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Simulation of simple movements of Arm-Z oblique swivel joint chain manipulator

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Abstract: Arm-Z is a concept of a hyper-redundant manipulator based on linearly joined sequence of congruent modules by oblique swivel joint mechanism. Each module has one degree of freedom only, namely a twist relative to the previous module in the sequence. Although the concept of this type of manipulator is relatively old and simple, its control is very difficult an nonintuitive, which results in a limited use in industrial practice. This paper presents a simple simulation of Arm-Z in Mathematica programming environment which demonstrates a few simple but potentially useful movements.

Keywords: Extremely Modular System, Arm-Z, Hyper-redundant manipulator, Mathematica, oblique swivel joint

1. 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. The snake-resembling robots are researched already for a few decades. This type of locomotion has been studied since the 1940s [1], and a half century later, its rigorous mathematical model has been developed. Shigeo Hirose at Tokyo Institute of Technology introduced so-called ”active chord mechanism” (ACM), and the first successful snake locomotor ACM III was built in 1972–75. In the late 90’s, a trunk-like locomotors and manipulators have been introduced in [2]. Kinematic modeling and control of hyper-redundant robots inspired by the octopus arm based on a discrete multi-segment model in which each segment is a 6-DoF Gough--Stewart parallel platform has been proposed in [3]. Various snake-like robots have been built [4]; most of the designs were intended for crawling on ground [5–9], some of them for swimming [10, 11], and even fewer for both swimming and crawling on the ground [12, 13]. Figure 1 shows an amphibious snake robot designed to perform underwater inspections and search-and-rescue missions in hazardous environments.

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.

In principle, six degrees of freedom (DoFs) are enough to complete any motion in three-dimensional space: displacement along three Cartesian axes X, Y, Z; and three rotations: yaw, pitch and roll. 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. Many robots use this kinematic arrangement. Such robots are called human-arm-like manipulators, e.g.: PA-10 robot by Mitsubishi, Lightweight Robot DLR (Deutsches Zentrum für Luft- und Raumfahrt), etc. DEXTER by Scienzia Machinale is an example of an 8-DoF manipulator. Systems with larger number of joints are called redundant robots, while term hyper-redundant refers to redundant manipulators with a very large, possibly infinite, number of DoFs [14]. They can be further classified in two groups: vertebrate-

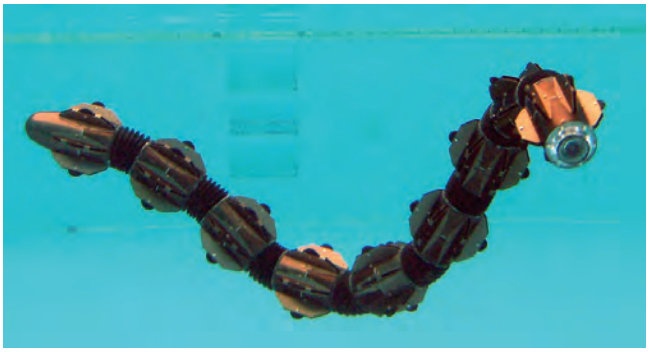

Fig. 1. A photograph of the modular amphibious (capable both of swimming and crawling) snake locomotor ACM-R5H, 2010. [Tokyo Institute of Technology]
Rys. 1. Zdjęcie modularnego ziemnowodnego robota wężowego ACM-R5H z 2010 r. wykonanego w Tokijskim Instytucie Technologicznym

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-like rigid link manipulators, e.g. such as snakes, and invertebrate-like continuum manipulators, such as octopus arms or elephant trunks. The inverse kinematics problem for a serial--chain manipulator is to determine the positions of joints given the position and orientation of the end-effector. So-called closed-form solutions are practical because they readily identify all possible solutions faster than numerical methods [15]. The inverse kinematic problem of a typical industrial manipulator can be solved easily [16].

As a result, 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 methods [17–19]. In has been postulated in [20] that immersive realities and natural language should

