Sequences, Tracks and Footprints: Graphic Lessons Gathered from Swarm and Spider Web Robotics

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Abstract. The development of automation in construction is opening up a whole field of research on how to optimise movements and manoeuvres.

Furthermore, important studies have also been conducted into the emulation of spider webs and the advances of swarm robotics. The latter consists of a series of identical robots that collaborate when performing tasks, covering a broad spectrum of situations without the need to specifically pre-programme each robot.

Graphics included in this paper demonstrate the potential of small robotic units with a certain autonomy. Some research and design cases created by Tomas Saraceno, Maria Yablonina and Gramazio & Kohler are referenced for discussion.

The methodology first translates, on a new digital graphic, how a spider of the Theridion sisyphium species builds its web through different stages sequenced by Benjamin and Zschokke [1]; second, it explains how a Delaunay triangulation that undergoes subsequent relaxation helps to obtain a plausible arrangement of tense strings that can then be manually replicated. At a real performance level, the study describes how a group of students from the University of Alicante emulates the filament-throwing techniques of the aforementioned arachnid species during a design workshop completed in May 2019.

Keywords: Graphic sequences · Swarm robotics · Spider-based design · Virtual-physical

1 Context

> "*By the means of Telescopes, there is nothing so far distant but may represented to our view; and by the help of Microscopes, there is nothing so small, as to escape our inquiry. Hence there is a new visible World discovered to the understanding*" [2].

In emerging fields such as virtual reality, augmented reality or component design, a single simulated image or graph is increasingly becoming insufficient to explain a final product. In any case, this fact helps us to understand that architecture, and the socio-cultural heritage it encapsulates, needs to reconsider the discipline's methodologies.

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1.1 Drawing the Living Being (Capturing Phases)

Tools such as the Kinect sensor, which probes people by recognising the human skeleton and then following its movements, or eye-tracking devices that translate the observer's eye movement trajectories into chromatic maps, are examples derived from the seminal studies conducted by Muybridge and Marey, who used chronophotography to obtain animal movement trajectories [3]. They even incorporated pneumatic and electrical sensors [4]. In the late nineteenth century, Muybridge succeeded in demonstrating that any racehorse will, at some point, just for an instant, have all its limbs in the air when galloping. This result was achieved via a system of high-speed captures, using white sheets in the background attached to one another with vertical lines (a timeline).

Almost a century later, Bernard Tschumi introduced the spectator to visible synthesis of space and human action based on a series of photographic drawings and diagrams, using codes learned from ballet choreographies. "Architecture is not simply about space and form, but also about event, action, and what happens in space" (see Fig. 1). Tschumi was attempting to incorporate elements usually absent from architectural or landscape representations. He was referring to relationships between spaces and uses, between type and programme, between objects and events. Relevant to this study, in his initial approach to his Manhattan Transcripts, he introduces a notation mode based on three-panel graphs to portray any experience (known as "chronotope" in language theory): the first component is composed of photographs showing the actions; the second consists of planimetric maps revealing changing architectural manifestations; and the third are diagrams presenting the movements of main actors [5].

