P2-06

Extremely Modular Hyperredundant *Arm-Z* for Emergency

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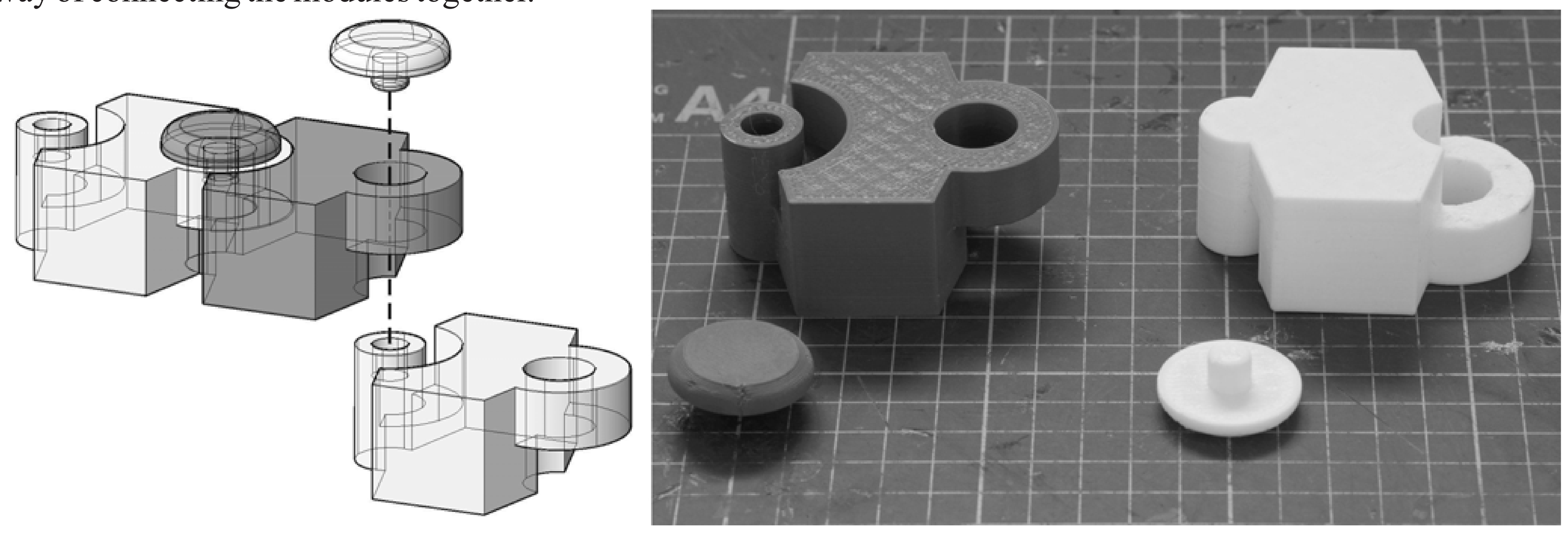
Introduction

Biological snakes are extremely well adapted for different environments. This is mostly the result of the high redundancy of the snake mechanisms. In many instances of irregular environments the bio-inspired robots outperform conventional wheeled, legged or tracked robots.Snake-resembling robots are researched already for a few decades. This type of locomotion has been studied already in the 1940s [1], and a half century later, its rigorous mathematical model has been developed. In late 90's, a trunk-like locomotors and manipulators have been introduced in [2]. Various snake-like robots have been built; most of the designs were intended for crawling on ground [3], some of them for swimming [4], and even fewer for both swimming and crawling on the ground [5]. The main disadvantage of such robots is the difficulty of control due to their high non-linearity.

