Modern lightweight deployable engineering structures

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Abstract. The paper concerns the formulations and areas of possible scientific research in the field of modern deployable structures. The key problem is to provide a precise definition of modern deployable structures and to define the inherent properties that such structures should have. The objective was accomplished by specifying how the words deployable and lightweight are understood and assigning the constructions the necessary smart features. The defined features are fulfilled by tensegrity structures whose characteristics, from the point of view of deployability, are given in the paper.

1. Introduction
The work is the result of the authors' considerations in the area of scientific research in the field of modern deployable structures. The key aspect seems to be giving a precise definition and specifying the research area - studies of the literature indicate a very wide spectrum of structures that can be considered. Even greater variety of studies concerns techniques and algorithms used in deployable structures, the computational methods used and potential implementation areas. Detailed discussion of the extensive literature on the subject exceeds the scope of this work. However, we will mention two particularly valuable papers [1,2] in which interesting classifications of deployable structures and their systematics can be found.

The extensive literature on the subject relates to a large extent of theoretical issues. There are fewer experimental works or works describing realized projects, and if they are, they are usually cycles of papers, describing research, algorithms and their implementation in the long term (even several years). This means that deployable structures is a difficult scientific and technological challenge.

An important aspect of the research is the scientific discipline in which we would place deployable structures. Most often, deployable structures are related to: mechanical engineering, robotics, aerospace engineering and civil engineering. Robotics and aerospace engineering are beyond the scope of the paper. The authors' considerations also focus on lightweight structures in the field of modern solutions that are dated, due to the development of technologies and materials, to the 21st century.

2. About definitions
The issues that are considered in the paper are differently defined or not defined at all in the literature, referring to the colloquial understanding of words or the reader's intuition. It seems, however, that the precise definition of certain concepts is most appropriate and even necessary when we want to deal with them for scientific purposes.
The most commonly used term is "deployable structure". According to English dictionaries, the word "deployable" means "able to be moved to a place where it can be used when it is needed". In turn, "deployable structure is a structure that can change shape so as to significantly change its size". It seems that when defining the term "deployable structure" with precision, three important features should be emphasized:

a. The structure should be assembled/disassembled by itself, based on built-in mechanisms, with limited external factors (human or assembly team), if possible.
b. After reaching the target configuration, the structure should be ready for implementation for the predefined purpose.
c. The structure should significantly change its shape during erection.

In fact, in the above-mentioned definitions, there is no information about two-way operation, i.e. there is no requirement that the structure, after unfolding, may also be folded back to its original or other form. Deployable is understood to mean joining together. Considering the assembly and possible disassembly of the structure should be defined more precisely. The above considerations look a bit like splitting hair, but they can be important in formulating algorithms and procedures for the practical functioning of this type of structures.

Other terms used in the literature are (following the dictionary of the English language):

"Erectable", “capable of being erected or raised up”,
"Temporary" - "not lasting or needed for very long",
"Mobile" - "moving or walking around freely" or "able to be moved from one place to another",
"Demountable" - “able to be dismantled or removed from its setting and readily reassembled or repositioned”,
"Retractable" - “that can be pulled back or in”.

The terms "inflatable", "articulated" and "foldable" are used less frequently. According to the authors’ opinion, these terms are narrower than "deployable", although they are related to specific and important features of this class of structures. When defining the area of scientific work it is necessary to use some of the above-mentioned terms additionally to the term “deployable”.

Smart structures are the structures with the ability to sense and respond adaptively to changes in their environment. This feature distinguishes them from the conventional ones. Whereas the main purpose of the traditional structures is to provide strength and carry loads acting on them, the smart ones adapt in a pre-designed manner to a functional need, modifying their shape, stiffness or damping characteristics in order to minimize deflection and possible damage.

Further considerations are dedicated to structures that meet the a-c features mentioned above, and are also lightweight and smart.

### 3. Heavyweight versus lightweight structures

According to Meriam-Webster dictionary heavy is something having great weight and lightweight is something having less than average weight. When it comes to distinguishing these features between erectable engineering structures a problem of a limit appears. Another need for a limit definition comes with ultralightweight structures.

It is not obvious where to set these boarders because they should be defined for specific groups of structures, not for structures in general. Authors propose aforementioned limits in terms of different aspects of analyzing deployable structures (Tab. 1). Most of the entries do not require additional comment since they are explained plainly in the table. Line no. 4 should be interpreted so that heavy structures meet all the requirements set for standard (not deployable) realizations. Lightweight structures in comparison to heavy ones are designed for limited, safe conditions of use. Ultralightweight structures are designed to be used in extreme conditions but their behavior differs significantly from heavy structures (e.g. high deformations, low lifecycle, resonance at unsafe frequencies for civil engineering etc.).

