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A Review on Planer Scissor Mechanisms for Spatial Deployable Structures

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Abstract—*this paper reviewed planar scissor mechanisms (SMs) in the applications of spatial deployable structures. These SMs consists of two beams connected by revolute joint behaves as mechanism during deployment and load bearing structure at deployed configuration. By altering the scissor unit middle joint position or modify scissor elements, various geometry shapes can be formed and additional locking devices is needed for SMs stabilization in final configuration. There are numerous studies have been conducted by experimentally, numerically and analytically to understand the SMs behaviour for spatial deployable structure applications. Although there are many studies dealing with designing new planar SMs in the application of spatial deployable structure and their calculation methods based on researcher's developed profiles, this topic still been an open topic to be carried out based on their geometric shapes and architectural functions. Therefore, this review aims to provide an overview of SMs behaviours in transforming the folded configuration structure element become spatial deployable structure. The reviewed papers covered the SMs problems, analysis methods and solutions in the application of spatial deployable structures. Based on the reviewed findings, stabilization is the main problem identified for the SMs. The simple geometry approach was used to analyse the system and various stabilization methods proposed subjected to the structures profiles and geometric principle. The deployability conditions and basic scissor unit types must be examined in term to understand their geometric design principles. On the basis of these SMs, the reviewed outcomes are herein will contribute to the better understanding of the SMs behaviours in spatial deployable structures application.*

Key words— *Scissor mechanisms (SMs), deployable structures, stability, geometric shapes, architectural*

I. INTRODUCTION

Transformable structures currently gained a recognition as fast assemblies technique to obtaine space and eliminate transportation constraint in prefab construction industry. The present transformable structure technique is aimed to achieve speedily construction with space, simple and practical, greater rigidity, transportable and embracing sustainable principle [1, 2]. This transformation actions required mobility called deployable mechanism to connect each other to transmit force and motion [3] and its behave as mechanism during deployment and load bearing at deployed configuration [4] known as Scissor Mechanisms(SMs). The SMs is the basic structural module [5, 6] consists of two beams connected by pivot at an intermediate point [6] and hinged at their end nodes to end nodes of other SMs. This concept also well-known as the lazy tong system [7]. The basic SMs is showed in Fig. 1.

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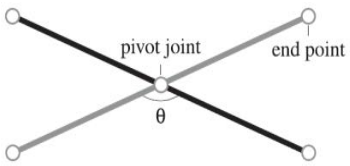

Figure 1: A typical Scissor Mechanisms (SMs)[8]

The SMs main disadvantage is it required additional locking device for stabilization at deployed configuration [9]. The stabilization of the SMs is subjected to the kinematic behaviour of the system and most common deployable scissor mechanism structures is one degree of freedom (DOF) which represents that only one actuator to move and fix the system [3]. The SMs behave as single element once locked in position through additional restraints devices in fully deployed state [10]. Apparently, the studies on SMs in the application of spatial deployable structures since 1960s have been found in various fields such as architecture [11], aerospace [12], aviation [6], civil engineering [13] and others technical applications. In civil engineering, the used of planer SMs in the application of spatial deployable structures was the most common method and currently adopted in prefab construction industry. This is because the prefab volume becomes increasingly large and the storage of the launch vehicles is limited. Therefore, the deployable spatial structure with compact folded configuration during manufacture and stably expanded as designated geometric configurations is sent to place for solution at site. Thus, the research associated with SMs in the application of deployable spatial structure has become a famous topic recently.

In line with this development trend, this paper aims at provide an overview of planer SMs behaviours in the application of spatial deployable structures. The final outcome targeted in providing the better understanding covered the SMs problems and solutions in the application of spatial deployable structures. Besides, the deployability conditions and basic scissor unit types also been explored to understand their geometric design principles. Therefore, the past and present SMs spatial deployable structures research papers will be reviewed and discussed. Finally, the reviewed outcome are herein contribute to the better understanding for the SMs behaviours in the application of spatial deployable structures.

