CCC 2024

Proceedings of the Creative Construction Conference (2024)
Edited by: Miroslaw J. Skibniewski & Miklós Hajdu
https://doi.org/10.3311/CCC2024-123

FOLDING MECHANISMS OF SELECTED EXTREMELY MODULAR SYSTEMS

Jacek Katzer[1], Machi Zawidzki[2]

1 University of Warmia and Mazury in Olsztyn, Poland, jacek.katzer@uwm.edu.pl

2 Institute of Fundamental Technological Research, Polish Academy of Sciences, Poland, zawidzki@ippt.pan.pl

Abstract

Extremely Modular System (EMS) is a relatively new concept introduced a few years ago. It represents a new approach to the design of engineering structures and architectural objects where assembly of congruent units allows for the creation of free-form shapes.
The main difference from the traditional modular systems used in engineering, is the emphasis of the minimal diversity of types of modules, ideally - just one. This is why these system are called "extremely" modular.
One of the most natural areas for use of EMSs are deployable structures.
This paper presents rigid body folding mechanisms for two selected EMSs: *Pipe-Z* - a parametric system comprised of one type of module allowing for creation of three-dimensional knots, and *Truss-Z* - a modular system for creating free-form ramps and ramp networks among any number of terminals.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2024.

Keywords: Extremely Modular System, Deployable Structure, Free-form, Pipe-Z, Truss-Z.

1. Introduction: Extremely Modular Systems

The idea of Extremely Modular System (EMS for short) has been introduced in [1]. It is a family of concepts where assembly of congruent units allows for creation of free-form shapes. Limiting the number of units to only one may seem as an exaggerated and impractical constraint, especially in the construction sector. However, besides the intellectual elegance, EMS have the following advantages:

1. Economical: as they are suitable for mass fabrication at relatively cost so they can be broadly applied;
2. Functional: as they allow for reconfiguration, expansion, reduction;
3. Robust: since every module which failed can be easily replaced with an identical but functional one;
4. Discrete: as they are suitable for intelligent mathematical modeling, and their configurations can be subjected to discrete (multi-objective) optimization using modern search algorithms;
5. Uniform: this feature is advantageous for rapid deployment and automated assembly;
6. Sustainable: as the entire modules can be reused (not only merely recycled).

A number of EMSs have been introduced and are being presently developed:

- **Pipe-Z** is a parametric design system introduced in [2] which comprised of one type of module allows for creation of complex three-dimensional, single-branch structures which can be represented by mathematical knots. *Pipe-Z* has been proposed for constructing conceptual extreme habitats such as deep-space and surface outposts, emergency passages etc. both permanent and temporary in [3].

- **Truss-Z** is a modular self-supporting skeletal system for creating free-form ramps and ramp networks among any number of terminals in space [4-9].
- **Ramp-Z** is a kit-of-parts modular system for creating free-form ramps and ramp networks, where each module stands individually on the ground [10].
- **Vault-Z** is a concept of parametric shell system for free-form multi-branch pipe-like and vault-like constructions [11].
- **Shelter-Z** is a system based on single type of spatial precast concrete module. It allows for the rapid construction of domestic convex shelters [12].
- **Arm-Z** is a conceptual hyper-redundant manipulator based on Pipe-Z, where each module has one degree of freedom - a twist relative to previous module [13].
- **Multi-branch Pipe-Z** is a recent further development of Pipe-Z allowing for construction of multi-branch pipe-like structures.

Deployable structures are used for ease of storage and transportation, and they are deployed into their operational configuration when required [14]. They have dual functionality: kinematic mechanisms during deployment and load-bearing structures after deployment [15]. Traditional deployable structures, although quite complicated as mechanical systems [16], in their final form represent relatively simple, symmetrical geometries and serve as: masts [17] (linear), antennas (rotational symmetry), pantographic roofs (uniform grid), pool covers, domes, etc. [18]. This paper presents systems, where the final assembly offers unprecedented geometrical freedom.

2. Foldable Pipe-Z

The basic module of *Pipe-Z* is a geometrical object analog to a sector of circular torus presented in [19]. It is defined by the following parameters: radius (*r*), corresponding radius (*d*), and central angle (*ζ*). Despite its simplicity, this system allows for creation of relatively complex shapes, as shown in Fig. 1.