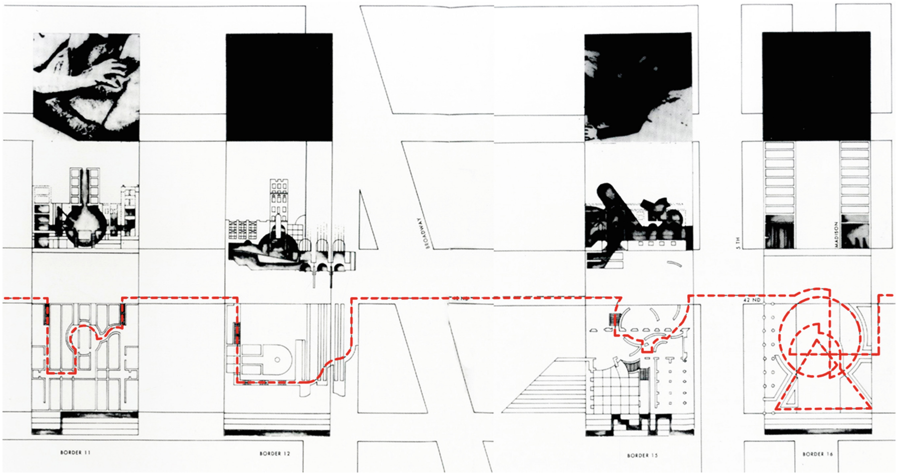

Fig. 1. Bernard Tschumi. The Manhattan Transcripts 1976–1981.

1.2 Drawing the Robot (Capturing Phases in Automatons)

Moveable Generative Units. John and Julia Frazer pioneered the architectural use of individually operated robotic units, with their project "The Universal Constructor" [6]. In this project, they illustrated the functioning of a self-organised environment of small cells able to communicate with the neighbour ones. Project's definition referred to John Von Neuman's research on self-replicating machines. They succeeded in designing devices called cellular automata, in which the communication through cells included instructions on how to proceed with evolutionary disposition. Each unit explores its sides, looking for the presence of neighbouring units, using processing times based on LED lighting. In this case, the light draws and reports the process. The information flow is equivalent to what Neuman developed with his "instruction string". Frazer turns the visitor into a necessary actor who participates in the information process. This auto-generation path was also explored by cellular automata such as "Game of Life" (John Conway) or the making of the Universal Computer Turing machine, thanks to which any complex problem could be oriented to solutions.

Automata Functioning as Swarms. In more recent times, other researchers have been able to create and use robots to weave thread systems over a range of different supports [7]. In a similar way to Saraceno, Yablonina based her research on observing how a spider builds its web [2]. In Yablonina's experiment, a spider of the *Tegenaria Atrica* species was placed inside an clear box and its movements were recorded using infrared cameras that captured images every 30 s, and a laser scanner that scrutinised the clear box space in a succession of horizontal slices. The experiment resulted in defining the spider's web path and obtaining a digital file with a three-dimensional mesh so as to analyse the thread's orientation. In addition, geared robotic devices created protocols to sew strings (Fig. 2).

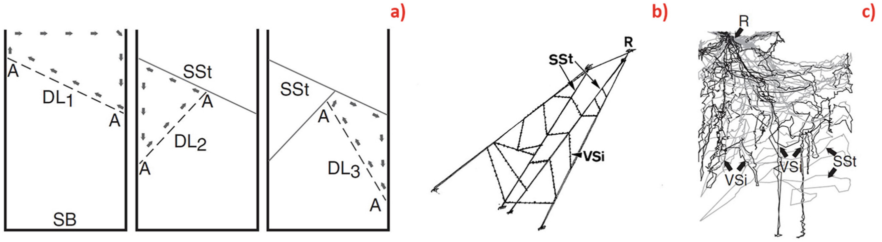

Fig. 2. Graphic formats in Benjamin and Zschokke: movements (a); stages (b); result (c).

In another model, Yablonina created a series of robots specialised in different structure-weaving tasks. Some moved along vertical surfaces to which they adhered thanks to a fan that creates a vacuum between the surface and the robot itself; others moved by means of a carriage-like system through pre-installed ropes. Both types of robots carried string coils to produce fastenings to points on the wall. Using an electromagnet system, robots can pass the coil from one to another so that, all together, the automata can weave on different planes. The result was a three-dimensional tense configuration made up of intertwining strings (see Fig. 3).

