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A review on elastic storage mechanisms with a programmable cyclic output

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Abstract

In this review a comprehensive list of elastic energy storages with a programmable cyclic output is constructed. These systems can simultaneously replace the conventional use of springs to store energy together with a gear train to create a programmable cyclic output. Without showing any disadvantages like poor mechanical efficiency and rigid body interactions. All found designs were categorized based on an established classification. Afterwards a metric was constructed to evaluate each design based on criteria important for energy storages and frequency multipliers. The most promising design is an eight-bar singularity based mechanism, which if statically balanced, can fill the gap regarding maximum reached frequency multiplication reported in literature. The capability of these mechanisms to controllably store energy and create a programmable cyclic output can be exploited for the actuation of soft robotics.

Introduction

Programmable elastic energy storages with a cyclic output are needed for a lot of applications. They can be used, among others, to actuate soft robotics [1], for instance to mimic gait or any other cyclic movement, to innovate modern watch design by replacing the main spring and gears, in piezoelectric energy harvesting to store external energy and multiply it to the correct frequency of the harvester [2] and in tailoring micro-actuators [3, 4].

The conventional method to store elastic energy while simultaneously utilizing this stored energy to get a programmable cyclic output is to separate the functions into two discrete building blocks. One, that can store the elastic energy and the other one to extract and convert the stored energy into an alternating output, analogous to a frequency multiplication. A well known example can be found in the commonly used mechanical wrist watch that firstly stores its energy in the mainspring and uses a gear train to transform the stored strain energy and multiply the motion frequency to correctly depict time. Classical gears are not just essential in watches but are the most prevalent method of mechanical frequency multiplication and speed conversion. They consist of discrete components which rely on rolling based contact to transmit torque and speed. This, however, engenders a lot of shortcomings such as backlash, friction, wear, poor mechanical efficiency and the need for lubrication. Already adding up with the fact that the multiple parts ask for the need of assembling.

This is where elastic compliant mechanisms can prove to be useful. Exploiting the deformation of slender beams to transmit forces and motion, and as such avoiding the relative motion between parts seen in conventional gear and energy storage mechanisms. This results in the omission of friction and backlash and the need for assembly [5]. Besides, elastic potential energy is stored due to the deformation of elastic beams, circumventing the need for an independent elastic energy storage system, constituting to the possibility of making the whole system monolithic and thus not demanding assembly. Recent advances in frequency multiplier transmissions have shown that it is possible to achieve a frequency multiplication, even trough the inherent limitation in range of motion of elastic mechanisms. These advances have however only been limited to conceptualizing higher frequency multiplication transmissions while only a frequency quadrupler has actually been manufactured and tested. This is attributed to, among other challenges, the high forces and stresses encountered while trying to reach higher multiplications, due to the increasing stiffness. To optimize the use in applications mentioned earlier usually these low frequency multiplications do not suffice. This is why an energy storage with programmable alternating output is desired of which the frequency can be optimized to correctly suit its application. This report serves to answer the question: “How can elastic energy be stored and converted into a programmable cyclic output?” With 'programmable' the ability to adapt the outgoing frequency multiplication is meant. In order to answer this question research will have to be conducted into improving existing solutions found in literature or by finding new concepts.

The aim of this literature study is to find the most promising solution to the research question. In the results a comprehensive list of all possible solutions was made and all designs, from literature or merely conceptual, were categorized and evaluated using established criteria. In the discussion the devices were compared and the most promising solutions recognized.

Method

The aim of this literature study is to find as many solutions to the research question as possible within the time limit.

Because the field of research is very new and only a handful of designs have actually been realized, this literature study focused on three separate activities which were all conducted parallel to eachother. The first activity consisted of a comprehensive research into the recent discoveries in the field of elastic energy storages with programmable cyclic output. Trying to find solutions for challenges that were not solved yet. The second activity focused on purposefully looking at other fields of research to see if solutions could be adopted and turned into their elastic counterpart. Some of these research fields include, magnetism, electronics, pneumatics and shape changing polymers. The third activity consisted of brainstorming for new ideas in all these fields to find even more concepts and possible solutions for other challenges.

After the initial literature research and when all concepts were finalized, these were all evaluated using the same metrics. The complete metric with a short elaboration can be found in Table 1. The metric was setup following the important aspects of an energy storage, like energy density, combined with the important aspects of a frequency multiplier, like programmability and frequency range. Some other criteria were also added to help distinguish between suitable applications. For example force variation is not important for actuation of soft robotics but any task that involves precision, like the mechanism in a wrist watch, does reap benefits from it. The metric is constructed and evaluated without an implementation in mind but results will discuss suitable implementations.

To correctly give an approximation of energy density in a concept, and make the results comparable the final value should not depend on the scale of the design. This was done through non-dimensionalizing the energy density by multiplying it with the Range of Motion (RoM). The RoM entails the entire path of the output during a full cycle of the input and has been chosen instead of another length scale due

Criteria	Elaboration
Energy density*RoM	How much energy can be stored in the device without hindering the range of motion (RoM)? Quantative evaluation per design.
Scalability	What are the effects of scaling the device? Qualitative evaluation of drawbacks at the microscale and macroscale.
Number of cycles	How can a higher number of cycles be reached and programmed? Qualitative evaluation of what determines the number of cycles, the challenges that need to be solved in order to reach a higher number of cycles and a quantative relation for scaling is given.
Force variation	How constant is the output force interperiodic and intraperiodic? Qualitative evaluation of the linearity of the force variation
Frequency range	What limits the frequency range of the device? Qualitative evaluation on what the frequency range depends on and its complications.

Table 1: Metric used to evaluate all designs

to its interdependence with energy density. Notice that the remaining equations are still dependent on material properties and the time scale. However, this is seen as an essential attribute to the performance and is thus left intact, but could also show where improvements can be made. The energy density was approximated using three different methods depending on the availability of data in literature. The first method consisted of calculating the input work by the area under the force-displacement graph and dividing by the volume to get the energy density. The second method calculated the energy density using the area under the stress-strain curve. And the last method was used if no data is available and consisted of estimating the energy density by using Euler-Bernoulli beam theory. For scalability the effects at microscale and macroscale were investigated using available literature solely during operation. No complications during manufacturing were taken as an assumption. The Force variation criteria looks at how linear the force variation between input and output is. This is done by taking the derivative of the input-output displacement, in order to get a velocity relation between input and output. Because of the known power relation, which is simply a multiplication between force and velocity, the force variation can thus be determined.