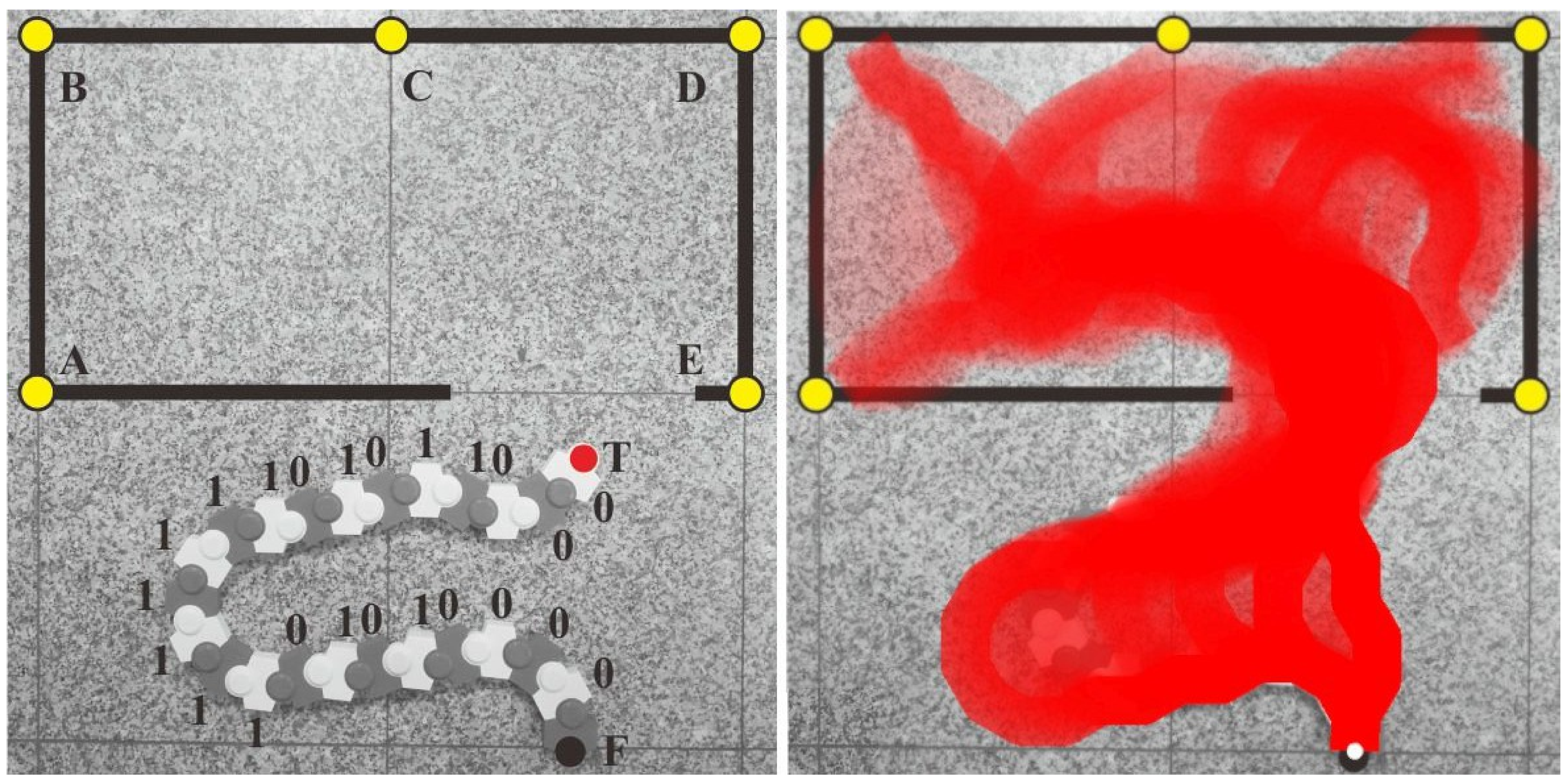
Discrete planar *Arm-Z*

A concept of an extremely modular planar manipulator composed of a single type of module was presented in [6]. In order to make it as simple conceptually as possible, the relative states have been discretized to only two possible positions: -π/6 (left, encoded as 0) and π/6 (right, encoded as 1), but it still is considered as a hyper-redundant-manipulator (HRM [7]). This manipulator is a chain of 24 congruent modules linked together by pivot joints. *Arm-Z* manipulators have as many degrees of freedom (DOFs) as the number of units less of one. Figure below illustrates the way of connecting the modules together.