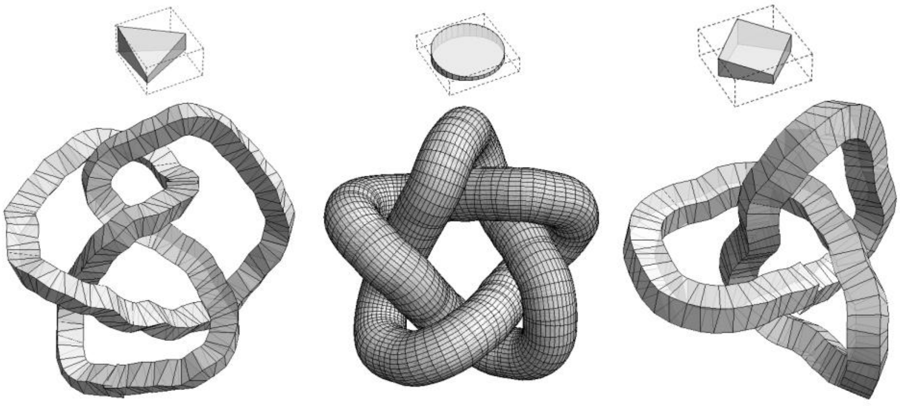

Fig. 1. Three *Pipe-Z* knots constructed with different basic modules. From the left: Figure-eight (4_1), Pentafoil (5_1), and Trefoil (3_1).

2.1 Foldable Pipe-Z module

Folding of *Pipe-Z* takes advantage of planar symmetry between top (T) and bottom (B) faces of the basic module. The intersection of that symmetry plane and vertical trapezoidal sides form the axes of revolution for the fold. The fold of the entire unit is a function of angle ψ between those halves of the side facets. For each facet ψ is the same. Fig. 2 shows a cardboard model of a foldable *Pipe-Z* module.

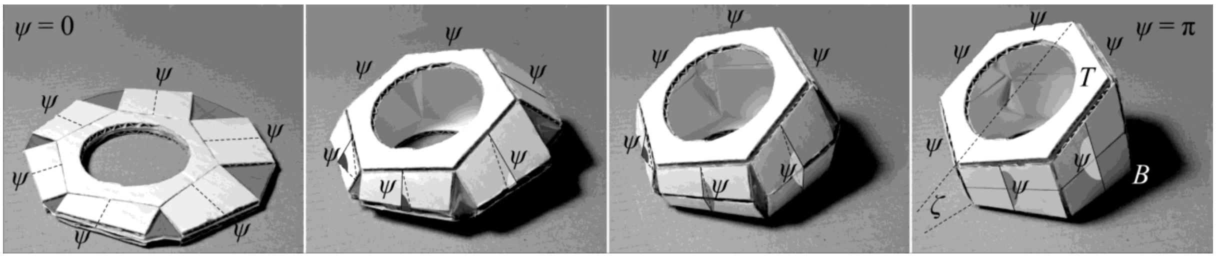

Fig. 2. Four stages of unfolding of a physical model of the foldable *Pipe-Z* module. From the left: $\psi = 0$ at stowing configuration, two intermediate positions and $\psi = \pi$ for full deployment. At the deployed position the angle between faces B and T reaches ζ.

Foldable *Pipe-Z* module is a rigid-panel structure composed of trapezoidal panels connected by cylindrical hinges. Fig. 3 shows the geometrical analysis of this folding mechanism.