Results

Concepts

The first idea of an elastic frequency doubler transmission reported in literature can be seen in Figure 1 a [6], essentially modifying the boundary condition (B.C.) of the mechanism during operation using an intermittent contact between the device and a rigid surface. Upon engagement of the contact the displacement direction of the output point switches. This method of altering the boundary conditions has not only been solved by using a contact surface. Another example (Figure 1 e[7]) replaces a contacting surface with microflexures that serve the same purpose as the contact surface. During operation, depending on the actuation direction of the input shuttle, either one of the microflexures will buckle shifting the instant center of rotation of the beam. Resulting in an output that is, regardless of the input direction, always upwards. The concept seen in Figure 1 d is a concept derived from the buckling beam mechanism. Similarly, it uses tensioning flexures to change the boundary conditions of the output beam, which alters the instant rotation point of the output. This device can be seen as a building block which can relatively easily be concatenated and manipulated to reach higher programmable frequency multiplications. As the concepts using tensioned flexures exploit the same working principle as the contact-aided designs, these can be interchanged with a contact surface to produce a similar result. The complications of this interchangeability will be discussed when the devices are evaluated. The last two concepts (Figure 1 b-c) can be classified as contact-aided, however they employ direct contact with the output through plucking pins to alter its direction. This can be done by either pushing a bistable beam into its other stable state (Figure 1 b) or by forcing a flexure to follow the pin until the parasitic displacement releases the output flexure and causes contact with the next pin (Figure 1 c).

Figure 2 shows frequency multiplication concepts based on exploiting the displacement around the singularity point of a mechanism, analogue to parasitic displacement in a double flexure guidance. The use of a singularity in a device to double the frequency was first mentioned by Haridrabhai et al. [10], but further developed and researched by D. Farhadi Machekposhti [9]. The working principle can be illustrated with a double-slider four-bar mechanism (Figure 2 c.1). Upon applying a reciprocating input displacement the output displacement reciprocates with double the frequency of the input (Figure 2 c.2). One of the big disadvantages of using singularity in a four-bar mechanisms is the inherently low geometric advantage ($G.A.$), i.e. input-output velocity ratio. Resulting in the need of a stroke amplifier to amplify the output displacement (Figure 2 a). A solution to this has been reported in literature [9], which instead uses an eight-bar mechanism that enables optimization to achieve a higher $G.A.$

The devices seen in Figure 1 a,d,e and Figure 2 a,b, can be made programmable by concatenating its working principle as building blocks and using a single modified building block with higher stiffness to store energy. In theory creating an architected material on which building blocks can be attached to modify the frequency of the output. The feasibility of this concept will be further elaborated during the evaluation.

For now all the devices introduced have been transmission based mechanisms that have a continuous input-output relation. These devices would need an extra mechanism to allow for storing strain energy without the device instantly going back to its only stable state. Multistable elements can overcome this problem by trapping strain energy while being in a higher energy state. Transition wave based mechanisms are metamaterials build up of these multistable elements, that can support a nonlinear pulse that sequentially switches its elements form one stable state to another. They trap strain energy that upon an external impact, which overcomes the energy barrier, is released and supports the further propagation of the wave. Due to the nonconvex multiwelled energy landscape of a unit cell these transition waves are strongly nonlinear. Typical energy landscapes of bistable unit cells can be seen in Figure 3 a.3. To obtain an alternating output, rotation points in the metamaterial can be created by altering the propagation of the wave along the lateral direction. A re-