Left: CAD drawing of two modules linked together and exploded view showing the connection. Right: top and bottom of the 3D-printed prototype).

The modules for the mock-up prototype have been 3D printed with PLA filament. The experimental environment was defined by geometry of given space and location of points to be inspected as well as the placement of the base of manipulator. At first, the manipulator must crawl inside the inspection space. Next, the tip of manipulator must visit five given points (A -- E). Finally, it must crawl out of the inspection space. Each configuration was encoded in binary list of 0s and 1s starting from the base and ending at the tip. The left sub-figure below shows the experimental setup with the mock-up manipulator in the initial configuration (before entering the test area A-E) with its binary representation.



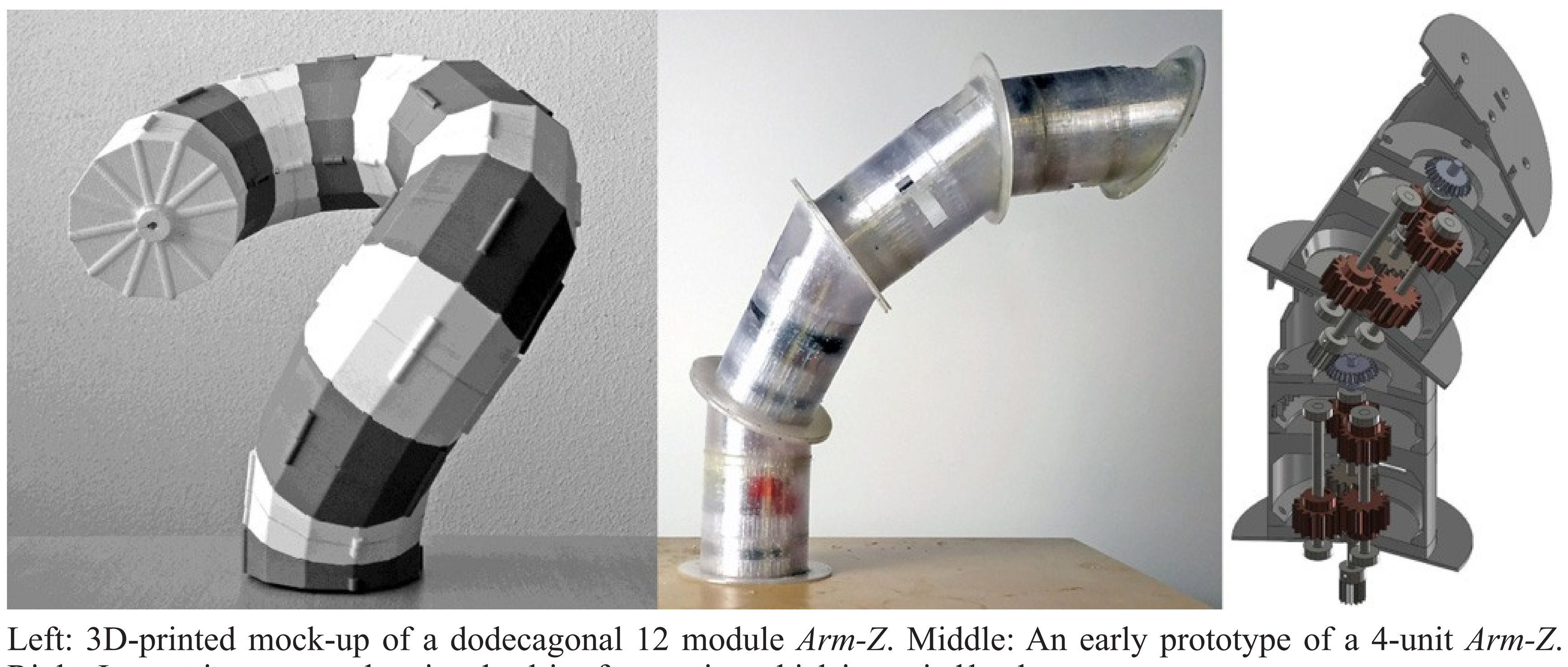
Left: Experiment with 5 inspection (yellow) points. The tip of the manipulator (T) is shown in red. Right: The envelope of all configurations during experiment including generated intermediate transitions is shown in red. Fixed unit (F) is indicated by the white dot.