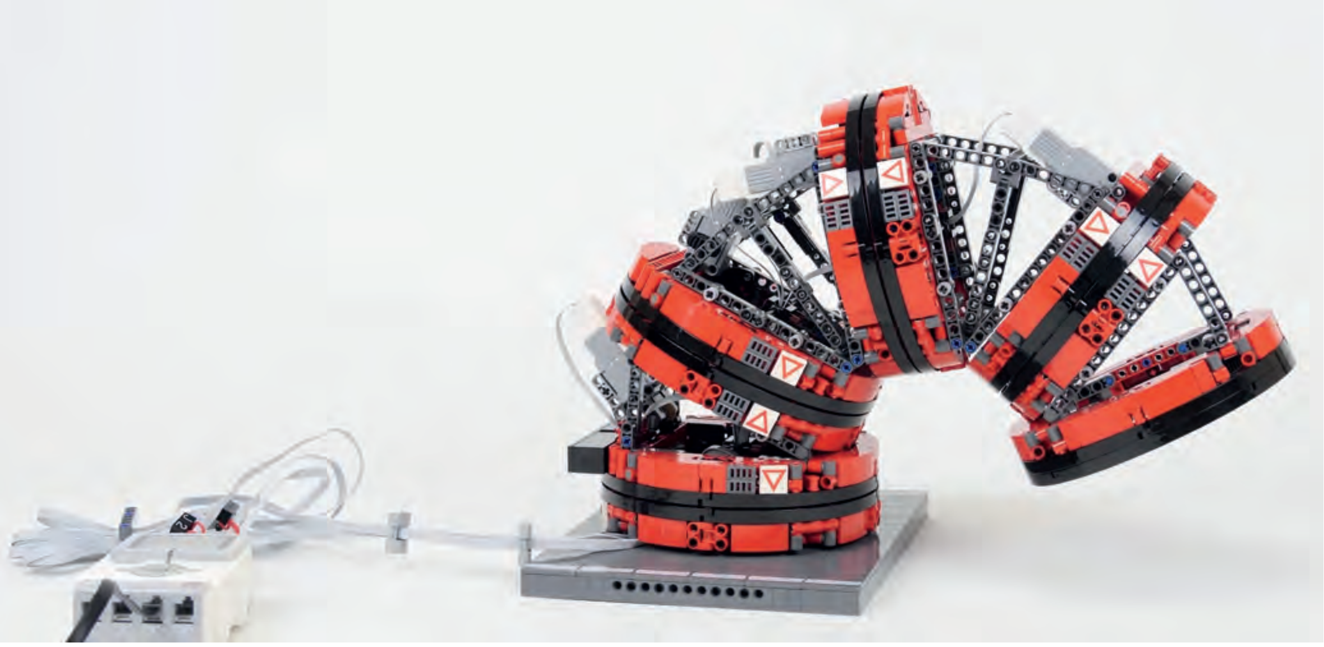

Fig. 2. A screenshot of a YouTube movie showing a 4-DOF oblique swivel joint robot made with LEGO in action. Four LEGO Mindstorms EV3 medium servo motors controlling the relative twist of each module can be seen. [Akiyuki Brick Channel: https://akiyuki.jp/]
Rys. 2. Zrzut ekranu z filmu w serwisie YouTube przedstawiający ruchy robota o skośnych przegubach obrotowych 4-DOF wykonanego z LEGO. Widać cztery średnie serwomotory LEGO Mindstorms EV3 sterujące względnym skrętem każdego modułu. [Akiyuki Brick Channel: https://akiyuki.jp/]

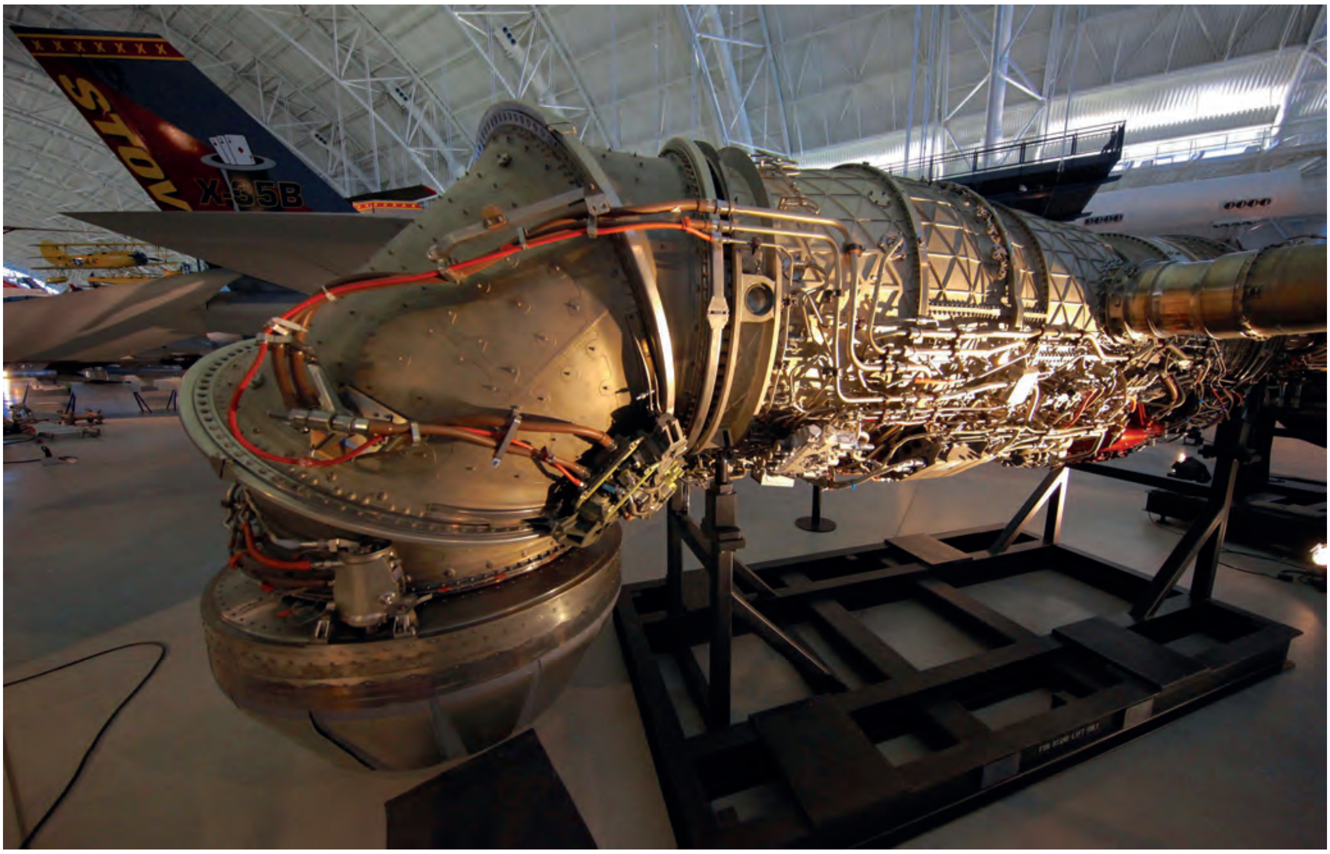

Fig. 3. A three-bearing swivel module (3BSM) of the Rolls-Royce LiftSystem. [Photograph by Steve Jurvetson]
Rys. 3. Trójłożyskowy moduł obrotowy (3BSM) układu LiftSystem firmy Rolls-Royce. [Zdjęcie autorstwa Steve'a Jurvetsona]

