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Giorgio Scarpa's Model of a Sea Urchin Inspires New Instrumentation

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Abstract

Giorgio Scarpa (1938–2012) was an Italian designer, artist and teacher who worked in bionics, topology and rotational geometry. This article describes Scarpa's bionic model of "Aristotle's Lantern"—the mouth of the sea urchin. The technical literature on Echinoidea lacks a detailed study of its remarkable mouth mechanism. Scarpa's model is the only known analysis and physical analogue of the mechanism. It is a striking example of geometrical analysis and craftsmanship, bridging science and art. Built in the early 1970s and described in 1988 in *Modelli di Bionica*, his model has inspired designs for a biopsy harvester and for a mini-rover to collect soil samples on Mars.

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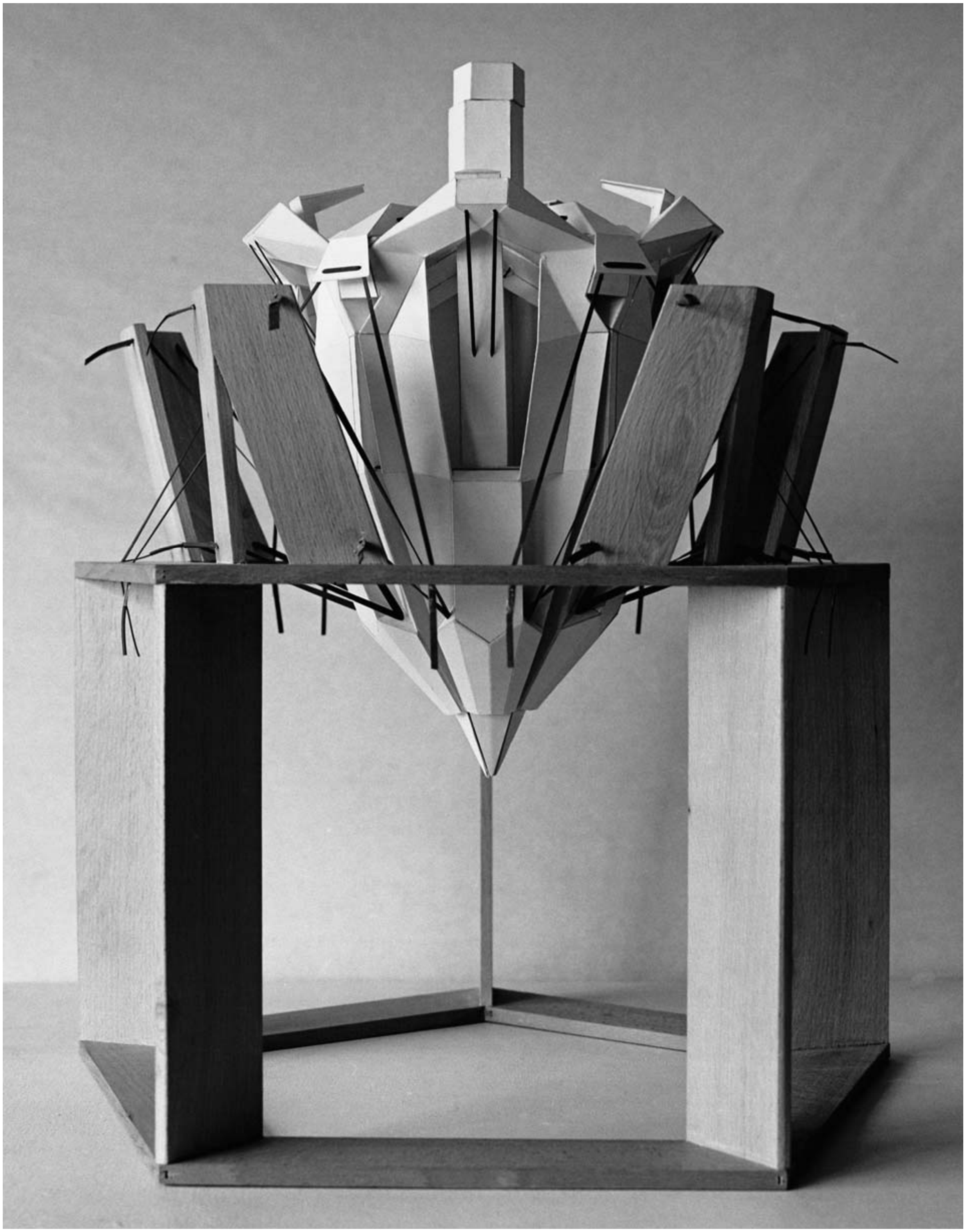

Frontispiece. Giorgio Scarpa, sea urchin lantern, full model.
(© Pino Trogu. Photo: Giorgio Cireddu.)

