown. A subsequent optimization of these additional points is implemented.

Table 2: Deviations of all points on profile 3 in [*mm*]

| Points | x-deviation | y-deviation | z-deviation | res. deviation |
|---|---|---|---|---|
| 1 | 0,024 | 6.194 | 0.448 | 6,210 |
| 2 | 4,115 | 7,173 | 0,258 | 8,295 |
| 3 | 6,901 | 2,843 | 0,252 | 7,449 |
| 4 | 4,100 | 1,300 | 1,667 | 5,015 |

These points are distributed over the whole profile and therefore, specify the contour-accuracy of a profile. The deviations of these points are displayed in table 2.

As already described in [9], the optimization of the profiles is generally carried out based on the least squares approach which is fundamentally the minimization of a function generating the sum of squares as following:

$$\min_x \|F(x)\|_2^2 = \min_x \sum_i F_i^2(x) \qquad (1)$$

This indicates the squares of the distances between an individual point on a profile selected to optimization and the fitted point given by a theoretical contour.

In the subsequent optimization of the additional points, all end points compose the target function. A specific number of contour-points can be taken into consideration as side conditions, depending on the accuracy requirements of a specific profile. With these side conditions, it is also guaranteed, that specific points or areas on a profile match pretended accuracy. For example, if there are any cut-outs on a profile which represent the connection-section for another component, these points always have to be part of the optimization. After the optimization, the processing data can be generated.

Figure 3 shows the structure after the optimization of all profiles. In the present case, all profiles were optimized with respect to the distance of their end points regarding the theoretical-contour.

Additional, between 1 and 4 contour points were selected on each profile to achieve a high accuracy of the whole structure. As it can be seen in figure 3, the deviation could be minimized over the whole structure. Especially in terms of "closing" the structure and sub-parts of the structure, a significant increase of the accuracy was accomplished. Besides this improvement, the accuracy of the whole structure was increased as well. In table 3 the deviations of the end points of profile 1 and 2 after the optimization are displayed.

In General, the accuracy requirement by each joining process is different. One joining process of space frame structures which is frequently used is laser welding. The process required accuracy in term of the maximum allowed gap by laser welding is 0.2 mm [7]. Thus, an alignment of the joining partners has to be very accurate in order to ensure that the required tolerances are met.

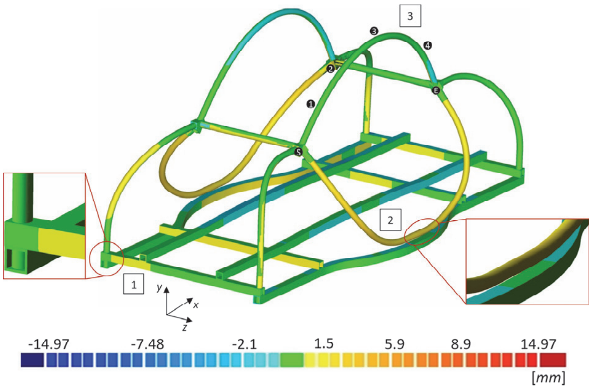

Fig. 3. Virtual assembly of demonstration structure after optimization; the critical positions regarding added deviations by closing the structure (in circles) and the added deviations (in squares)

Table 3: Deviations of end points after optimization in [*mm*]

| Profile | x-deviation | y-deviation | z-deviation | res. deviation |
|---|---|---|---|---|
| 1 | 0,0016 | 0,007 | 0,022 | 0,023 |
| 2 | 0,464 | 0,348 | 0,409 | 0,712 |
| 3 | 0,300 | 1,700 | 0,968 | 1.981 |

In table 4 the deviations of all contour-points of profile 3 after the optimization are displayed.

Table 4: Deviations of all points on profile 3 after optimization in [*mm*]

| Point | x-deviation | y-deviation | z-deviation | res. deviation |
|---|---|---|---|---|
| 1 | 0,005 | 0,692 | 0,002 | 0,692 |
| 2 | 0,210 | 0,304 | 0,049 | 0,373 |
| 3 | 0,400 | 0,155 | 0,284 | 0,514 |
| 4 | 0,200 | 0 | 1,059 | 1,078 |

The results show that the machining of the profile end sections is a flexible way to compensate production related deviations. By executing the methodical procedure, the accuracy of the demonstration structure could be increased significantly. Thus, the requirement for an automated assembly of space-frame-structures without specific devices is given.