play a very important role in the near future of hyper-redundant robots and their tele-operation. A method of solving the closed-form solution to the inverse kinematics of a planar redundant manipulator has been proposed in [21]. It was based on employing the Frechet differential of a certain criterion function introduced to resolve the redundancy. However, that model did not include any constraints on the range of motion of the joints – which in fact makes the formulation much more complicated.

Moreover, already in the forward kinematics, the analytical description ”explodes” with the number of links (DoFs), not to mention the inverse kinematics which by nature is more difficult. Therefore the proposed approach is not practical for hyper-redundant manipulators. The pioneering work of mathematical modelling of a discrete redundant planary manipulator in the Cartesian space has been presented in 1989 [22]. In Ref. [23] the same author presented a model of the kinematics of a rotary, redundant manipulator, in the form of a Finite State Machine. An improved inverse kinematic and velocity solution for spatial hyper-redundant robots based on backbone curve concepts and a modal approach for resolving the manipulator’s redundancy in [24]. A technique to solve the inverse kinematics of redundant manipulators, using a multi-objective genetic algorithm based on combination of the closed-loop pseudo-inverse method with a multi-objective genetic algorithm to control the joint positions has been proposed in [25]. An implementation of a heuristic graph searching algorithm for finding collision-free trajectory for a (5-link) planar redundant manipulator has been presented in [26]. A method for studying the trajectory control of planar manipulators using the Moore-Penrose pseudoinverse based on fractional calculus and fractional matrix powers has been proposed in [27]. An optimization algorithm for the motion planning of a hyper-redundant robot where the motion of one end follows arbitrary path and all links of the locomotor avoid all obstacles present in the environment has been presented in [28]. For obstacle avoidance problem of planar hyper-redundant manipulators, so called ”tunneling” approach has been presented in [14]. In the next paper [29] the same authors presented hyper-redundant robot mechanisms and their applications, including a 30-DoFs hyper-redundant robot. In Ref. [30] the dynamics of hyper-redundant manipulators has been formulated as a continuum mechanics problem. The advantage of the presented method was that it can be easily parallelized. Regarding building physical prototypes, a comprehensive study of a cable-driven hyper-redundant robot in terms of mechanical design, kinematics analysis, and experimental verification has been documented in [31]. The property of shape memory polimer (SMP) has been explored for the design and fabrication of a 3D-printed modular omni-directional joint with variable stiffness in [32]. A lightweight hyper-redundant manipulator driven by embedded dielectric polymer actuators with binary actuation has been documented in [33]. For more information on this type of manipulators see [30].

This paper was inspired by oblique swivel joint mechanism robot made with LEGO system [34], as shown below.

Three-bearing swivel module based on the concept of oblique swivel joint mechanism has been used in the Rolls-Royce LiftSystem designed for use in the short take-off and vertical landing (STOVL) military aircraft, shown in Fig. 3. In 2001, the LiftSystem propulsion system was awarded the Collier Trophy, in recognition of ”the greatest achievement in aeronautics or astronautics in America”, specifically for ”improving the performance, efficiency and safety of air or space vehicles, the value of which has been thoroughly demonstrated by actual use during the preceding year. This means that properly designed, oblique swivel joint mechanism is extremely reliable and robust.

2. The concept of Arm-Z

A conventional industrial manipulator has low number of degrees of freedom, whereas a trunk-like or snake-line manipulator has redundant (considerably large) number of degrees of freedom. In Arm-Z manipulator, each link between modules has exactly one degree of freedom (1-DoF). A design for a two degrees of freedom joint mechanism optimized for compactness, strength and range of motion for three-dimensional hyper redundant robots has been presented in [35]. A mechanical design for a compact three degrees-of-freedom joint mechanism for hyper-redundant or snake-like robots has been presented in [36]. Arm-Z manipulator has as many degrees of freedom as the number of units less of one. This redundancy allows the Arm-Z to perform complicated spatial movements, but also may improve the robustness and fault tolerance of the system. Therefore Arm-Z belongs to the family of so-called hyper-redundant-manipulators (HRM [37]).

The Arm-Z modules are geometrical objects which are analogous to sectors of circular tori. Each module is defined by the following parameters: size r, offset d, and ζ, that is the angle between upper (**T**) and lower (**B**) faces of the module (see Fig. 4).