The experiment was performed by setting manually the mock-up prototype with fixed base module in 7 main configurations (initial, A, B, C, D, E, final = initial). By using binary encoding of manipulator states, the transition from one configuration to another is straightforward. Simple subtraction of respective encodings identifies the differences. This method was applied to all key configurations and produced quasi-continuous operation of the manipulator. The rotation rate was the same for each module. The right sub-figure above shows the envelope.

Arm-Z (3D) manipulator

In principle, six degrees of freedom (DOFs) are enough to complete any motion in three-dimensional space. A conventional industrial manipulator has low number of DOFs - usually just six. On the other hand, human arm is the biological archetype of a kinematically redundant manipulator with 7 DOFs: 3 at the shoulder, 1 at the elbow and 3 at the wrist. Alike biological snakes or bionic trunks, in various environments the characteristic type of motion gives this type of manipulators certain advantage over conventional robotic manipulators.They can operate in geometrically complicated environments which are not accessible by other approaches. Depending on the required task, various working heads can be installed on such manipulators, e.g. for: welding, cleaning, monitoring, etc.

The redundancy in DOFs allows *Arm-Z* to perform complicated spatial movements, but also may improve the robustness and fault tolerance of the system.Figure below shows an early mock-up of a 12-unit *Arm-Z*, and the preliminary 4-unit *Arm-Z* prototype.



Left: 3D-printed mock-up of a dodecagonal 12 module *Arm-Z*. Middle: An early prototype of a 4-unit *Arm-Z*. Right: Isometric cutaway showing the drive for rotation which is carried by the gear system.

The actual (3D) *Arm-Z* manipulator is also comprised of linearly joined congruent modules. The first module in the sequence is fastened to a solid base. In the preliminary prototype, for simplicity, the drive was applied directly to the first module and transferred to subsequent units by internal gears. Each module was equipped with a set of cylindrical and bevel gears with straight teeth with involute profile.Inverse kinematic problem of typical industrial manipulator can be solved easily [8]. Thus, its control is straightforward. However, HRMs are highly non-linear systems, therefore their control is by no means straightforward, and requires application of artificial intelligence [9].