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Who Was Giorgio Scarpa?

Giorgio Scarpa taught Descriptive Geometry for forty years at high schools in Oristano and Faenza, Italy. He also taught Theory of Perception at the Institute of Design (ISIA) in Faenza. He worked first as a ceramist and painter, before focusing his work on topology and bionics. He published *Modelli di geometria rotatoria* [1] in 1978 and *Modelli di bionica* [2] in 1985. His pioneering work on Aristotle's Lantern and on rotational geometry allowed him to achieve extraordinary results with ordinary means [3]. Scarpa uses almost insignificant materials: paper, glue, elastics, to produce results that are aesthetically and functionally astounding.

Paul Klee, one of Scarpa's early inspirations, noted that: "The artist cannot do without his dialogue with nature, for he is a man, himself of nature, a piece of nature and within the space of nature." [4] Scarpa always pointed out the difficulty in observing nature. It grows from the inside outwards, while we can only observe it from the outside. This difficulty did not stop his curiosity and thirst for understanding. His aim was not use but understanding. Scarpa's answer to the question: "What does the model of the lantern do?" was always the same: "It does nothing." Yet the model's "action" did in fact illuminate the basic working of the mouth of the real sea creature.

One can peek at Scarpa's discovery process in this unpublished note titled "Bionics: exploration between play and research":

> To play (to explore) is something that costs nothing and brings the mind closer to its desires by asking about the goals and function of every choice, so that every project, before it even becomes an application in its diversified specificity, every project should mean freedom and spontaneity in making, a non-polarizing inversion, a contrast to what surrounds us, in a seamless process. [...] The image of destroyed sea urchins, their scattered fragments in the sand, and of the live sea urchins observed in their marine habitat, are the source of this study. [...] Not a single sea urchin was sacrificed in order to study it. [5]

Aristotle's Lantern

The masticatory apparatus of the sea urchin was first referred to as "Aristotle's lantern" in 1734, in Jacob Klein's *Naturalis Dispositio Echinodermatum* [6], after Aristotle's own description in his *Historia Animalium* [7]. Around 1970, Scarpa built a large, physical model of the lantern (Fig. 1D) of the common purple sea urchin.

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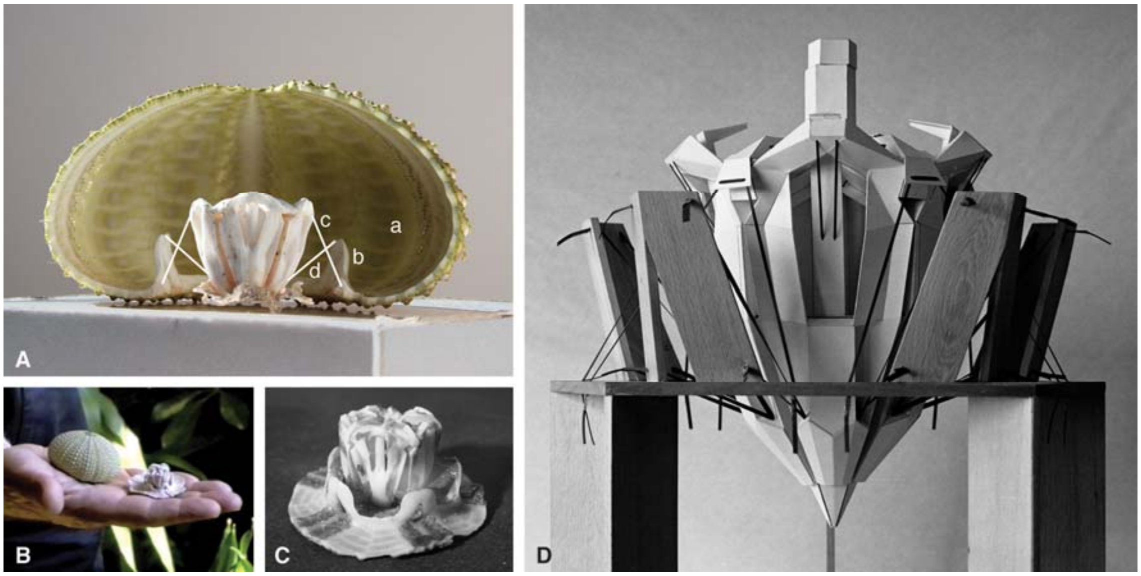