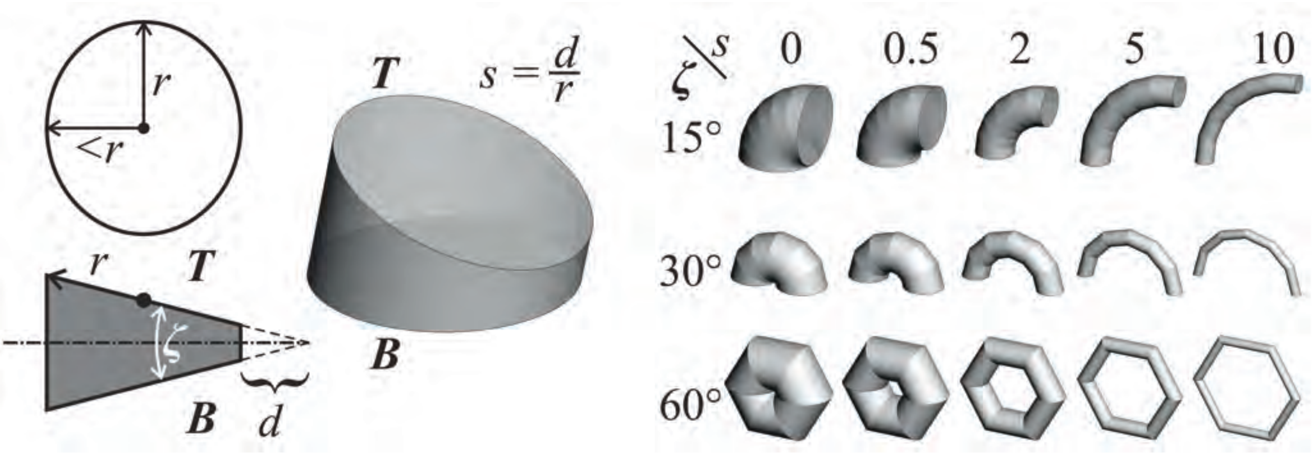

Fig. 4. On the left: visualization of the Arm-Z unit defined by three parameters: *r*, *d* and *ζ*. On the right: simple examples of assemblies of units for various values of *ζ* and *s* (slenderness), which is an additional parameter, a *d* to *r* ratio

Rys. 4. Po lewej: wizualizacja modułu Arm-Z określonego przez trzy parametry geometryczne: *r*, *d* i *ζ*. Po prawej: proste przykłady złożenia modułów dla różnych wartości *ζ* oraz *s* (smukłość), czyli dodatkowego parametru – stosunku *d* do *r*

The overall shape of Arm-Z depends on: the number of modules, the geometric parameters of each module, and the relative twists between the modules.

3. The virtual model of Arm-Z

The main limitation of the LEGO oblique swivel joint mechanism robot presented in [34] was the structural limit of the LEGO elements. As a result the physical limit of the system is only four modules (4-DoFs). Virtual model is obviously free from such constraints. A simple virtual model of Arm-Z has been made with the most intuitive programming environment – Mathematica. It has been adjusted to match the manipulator presented in Ref. [34], that is: there are four modules (4-DoF); the base and top are made of half-modules. In this way the manipulator can form a perfect pipe with base and top parallel to the working table and horizon, which is advantageous form the practical point of view. Moreover, the problem of intersections has not been implemented. However, due to the friendliness of the user interface, it can be easily visually inspected. The movements presented in Ref. [34] have been replicated and expanded. Table 5 shows 11 time-steps of the first experiment.

In this case the base module turns by half-turn from $-\pi/2$ to $\pi/2$. Simultaneously the rest of the modules turn twice as fast (performing a full turn) in alternating directions. The motion is perfectly smooth and there is no wobbling sideways.

