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THE DESIGN OF GRAPHICAL SYMBOLS FOR THE TECHNICAL DOCUMENTATION OF PRODUCTS WITH SHAPE TRANSFORMING 4D PRINTED PARTS

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Abstract

The term “4D Printing” (4DP) is defined as the ability for a part produced using an additive manufacture process to change its shape when activated by or exposed to one or more stimuli over time. This emerging technology offers unique advantages over conventional Additive Manufacturing (AM) by extending the three dimensions of space into the fourth dimension of time. 4DP parts can be programmed to actuate passively without the need for an external power source such as an electromechanical or other active system, thereby reducing the probability of failure and the complexity of components.

This work attempts to address some of the challenges faced by the design engineer in a project team when producing technical documentation to specify the desired shape transformation of a 4DP part with a structured graphical representation at an appropriate level of abstraction. In this paper the requirements for a shape transforming 4DP part are represented as the allowable variation in dimensional size and tolerance in geometric form of the functionally critical features on the part for each function that the transformed shape serves.

In this paper, the authors describe how the proposed standard to specify the desired shape transformations of a 4DP part could use graphical symbols in a structured specification by means of a Transformation Control Frame (TCF) to define the rules of transforming between shapes and a Bill of Transformations (BoT) to enumerate all the Transformation Control Frames (TCF) necessary to describe the intended sequence of shape transformations. To illustrate how the graphical symbols could be applied, a SMA actuated gripper is presented as a use-case.

1 INTRODUCTION

Shape Memory materials have been used in a growing number of commercial applications, including stents, heart valves and guidewires in medical applications, anchor, sleeve and screw devices in mechanical applications, vortex generators, torque tubes and flaps in aerospace applications, industrial bearings, gears and ventilators in automotive applications to name a few. Research over the last decade has shown that Shape Memory materials can be effectively utilized using Additive Manufacturing (AM) processes to produce devices for applications, more commonly known as “4D Printed” (4DP) parts that are a near net shape with complex geometries [1]. 4DP processes selectively distribute the stimulus responsive properties of shape memory materials to program the desired shape transformation when exposed to the actuating stimuli. Exploiting this property of 4DP parts opens the potential to further develop specialized high-value products with a reduced need for an external power source, fewer electromechanical or other active parts and the ability to operate passively by the free exchange of energy between the part and its surroundings. In turn, these properties of a 4DP part could lower the complexity of manufacture, reduce part-count and contribute to savings in time, cost and weight [2].

2 PROPOSAL FOR A NEW STANDARD

For a 4PD part to be reliably designed, manufactured and tested for its fitness for purpose, it is important that the design intent is accurately and unambiguously communicated between stakeholders contributing to the value chain. This poses a challenge for Engineering Design: How do we accurately and unambiguously represent the design intent for a non-rigid body to undergo shape transformation with existing Technical Product Documentation? An existing GPS standard intended for specifying non-rigid bodies [5] uses ad-hoc annotations rather than a structured specification for the forces acting on a part compared to its free state and it does not provide a means to specify shapes that transform. The proposed standard could allow Shape Memory products to be more widely used, provide testable criterion for metrologists and test engineers to verify a 4DP part's conformance, leading to wider industrial acceptance [3].

The UK’s national standards committee for Technical Product Realization (TPR) at the British Standards Institution is TPR/1 provides the UK’s input to the international ISO/TC 10 committee for Technical Product Documentation as well as ISO/TC 213 for Dimensional and Geometrical Product Specifications and Verification. These cover design implementation, geometrical product specification, graphical representation of Engineering Drawings, 3D modelling and other technical documentation. The sub-committee TPR/1/8 for the standard BS 8888 Technical Product Specification committee established a sub-group TPR/1/8/1 in September 2022 for the “Design of graphical symbols for use in the technical documentation of products - 4D Printed Parts - Shape transformations” contributing to the work described here.

3 PROPOSED FRAMEWORK

The proposed new standard aims to extend the existing Technical Product Documentation (TPD), Geometric Product Specification (GPS) and Engineering Drawing standards in British Standard BS 8888 for the technical specification of products. To implement the proposed standard, three new concepts are introduced; the Shape State, the Transformation Control Frame and the Bill of Transformations. To illustrate how these three concepts can be applied, we consider the use case of a SMA actuated mini-gripper as shown in Figure 1.