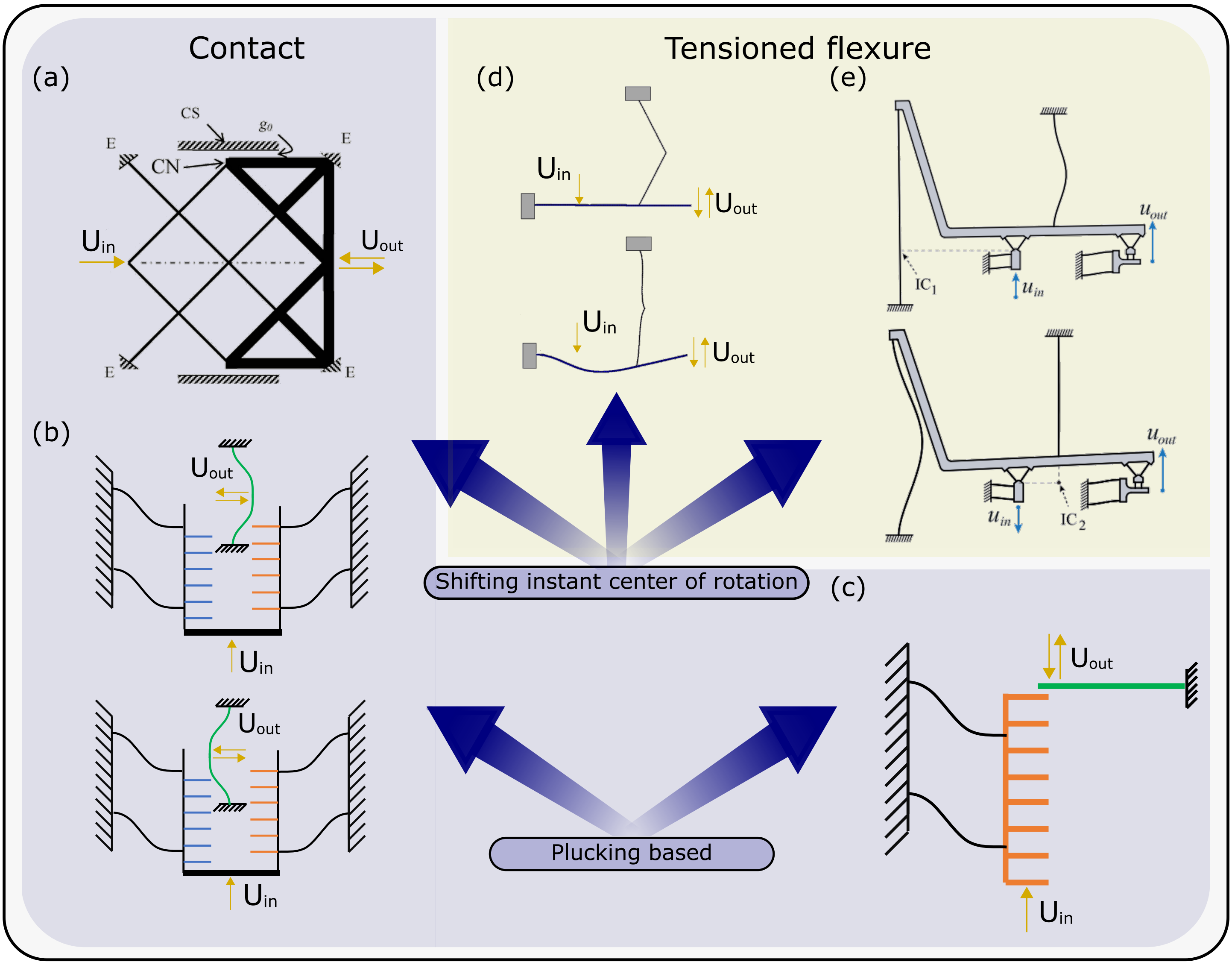

Figure 1: Concepts that work on the basis of restricting motion in a certain direction via contact or buckling. (a) A frequency doubler mechanism using contact to change the boundary condition during operation [6]. (b) Concept that uses contacting pins to push a bistable beam into its other stable position. (c) Concept that operates by pins plucking a flexible beam. (d) Concept frequency doubler that uses tensioned flexures to change the boundary condition. (e) Frequency doubler mechanisms using buckling microflexures to interchange boundary conditions [7].

duction in area of the unit cells switching states facilitates the creation of this rotation point. Multiple methods can be employed to modify the propagation of the transition wave. The first method makes use of a velocity gradient caused by adjusting the energy density of individual cells Figure 3 a. The second method to create a rotation point is using defects to preclude certain cells from switching states, thus not reducing area in predetermined areas Figure 3 b. Another method to alter the area reduction in the lateral direction is to use triangular cells, where the relative area reduction is smaller closer to the vertex with the smallest angle Figure 3 d. The deformation sequence of this design can also be made deterministic with a predetermined pattern by altering the energy density between individual cells [13]. The last method that will be discussed uses the concept of compartments to control the propagation of the transition wave. These compartments consist of barriers that only let the wave propagate in the direction of least resistance, i.e. where no barrier is present. By modifying these compartments a rotation point can be created.

For now all discussed designs have had a translatory input-output, however the search for a programmable cyclic output does not limit itself to this, and as such also rotary outputs should be considered. Examples of systems that possess this output characteristic can be seen in Figure 4. Rational design of metamaterials enable systems endowed with properties that are unattainable in conventional materials. One group of systems are the twisting mechanical metamaterials (TMM), these materials possess the property of compression-twist coupling. Allowing a longitudinal strain to be transformed into axial twisting. The first to illustrate the possibility of TMM are Frenzel et al. [14] (see Figure 4 a), converting a compression into a rotary output using a three-dimensional array of tetrachiral unit cells. In this paper only small twists were reported, not larger than 3°, another disadvantage is the inherent large dependence on number of unit cells and its size effects. Increasing this number leads to stiffening of the device, essentially leading to a smaller twist per longitudinal strain. A device showing larger twists, makes use of tensile strain instead of compressive strain (see Figure 4 b). Avoiding the limitations of twist seen in compression-twist mechanisms due to buckling, and reports a fabricated sample reaching 60 degrees of axial twist. The property of compression-twist coupling has also been shown using a metamaterial comprised of