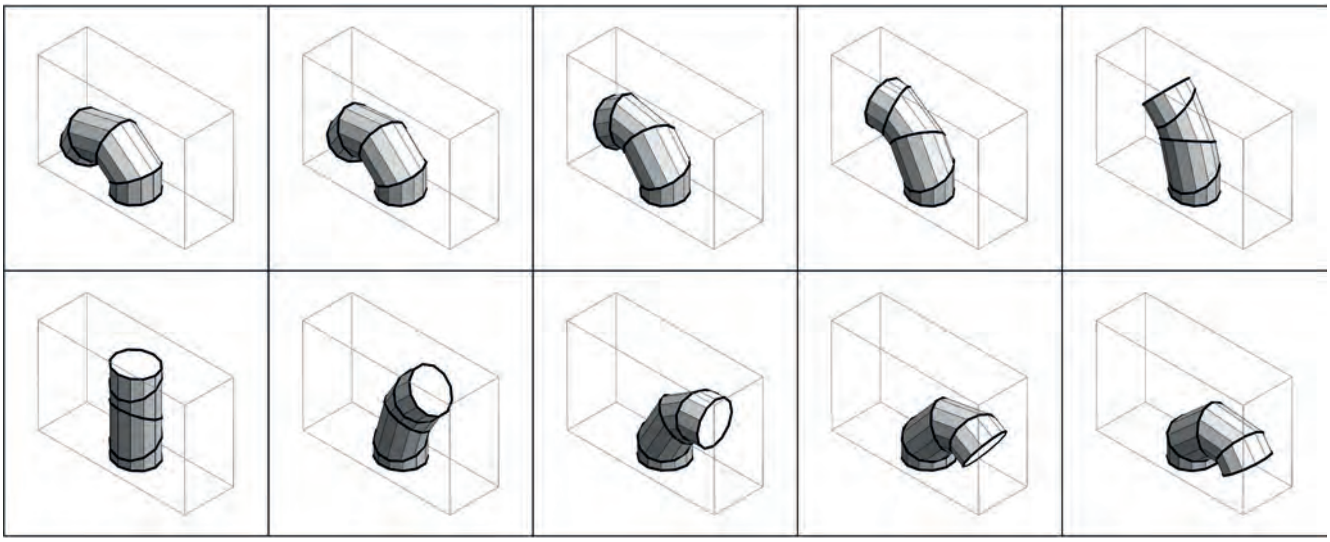

Fig. 5. From top left to bottom right: at first Arm-Z straightens from partial torus to straight pipe in 5 time-steps, and bends symmetrically on the other side
Rys. 5. Od góry po lewej do dołu po prawej: początkowo Arm-Z prostuje się z częściowego torusa do prostej rury w 5 krokach, następnie zgina się symetrycznie po drugiej stronie

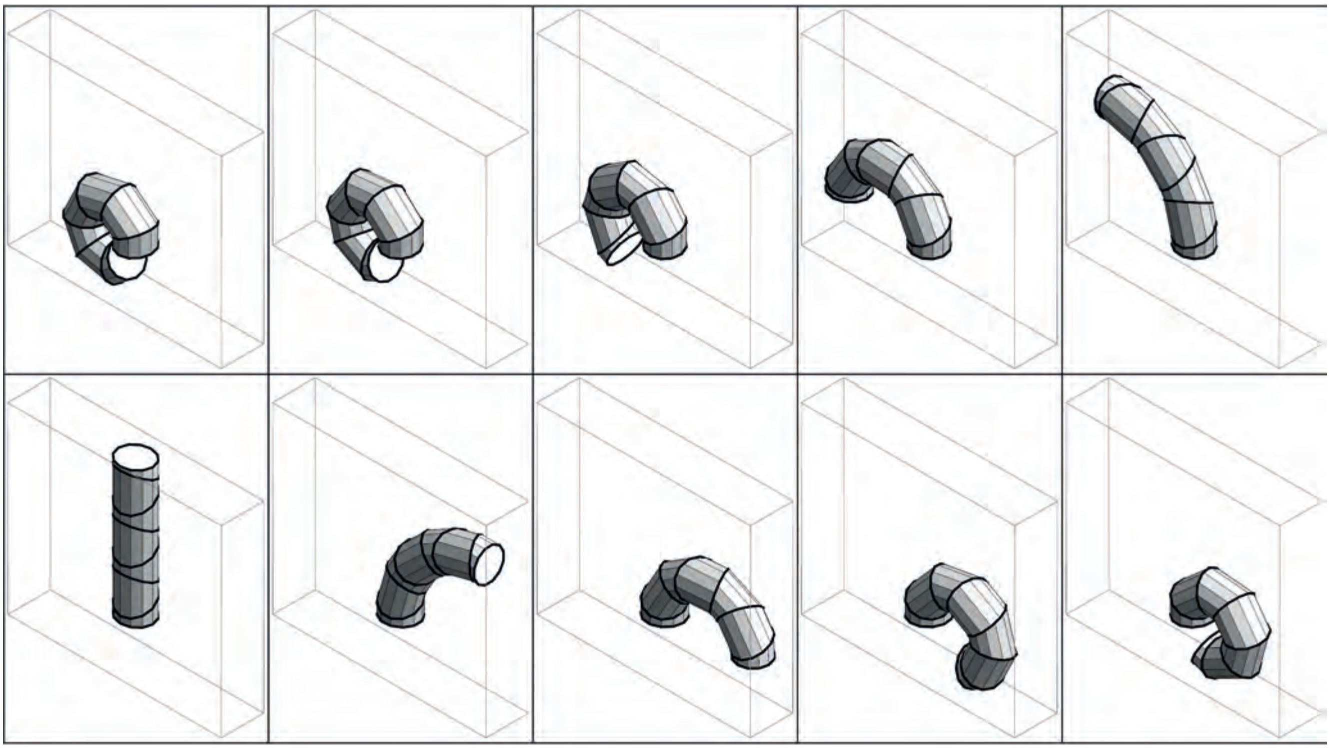

Fig. 6. The same setup as in Table 5 but with increased number of modules from 4 to 7
Rys. 6. Ta sama operacja jak na Rys. 5, ale ze zwiększoną liczbą modułów z 4 do 7

Fig. 7. From slightly unwound spiral to straight, and back to slightly unwound spiral on the opposite side. As the narrowness of the bounding box indicates – the wobbling is unnoticeable

Rys. 7. Od lekko rozwiniętej spirali do prostej rury i z powrotem do lekko rozwiniętej spirali po przeciwnej stronie. Jak wskazuje szerokość pola ograniczającego – chybotanie jest niezauważalne