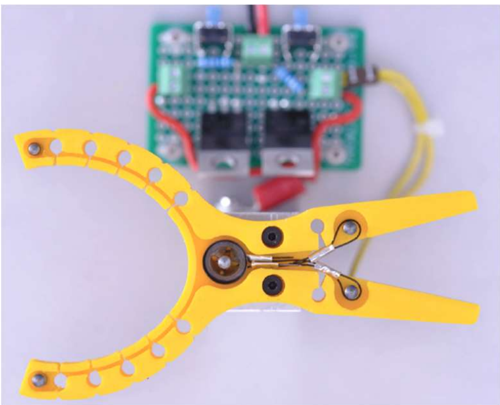

Figure 1: Mini-gripper use-case

3.1 Shape State

To aid the designer engineer express the functionally critical features on a 4DP part in each of its transformed shapes using the Geometrical Product Specification (GPS) language, we introduce the Shape state. For each of the different functions that the 4DP part serves, the designer expresses the allowable variation in dimensional size and tolerance in geometric form of the functionally critical features on the part using the GPS language. Each Shape state is given a unique numerical suffix (S<num>), with this reference, the direction from one Shape state that a part transforms to another Shape state can thus be specified unambiguously.

In the mini-gripper use-case, the 4DP part serves four functions: idle, constricting a flexible tube, gripping a rigid rod and constricting with gripping. For each function a Shape state specifies the part's critical features using GPS as shown in Figure 2. The idle Shape state (S2) approximates the free state under ISO 1 reference conditions [6] where datum features are defined that do not undergo shape transformation between the other Shape states (S1, S3 and S4). It is expected that in practice, one of the Shape states will be representative of the part "as manufactured" under reference conditions. With the Shape states defined, the designer can express the conditions for each shape transformation. In this way, a multi-way reversible shape transformation is distinguished from a one-way non-reversible shape transformation. The directionality of transformations are indicated in the Transformation Control Frame described in the next section.

3.2 Transformation Control Frame (TCF)

Programming shape transformation properties into a part using 4DP extends design possibilities into autonomous behaviors such as self-assembly, for example from a flat pattern to a volumetric form without the need for human involvement or additional energy input if passive energy exchange between the part's shape memory properties and the surrounding environment are used. To aid the designer engineer express the intended conditions for transformation of the 4DP part between each Shape state, we introduce the Transformation Control Frame (TCF) as shown in Figure 3. The TCF is structured into five elements to be read from left-to-right. The first element in the TCF specifies which type of shape transformation the part is intended to undergo using symbols shown in Figure 4.