Acknowledgements

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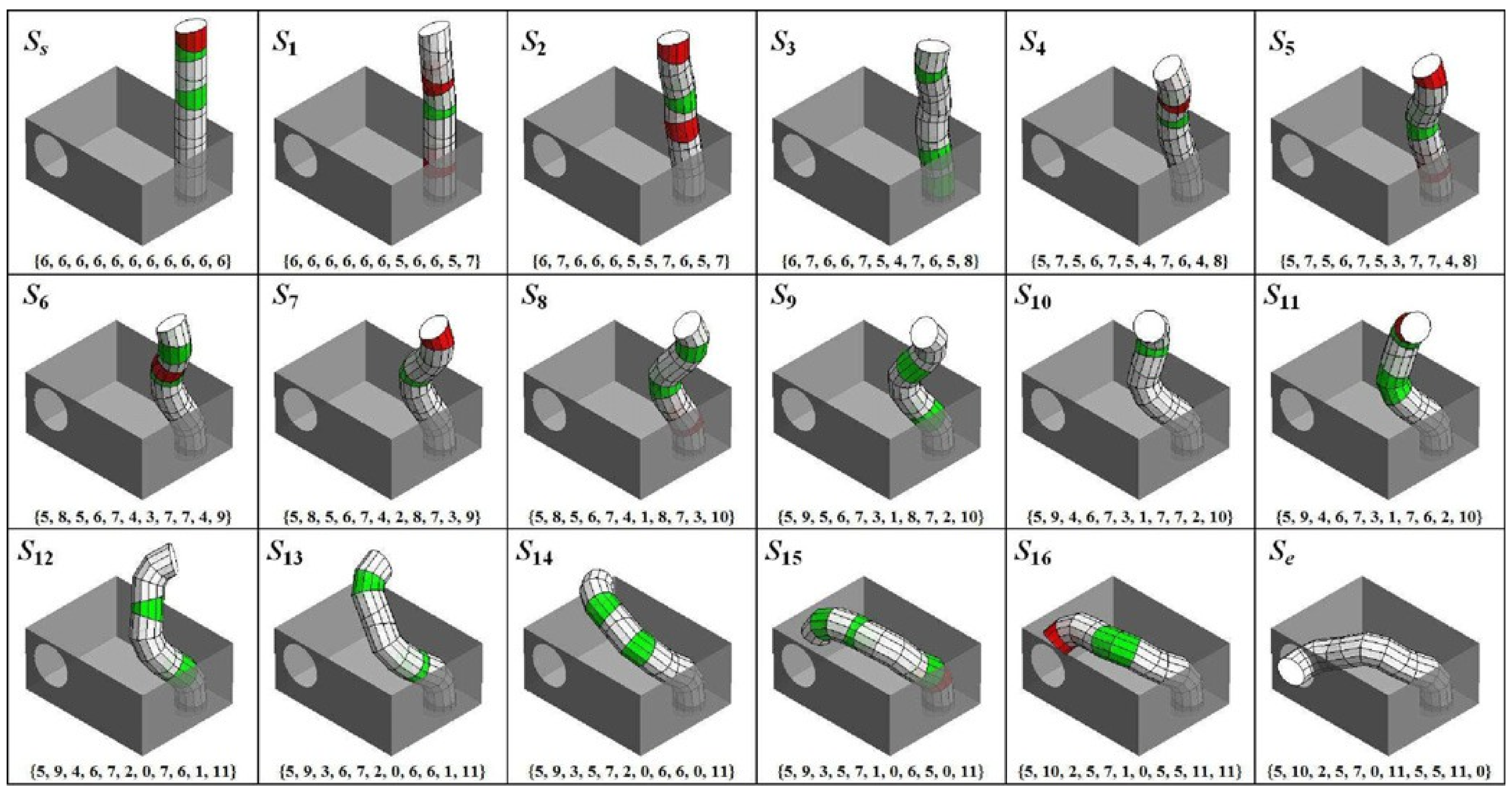
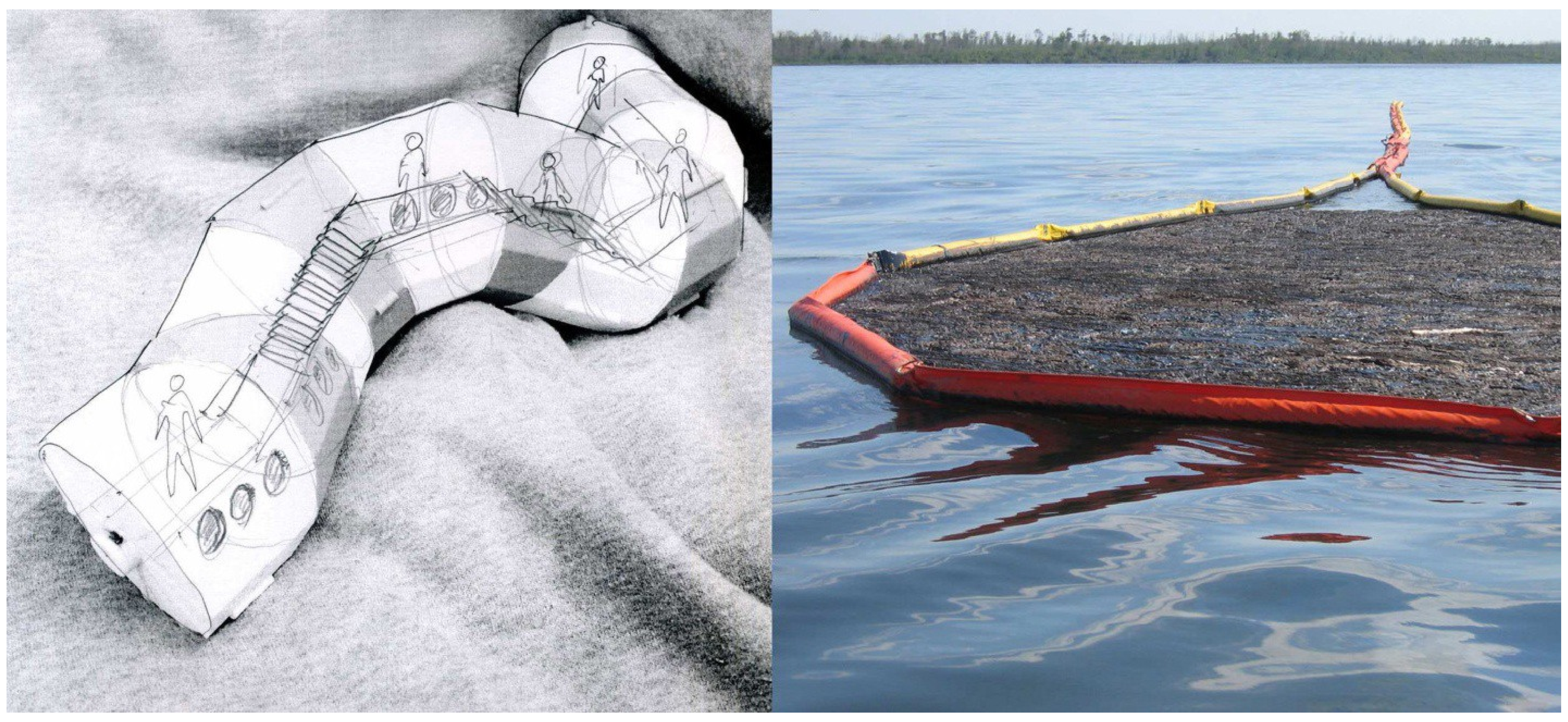
Control methods of *Arm-Z*