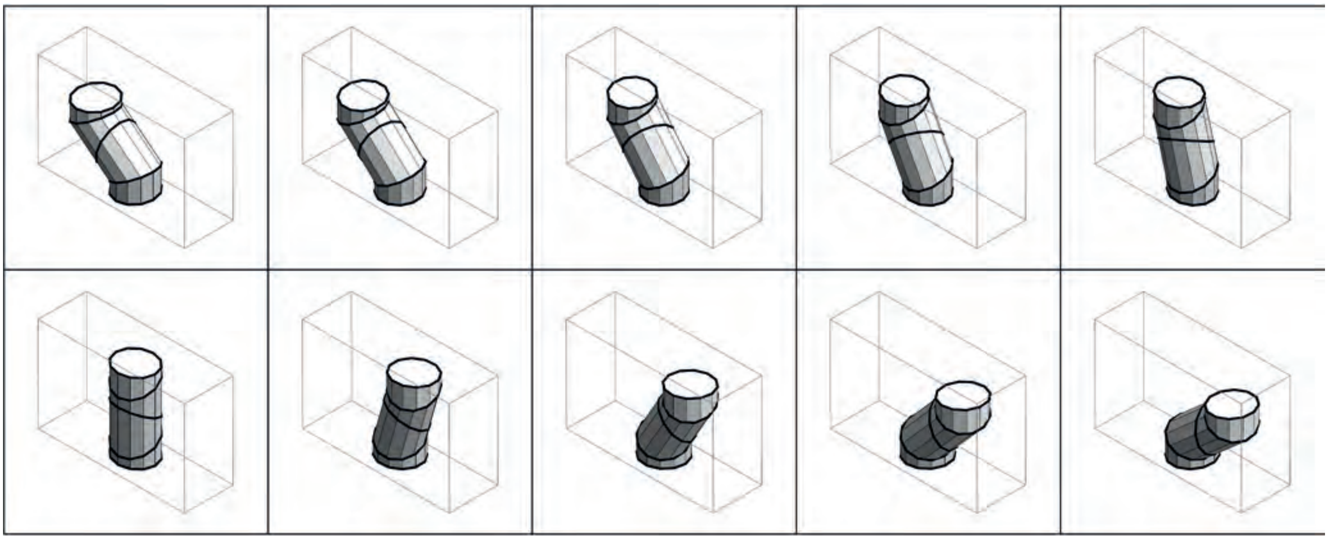

Fig. 8. From top left to bottom right: at first Arm-Z straightens holding the tip levelled in 5 time-steps, and bends symmetrically on the opposite side. The motion is perfectly smooth and there is no wobbling

Rys. 8. Od góry po lewej do dołu po prawej: początkowo Arm-Z prostuje się trzymając wypoziomowaną końcówkę w 5 krokach, następnie zgina się symetrycznie po przeciwnej stronie. Ruch jest idealnie płynny i nie ma chybotania

The same experiment can be easily done for a larger manipulator (with 7 modules, thus 7-DoFs), as shown in Table 6. The number of modules is small enough to naturally exclude self-intersections.

In the next experiment, the number of modules is 11. Thus the self-intersections are possible. In order to avoid them, the initial twists have been increased to slightly "unwind" the manipulator, as shown in Table 7.

In all previous experiments, there was practically no wobbling. This is, however, a major issue of discrete version of Arm-Z manipulator presented in [38]. Discrete means that the relative twists of the modules were not continuous, as in the case described in this paper, but discrete.

In the next experiment, manipulator also moves inside a narrow gap, but the tip of the manipulator remains parallel to the working table and horizon throughout the entire action, as illustrated Table 8.

The same experiment can be easy expanded to any number of modules, as shown in Fig. 9 below.

Figure 9 shows a variation of the same experiment with reduced range of motion.