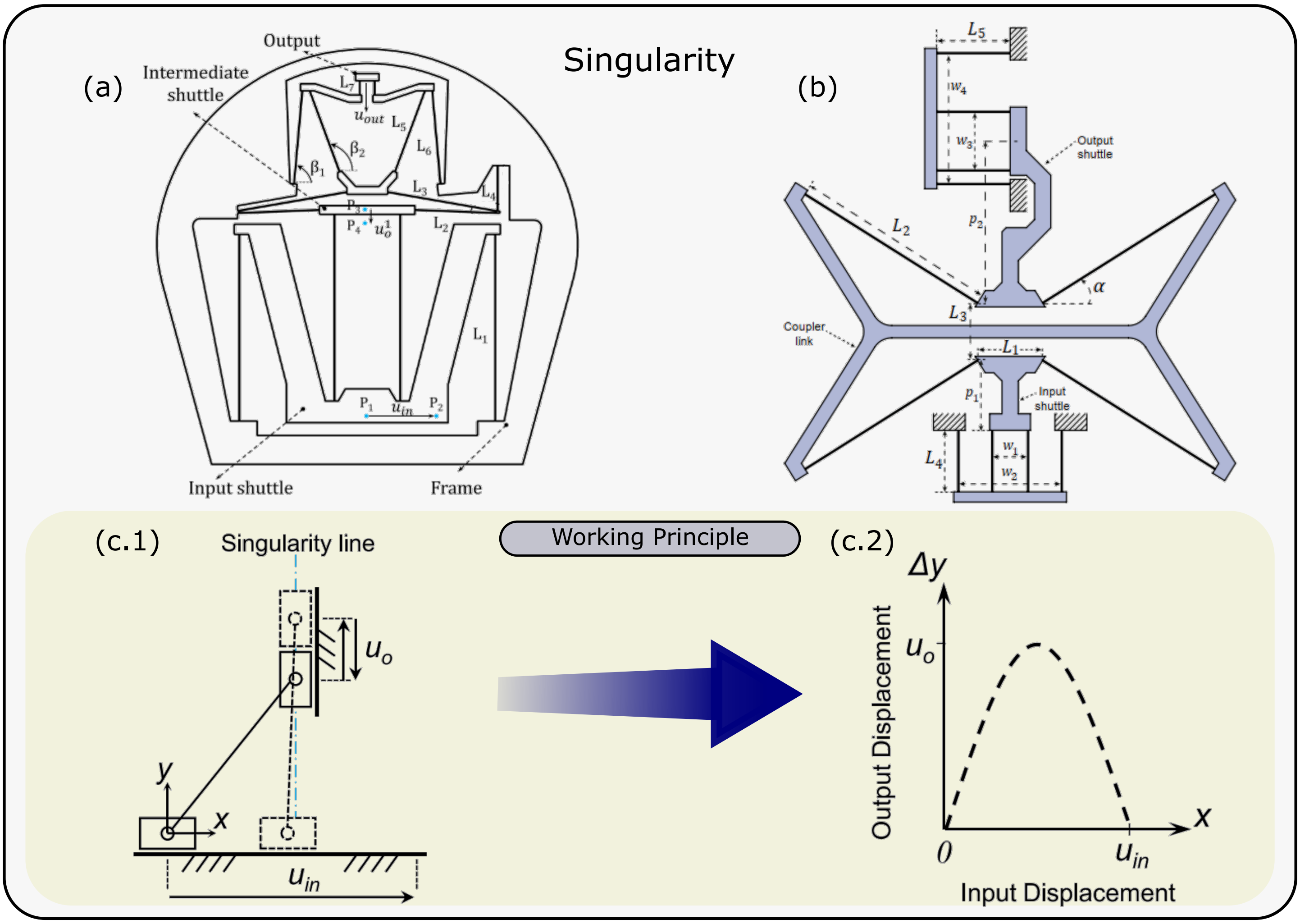

Figure 2: Frequency multiplier transmissions based on the concept of exploiting the singularity point in a double-slider mechanism. (a) Frequency quadrupler using two concatenated singularity based four-bar frequency doublers with an intermediate stroke amplifier [8]. (b) Singularity based frequency doubler using an eight-bar linkage to additionally double the geometrical advantage [9]. (c) Working principle of singularity based frequency doublers (c.1) four-bar double-slider mechanism showing the input-output around the singularity line (c.2) Graph showing output displacement versus input displacement for a singularity based four-bar frequency doubler.

bistable origami cells Figure 4 c. A device that overcomes the size effects present in the device by Frenzel et al. [14] is shown in Figure 4 d, enabling the potential for local and global scalability. This device was capable of reaching 38 degrees of twist. Transforming a translatory input into a rotary output is not a contemporary concept. Examples date back to prehistoric times Figure 4 e,f. These devices use friction between a wire and a pole to create a rapid rotary output motion, which is exploited for the purpose of making fire and drilling.

The penultimate design that will be discussed relates a rotational input to a rotational output, similar to a revolute joint Figure 5. Because of its compliancy the design allows for storing elastic energy which can be released on either side, analogue to a spiral spring or torsional spring. The reported design has a constant motion in a large part of the motion range. The range of motion can be increased due to the positive linear relationship with the height, however increasing the height has a negative impact on the lateral stiffness.

The last concept employs the basics of a ring oscillator (see Figure 6), to create an oscillating output. A ring oscillator is a device that exploits the delay of an inverter gate, by concatenating an odd number of inverter gates in a ring. The output of the last inverter gate, which is essentially the inverted signal from the input, is fed back as an input to the first inverter gate, which causes oscillation. The possibility to use a ring oscillator as a soft device has already been reported in literature [20, 21] using pneumatics. To create a higher oscillation the signals between the inverter gates can be summed, indicated in Figure 6 with A, B and C.

Classification

The classification (see Figure 7) categorizes all designs based on basic principles and characteristics. As a consequence the groupings used in the previous section do not all fit in the same class, but are indicated in the classification as groups (orange).

The first step of the classification separates the designs based on the motion of their input-output relationship, i.e. rotational and translational. Because all of the translational to rotational devices are backdriveable no separate class was created for rotation-translation. The second step divides all the designs based on the underlying mechanism to create a cyclic output. This can either be done through a transmission based mechanism, which is a system interposed between a source and an application for the purpose of adapting one to the other. Or an instability based mechanisms that exploit instabilities to store and rapidly release energy. An example of instability based systems are mechanisms that can support transition waves through their multistable unit cell behaviour. The last step in classification only adds to the translational