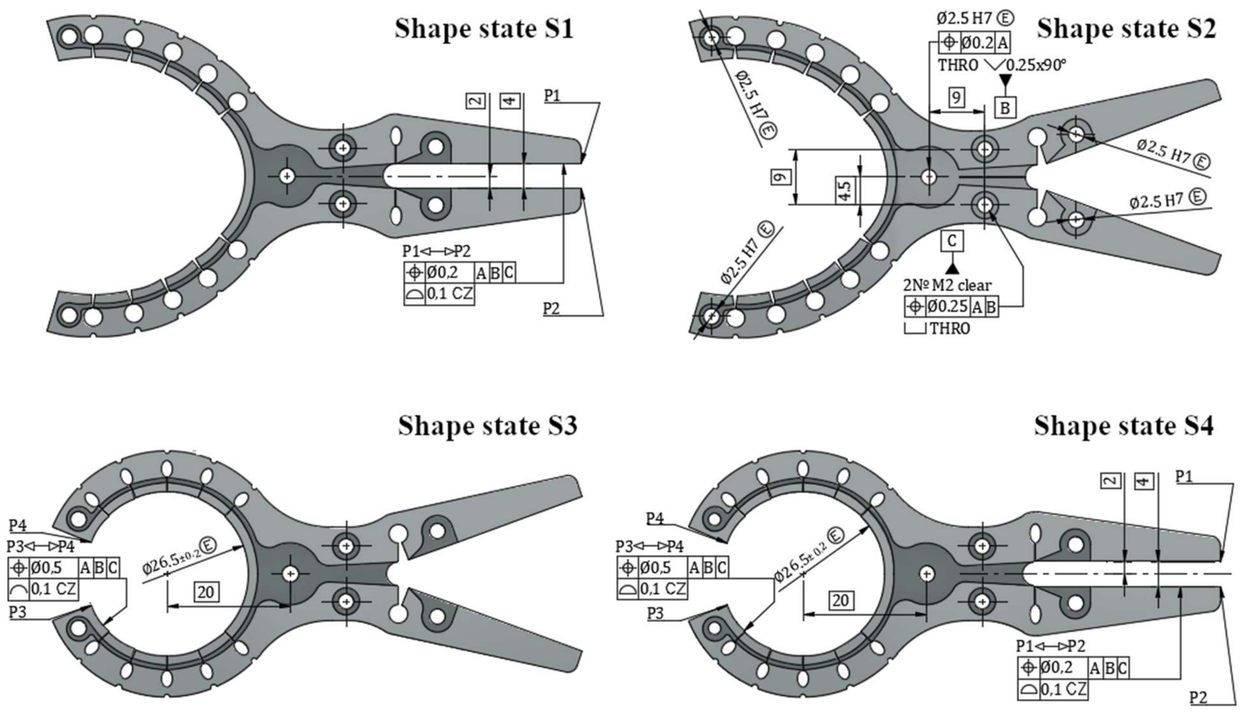

Figure 2: S1, S3 and S4 share a common DRF (Datum Reference Frame) defined in S2
Where S2 is representative of the free state in the reference condition to ISO 1

Shape Transform	Stimuli	Magnitude and intensity	Threshold	Latency
from → to	mode	Spec. Tol	Spec. Tol	Spec. Tol

Figure 3: Transformation Control Frame (TCF)

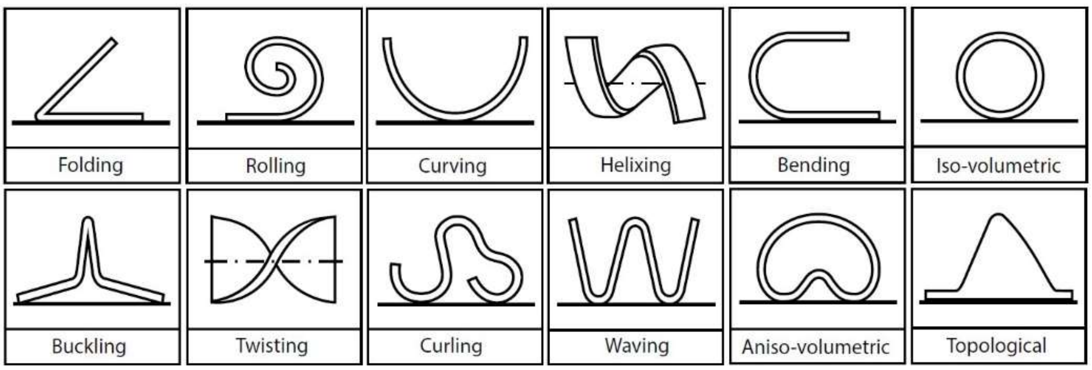

Figure 4: Symbols for Shape Transformations

The range of shape transformation types include: folding, rolling, curving, helixing, bending, iso- and aniso-volumetric transformation, buckling, twisting, curling, waving and topological transformation [4] as shown in Figure 4 and described as follows:

- **Folding** is defined as a deformation whereby the in-surface distance between the sheet's two distinct points is kept without self-intersecting. The fold is a sharp curvature that is caused by a deformation along a crease and with sharp angles
- **Rolling** is a behavior where the shape moves by turning over and over on its own axis. This deformation process enables the component to maintain a constant cross section throughout the deformation process. The size of the curvature depends on the design variables, the material, geometry, applied mechanical load and the stimuli.
- **Curving** is defined as the amount by which the surface of a geometric object deviates from a flat plane. This shape-changing behavior is enabled by a stress mismatch between rigid ad non-rigid materials due to their different swelling properties when in contact with water or other stimuli.
- **Helixing** is a type of smooth space deformation whereby a curve appears in a three-dimensional space. By adjusting the print angle of the active fibers, it is possible to change the helixing behavior.
- **Bending** is a distributed deformation of a material along the area of deflection that creates the curvature. Bending is a global deformation that results in a smoother curvature as compared to folding which is a localized deformation that has sharp angles occurring within a narrow hinge area.
- **Iso-volumetric transformation** refers to expansion and contraction behaviors of linear free swelling and shrinking of materials such as thermo-responsive hydrogels that are repeatedly immersed in hot and cold water, allowing the material to expand when heated and contract when cooled leading to material changes as temperatures fluctuate.
- **Aniso-volumetric transformation** can be defined as having an unequal or uneven transformation in terms of its volume. This is in contrast to iso-volumetric transformation that has even expansion and contraction behaviors of swelling and shrinking.
- **Buckling** occurs often due to a sudden sideways failure of a structural member when encountering high compressive stress. The compression force can be applied directly to the passive material layer to induce a non-planar buckling effect.
- **Twisting** is often used for small widths to achieve shape change behaviors. It occurs due to in-plane stretching and this can be controlled by increasing the twisting widths so that the stretching energy increases lengthwise across the material. The main difference between twisting and helixing is that the axis of a twist is centered, whereas a helix has various axes.
- **Curling** is an alternative to waving and the main difference is that curling is creating by having multiple continuous surfaces that are not uniformed, whereby the large surface area provides an even expansion force across the material.
- **Waving** results in a shape that has undulating features such as a wavy or up-and-down profile. The key difference between waving and curling is the regularity of the curves after deformation in which waving has more regular curves, as compared to that curling consists of having irregular curves.
- **Topographical transformation** resembles a ground terrain and is a result of a distorted shape. The hypotenuse is fully straight near the apex and it becomes more curved further away from the apex. The corners of a topographical transformation bend into the shell.

Continuing to read from left-to-right, the next element in the TCF specifies the stimuli driving the shape transformation. This is followed by graphical specifications from ISO 7000 that represents the type of stimuli, a selection of stimuli that are typical in a wide range of industrial and research applications of 4DP parts are shown in Figure 5. The ISO 7000 standard provides graphical symbols for use on equipment, published by ISO/TC 145/SC 3. The other three elements in the TCF specify the magnitude and intensity of the stimuli, the relevant threshold for change and the latency of response for each shape transformation when attached to each functionally critical feature of the part as it undergoes a shape transformation between each Shape state.