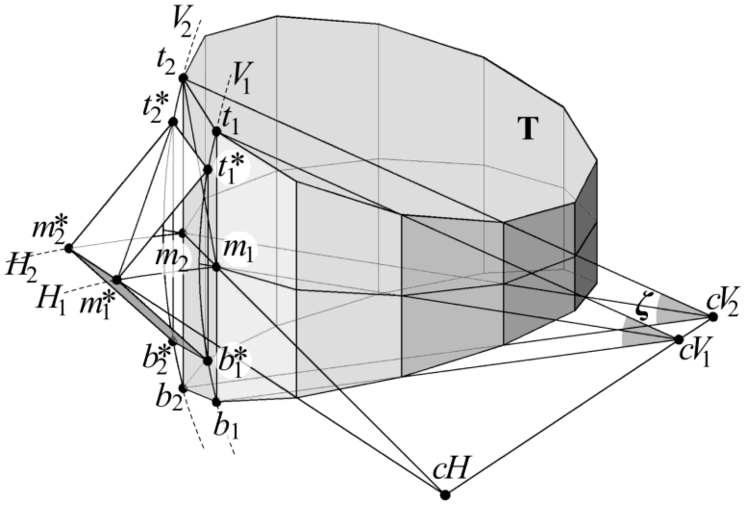

Fig. 3. Line defined by points cH and cV_1 is the axis of the central angle ζ. Arc V_1 with center in cV_1 is the trajectory for points $t_1 \rightarrow t^*_1$ and $b_1 \rightarrow b^*_1$. Analogously, V_2 with center in cV_2 is the trajectory for points $t_2 \rightarrow t^*_2$ and $b_2 \rightarrow b^*_2$. These trajectories are perpendicular to the horizontal plane (m_1, cH, cV_1). Concentric arcs H_1 and H_2 with center in cH lying in the same horizontal plane are trajectories for points $m_1 \rightarrow m^*_1$ and $m_2 \rightarrow m^*_2$, respectively. The distances are preserved during this transformation, e.g.: $t_1 t_2 = t^*_1 t^*2$, $m_1 m_2 = m^*_1 m^*_2$, $b_1 b_2 = b^*_1 b^*_2$, $t_2 m_1 = t^*_2 m^*_1$, $t_1 m_1 = t^*_1 m^*_1$, etc.

Although the folding is a function of the side angles ψ, it is linked to the angle (ζ^* - the angle between B and T planes during folding and unfolding). Obviously, for ψ equal to: 0 and π, the values of this corresponding central angle are: 0 and ζ, respectively. Angle ψ does not depend on the number of sides (n) of the polygonal base of the module. The intermediate values of the central angle ζ^* for foldable *Pipe-Z* module during folding can be calculated as follows:

$$\zeta^* = 2\,\mathrm{ArcSin}[\mathrm{Sin}(\tfrac{1}{2}\zeta)\,\mathrm{Sin}(\tfrac{1}{2}\psi)] \qquad (1)$$

where $\mathrm{Sin}(\tfrac{1}{2}\zeta)$ is a constant parameter for a given module.

Such folding is intuitive and practical, as the module is constructed from rigid plates with revolute hinges only.

2.2 Folding of a multi-module Pipe-Z

The deployment process in such mechanisms pose several geometrical and practical difficulties. One of the fundamental problem is the avoidance of collisions, in other words, self intersections. It becomes particularly challenging for complicated three dimensional structures. To mitigate this problem, the unfolding rate of individual modules can be controlled. As an example an additional function ψ (t, f) has been introduced, so the angle ψ depends on two parameters: t (threshold) and f (normalized unfolding rate):

$$\psi(t,f) = \begin{cases} 0 & f < \frac{t}{2} \\ 1 & f > \frac{t+1}{2} \\ 2f - t & \text{else} \end{cases} \tag{2}$$

where parameter f changes continuously from 0 to 1 and uniformly for all modules; the threshold parameter t is assigned to the modules individually.

2.3 A low-tech preliminary prototype

A simple six-unit octagonal deployable *Pipe-Z* prototype has been made of corrugated cardboard. For easy identification the modules have contrasting colors. The units are connected by tubular elements forming revolute joints. The modules gain quasi-rigidity from the compression bands, as shown in Fig.4.

Fig. 4. A sequential deployment of a *Pipe-Z* spiral comprised of six octagonal foldable modules. The deployed units gain quasi-rigidity from the white compression bands.

3. Foldable Truss-Z

Truss-Z is a system composed of basic module (R) and its mirror reflection (L). R ascends and turns right, L ascends and turns left. Rotations give two additional configurations: rotated R (R2), which descends and turns right, and rotated L (L2), which descends and turns left. Fig. 5 shows basic examples of Truss-Z structures and a relatively complex two-part free-form slope.