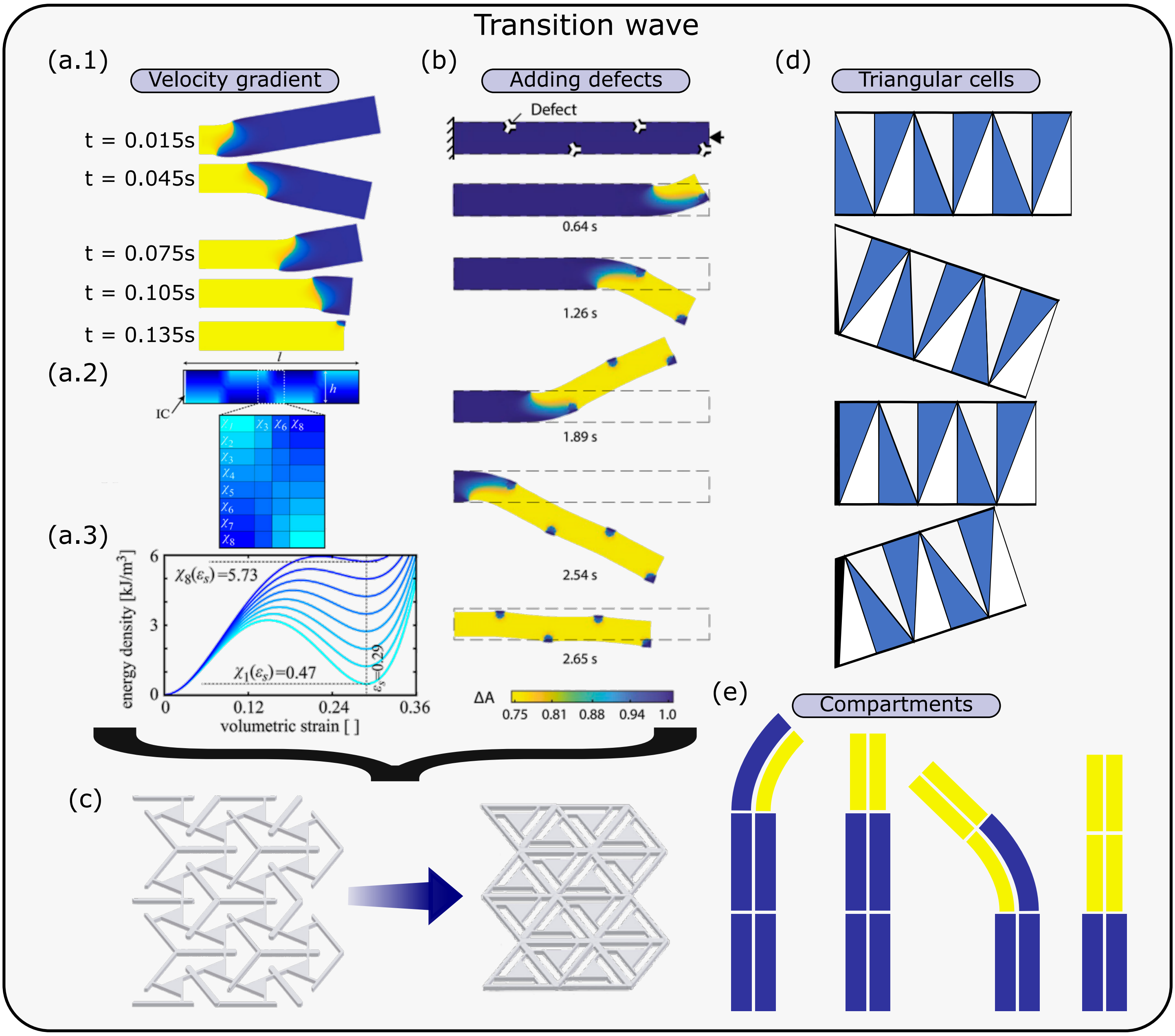

Figure 3: Concepts that modulate transition waves to create rotation points resulting in an alternating output. (a) Transition wave with an energy density induced velocity gradient to create rotation points in the high velocity parts [11]. (a.1) Resulting serpentine motion. (a.2) Velocity gradient shown as distributed through the metamaterial. (a.3) Graph showing the different energy densities of the gradient. (b) Using defects to manipulate bistability, precluding closing of the unit cell, in order to guide the transition wave [12]. (c) Matrix of 2x2 unit cells [12]. (d) Concept utilizing a single row of triangular cells to create a rotation point. (e) Using compartments to guide the transition wave

input-output and transmission based mechanisms due to their more extensive literature reportings, however these classifications could also be applied to the other classes. It divides the systems into whether their input-output relation is linear or nonlinear.

Evaluation

The metric with a short description of evaluation can be found in Table 2, the comments made will be elaborated upon further in this section. Also the numbers in the table will be used to indicate the different designs. The methods used to calculate and quantify the metric were discussed in the method section and further elaborated upon in the supplemental material.

As can be seen from Table 2, the transmission based devices (1-5, 14 and 15) generally score way lower regarding the energy density criteria, this is mostly caused by the effectiveness of trapping energy in a multistable system with a metamaterial like structure compared to storing potential strain energy. For transmission based devices this criteria can be increased through the RoM of a device by concatenation. It is expected that even though no value could be found for designs (6-8, 13) their energy density would be of similar order of magnitude as the other transmission devices. Designs (17,18) only have relatively small areas of energy storage, e.g. through tensioning of the rope, and as such their score on this criteria can be expected to be lower than any of the other concepts.

For the scalability the behaviour at microscale and at macroscale is investigated and challenges recognized. One of the most common problems is the use of contact between rigid parts in the mechanism (designs 2,10,11,14,15,17,18). At a microscale this can lead to stiction and wear during opera-