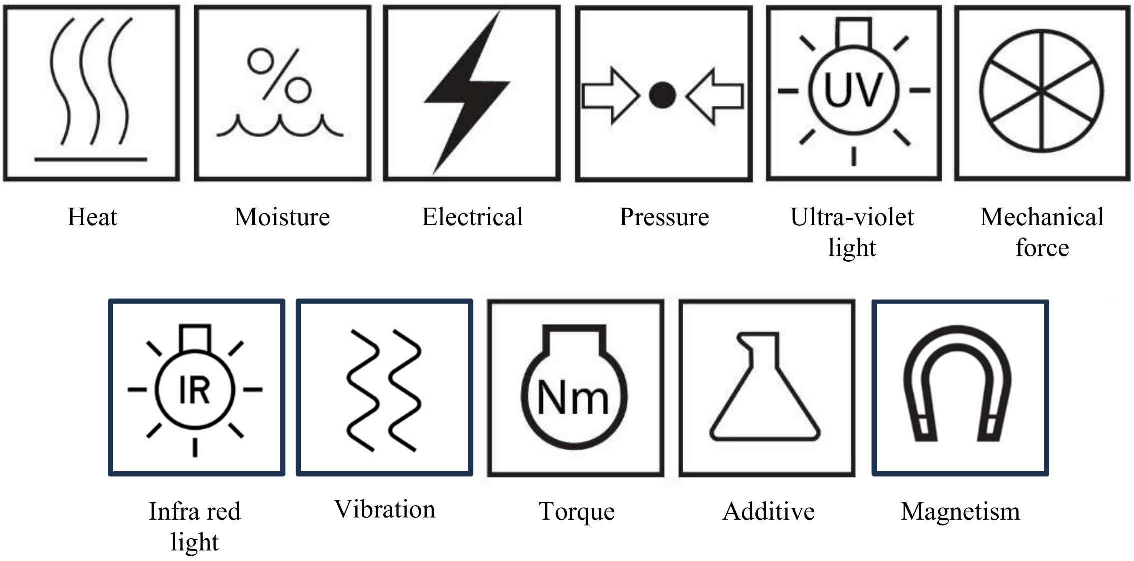

Figure 5: Symbols for Stimuli adapted from the ISO 7000 symbols

When applied in practice to the use-case of the mini-gripper, the design engineer can express the conditions necessary for the shape transformation between the four Shape states (S1 to S4 inclusive) as shown in Figure 2 with the TCF structure as shown in Figure 3. Specifically, the TCF structure is used to specify the values for parameters and variables of the SMA (Shape Memory Alloy) actuator that operates the mini-gripper's shape transformation from Shape state S2 to S3 as shown in Figure 6.

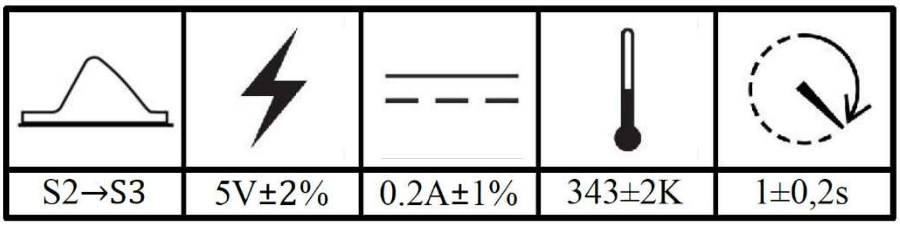

Figure 6: TCF with specifications for the shape transformation from Shape state S2 to S3

3.3 Bill of Transformations (BoT)

To aid the designer engineer express the intended sequence of shape transformation between each Shape state defined by the rules in each TCF, we introduce the Bill of Transformations (BoT). There are antecedents to the BoT used in technical documentation such as the BoM (Bill of Materials) for scheduling the parts in an assembly and the BoC (Bill of Characteristics) used by metrologists to schedule the inspection of features on a part or assembly of parts.

The first element in the TCF specifies the directionality of each of the 4DP part's shape transformation, for example the annotation S1→S2 is defined as a Shape transformation from Shape state S1 to Shape state S2. Annotation S1↔S2 is defined as a reversible Shape transformation between Shape state S1 and Shape state S2. Annotation S1→|S2 is defined as a non-reversible Shape transformation from Shape state S1 to Shape state S2 only. Once a TCF is defined for all the part's shape transformations the BoT enumerates these, in the use case of the mini-gripper this is shown in Figure 7.

4 CONCLUSIONS

This paper describes a proposed standard to be used for producing technical documentation to specify the shape transformation of 4DP parts where three new concepts were introduced: the Shape state that expresses the conformance requirements for dimensional size and geometric form for the functionally critical features on the 4DP part in each of its transformed shapes, a Transformation Control Frame (TCF) that defines the rules of transforming between shapes states and a Bill of Transformation (BoT) that enumerates all of the Transformation Control Frames (TCF). The paper describes various shape transformations that can be achieved, including but not limited to folding, rolling, curving, helixing, bending, iso-volumetric transformation, buckling, twisting, curling, waving, aniso-volumetric transformation and topological transformation. A use case was presented to illustrate how these three concepts could be applied to a mini-gripper 4DP part.

It is anticipated that the proposed standard could be adopted into the workflows of design engineers and project teams within academia and industry who are developing applications using 4DP parts as well as innovating the AM processes necessary to produce it. In this way, adoption of the proposed standard could support improvements to the dialogue between design engineers and material scientists through accurate and unambiguous technical product specification.

Future work aims to showcase more examples of applications and to further establish the work of "Design of graphical symbols for use in the technical documentation of products - 4D Printed Parts - Shape transformations" in TPR/1/8/1". Future work will focus on Model Based Definitions (MBDs) for each Shape state, annotating the features in the 3D models directly to provide better visualization, leading to clearer communication across the workflow. Similarly, the possibility for structuring the TCF such that it is machine-readable to support digital exchange between stakeholders across the value chain, and enable advanced techniques such as the computational search for a solution space in the part's design and manufacture with 4DP processes. By having a better way to illustrate the defining properties of the 4DP part, it will also provide a testable criterion for metrologists and test engineers to verify the 4DP part's conformance for use.