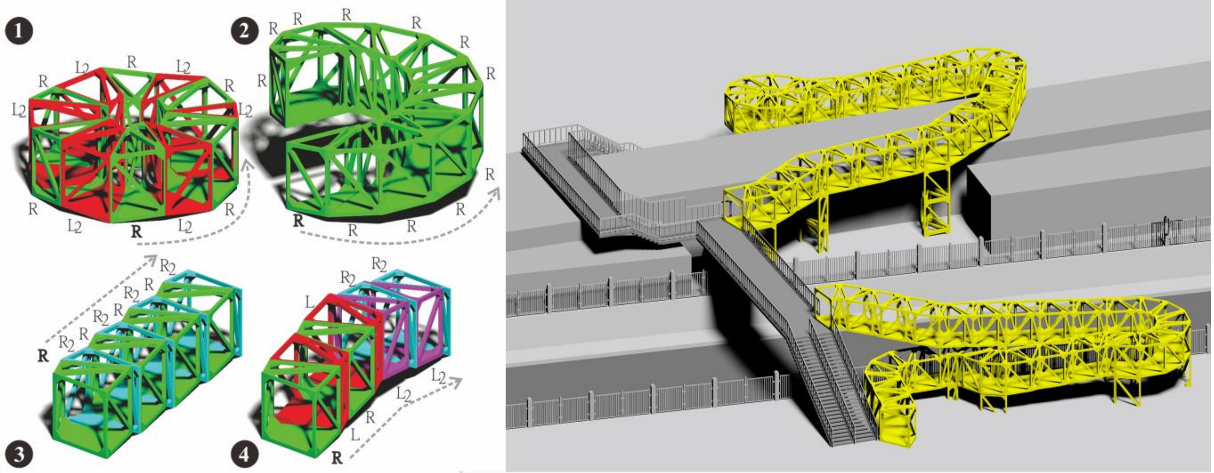

Fig. 5. On the left: 1) torus, 2) spiral, 3) flat bridge and 4) "gabled" bridge. On the right: a computer visualization of an existing foot-bridge retrofitted with a two-part *Truss-Z* pedestrian ramp in order to improve accessibility.

3.1 The foldable Truss-Z module

The main purpose of folding of the module is to reduce its volume. The envelope volume reduction is calculated as follows:

$$VR(TZ) = \frac{V_S}{V_D} = \frac{4.212m^3}{12.171m^3} \approx 0.35 \tag{3}$$

where V_S and V_D stand for volumes of the module in: the stowed and deployed states, respectively.

The foldable *Truss-Z* modules take advantage of the glide reflection which is executed in two phases: unfolding of the side frames and deployment of the bottom and top plates as shown in Fig. 6.

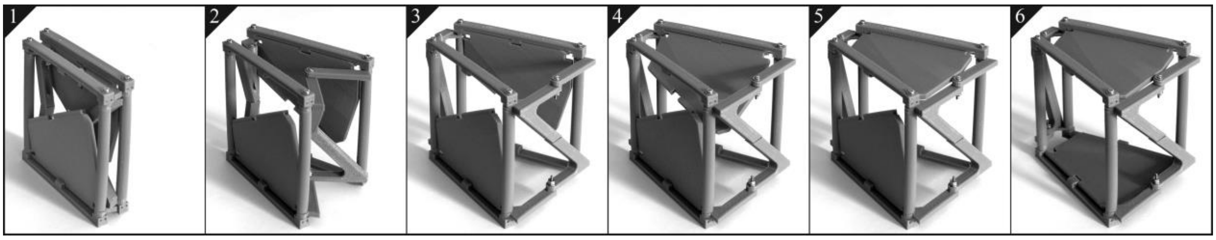

Fig. 6. Selected steps of deployment of the foldable *Truss-Z* module from stowed to deployed state.

3.2 Folding of a chain of Truss-Z modules

It is also possible to simultaneously deploy or stow a pre-assembled chain of modules, as shown in Fig. 7.