Fig. 1. A: Aristotle's lantern, shown inside the urchin's *test* or shell *a*; five *auricles b* form the support structure to which the lantern is attached. The white lines represent some of the muscles connecting the lantern to the shell: *protractor* muscles *c* and *retractor* muscles *d* contribute to the lantern's opening and closing. B: Scarpa's hand holding specimens of a shell and lantern, as seen in a 1994 video [9]. C: detail of lantern still attached to shell. D: front view of Scarpa's original model, circa 1970. (© Pino Trogu. Photos C and D: Giorgio Cireddu.)

Modelli di bionica details the process of discovery from schematic models to a fully functional prototype of the lantern [8] that is 30 cm in height, much larger than his 1–2 cm natural specimens [9]. Although many morphological studies of the lantern exist, [10,11], Scarpa's model was until recently the only known physical model [12–14]. It remains the only example that includes components analogous to each of the forty *ossicles* that form the lantern.

In 2014, I built a 3D-printed replica of the model based on Scarpa's original drawings, and made a presentation at the Third International Conference on Biomimetic and Biohybrid Systems [15–17]. In 2015 I presented the same replica at the Design of Medical Devices Conference Europe Edition (DMD EU 2015) in Vienna, Austria [18] (Fig. 3H).

The Real Lantern: Bones and Muscles; the Model: Paper and Elastics

The lantern of the sea urchin "consists of forty different ossicles" connected together by "bands or bundles of specialized ligaments" [10]; that is: forty bones connected by various muscles. Five jaws contain five teeth that grow continuously yet are firmly in place when grabbing, scraping,

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boring through rock, cutting, and collecting food. When closed, the tips of the teeth form a pattern similar to a lens diaphragm (Fig. 2C). Five *rotulae* act as hinges between jaws, with five other ossicles, the *compasses*, positioned above them. The five ridges or *auricles* that are part of the shell complete the set (Fig. 1A–*b*).

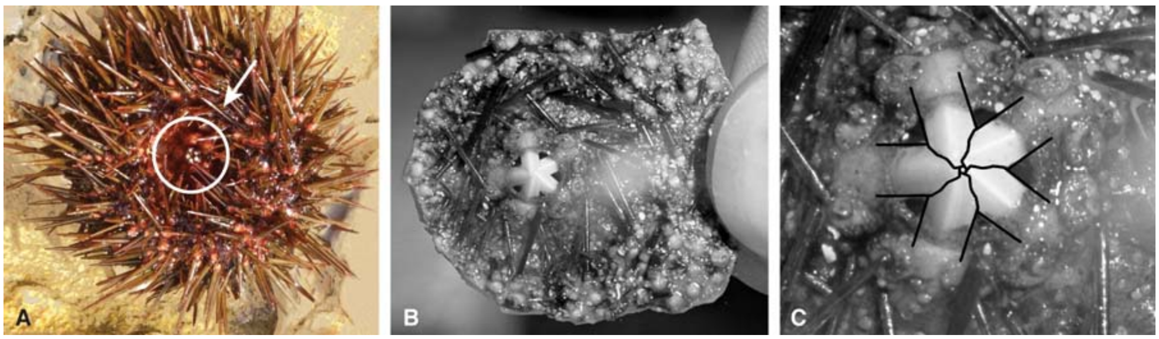

Fig. 2. A: upside-down sea urchin, the five teeth visible in the middle. B: close-up view of the underside membrane and teeth. C: sea urchin's teeth, in closed position, with diagram showing their partial overlap. (© Pino Trogu. Photos B and C: Giorgio Cireddu.)

Scarpa's model of the lantern is highly analogous to the animal's real organ. Every bone element is represented by a corresponding solid piece made of construction paper. It's also remarkable that his lack of formal zoological training did not stop him from devising a very elegant solution to the complex task of "modeling" the muscles and the overall coordinated movement of the jaws and teeth. Armed with little more than a magnifying glass and specimens found on the beach or donated by friends, he set out to engineer the basic motion of the lantern: jaws and teeth moving forward in unison when opening and moving backward when closing.