Parallel to Yablonina's climbing species, Fabio Gramazio and Matthias Kohler explored self-construction using drones, which present a greater capacity to access any point in 3D space, beyond that allowed by a real room's surfaces or a virtual prismatic

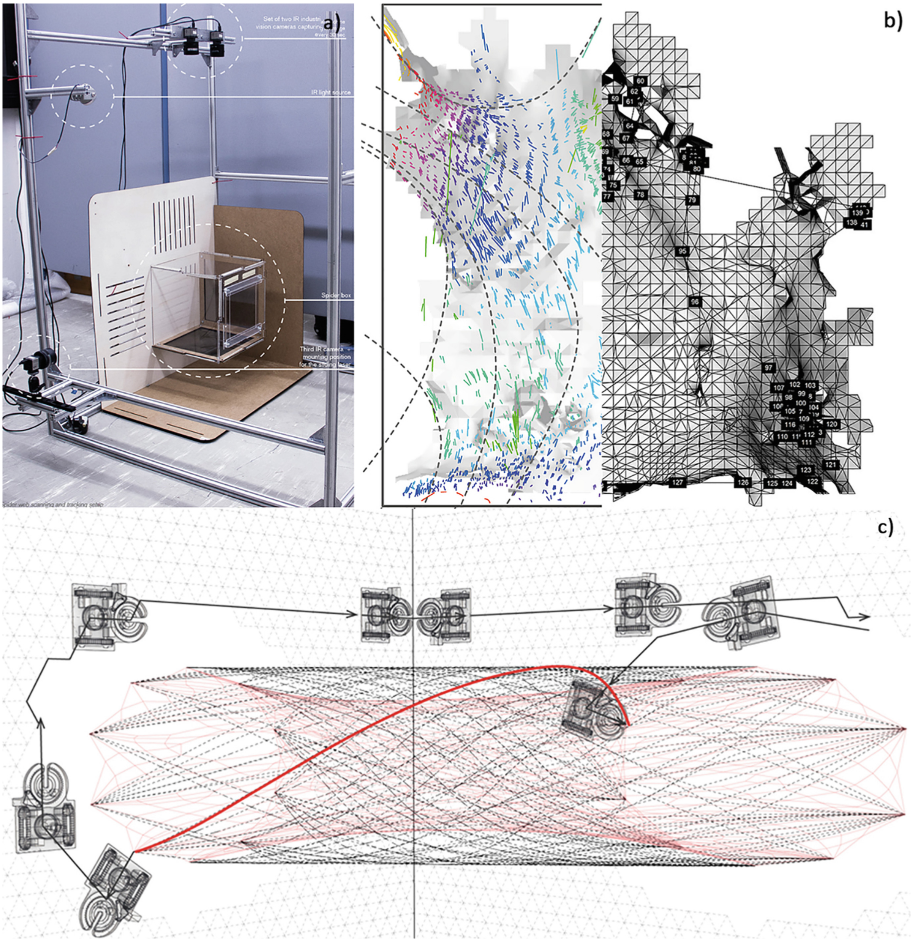

Fig. 3. Yablonina. Spider Web, Stuttgart University, in 2013 (a, b); spider-robots passing the string to each other (c).

universe [8]. In this case, they used quadcopters loaded with string coils that progressively extend, creating fastenings and knots between the strings themselves (see Fig. 4). The contribution at the code level is that this swarm of drones needs to regulate three parameters: the flight path that each drone follows; the force they apply to the string when tied; and the drone's orientation when dragging the string. This enables "constructive primitives" to be obtained that, when concatenated, define each drone's flight path to build a structure designed beforehand. The interesting point is the fact that the interaction between the drones and their environment generates a family of visualisations and graphs, which is related exclusively to coordinated movements to avoid collisions.