## 3. Flexible clamping-gripper for the assembly

As already stated, the automated assembly of space-frame-structures is preferred because of quality and economic aspects. One way to align the joining partner without specific devices and therefore automate the assembly is to use industrial robots.

Given the fact, that accuracy problems for the assembly that result from the production process are under control by using the introduced method, there are still deviations, which are caused by the accuracy of the robot as well as errors resulting from the impreciseness of gripping a joining partner. However all types of errors combined add up to deviations higher than *1 mm* at the joining spot for each profile. Therefore the achievable alignment is not sufficient for the required joining process [7]. For the assembly with industrial robots, an additional system with a higher accuracy is required, to ensure the correct alignment of the components.

Therefore, an approach based on component inherent markings was developed at the wbk Institute of Production Science. The markings, which are applied on the profile during the production process “curved profile extrusion”, represent a 3D coordinate system. During the assembly process, two profiles are roughly arranged and the markings can be captured with a stereo camera system. Therefore, the position and orientation of the components can be determined precisely. Afterwards the deviations between the two joining partners can be determined and with the help of an implemented close-loop-control, the industrial robots can execute a compensation-movement to align the joining partners precisely. The approach has been validated in first experiments, where one profile was aligned with an industrial robot, while the other profile was fixed in device. Details can be found in [7].

Even the renouncement of specific devices demands a fixation of the joining partners during the joining-process. Thus, the use of one clamping-device is essential. The device must have a maximum flexibility while ensuring that the two joining partners can be aligned precisely to each other. For this reason, a clamping-gripper was developed at the wbk Institute for Production Science which offers both, a high flexibility in regards of different connection-types as well as the ability for a precise alignment. Therefore, the stereo-camera system, which forms a closed-loop control in combination with the component-markings and the industrial robot, was integrated in the clamping-gripper. Figure 4 & 5 show the prototype of the clamping-device.

The gripper has the shape of square and is mounted on an industrial robot. The stereo camera system is fixed on two linear axles. Therefore, a large workspace is created and various types of profile-joints can be processed. In addition it is possible, that the camera can always be aligned perfectly in focus to the profiles.

To create different profile-joints, it is also necessary, that the clamping devices can be adjusted in the workspace. Therefore, the two devices are mounted on two axles on the lower side of the framework, which can be moved independently to the camera-axles. To be able to perform profile connections between *0°* and *+/- 90°*, the two clamping devices can also rotate around the *z*-axis. Figure 5 illustrates the described context and shows two exemplary connection-types.

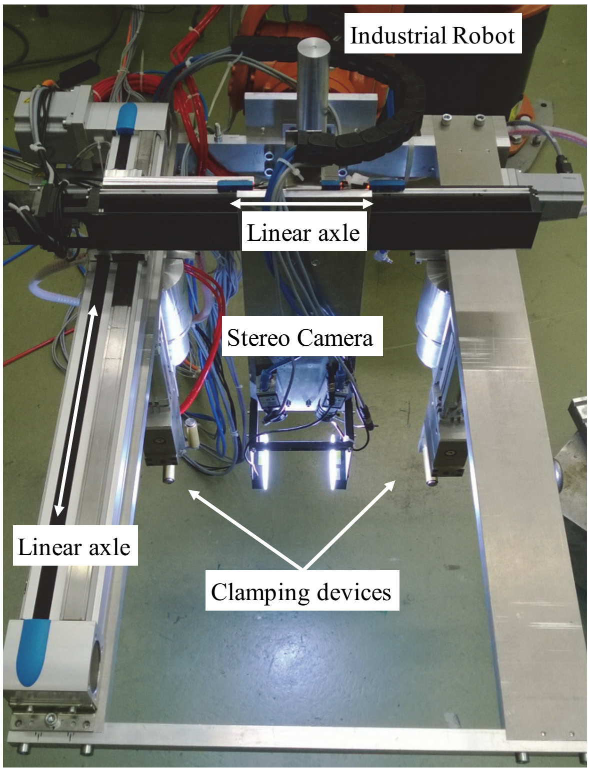

Fig. 4. Prototype of the flexible clamping gripper.