Forty-five years later, with that model of Scarpa's as inspiration, Filip Jelínek realized that its continuous motion would be the key to his design of a novel biopsy harvester [12]. His instrument is just a handful of millimeters in diameter. Due to exigencies of size, Jelínek's prototype compresses the forty original elements into a single compliant one.

Later, Michael Frank built on Scarpa and Jelínek's work to make a prototype of a Mars ground sampler. It includes the original five hinged teeth and a slider crank system that pushes the teeth open. His model, like Scarpa's, includes elastics that return the teeth to their closed, at rest position [13,19].

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Let's take a closer look at the inspiration for these later applications—Scarpa's original. Cutting elastic strips out of pure, very thin rubber sheets, Scarpa used that simple material as an analog for the muscles. His model features replacements for all the animal's muscles except for the *protractor* muscles that move the jaws forward. In his model, the jaws are instead pushed open by a prism-and-spokes system. Fig. 3F shows how a smaller spoke *d* pulls a thread *f* connected to the tooth *b*, causing it to slide outward. This real-time, forward movement of the teeth—a brilliant time-lapse image of the urchin's development—is unique to Scarpa's model. In the real urchin the movement occurs over a lifetime of continuous growth [20] and "self-sharpening" [21] during which the teeth always appear stationary. In the model, elastics become stand-ins for four elements: the *retractor* muscles (Fig. 1A–*d*) that connect the auricles (Fig. 1A–*b*) to the lantern, the *interpyramidal* muscles that connect the jaws together, the *compass elevator* muscles that connect the five *compasses*, and the *compass depressors* that connect the compasses to the shell [10,11,22].

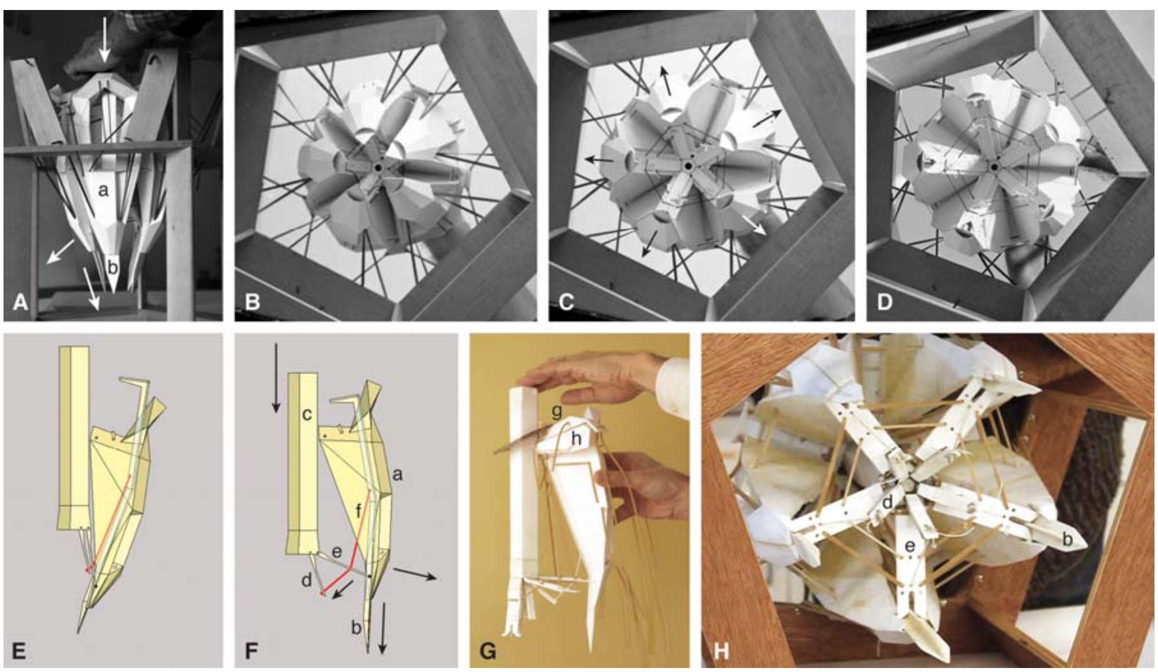

Fig. 3. A: in Scarpa's model, pushing down the central prism causes the jaws *a* to open and the teeth *b* to slide forward. B–D: underside view of the model in various stages of opening. E: diagram of system at rest. F: downward pressure of prism *c* causes hinged spoke *e* to push jaw *a* laterally, while smaller spoke *d* pulls string *f* through a hole in spoke *e*. The string is attached to tooth *b* which moves forward as a result. G: replica of prism and jaw system. The compass *g* and rotula *h* are visible above the jaw. H: lantern's replica in fully opened position. (© Pino Trogu. Photos A–D: Giorgio Cireddu.)