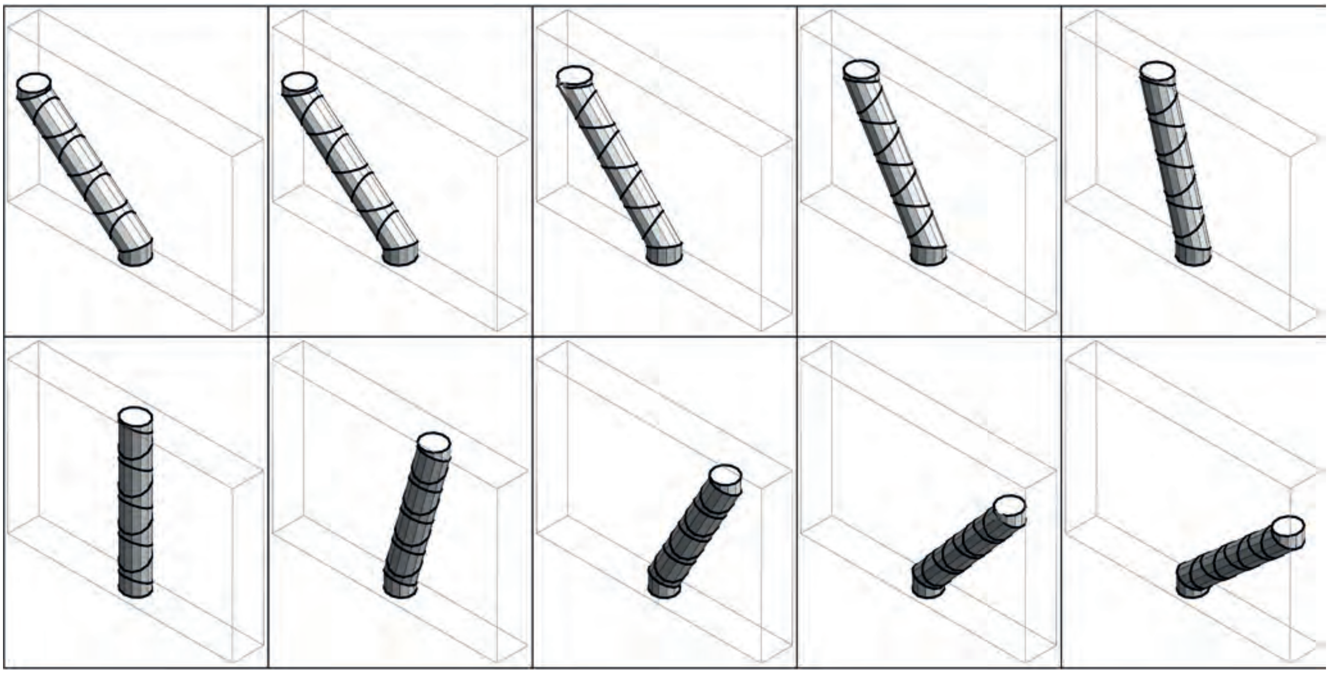

Fig. 9. The same experiment as before but with increased number of modules from 4 to 10
Rys. 9. Ten sam eksperyment co poprzednio (Rys. 8), ale ze zwiększoną liczbą modułów z 4 do 10

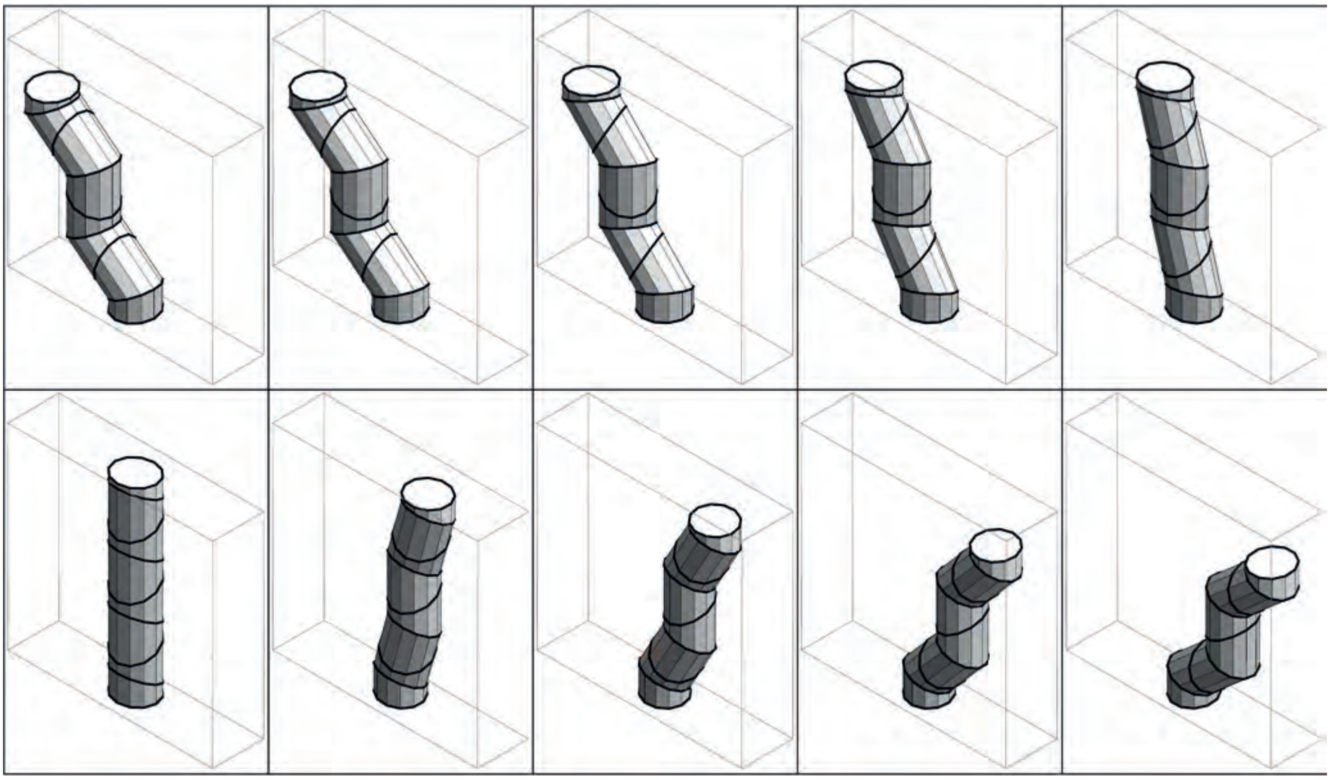

Fig. 10. Similar experiment with fewer modules and different bending pattern
Rys. 10. Podobny eksperyment (patrz Rys. 8 i 9) z mniejszą ilością modułów i innym wzorem gięcia