II. Scissor mechanisms (SMs) deployable structures

A. Basic scissor unit

The initial determination of basic scissor unit in designing the deployable scissor structures is the most importance stage due its influence to the geometric shape. The basic scissor unit is two straight bars connected at their intermediate points by pin joint. By altering the location of the scissor hinge, three distinct basic scissor units called translational, polar and angulated units were obtained [14]. The geometry shapes and characteristics of these three scissor units were showed in Table 1.

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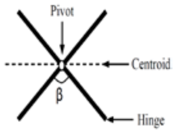
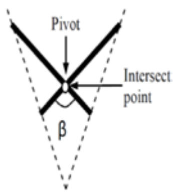
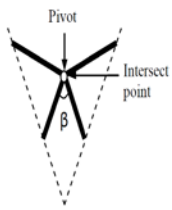
Table 1: Scissor units' types, geometry shapes and characteristics [14]

Types and Geometry shapes	Characteristics	Remarks
Translational unit  	• Centroid connect upper and lower nodes. • Form rectilinear unit and only can translate without rotation. • Remain parallel (Upper and lower) during and after deployment. • Trigonometry method used to solve the unknown parameters of the system.	• β is deployment angle. • Pin joint. • Introduced by Pinero in year 1961 for portable theater[15].
Polar unit  	• Scissor hinge away from the mid-point of the two straight bars. • Intersect at one point. • System generate a curvature during deployment and form curvilinear unit. • Top, bottom and scissor hinge lie on concentric circles. • Curvature increases if intersection point closer to unit[18]. • Trigonometry method used to solve the unknown parameters of the system.	• β is deployment angle. • Pin joint. • Introduced by Kwan in year 1993 & 1995 for satelite panel in space technologies [16, 17].
Angulated unit  	• Intersect at one point. • Consist two identical angulated bars. • Used for radially deploying closed-loop structures. • Capable of retracting to their own perimeters. • Trigonometry method used to solve the unknown parameters of the system.	• β is deployment angle. • Pin joint. • Introduced by Hoberman in year 1990 for dome and sphere shapes structures[19] .

The scissor mechanism also called pantographic with the structural system is based on their morphology and kinematic behaviour [20, 21]. The spatial bar transformable lattice structures consisting of hinged bars may use to produce different types of SMs deployable space structures [20, 21].

B. Scissor mechanism in spatial deployable structures applications

The scissor mechanism in the application of spatial deployable structures has keeping changes and improvement to produce innovative transformable structures since first establishment by Spanish architect Pinero in year 1961 with his mobile theatres as showed in Fig. 2. This is happened because of the transformable structures using scissor

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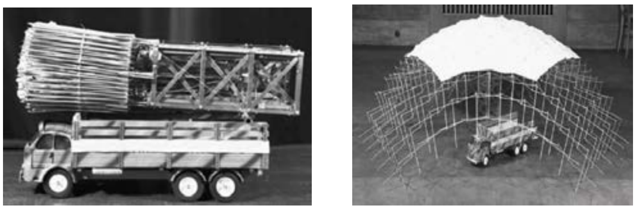
mechanism sometime facings problems during and after deployment such as stability issue, geometry constraints and etc. Therefore, a new stability profile of SMs spatial deployable structures has been introduced by several researchers based on a problems diagnosed. At the same time, the profiles of the SMs spatial deployable structures until today still an open topic and keeps changes with the innovative ideas created.



(a) Mobile theatres (b) 3D configuration

Figure 2: Pinero's mobile theatres [1]

The past researchers on the topic of using SMs in constructing spatial deployable structures have started with the initial geometry design to achieve architectural function. The geometric compatible issues will firstly solve since this problem is the main contributor to the transformable structures failure. After that, SMs as deployable mechanism with one degree of kinematic motion commonly used in pantographic spatial deployable structure in deployment stage and once reached their final designated configuration, the additional restraints is needed to stabilize the system. Based on these three stages, the past researches related to SMs for spatial deployable structures lies in the issue related to the final configuration stabilization matter. A review through the past research on each structure profile under differences problems diagnosed, analysis results finding and finally proposed suitable solutions with new profile. Table 2 presents an overview application problems, analysis and solutions with of past research conducted to access the problems, analysis finding and solutions proposed with differences structure profiles for SMs application in spatial deployable structures.