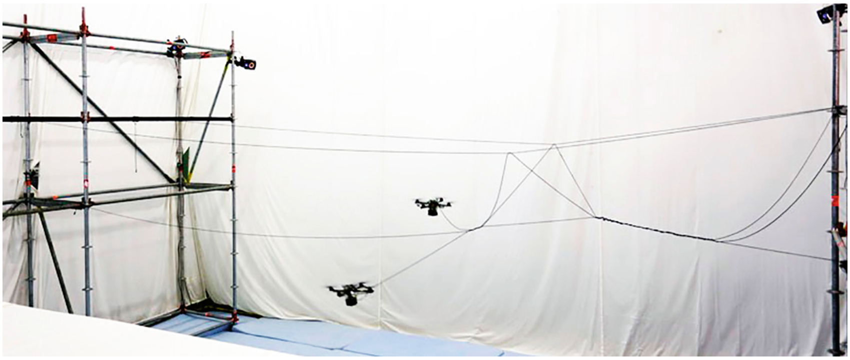

Fig. 4. Gramazio and Kohler. Tense strings placed by a swarm of drones.

1.3 Recording via Stereophotography and Sheet Laser Scanner

Working in an aeronautical hangar in Frankfurt, Tomás Saraceno and his team succeeded in replicating, at a scale magnified 30 times, the shape of a three-dimensional web created in a transparent plastic clear box by the black widow (*Latrodectus mactans*) spider. To do this, he used resources such as stereophotogrammetry or sheet laser, a new tomographic method (slice-based images) implemented in collaboration with the Darmstadt TU [9].

Spider webs, besides representing for many scholars a visualisation model of the origin of the universe, prove challenging for most scans: firstly due to the invisibility of the filaments, as their diameter nears a nanometre; and secondly, because of non-flat joining between more than two threads. In this case, stereo-photographs of the laser-lit slices (110 pairs of stereo-photographs) were taken, creating in each a sort of constellation, as if it were "a photographic image of a slightly starry night".

A script then attempted, unsuccessfully, to replenish the thread section corresponding to the unscanned space, that is, in the interstitial space between thin slices. The paradox, after using such cutting-edge technological resources, is that the problem had to be solved by four architects, adding lines, one by one, in a 3D space.

Before starting the installation of the spider web in Bonames (Frankfurt am Main), orthographic projections (specular images between them) were placed on the walls, floor and ceiling of the room.

Vertical nylon threads were used as master lines, tensed between floor and ceiling. The key to the procedure was that they hosted the web's initial knot positions, before losing their shape. Formally, they were small elastic ropes that would then become knots in irregular polygons [2] y [9] (see Fig. 5).

2 Methodology

Based on the studies referenced, this article begins by describing how one of the procedures, that of the silk thread web described by Benjamin and Zschokke, was parameterised using a generative algorithm to make it operable within a three-dimensional

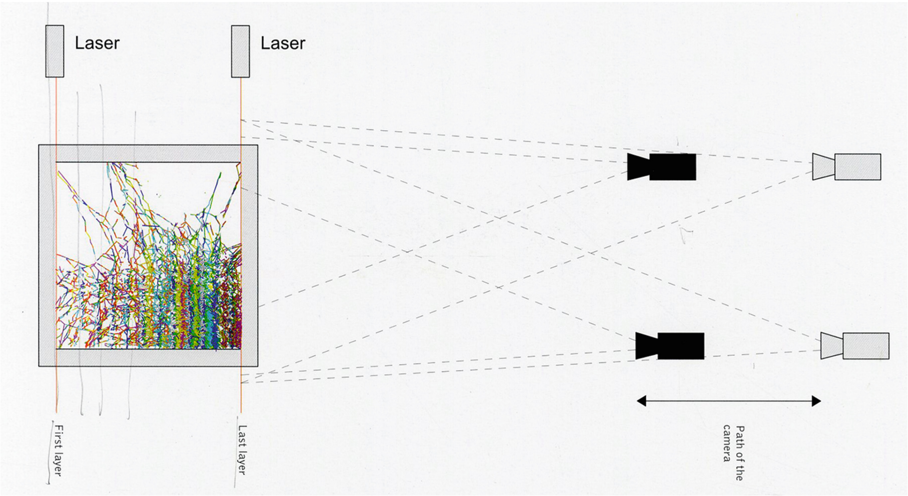

Fig. 5. Saraceno. Camera and laser placement map

universe of a prismatic envelope. It then goes on to show how another parametric version of a three-dimensional thread web is produced for a students' installation in a courtyard at the University of Alicante.