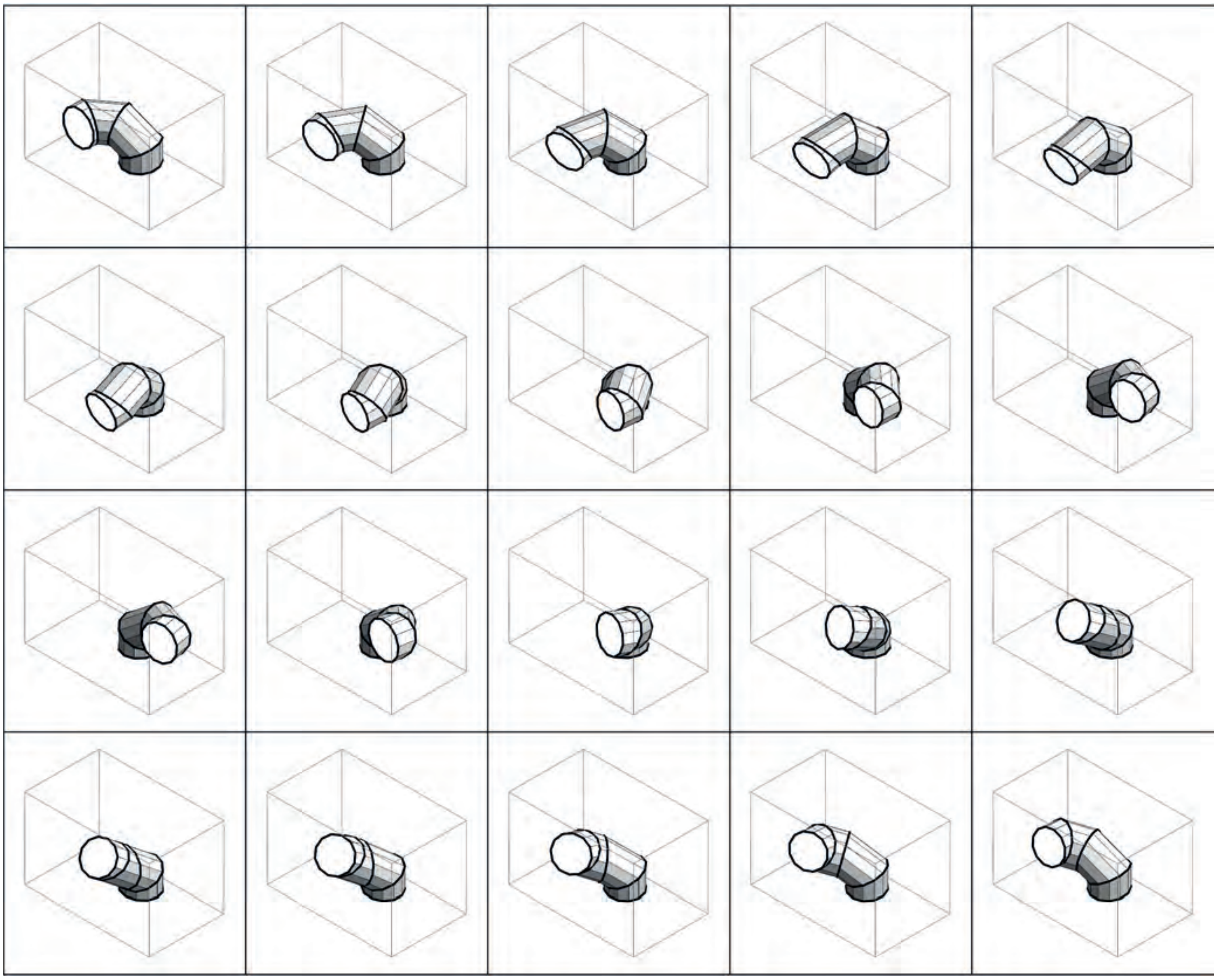

Fig. 11. From top left to bottom right: 20 time-steps of drawing an ellipse by the tip of the manipulator. The first and second parts of the motion draws the bottom and top of the ellipse, respectively

Rys. 11. Od góry po lewej do dołu po prawej: 20 kroków kreślenia elipsy w przestrzeni przez końcówkę manipulatora. Pierwsza i druga część ruchu kreśli odpowiednio dolną i górną część elipsy

Table 11 shows the last experiment, where the tip of the manipulator should draw an ellipse in vertical plane and remain parallel to that plane. The motion is not perfect, as the tip is not always facing exactly the vertical plane.

4. Conclusions

Oblique swivel joint mechanism is very attractive due to its simplicity.

However, the difficulty of its meaningful control makes is still practically useless for robotic manipulators.

This paper contribution is to bring this idea to broader audience and encourage for further experimentation by introduction of a simple but friendly user interface created in Mathematica environment.

In all experiments, the relative twists throughout entire motion is continuous and constant. The relations of values between angular velocities are very simple. This means that each experiment could be realized in reality by very simple systems described in Refs. [39, 40]. In such a case, the modules would not have to be quipped with individual motors and control units, but the motion could be transferred from one unit to another via simple gear system.

Thus we plan to build a low-tech, inexpensive street furniture with given purpose, such as sprinkler, sculpture, conveyor, etc. based on the presented types of motions.

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Symulacja prostych ruchów Arm-Z manipulatora łańcuchowego o skośnych przegubach obrotowych

Streszczenie: Arm-Z to koncepcja hiperredundantnego manipulatora opartego na liniowo połączonej sekwencji przystających modułów za pomocą skośnych przegubów obrotowych. Każdy moduł posiada tylko jeden stopień swobody, mianowicie skręt względem poprzedniego modułu. Mimo że koncepcja tego typu manipulatora jest stosunkowo stara i prosta, jego sterowanie jest bardzo trudne i nieintuicyjne, co powoduje ograniczone zastosowanie w praktyce przemysłowej. W niniejszej pracy przedstawiono prostą symulację Arm-Z w środowisku programistycznym Mathematica, która demonstruje kilka prostych, ale potencjalnie użytecznych ruchów.

Słowa kluczowe: System Ekstremalnie Modularny, Arm-Z Manipulator hiperredundantny, Mathematica, skośny przegub obrotowy

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