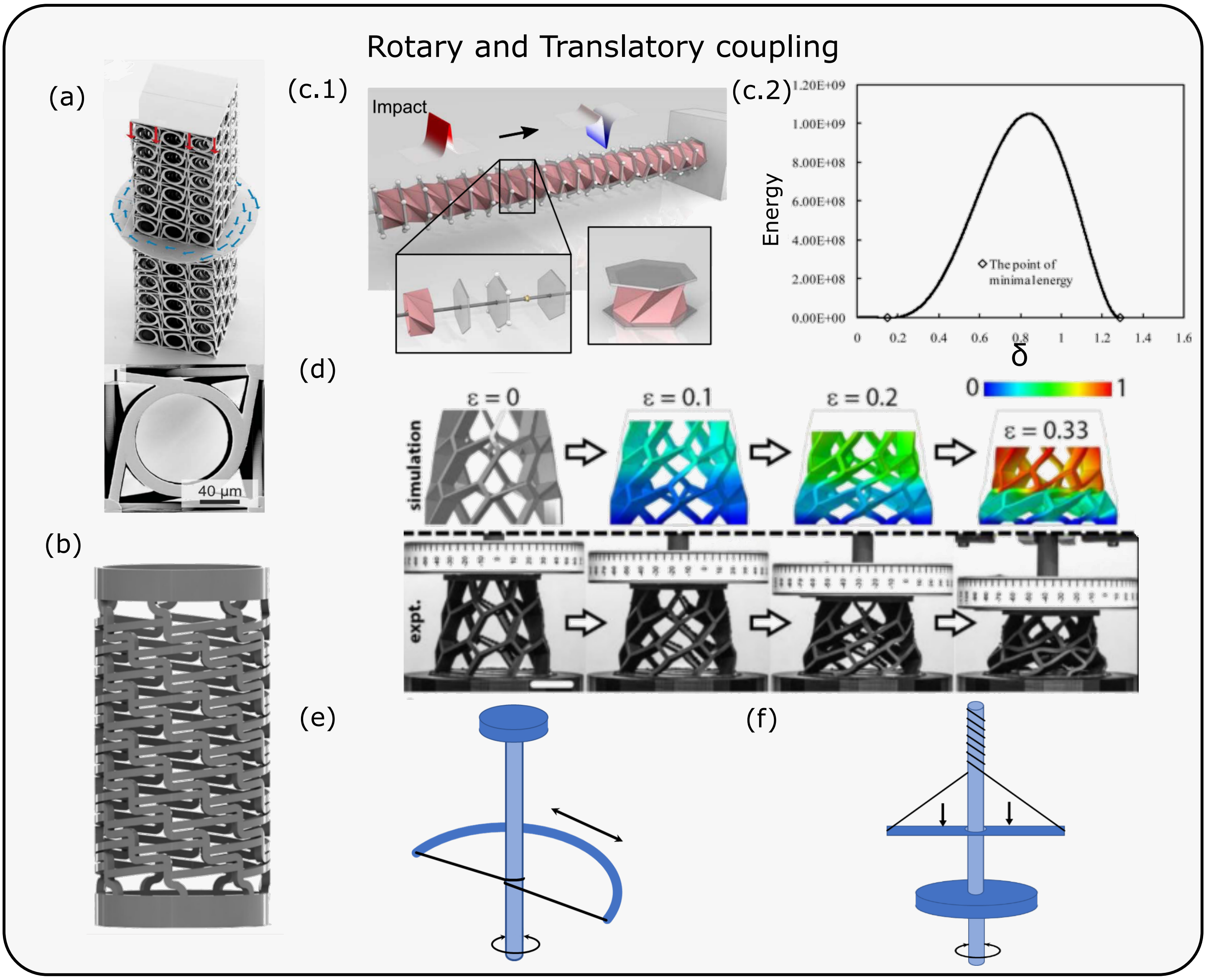

Figure 4: Concepts transmitting translatory motion into rotary motion. (a) Three-dimensional tetra-chiral metamaterial transforming an axial strain from compression into a twist [14]. (b) Cell-based tubular structure which exhibits extension induced twist [15]. (c) Origami-based metamaterial with bistable cells coupling an axial translation to an axial rotation. (c.1) Series of arranged origami unit cells [16]. (c.2) Energy landscape during folding process of one segment. The level of folding is indicated by δ, which is the angle between the horizontal and one of the concave creases [17]. (d) Metamaterial with programmable compression-twist coupling [18] (e) Bow drill. (f) Pump drill.

tion [22]. Stiction occurs when micro structures with a large surface-area-to-volume ratio adhere to eachother, because the restoring forces can not overcome the large interfacial forces present at such a small scale. Wear is caused by rubbing and contacting of surfaces in devices at the microscale, since material can be pulled from the two surfaces after bonding due to contact. There are some solutions to reduce the effects of these issues like reducing the contact area, but contact should still, if possible, be avoided at all costs on the micro scale. On the macroscale especially contact surfaces that show frictional effects, e.g. contacts that slide or roll, are undesirable. Frictional surfaces (designs 2,14,15,17,18) lead to unwanted energy loss during operation.

Increasing the number of cycles is perhaps the most important criteria in the attempt to create a programmable cyclic output. To increase the number of cycles in transmission based mechanisms, their input-output relation can be used advantageously by concatenating these cycle doubler principles (designs 1-5) in series. These designs have the fastest number of cycle growth, as for each concatenation the number of cycles doubles. However, concatenation of these devices is not so straightforward and certain aspects are necessary to allow concatenation to higher frequencies. First of all, because the output of the first system is fed as input to the second system the signal from input to output should show similar behaviour, unlike for instance design 1 of which the input is a sinusoidal signal and the output is cosinusoidal. Also the geometrical advantage ($G.A.$) should ideally be linear as any nonlinearity will be amplified during concatenation and restrain further concatenation. Secondly, because in elastic mechanisms the mechanical advantage ($M.A.$), output to input force ratio, is not simply the reciprocal of the $G.A.$ due to internal straining. Input force would increase if a similar displacement amplitude is required for input and output, upon concatenation, leading to higher stresses. Another approach to view this is by looking at each building block like a spring with a certain stiffness, while concatenating, these spring stiffnesses add, leading to high forces at the input. This can be resolved by statically balancing the mechanism, which would essentially limit the function of the

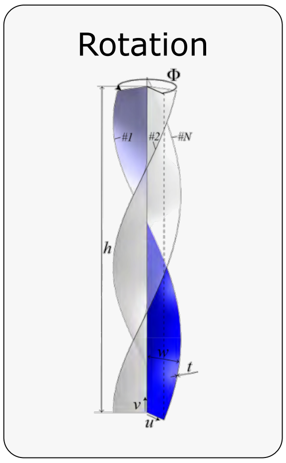

Figure 5: Compliant revolute joint made up of helicoidal shells featuring a large range of motion [19].

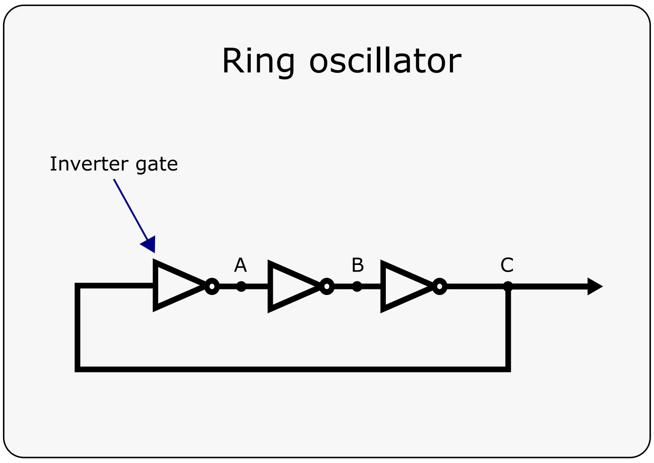

Figure 6: Ring oscillator concept, using an odd number of inverters to create an oscillation.

mechanism solely to transmitting forces and motion, jeopardizing the ability to function as an energy storage. However, a single non-statically balanced building block could be realized that serves the sole purpose to enable storage of strain energy which can be boosted by purposefully increasing flexure stiffness. Lastly, if a true transmission system is realized the work provided at the input is the same as at the output due to conservation of energy, i.e. $M.A.$ is the reciprocal of $G.A.$. This implies that a middle ground has to be chosen depending on the force or displacement amplitude necessary at the output. Also the force and displacement at the input are dependent on the maximum stress that the mechanism can handle. Increasing the number of cycles for the twist-coupling mechanisms (6-8) does not pose as many challenges, however the rate of increasing twist only grows linearly with the number of stacked elements. Also as these devices can simply be viewed as springs being loaded in compression or tension, the force required to double the twist on a stacked system is identical, as the stiffness halves. However a drawback to this is the fact that the bending and shear stiffness show a similar relationship when devices are stacked. Which is relevant if the longitudinal force is not perfectly placed in the center and with no angle. Also notice that to increase the twist, the best geometry is a long slender beam, which is easily subject to bending. The geometry would also lead to this concept being hard to put into a working system, because here rather the longest length scale than the volume is often of importance. Perhaps a solution to this problem would be to allow the material to roll up in a spiral to decrease the area required in a system, while still keeping the functionality. Transition wave based designs (9-12) show similar linear behaviour as twist-coupling devices, by increasing the number of rotation points. These mechanisms do not show any of the mentioned concatenation problems in transmission systems, due to the multistability of the unit cells. Design 13 has some similar disadvantages as earlier mentioned for the twist-coupling devices. Namely, to achieve a large rotation the optimal geometry is a long slender beam. Perhaps a solution is to exploit the inherent easy bending of such a geometry to put the design into a spiral form. Designs 14 and 15 both use contacting pins to push a beam into a specific position. These transmission systems should also be statically balanced to enable further concatenation, however due to the highly nonlinear contact forces this is significantly harder than for the previous mentioned transmission designs. The ring oscillator concept (16) requires a certain minimal delay to give the first inverter time to switch states. After this the number of cycles of the signal can be increased by adding to the odd number of inverters or by taking the sum of the multiple output signals in between the inverters.