Particle Swarm Optimization (PSO) has been successfully implemented for certain *Arm-Z* tasks in [10]. This heuristic method is suitable for this highly non-linear optimization problem as it allows to search a large and irregular space of potential solutions. Experiment has been set as follows: there is a given environment (a box with a hole in its side); the initial state of a 12-module *Arm-Z* is given S_s; the goal is to transition *Arm-Z* so the tip of the manipulator enters without collisions and at minimal wobbling through the hole in the box. PSO found the good result (see Figure below) already in a few minutes and improved it during approximately 3.5 hours

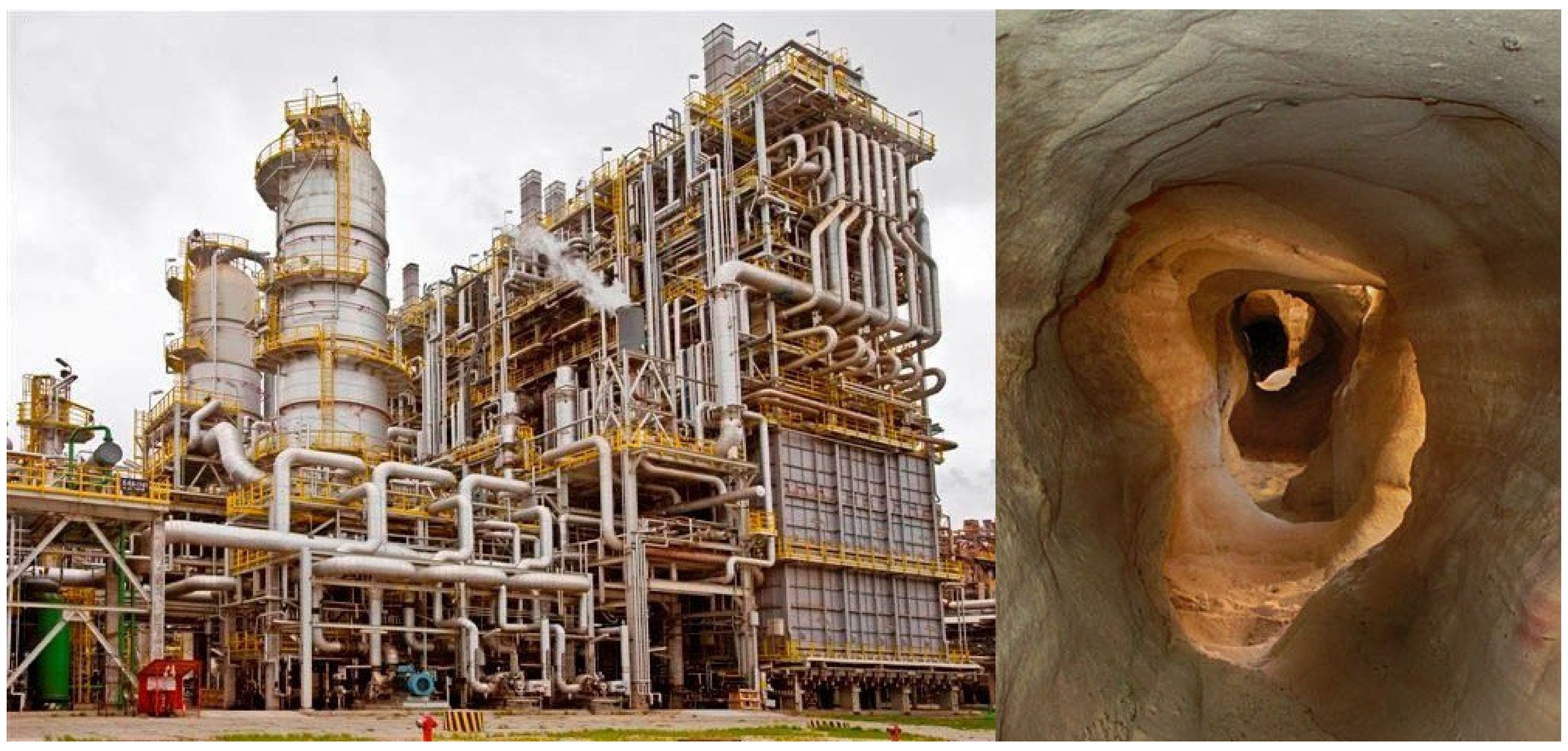




On the left - visualization of a habitat in extreme environment in „banana-split" orientation. On the right - an example of an oil spill boom system available at *Canadyne Technologies Inc.*

The concept of *Arm-Z* can serve in challenges of various scales:

1. Habitats and emergency structures for extreme environments both on: Earth, in outer space, under sea, etc. Analogous system has been recently proposed as a deployable construction system e.g.: for space habitats and emergency connectors [11].
2. Oil containment booms (see figure above). Such a system could be quickly deployed from an aircraft and could be globally controlled or self-organized based on the local neighborhood, i.e. water state (clean/contaminated) and/or state of adjacent modules.
3. Adaptive minimally-invasive industrial „endoscopes" for inspection of narrow channels, pipes and gaps for renovation and servicing. Such adaptive hyper-redundant mechanism could be used for maintenance of industrial facilities, where topology and geometry of objects and installations are known, e.g. in petrochemical pipe systems which have to be inspected from the inside (see figure below).
4. A tunnel boring machine (TBM) excavates tunnels with a circular cross section. It is an expensive, but much safer alternative to drilling and blasting (D&B) methods. The proposed system could be used for securing such circular or irregular tunnels; in particular for microtunneling (e.g. for emergency oxygen supply in a rock burst, seismic collapse etc.) with ability of „meandering" around particularly hard objects/layers or obstacles (see figure below).
5. Robotic hyper-redundant manipulator e.g. for cable or flexible pipe installations, especially in hazardous 3D environment with obstacles.



On the left - a complex pipe installation at petrochemical plant requires periodical inspection from the inside. On the right - an irregular tunnel which could be secured by *Arm-Z*.

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