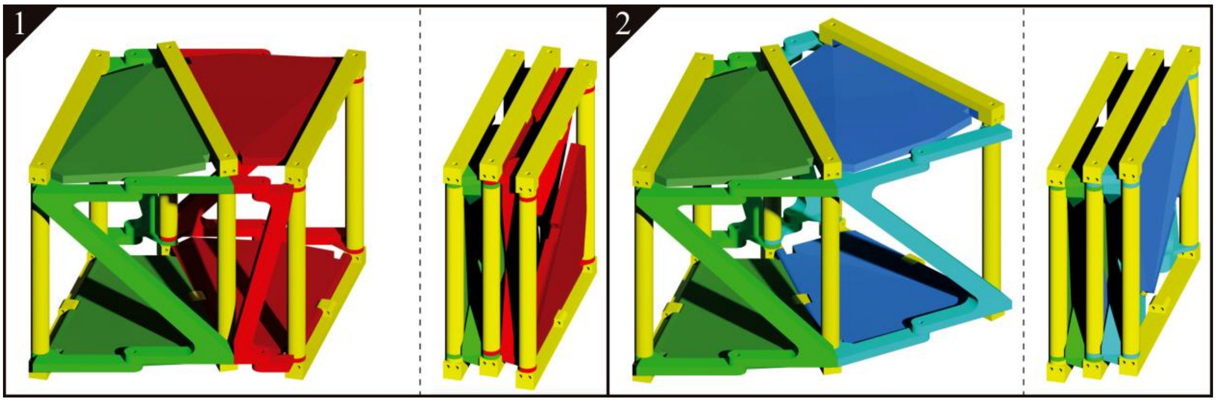

Fig. 7. 1) Deployed and stowed states of two modules: R (green) and L (red). 2) Deployed and stowed states of two R modules: shown distinctly in green and blue for clarity.

In the examples shown above, each subsequent module shares the main frame with the previous one. Fig. 8 schematically illustrates the deployment process of a multi-branched deployable *Truss-Z*. For more information see [20].

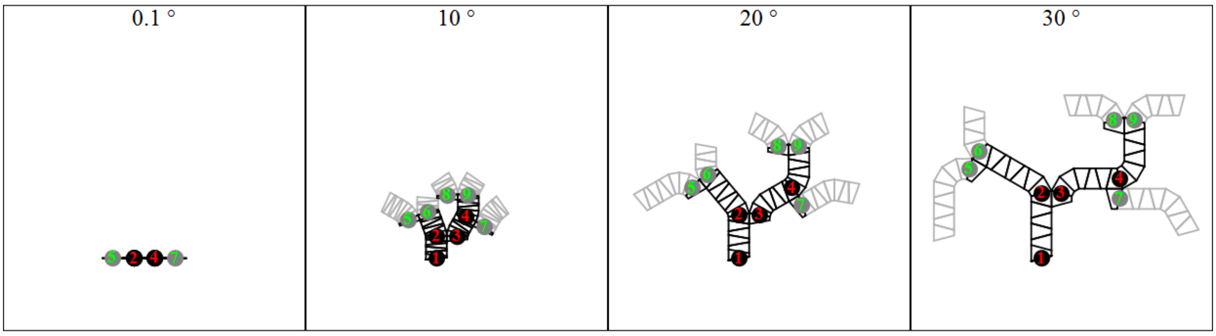

Fig. 8. From the left: folded state; two intermediate steps; and fully deployed *Truss-Z* network. The main branches are numbered from 1 to 4, and the sub-branches are numbered from 5 to 9.

Conclusions

This paper presents the folding mechanisms for two Extremely Modular Systems: *Pipe-Z* and *Truss-Z*. These systems are not only foldable for transportation and stowage, but their deployed states present unprecedented geometrical freedom. Folding of these systems is relatively straightforward. However, folding of other Extremely Modular Systems, in particular *Vault-Z* and multibranch *Pipe-Z* is substantially more challenging and is presently being under consideration.

References

[1] Zawidzki M. Discrete optimization in architecture: Extremely modular systems. Springer Singapore; 2017. https://doi.org/10.1007/978-981-10-1109-2

[2] Zawidzki M., Nishinari K., Modular Pipe-Z system for three-dimensional knots, Journal for Geometry and Graphics, 17(1), pp. 81–87, 2013. https://www.heldermann.de/JGG/JGG17/JGG171/jgg17007.htm

[3] Zawidzki M. Deployable pipe-Z. Acta Astronautica. 2016 vol. 1(127), pp:20-30. https://doi.org/10.1016/j.actaastro.2016.05.023

[4] Zawidzki M, Nishinari K. Modular Truss-Z system for self-supporting skeletal free-form pedestrian networks. Advances in Engineering Software. 2012 May 1;47(1):147-59. https://doi.org/10.1016/j.advengsoft.2011.12.012

[5] Zawidzki M., Nishinari K., Application of evolutionary algorithms for optimum layout of Truss-Z linkage in an environment with obstacles, Advances in Engineering Software, 65, pp. 43–59, 2013. https://doi.org/10.1016/j.advengsoft.2013.04.022