The force variation can be determined by looking at the linearity between input and output displacement. The only fully linear design found in literature is design 1. Any further, design 4 only shows a small non linearity compared to most of the other designs, due to the possible optimization of many design parameters. Also, the devices that have a rotary output are categorized separately (design 6-8,13,17,18), as force variations do not lead to a variation in output rotation. The transition wave based designs all show large nonlinearities in the output displacement, especially interperiodic, as the amplitude increases/decreases a lot from start to end. Design 2 has a largely nonlinear force variation due to an unwanted vibration in the output displacement. While design 3 and 5 show more of a nonlinear sinusoidal input-output relation. Design 14 and 15 both exhibit a nonlinear force variation due to the contact between the pins and the beams. Design 14 does have the advantage of resisting a constant force while the buckling beam is in one of its states.

Transmission based devices show the largest frequency range of the output, due to their dependency on the input. Which is ultimately limited by the eigenfrequency causing too high deformations. The transition wave based designs are dependent on the propagation velocity of the wave, which can be tailored but shows less variation than the transmission based designs. The rotation based design (13) only has a small range depending on the geometry and induced strain.

Lastly, it is important to mention some of the yet unsolved challenges regarding the ring oscillator. Creating a mechanical ring oscillator is not so straightforward. First of all, the mechanical inverters found in literature (some examples, [23, 24, 25]) have inputs and outputs in a continuous form, i.e. are analog. This means that before the first inverter is done switching states, the input can already have changed which would block the whole system. This can be compared to having three gears in a ring which unless a delay is added between the gears would never be able to move, owing to the fact that gears can be seen as inverter gates inverting the rotation direction. The second challenge is how to supply energy to the system such that the output of the system does not attenuate. In the pneumatic soft ring oscillator the energy is supplied in the form of pressure, which is simultaneously one of the states of the system. The mechanical inverter blocks

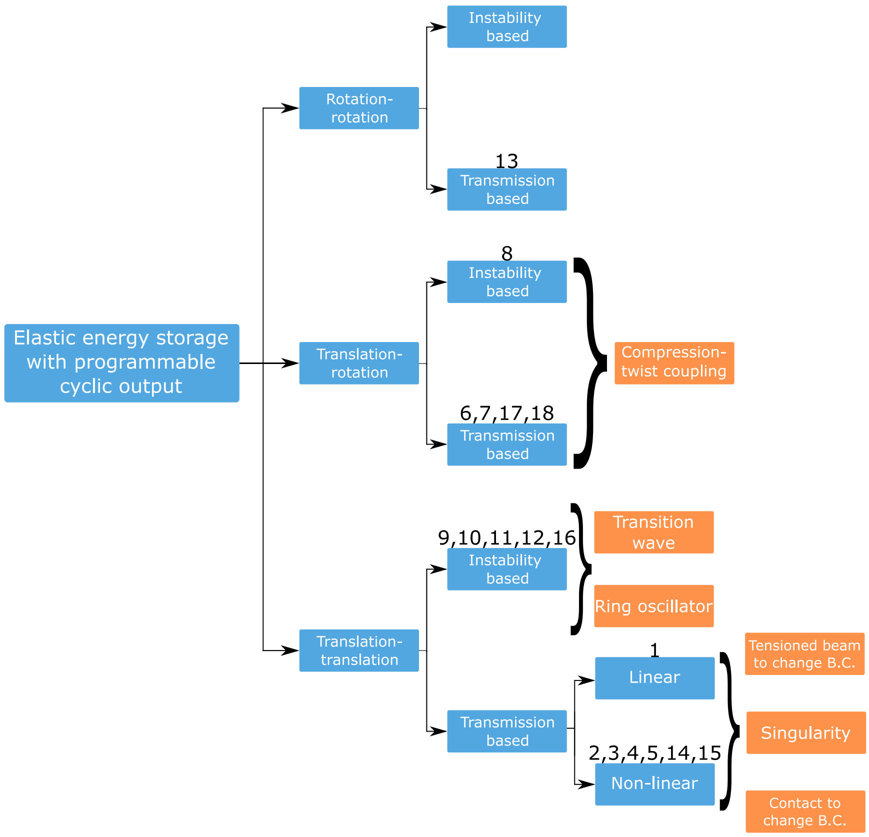

Figure 7: Classification of the designs (blue) and the groups found in literature (orange). The numbers indicate a certain design (see Table 2), but are not based on any sort of ranking.

have similar energy for both states and can as such not add energy. The last challenge would be how to connect the logic gates. From some of the example mechanical logic gates it is apparent that the state of an inverter gate is programmed as an analog displacement. This could lead to stresses in the system as deformation occurs during operation.

Discussion

To asses the evaluation and bring forward the most promising design, it is useful to limit the possibilities by eliminating some of the designs. This will be done by selecting the most promising design from the categories of translation-translation transmission based designs, transition wave based design and the twist-coupling devices. Design 13 will further not be taken into account due to the limitations regarding the rotation angle and bad geometry, however perhaps in the future a design could be thought of which would overcome this flaw through stacking of the design and solving the bad geometry by creating a spiral from the resulting design. Design 14 and 15 are both excluded due to their huge limitation regarding the frictional contact which is the basis of its functionality. Perhaps an exchange from contact-aided towards using a flexure to change the B.C. could solve this limitation. The ring oscillator design shows a promising method to create an oscillating output by arranging an array of an odd number of inverter gates, however further research is necessary to achieve a functional mechanical example which overcomes some of the yet unsolved challenges. Designs 17 and 18 both rely on the frictional contact between the rope and pole, which hugely limits the efficiency. This challenge would first have to be resolved to even contest the potential of other designs.