The method is based, firstly, on the translation of Benjamin and Zschokke's rules into an algorithm that generates a spider web–of the Theridion Sisyphium species–in a three-dimensional modelling environment, simulating the natural process. Secondly, the method reduces the system to another algorithm based on Delaunay triangulation, which then undergoes relaxation to facilitate the installation of a real string system in a few hours of assembly.

3 Results

3.1 Running the Virtual

To translate Benjamin and Zschokke's rules into an algorithm, the Grasshopper visual programming environment was used within the Rhinoceros software. Using these digital tools, we built an algorithm that reproduces the spider's action when weaving the web within a virtual urn-universe. Benjamin and Zschokke observed three different types of thread in the web of the *Theridion Sisyphium*: the fastening thread, which functions as a guide and is not definitive; the structural threads, which act as a general web support; and the viscous thread, which aims to capture prey.

In a first iteration, the virtual spider creates a fastening thread. The ends of this latter thread rest on the walls of the delimited virtual urn, and the virtual spider moves along it, adding more silk, thus reinforcing it and turning it into structural thread. At each successive iteration of the algorithm, the virtual spider adds a new fastening thread that connects an existing one to one of the urn walls, repeating the previous process and resulting in a new structural thread. Once there are a sufficient number of structural threads, the virtual spider begins to create viscous threads. These threads do not rest on the urn walls: their two ends rest on previously created structural threads.

The process is stochastic, because threads and wall positions to place new threads are randomly selected. This condition derives from the observation made by Benjamin and Zschokke that there is apparently no pattern of preference when the spider adds threads.

At each algorithm iteration, that is, each time a thread was added to the fabric, a relaxation process was executed using the Kangaroo plugin, adopting a shape that matches with the structure's state of minimum energy (see Fig. 6).