The Biopsy Harvester of Jelínek et al.

Let's look more closely at the recent applications. Forty-five years after Scarpa, Filip Jelínek et al., at the time all members of the BITE group [23] led by Professor Paul Breedveld from Delft University of Technology, built a "Bioinspired Spring-Loaded Biopsy Harvester" prototype [12] featuring a crown-shaped "thin extruded steel tube" 0.15 mm in wall thickness and 4.3 mm in diameter, capable of performing, *in vitro*, a very precise biopsy in less than a millisecond. Jelínek credits Scarpa's model for demonstrating how "the sea urchin can simultaneously cut off and enclose its food in a seemingly unified and continuous motion" [12,24] and showing that the lantern "is open when protruding outwards and closed when retracted inwards" [12]. In Jelínek's prototype, the crown cutting tip of the tube is "open" at rest, and collapses into a "closed" position when pushed by a spring (Fig. 4). The inward closing motion of the sea urchin is inverted in the biopsy prototype, which employs an "inner taper of [its] cap" that forces the crown cutter to automatically close when propelled forward by a "strong compression spring situated behind it" [24], yet the continuous motion of simultaneously cutting and enclosing the tissue is preserved.

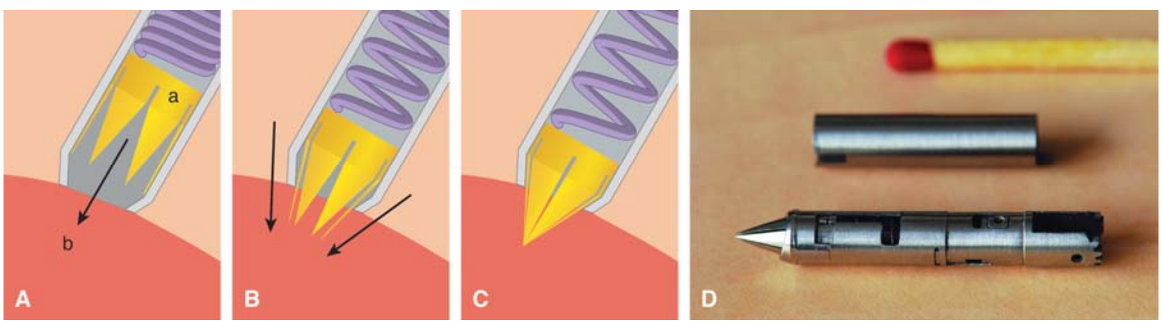

Fig. 4. A: Jelínek's crown cutter *a* at rest. The cutter surrounds a 2 mm diameter fiber-optic bundle (not shown) for *in situ* optical analysis of tissue *b* [23]. B–C: intermediate and final stage of crown closing. D: "final manufactured steerable opto-mechanical biopsy harvester prototype". (© Filip Jelínek. Illustrations A–C redrawn by Pino Trogu, after Jelínek [24]. Photo D: Filip Jelínek, courtesy of Delft University of Technology, The Netherlands, and the Austrian Center for Medical Innovation and Technology, Wiener Neustadt, Austria [25]. Illustrations and photo used by permission.)

Jelínek's prototype confirms the validity of Scarpa's earlier model as an example of "pure research" that leads to practicality, and that also shows the important role played by aesthetics and design during the discovery process. It illustrates the value of research that combines science,

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art, and empathy in a work of intellect and sensibility that is not motivated only by practical applications and immediate results.

The Ground Sampler of Frank et al.

Recently, Michael Frank in the group of Professor Joanna McKittrick at the University of California, San Diego, helped lead a team of undergraduate mechanical and aerospace engineers to build a "ground sampler based on the sea urchin jaws." Inspired by Scarpa's original model, Frank's team built a "fully functional remote controlled sand and rock sampler that utilizes a bioinspired [application of] Aristotle's lantern" [13]. The sampler might perform "arduous sample collecting tasks" on the surface of Mars, its small scale coming in aid of a less mobile rover. The mechanism of the model closely mimics the urchin's five-fold symmetry. It also mimics Scarpa's model by utilizing a "micro linear actuator" that opens and closes the teeth, a process shown in a video that beautifully shows, side-by-side, the motion of the real sea urchin's mouth [14] (Fig. 5). In Jelínek's prototype the urchin's mouth had been a small six-point crown due to manufacturing restrictions, while Frank's model employs a set of five large curved teeth.