The most auspicious concept for the translation-translation transmission based designs is design 4. This is because the first design can not be concatenated due to the inherent input-output relationship. The second design has bad scalability due to the use of a frictional contact to change B.C. during operation. And together with design 3 and 5, the *G.A.* is largely nonlinear restricting the possibility of concatenation. Regarding the twist-coupling devices the solution with the most potential is design 8, because of the similar disadvantages to the other twist-coupling devices but the promising possibility of exploiting the instability in the unit cells. However, a design like this has not been reported yet, but the bistability of the unit cells and the rotation mode have been investigated. Concerning the transition wave based designs, all designs are very similar, but design 10 has a small advantage due to the size required to create a rotation point using velocity gradients compared to adding a defect. Besides, design 9 shows a promising method of creating a rotation point but no such unit cell has been reported yet in literature. The same can be said for design 12 but due to the compartments the size would already be larger than if a defect is used.

Now, only three designs are left. Specifically, design 4 that uses a singularity based eight-bar mechanism to double the frequency. Design 8 that uses multistable origami-based cells that couple compression to a twist. And design 10 which makes use of a transition wave that switches states of individual unit cells, releasing energy, which further propagates the wave. The twist-coupling design has only small rotations compared to the singularity based design, and even when concatenating it only scales linearly with the number of stacked elements compared to singularity based design that scales exponentially with base 2. There could however be applications where a rotary output is required, and for this design 8 would be best suited. Comparing the singularity-based design with the transition wave, the singularity based design comes on top. This is because of the large nonlinearities in the transition wave based design and similar to the twist-coupling idea the relatively worse linear scaling. The transition wave seems to score the best by far regarding the energy density multiplied with the range of motion, settling itself as a good solution where a smaller number of cycles and a larger non-linearity suffices. However, because of the beneficial scaling of the singularity based design, it facilitates rapid-growth of the RoM, and thus of the criteria where the transition wave excels. This could be accomplished by statically balancing the design to allow for further concatenations and would thus be the overall preferred solution. With the statically balanced frequency doubler building block a separate specially designed building block will be needed which focuses solely on storing the required strain energy. By optimizing the singularity based eight-bar mechanisms and statically balancing the building block it is expected to fill the gap in literature of transmission based mechanisms not reaching higher than a frequency multiplication of four times.

Some other areas where more research could be conducted to further increase the possibilities of storing energy and creating a programmable cyclic output are mentioned here. First of all, from the classification Figure 7, it can be seen that designs creating a rotary input-output relation are almost non-existent in literature. Perhaps a multistable unit cell which traps energy can be thought of which instead reduces its radius upon switching states, triggering the other stacked unit cells to propagate the transition wave. Another large gap which has not been solved yet is how to autonomously recharge such a energy storage system, in order to make the system work for extended periods of time. A possibility could perhaps be a pendulum which is able to deform the system, i.e. store strain energy. The solution could also lie in producing a rotary spiraling system, similar to the mainspring in a wristwatch where energy can be stored on one side and simultaneously extracted on the other side. Further research could also be conducted into solving challenges to create a mechanical ring oscillator. For instance using a transition wave with a slow wave velocity could be used to create a delay between the inverter gates, but then another challenge regarding the rechareability of the transition wave might only complicate things more. Perhaps a new representation of states in a mechanical inverter could solve these problems, replacing the conventional displacement-based read out. Lastly, research could be conducted into creating the most auspicious plucking based design (14), evaluate the impact of the contact, and try to optimize the guiding of the pins to enable high enough forces for the bistable element to switch states for all pins.

Conclusion

By creating a statically balanced singularity based eight-bar mechanism with a separate building block solely focused on storing energy, a possible solution is provided to the conventional problem of high forces not allowing for higher concatenation when creating an elastic energy storage with a programmable cyclic output. This would allow the possibility to exceed the frequency multiplication of the frequency quadrupler reported in literature. When a smaller number of cycles and a large nonlinearity in the output displacement suffices the application, a transition wave based design exploiting the instability in its unit cells is the preferred choice. If a rotary output is favoured, a meta-material with compression-twist coupling can be used. These solutions pave the way to mechanical actuation of soft robotics where a programmable cyclic output is required.

Criteria	1 Figure 1 e	2 Figure 1 a	3 Figure 1 d	4 Figure 2 b	5 Figure 2 a	6 Figure 4 a	7 Figure 4 d	8 Figure 4 c	9 Figure 3 d
A	0.0025-0.0046			0.0064-0.0945		-	-	-	700-3179
B	No problems	Frictional contact	No problems	No problems	No problems	No problems	No problems	No problems	No problems
C	input $\neq$ output	$\mathbf{2^n}$ n = # of contact points	$\mathbf{2^n}$ n = # of buckling beams	$\mathbf{2^n}$ n = # of singularities		$\mathbf{c * n}$ n = # of stacked elements c = constant			$\mathbf{c * \frac{n}{2}}$ n = # of rotation points c = constant
D	Linear	Largely nonlinear	Largely nonlinear	Nonlinear	Largely nonlinear	Rotary	Rotary	Rotary	Largely nonlinear
E	Large range due to input dependency								Limited range depending on transition wave velocity

Criteria	10 Figure 3 b	11 Figure 3 a	12 Figure 3 e	13 Figure 5	14 Figure 1 b	15 Figure 1 c	16 Figure 6	17 Figure 4 f	18 Figure 4 e
A	700-3179			-	79-158		-	-	-
B	Contact in bistable elements	Contact in bistable elements	-	No problems	Frictional contact	Frictional contact	-	Frictional contact	Frictional contact
C	$\mathbf{c * \frac{n}{2}}$ n = # of rotation points c = constant			$\mathbf{\frac{c*h}{J}}$ h = height c = constant J = torsion constant	$\mathbf{\frac{n}{2}}$ n = # of pins	$\mathbf{n}$ n = # of pins	Increase by adding inverters	$\mathbf{c * n}$ n = # of rope rotations c = constant	$\mathbf{c * \frac{w}{r}}$ r = radius pole w = length rope c = constant
D	Largely nonlinear	Largely nonlinear	Largely nonlinear	Rotary	Largely nonlinear	Largely nonlinear	-	Rotary	Rotary
E	Limited range depending on transition wave velocity			Small range	Large range due to input dependency		Small range depending on delay	-	-

Table 2: Metric with evaluation of each concept. Criteria A: Energy density * Range of motion, Criteria B: Scalability, Criteria C: Number of cycles, Criteria D: Force variation and Criteria E: Frequency range. For further explanation of the values see the supplemental material

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