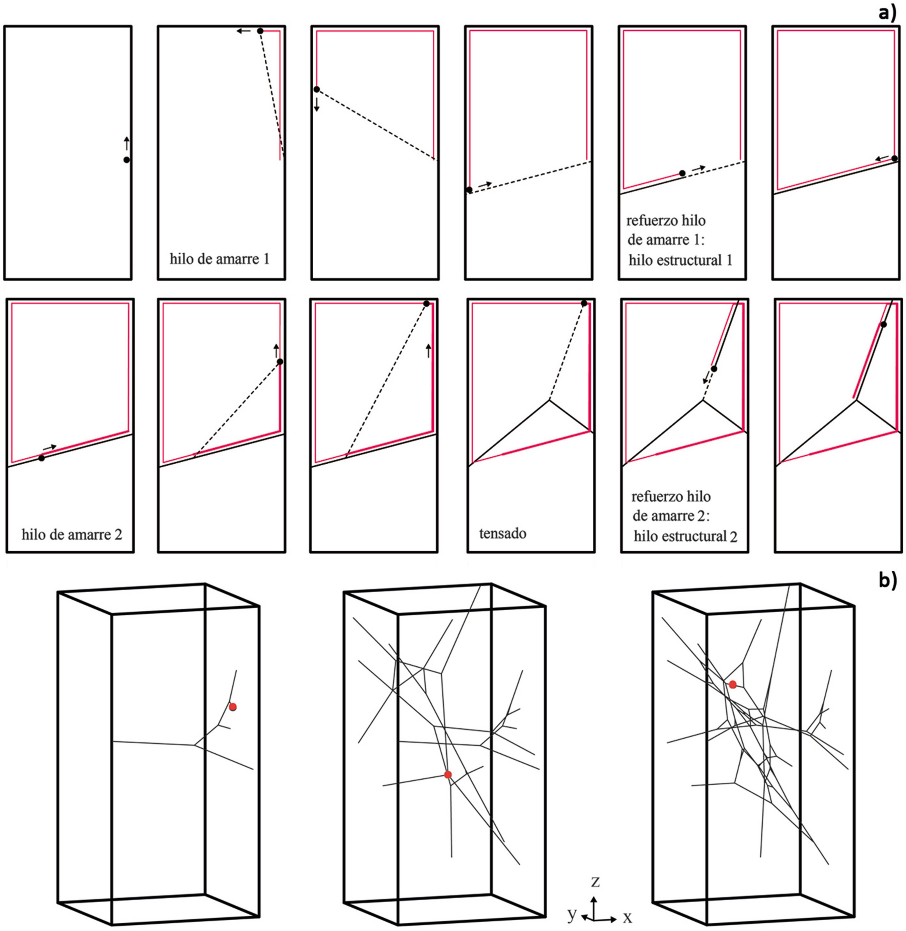

Fig. 6. Stages of structure set-up in 2D (a) and 3D (b). Author: Serrano, 2019.

3.2 Building the Physical

Once the algorithm had been defined, the next step was to physically apply what had been learned: a tensed structure was made and assembled in May 2019 in which devices designed by students of the University of Alicante were incorporated using point loads.

At this stage, an alternative model was explored to approximate the virtual generation of three-dimensional spider webs based on Delaunay triangulation. This new algorithm begins with a cloud of dots located within the clear box-universe, distinguishing the fastening points–allowing the fabric to be attached to the support–from loading points, where the devices were placed for point-in-time loading.

Delaunay triangulation was generated from these points. The algorithm then removes threads that go from one fastening point to another from the structure, as these threads do not help to support the loads. Finally, a relaxation process was carried out on the resulting wire mesh, so the loading points acquired a determined position within the urn-universe (see Fig. 7).

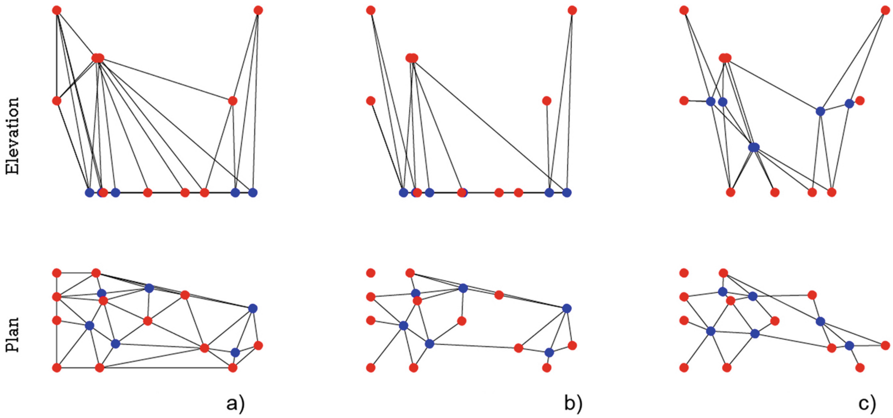

Fig. 7. Delaunay triangulation on 2D cloud of dots on base surface (a); removal of strings with no load (b); relaxation of the whole (result, c).

The urn-universe was, in this case, a courtyard measuring approximately 4.50 m (width) × 8.50 m (length) × 8.50 m (height) in the Polytechnic building of the University of Alicante. The behaviours of the collaborative robot of Maria Yablonina's installations (or of the Theridion Sisyphium spider that walks on its own thread, throws new filaments, goes back in search of new positions, segregates gluey silk for fastenins, etc.) were somewhat reproduced by the team of students-teachers in their attempts to throw ropes, add sliding knots, tie ends to gravel bags, design knots allowing for six passing ropes, etc. (see Fig. 8). Some of the contents tested consisted of using a spatially dimensioned universe, geometry controlled using analogue references and stereographic projections, and a parametric method to obtain node positions.