A profile-profile connection with an I-joint, where both clamping devices have the same position and orientation (top) and a profile-profile connection with a T-joint (bottom), where both devices differ in position and orientation. Indirect profile-connections with the help of connection components may also be performed with the gripper. The shown structure therefore has high degree of flexibility regarding different profile connections.

The actual process for the alignment of two profiles contains six steps.

- The data for programming the industrial robots and the gripper is determined from an offline model. From this model, the data for the motion of the robots as well as for the individual axles of the gripper are identified.
- Afterwards, profile 1 is set up and fixed within the clamping device.
- Profile 2 is positioned. Here, the profile is not set up in the exact target-position but placed with a safety distance to avoid collisions, that may result from deviations of the robot as well as the impreciseness of the gripping spot for a profile.
- The markings of both profiles are detected and the deviation between the two joining partners is calculated.
- With a closed-loop control, profile 2 is then aligned precisely with profile 1.
- In the last step, profile 2 is fixed with the clamping device for a possible joining-process of the profiles afterwards. The required force for individual profiles' fixing are not hereby precisely specified, since possible effects on a profile in terms of elastic deformation are not the main purpose of this presenting paper.

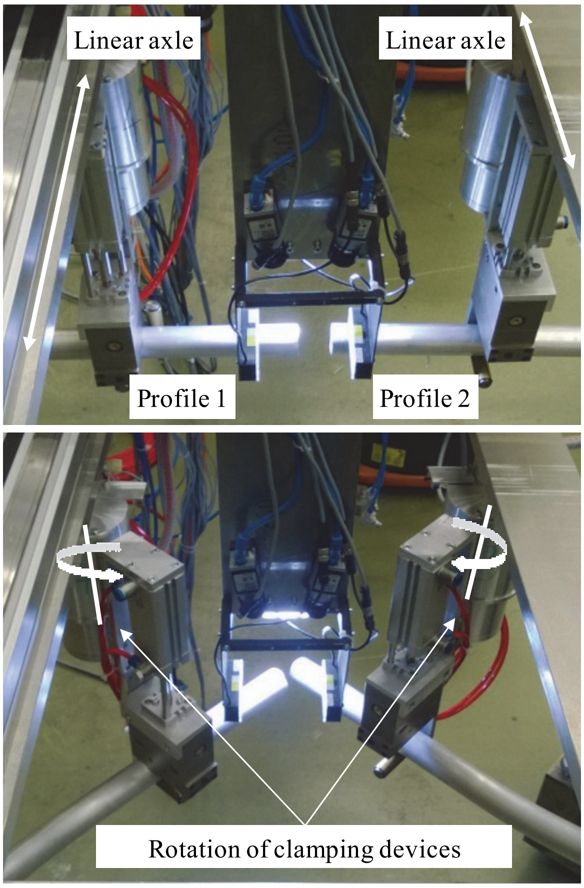

Fig. 5. Alignment of clamping devices for different profile-connections

The camera system and as well as the clamping-gripper were both already tested separately. Here, the precise alignment of two profiles by using component inherent markings has been proven successfully [7]. The components of the clamping-gripper were calibrated, thus allowing an exact positioning of the clamping devices as well as the camera. By the integration of both systems on an industrial robot, the coordinate system defined by the camera can no longer be served as the reference base for the used robots, as it is now spatially moved as well.

Current research is therefore focused on the calibration of the entire system, consisting different axles of the gripper, the industrial robots as well as the camera. For this purpose, a base-coordinate system has to be defined, in which the camera coordinate system can always be definitely determined. Therefore, the same basis-coordinate system is assigned to each industrial-robot. Subsequently, the position information of every axis of the clamping-gripper, as well as the position of the robot the gripper is mounted on, is read-out and converted to the basis-coordinate system. Thus, all calculated deviations and the compensation movement of the robot can be determined with respect to the common base.

First tests for the calibration of the whole system were successfully, but further measures to increase the accuracy of the whole system are planned in order to realize the entire process properly.

## 4. Summary and Outlook

In this paper an approach for a precise assembly was presented, which addresses two main issues.

Regarding production-related deviations of single components that may add up during the assembly and therefore, prevent an automated "closing" of a space-frame-structure, a new approach for the compensation of these deviations was presented. The general approach contains the machining of the profile end segments which allows a spatially alignment of the profiles and therefore, leads to an optimization of the whole structure regarding the accuracy.