[6] Zawidzki M., Retrofitting of pedestrian overpass by Truss-Z modular systems using graph-theory approach, Advances in Engineering Software, 81, pp. 41–49, 2015. https://doi.org/10.1016/j.advengsoft.2014.11.004

[7] Zawidzki M., Optimization of Multi-branch Truss-Z based on Evolution Strategy, Advances in Engineering Software, 100, pp. 113–125, 2016. https://doi.org/10.1016/j.advengsoft.2016.07.015

[8] Zawidzki M., Jankowski Ł., Multiobjective optimization of modular structures: weight versus geometric versatility in a Truss-Z system, Computer-Aided Civil and Infrastructure Engineering 34(11), pp. 1026-1040, 2019. https://doi.org/10.1111/mice.12478

[9] Zawidzki M., Szklarski J., Effective multi-objective discrete optimization of Truss-Z layouts using a GPU, Applied Soft Computing, 70, pp. 501–512, 2018. https://doi.org/10.1016/j.asoc.2018.05.042

[10] Zawidzki, M., Modular system for creating slipways with any projection and permanent inclination angle and a method of assembling thereof, Polish Patent Office Pat.236119, 2020. https://worldwide.espacenet.com/patent/search?q=ap%3DPL426131%2A.

[11] Zawidzki, M., Modular system for creating rigid pipe structure of any shape, Polish Patent Office Pat.245063, 2024. https://worldwide.espacenet.com/patent/search?q=ap%3DPL428406%2A

[12] Zawidzki. M. Construction module for free-form convex structures, Polish Patent Office (P.448577, pending) 2024.

[13] Zawidzki M, Szklarski J. Transformations of Arm-Z modular manipulator with particle swarm optimization. Advances in Engineering Software. 2018 Dec 1;126:147-60. https://doi.org/10.1016/j.advengsoft.2018.05.003

[14] Sergio Pellegrino. Deployable structures in engineering. In S Pellegrino, editor, Deployable structures, pages pp.1–35. Springer, 2001. doi: https://doi.org/10.1007/978-3-7091-2584-7_1.

[15] L Alegria Mira, Niels De Temmerman, and Clemens Preisinger. Structural optimisation of deployable scissor structures using new computational methods. WIT Transactions on The Built Environment, 124: pp.469–80, 2012. doi: 10.2495/HPSM120421.

[16] M. Taraba, K. Zwintz, C. Bombardelli, J. Lasue, P. Rogler, V. Ruelle, J. Schlutz, M. Schüßler, S. O'Sullivan, B. Sinzig, M. Treffer, A. Valavanoglou, M. Van Quickelberghe, M. Walpole, L. Wessels, Project —a study for a manned Mars mission in 2031, Acta Astronautica, Volume 58, Issue 2, January 2006, Pages 88-104, ISSN 0094-5765, http://dx.doi.org/10.1016/j.actaastro.2005.04.013.

[17] Howe, A. Scott; Pólit-Casillas, Raúl (2014 July). Random Access Frames (RAF): Alternative to Rack and Standoff for Deep Space Habitat Outfitting (ICES-2014-038). 44th International Conference on Environmental Systems (ICES), Tucson, Arizona, USA, 13-17 July 2014. http://hdl.handle.net/2014/45586

[18] A.S. How, B. Wilcox, C. Mcquin, D. Mittman, J. Townsend, R. Polit-Casillas, T. Litwin, “Modular Additive Construction Using Native Materials”, Proceedings of the Fourteenth Biennial ASCE Aerospace Division International Conference on Engineering, Science, Construction, and Operations in Challenging Environments (Earth & Space 2014). St Louis, Missouri. Reston, Virginia, USA: American Society of Civil Engineers, 27-29 Oct 2014. https://doi.org/10.1061/9780784479179.034

[19] Fuhs W, Stachel H. Circular pipe-connections. Computers & Graphics. 1988 Jan 1;12(1):53-7. https://doi.org/10.1016/0097-8493(88)90007-6

[20] Zawidzki M., Nagakura T., Foldable Truss-Z module, Proceedings for ICGG 2014: 16th International Conference on Geometry and Graphics, Innsbruck, Austria, 4-8/8/2014.