Introduction The proposed project focuses on: **modeling** and **control** algorithms of Arm-Z, since:

►**Pipe** is simple and relatively easy to make structural element, particularly efficient in omni-directional bending. This is the case when a structural system is to be universal, i.e. when the bending direction is unknown beforehand.

►Pipe-like structures allow for **internal communication/transportation** as shown in Fig 1.

►**Modularity** is a rational way of economization of construction. It allows for mass-production of congruent elements which can be relatively sophisticated but inexpensive. It also enhances the system robustness, as the malfunctioning units can be replaced.

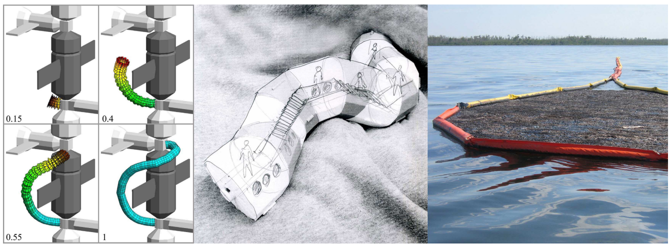


Fig.1. On the left: selected steps of continuous deployment of 40 Arm-Z modules to bypass *Zarya* module (shown in dark gray) of the *International Space Station*. Hue indicates the unfold angle for the individual units. Red and cyan indicate fully stowed and deployed positions, respectively. For each state the unfolding rate is shown in the bottom left corner. In the middle: conceptual visualization of Arm-Z habitat in extreme environment in "banana-split" orientation. On the right: An example of an oilspill boom system available at *Canadyne Technologies*.

►**Responsiveness**, **adaptation**, **reconfigurability**, **deployability** and **dynamic control** are major challenges in modern engineering addressing problems in always-changing environment. Moderns structures must not only be structurally sound, but should also intelligently respond to the changes of both environment and the users' requirements.

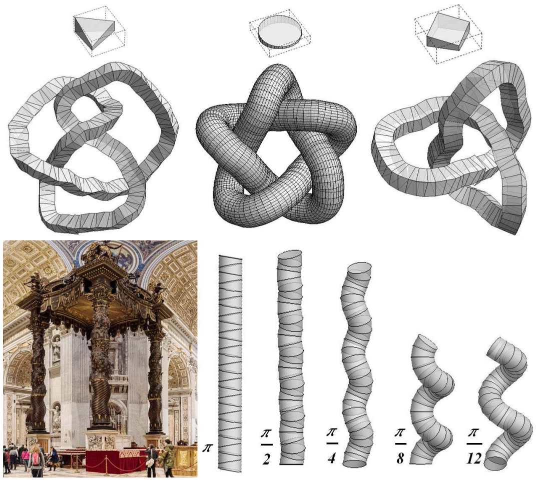
The basic concept Extremely Modular System (EMS for short) is the family of concepts where assembly of congruent units allows for creation of free-form structures. Arm-Z is a concept of a hyper-redundant robotic manipulator composed of congruent modules each having one degree of freedom and capable of complex movements. It has been recently proposed as a deployable construction system e.g.: for space habitats and emergency connectors (Fig.1). Arm-Z is comprised of one type of module and allows for creation of complex 3D, single-branch structures which can form mathematical knots (Fig. 2).

The <u>advantages</u> of EMSs are:

►**Economization** – due to potential of mass-production, and

►**Robustness** – the modules which failed can be easily replaced, also if some fail, it may still perform some desired tasks.

The <u>disadvantage</u> of EMSs is that their assembly & control is non-intuitive, and rather difficult. As a result, combination of nontrivial congruent units forming meaningful structures or their kinematic transformations are computationally expensive. Nevertheless, proposed approach is rational, due to availability of enormous computational power contrasted with the high costs and sensitivity of custom-made structural elements and devices.



Top: knots assembled with different basic units (shown for each case): Figure-eight (4_1),Cinquefoil (5_1), and Trefoil (3_1). Bottom: historical example of spiral columns: Baldachin in St. Peter's Basilica (A.D. 1634), and 5 examples of spiral columns of controllable parameters constructed with congruent units at various relative twists (shown for each case).

Research Objectives Definition of criteria for evaluation of effectiveness of the global Arm-Z hyper-redundant structures, methods of module optimization and optimal control, namely:

►Study of <u>**structural and functional design of the basic module**</u> of Arm-Z for various applications. Since global properties of entire structure are determined by single module, nontrivial questions to be addressed:

● what is the operational range of the global shape and how efficiently can it fill 3D space around it?

● what is the expected accuracy of control at discrete relative twists (as is the case, e.g., for step motors)?

● what are the physical, mechanical limits regarding stability and strength of the chained structure and how are they related to the local internal structure of the unit; what are the requirements for module joints to bear expected loads? Vibration and stress/deformation analysis needs to be performed;

● how to quantify these and, perhaps, other criteria for the most versatile design?

►<u>**Mathematical formulation and optimization of dynamical shape transitions**</u> of Arm-Z. Connected modules form a global shape which should dynamically transform from a current to a desired state. As the system is highly nonlinear, the problem of such transitions is difficult and not studied in the literature. Heuristic and other control methods will be applied for evaluation towards real-time control of global shape. Apart of avoiding self-collisions, it takes into account dynamical changes of environment. One of objectives will be evaluation of robustness and fault tolerance.

Expected impact ■ Structural mechanics: basic unit to be structurally optimized for performance of the entire structure. ■ Control Theory: due to high non-linearity classic approaches are ineffective for finding shape transitions. We propose application of AI/heuristics for finding solutions.

■ Novel implementations of heuristic optimization to be enhanced by massive parallelization with GPU.

■ Theory of Design. Introduction of modular kinematic elements for architectural design.