The table does not include amount of the load acting on the structure since the difference between deployable applications is vast e.g. between a bridge and a supporting column. This parameter could be
compared indirectly by introducing a dimensionless parameter of load carrying capacity (LCC) that is a ratio of a load capacity and a weight of the structure.

| No. | Category                                      | Heavyweight            | Lightweight            | Ultralightweight      |
|-----|----------------------------------------------|------------------------|------------------------|-----------------------|
| 1.  | Density of the structure                     | >100 kg/m³             | 30-100 kg/m³           | <30 kg/m³             |
| 2.  | Equipment needed for deployment              | Deployable using       | Deployable using       | Deployable with hands |
|     |                                              | equipment with         | equipment with         |                       |
|     |                                              | >1kW power             | ≤1kW power             |                       |
| 3.  | Ability to be deployed with hands           | Not possible           | More than one person   | One person needed     |
|     |                                              |                         | needed                 |                       |
| 4.  | Sensitivity to external loads                | Insensible             | Not designed for       | Typical limits: e.g.  |
|     |                                              |                         | extreme conditions     | deformation do not apply |
|     |                                              |                         |                        | also in standard conditions |
| 5.  | Dimensionless load                           | LCC<0.04               | LCC=0.04÷0.2           | LCC>0.2               |
|     | carrying capacity (LCC)                      |                        |                        |                       |

Table 1. Classification of structures according to their weight

Various comparison tests are proposed in the literature. A good example is [3], where authors compared pantographic structures with membranes between struts that were to be used as temporary roof structures. They defined following parameters for comparison:

- the minimum dimensions of the boundary edges of the unfolded structure (when it lays flat on a ground),
- effective floor space range that the structure can assure once it is deployed and acceptable height is reached,
- the minimum folding angle understood as the smallest angle between two adjacent surfaces during the deployment – authors point out that it is important because it determines the minimum rotation angle which the joints(hinges) have to assure without limiting the adaptability,
- variety of triangles that is a characteristic feature of compared structures and influences the complexity of the structure – it affects the transportability and deployment procedures,
- the minimum number of hinges for a real structure assuming minimum two hinges per internal fold line,
- estimation of the weight.

The above information (first of all table 1) allow to define the lightweight structure sufficiently.

4. Selection of the concepts

The most important feature of a deployable structure is the deploying mechanism which characterizes the behavior of the system and its mechanical properties. Due to this concepts from the literature can be divided into groups that focus on separate mechanisms. These groups are: pantographic mechanisms (scissor-like mechanisms, Bennett mechanism, Myard linkage, coilable structures etc.), tensegrity mechanisms, mechanisms based on air-filled elements, origami based mechanisms, mechanisms based on shape memory materials. Since these structures are morphing from time to time, there are analyses in terms of utilized control algorithms that were also reviewed by the authors.

Promising type of structures which allow to build deployable structures are tensegrities [4]. Tensegrity structure can be defined as a pin-jointed system with a particular configuration of cables and struts that form a statically indeterminate structure in a stable equilibrium. Tensegrities consist of a discontinuous set of compressed elements inside a continuous net of tensioned members, which have no compressive stiffness. Infinitesimal kinematic mechanisms, that occur in tensegrity structures, are balanced with self-stress states [4]. Occurrence of a self-stress state in a structure indicates that there is a certain set of internal forces in structural members, which are independent from external loading and boundary conditions because they are in self-equilibrium.

To major advantages of tensegrity systems belong: large stiffness-to-mass ratio, deployability, reliability and controllability [5]. Moreover, tensegrities have some unique features that result from
infinitesimal mechanisms, which are stabilized by self-equilibrated normal forces. It is possible to control their static and dynamic properties by adjusting the pre-stressing forces [5]. It is also to identify and control of mechanical properties of tensegrity systems [6].

As it was presented in [7] there are some particular features of tensegrity structures following which one can classify them as smart structures. There are: self-control, self-diagnosis, self-repair and self-adjustment (active control) with the use of self-stress as well as geometrical properties of the structure.

From the point of view of deployable structures, it is proposed to classify tensegrity structures as:

- **0D** - this class includes all regular tensegrity modules; if the module is a "pure tensegrity" (according to the definitions [4,5,7]) it is deployable in a natural way with controllability by a single cable or strut.
- **1D** - structures made of many modules connected along one straight line or curve; we can distinguish here: tensegrity beams, columns and arches, flat or spatial; the class of 1D structures can be extended to structures that are not made of modules but have tensegrity features.
- **2D** - structures made of many modules connected on a plane or curved surface; we can distinguish between tensegrity plates and shells; non-modular structures are also allowed in this class.
- **3D** - structures made of many modules connected in three directions; non-modular structures are also allowed in this class.

5. Conclusions

The analysis of the literature on the subject and the authors' preliminary computational simulations [8] indicate the great potential that lies in the application of the tensegrity concept to the construction and operation of deployable structures. Applications in civil/mechanical engineering is a challenging task.

The structure referred to as "modern lightweight deployable engineering structure" should have the following inherent properties:

- Should be assembled by itself, based on built-in mechanisms, without external factors.
- After reaching the target configuration, the structure should be ready for implementation for the predefined purpose.
- Should significantly change its shape during erection.
- Should be lightweight or ultralightweight in the sense of table 1.
- Should be smart in the sense of ability to: self-control, self-diagnosis, self-repair and self-adjustment (active control).

References

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