Frank's paper and video published by the Journal of Visualized Research (JoVE) generously acknowledge Scarpa's contribution to bionics [13].

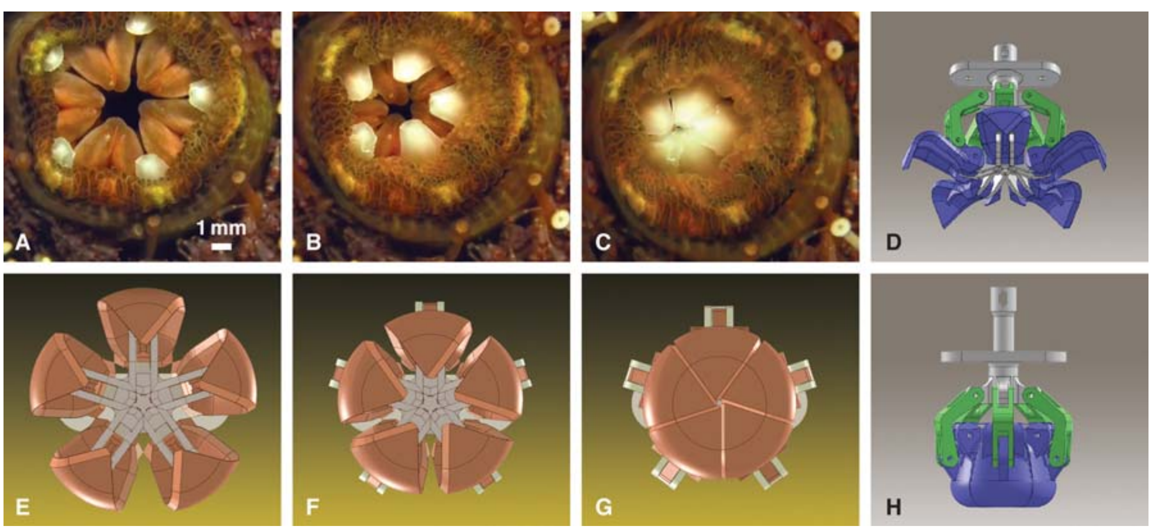

Fig. 5. A–C and E–G: still frames from a video showing the opening and closing of the sea urchin's mouth and of the ground sampler prototype (teeth shown in red) built by Frank et al. [14]. D and H: side views of the prototype in open and closed position (teeth shown in blue) [19]. (© Michael Frank. Photos and illustrations: Michael Frank and Taylor Wirth, courtesy of the University of California, San Diego. Used by permission.)

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Conclusion

Scarpa's goal was not to find practical applications but to understand nature at a deeper level than is afforded by external appearances. He consistently returned to Paul Klee's *The Thinking Eye*, and to a note on his sketch of a cube's internal planes. It reads: "The inward plays the dominant part. The whole inward territory designated by the word *content*" [26].

The "inward territory designated by the word *content*." The Klee's phrase resonated for Scarpa as that reality is out there, but hard to penetrate. A genius like Leonardo da Vinci literally applied his scalpel to his anatomy sections. A spiritual artist like Klee sought to understand nature through painting. Scarpa, like Klee, collected plants and seeds, nature's humble but important creations (Fig. 6):

> "If you are going to do research in bionics, don't forget to study seeds, for the knowledge that nature displays in their creation, and for the originality and unpredictability of some of their self-dispersal mechanisms." (pers. comm. 1988)

Fig. 6. Giorgio Scarpa's collection of seeds on his workshop's desk in Castel Bolognese, Italy, 2002. (© Pino Trogu)

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Many of Scarpa's bionic models of seed dispersal mechanisms remain unpublished, but whether his focus was on a complex mechanism such as the sea urchin, or on seemingly simpler organisms as seeds, his approach of pure exploration remains valid today as was then. Simply understanding nature, and gaining aesthetic pleasure by constructing analog systems that are not copies, these were in themselves the rewards of his research. Today, as the work of Jelínek and Frank demostrate, seeds that he scattered more than forty years ago can still generate new discoveries and applications.

Acknowledgments

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