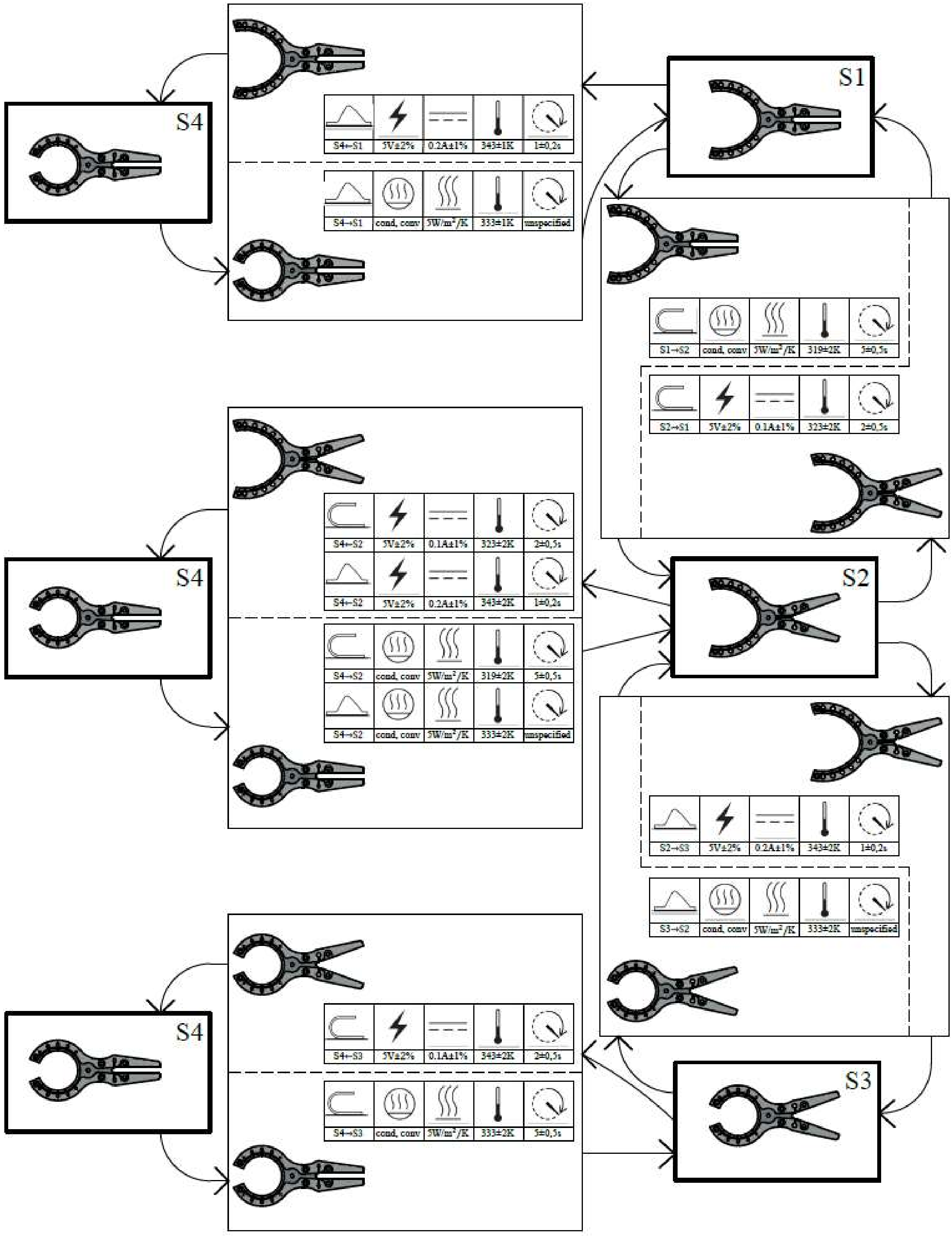

Figure 7: Bill of Transformations (BoT) for the mini-gripper use case

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