To build the structure, almost 200 m of jute rope, 6 mm in diameter, were used. Printed knots were made in 3D, and bags full of stones were placed as counterweights. Student's productions were laid out, hanging from each knot and contributing to the final

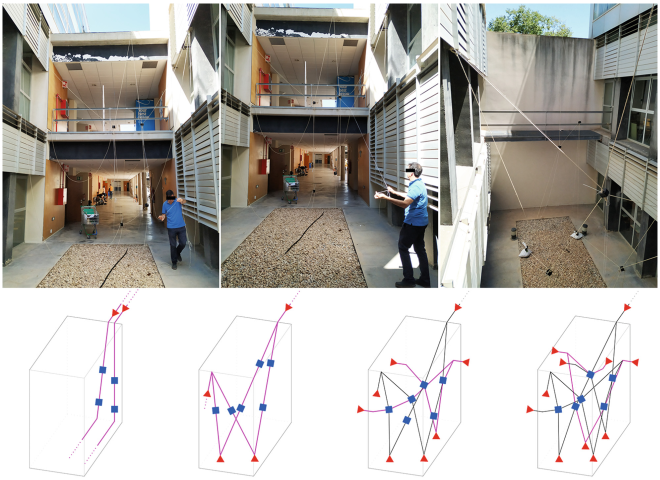

Fig. 8. Installation "La ruta de la seda". Assembly stages, UA. May 2019.

tightening. They generated interactions with observers using social media data to make certain decisions regarding the design itself (Data Driven Design).

4 Discussion and Conclusion

What can we learn from how spiders weave? How can this knowledge contribute to new automation methods in construction thanks to advances in robotics? The use in architecture of robotic units, which work individually with nearby inputs generating a higher-order global behaviour, foreshadows a new construction paradigm: that of a shift towards the process rather than remaining focused on the object. Research efforts should focus, therefore, on how to recognise behaviours and draw the itineraries of these particle systems.

"*Architecture is everywhere and cannot be viewed essentially as the science of constructing houses, cities, etc. I think that the aims and interactions between disciplines must be continuously re-invented for each specific context. …We have to try to activate a process of re-actualization in relation to ever-changing contexts (to become) capable of imagining more elastic and dynamic rules*". [2]. Kastner, Saraceno and other researchers use the term "ecology principle" to denote the framework that connects academic disciplines currently operating separately (engineering, social sciences and humanities) and which give meaning to future societies, learning how nature self-regulates through rules of cooperation and survival. In addition, thinking about sequences or stages gives value to other types of graphic depictions that go beyond the usual planimetric maps or deployments using cylindrical projections. It is something linked to digital production and its direct robot execution. (see Fig. 9).

The above supports the recognition of space-time as an inseparable cathegory within the creative process, and not only in architecture and urban design. In fact, it is hugely useful, since it constitutes a value that can be approached from diverse disciplines, leading