Controlling these deviations, single profiles have to be aligned and fixed precisely for an assembly. With the use of industrial robots for the assembly, challenges arise regarding the accuracy of this process-step. For this reason a flexible clamping gripper was developed. The gripper features a stereo camera system, which is used to detect component inherent markings on the profiles. Therefore, deviations during the alignment process can be detected. A closed loop control between the camera system and the industrial robot allows the compensation of deviations during the process.

## Acknowledgements

The work is based on the investigations of the subproject C4 - "Combined application and processing kinematics" - of the Transregional Collaborative Research Center/Transregio 10, which is kindly supported by the German Research Foundation (DFG).

## References

[1] Kleiner, M.; Tekkaya, A.E.; Becker, D.; Pietzka, D.; Schikorra, M.: Combination of curved profile extrusion and composite extrusion for increased lightweight properties. In: Production Engineering, Volume 3 (2009), Number 1, p. 63-68

[2] Zäh, M.F.; Gebhard, P.; Huber, S.; Ruhstorfer, M.: Bifocal Hybrid Laser Beam Welding and Friction Stir Welding of Aluminium Extrusion Components. In: Advanced Material Research: Flexible Manufacture of Lightweight Frame Structures, Volume 43 (2008), p. 69-80

[3] Hu, S.J.; Ko, J.; Weyand, L.; ElMaraghy, H.A.; Lien, T.K.; Koren, Y.; Bley, H.; Chryssolouris, G.; Nasr, N.; Shpitlani, M.: Assembly system design and operations for product variety. In: CIRP Annals – Manufacturing Technology, Volume 60 (2011), p. 715-733

[4] Krüger, J.; Surdilovic, D.: Robust control of forced-coupled human-robotinteraction in assembly processes. In: CIRP Annals – Manufacturing Technology, Volume 57 (2008), p. 41-44

[5] Jonsson, M.; Ossbahr, G.: Aspects of reconfigurable and flexible fixtures. In: Production Engineering, Volume 4 (2010), p. 333-339

[6] Feldmann, K.; Müller, B.; Haselmann, T.: Automated assembly of lightweight automotive components. In: CIRP Annals – Manufacturing Technology, Volume 48, Issue 1 (1999), p. 9-12

[7] Fleischer, J.; Lanza, G.; Otter, M.; Elser, J.: Spatial alignment of joining partners without fixtures, based on component inherent markings. In: Journal of manufacturing systems, 2013, DOI: http://dx.doi.org/10.1016/j.jmsy.2013.04.004

[8] Cetin, O.L.; Saitou, K.: Decomposition-Based Assembly Synthesis of Multiple Structures for Minimum Production Cost. In: Proceedings of IMECE 03, ASME 2003 International Mechanical Engineering Congress and RD&D Expo, November 2003, p. 1-10

[9] Fleischer, J.; Otter, M.; Beuke, F.: Method to compensate production related deviations for the assembly of space-frame-structures. In: Production Engineering, 2013, DOI 10.1007/s11740-013-0501-3

[10] Becker, D.; Schikorra, M.; Tekkaya, A.E.: Manufacture of 3D curved profiles for structure components. In: Advanced Material Research: Flexible Manufacture of Lightweight Frame Structures, Volume 43 (2008), p. 1-8

[11] Ding, Y.; Jin, J.; Ceglarek, D.; Shi, J.: Process-oriented tolerancing for multi-station assembly systems. In: IIE Transactions, Volume 37/6 (2005), p. 493-508

[12] Fleischer, J.; Otter, M.: Compensation of shape deviations for the automated assembly of space frame structures. In: Proceeding of the 4th CIRP Conference on Assembly Technologies and Systems, Ann Arbor, Michigan, USA, 2012, p. 105-108

[13] Xie, K.; Camelio, J.A.; Izquierdo, L.E.: Part-by-part dimensional error compensation in compliant sheet metal assembly processes. In: Journal of Manufacturing Systems, Volume 31, Issue 2 (2012), p. 152-161

[14] Mantripraga, R.; Whitney, D.E.: The Datum Flow Chain: A Systematic Approach to Assembly Design and Modeling. In: Research in Engineering Design, Volume 10 (1998), Number 3, p. 150-165