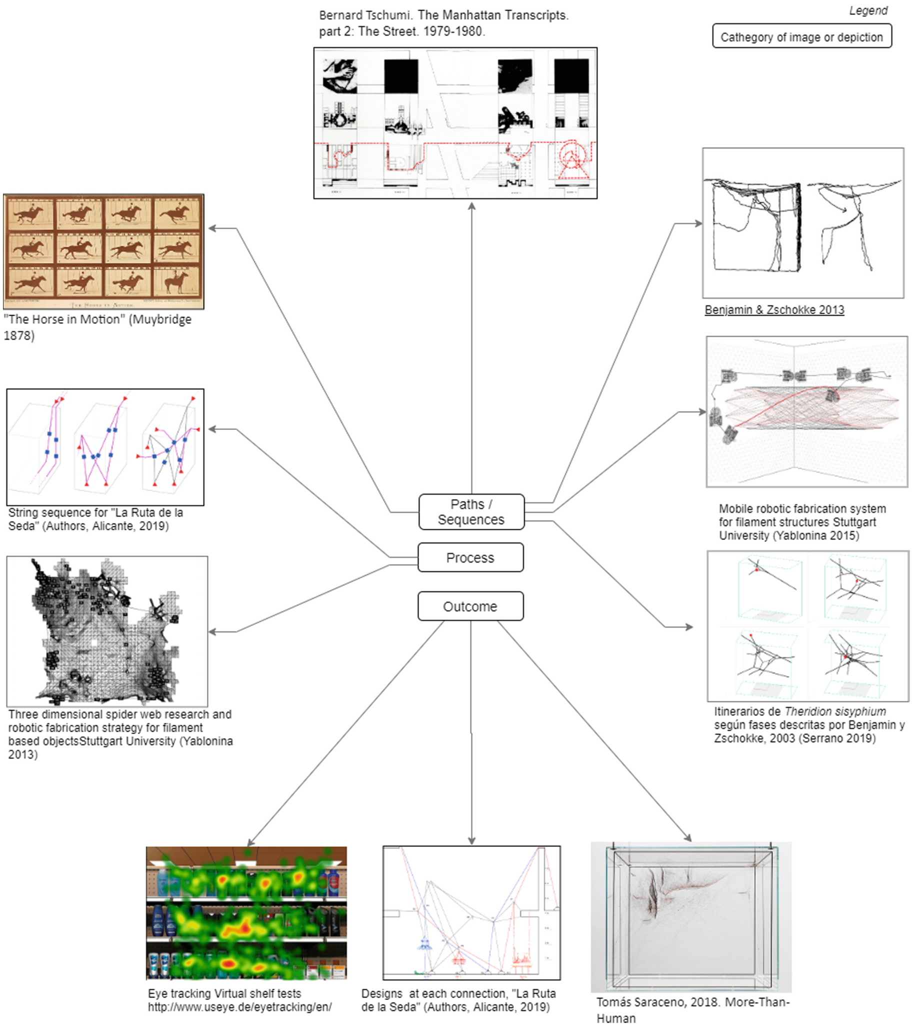

Fig. 9. References and productions (diagram: authors).

to confluences. For example, *chronotope* is a term from the Theory of Language, created by Bakhtin. The term gives value to the components that provide a space-time meaning to the story: "*In the literary artistic chronotope, spatial and temporal indicators are fused into one carefully thought-out, concrete whole. Time, as it were, thickens, takes on flesh, become artistically visible; likewise, space becomes charged and responsive to the movements of time, plot and history. The intersection of axes and fusion of indicators characterizes the artistic chronotope*" [10]. Terms such as nature or landscape (scape) and any of their variants (literary, visual, tactile, sound, olfactory, gustatory…) imply a time for experience and the possibility of apprehending its elements [11]. Its recording or spectrum eventually requires a set of parallel tracks that can host contents digitally.

And the term *narrative,* applicable to all these variants, implies the need for a structure to explain the process in all its complexity [12].

Comparing the works of Yablonina (artificial spiders) and the work of Gramazio & Kohler (drons), the conclusion is that in both installations, points and itineraries were controlled within the space. In the first case by 2D movements, in the second by 3D movements. Comparing how real spiders build their webs and how "La Ruta de la Seda" installation" was mounted at the University of Alicante, both cases use threads that gradually increase their shape complexity. Control lines, tensed vertical cables, delimit the position of Saraceno web's knots, while a Delaunay on the ground defines the first distribution of points in the courtyard of the University of Alicante. They work taking into consideration gravity, continuous fastenings, ground adhesion or anchors and passing knots as if, at each iteration, the whole was achieving a new distribution of the balance; the parallelepipedal clear box in the real spider experiments is comparable to the courtyard space in the university building.

To conclude, this work shows the technical possibilities of a methodology that includes multiple stages, each of which requires a precise and exquisite exercise of creativity, definition, labeling, depiction, etc. taken to extremes and within the grasp of students in a learning exercise lasting a single term.

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