Table 2: Past research conducted on SMs deployable structures with difference profiles

Author(s)	**Structure profile**	**Problems Diagnosed**	**Analysis finding and solutions**
Esther[1]; Pinero [15]	Pinero's mobile theatres, (1961). Fig.3.	Stabilization at final configuration	A:System stability. S:Provide additional cable for stabilization.
Friedman & Ibrahimbegovic [22];	Zeigler's collapsible self-supporting dome shapes	Susceptible to catastrophic failures	A:Member buckling. S:Introduce sliding joints at some

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Zeigler [23]	scissor structure, (1974). Fig. 4.		intermediate nodes and flexible connections at end nodes by springs.
Raskin, [24]	Clarke's (1984), Hemispherical dome (Intersect three scissor units called "Trissor"). Fig. 5.	Snap through action at final configuration.	A:Geometric non-fit in all partially unfolded positions was compensated by bending of the relatively flexible struts. S:Reverse snap through by applying sufficiently strong pull at certain points(Structure easily folded back to compact bundle)
Raskin, [24]; Krishnapillai[25]	Krishnapillai's (1992), Hexagonal self-locking pantogra-phic unit. Fig. 6.	Snap through effect during folding and deployment due to difference bars lengths in the radial SLEs.	A:Number of configurations satisfying the zero stress requirements in folded and deployed form. S:Different polygonal shapes to form flat slabs as well as single and double curved structures.
Escrig & Valcarce	Deployable roof for a	Generating geometry	A:Stress-free during

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l [26, 27]	swimming pool in Seville. Fig. 7[28].	pantographic structures and performing analysis.	deployment. S:Additional members or locking devices to stabilize the system at final configuration.
Kwan et al.,[16]; Kwan[17]	Satellite panels using planer polar scissor. Fig. 8.	Deployment	A:Control the system S:Additional cable elements to move and fix the system
Atake, [29]	Towers, bridges, domes and spatial structures in 1995. Fig. 9[30].	Structures stiffness	A:Make the structures stiff. S:Use tension components such as wire or membrance.
Hoberman, [19]; You & Pellegrino [18]	Iris Dome at 2000 World’s Fair, Hanover, Germany using simple SLE angulated element. Fig. 10[31].	Perimeter inconsistency	A:Intersection of the neighboring angulated elements all four angulated element lie on different planes. S:Adopt multi angulated pantographic structures (elements have more than one kink angle) introduced by You and Pellegrino. Fig. 11.

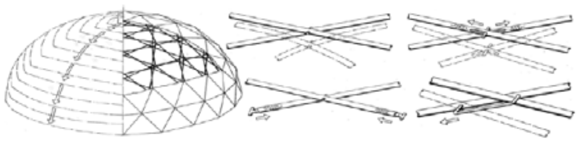
You & Pellegrino [18]; Kokawa, [32]	Ring structures. Fig. 11.	Susceptible to wind effects	A:Opened configuration forms a less aesthetic toroidal-like shape. S:Introduced aesthetic retractable dome system by Kokawa with pin jointed support. Fig. 12.
Kokawa, [33]	Cable scissors Arch (CSA)	Geometry shape problem	A:Achieving geometric flexibility. S:Innovative scissor convertible structure
Atake, [34]	Scissor shells polyhedral structure	Geometry shape problem	A:Achieving geometric flexibility S:Novel spatial scissor system to constitute
Akgun et al., [3]	Convertible roof	Geometry shape problem	A:Achieving geometric flexibility S:Adaptive deployable spatial scissor-hinge structural mechanism called Modified SLEs (M-SLEs).
Gantes et al., [35]	SLEs self-stable	System stability	A:Geometry design

	deployable structures		S:Adopted geometric incompatibilities principle and additional inner SLEs.
Guest et al., [36]	Triangular panel model on a helical strip	System stability	A:Geometry design S:Adopted geometric incompatibilities principle and additional inner SLEs.
Zhang et al., [37]	Deployable flexible beam	System stability	A:Dissipate the unwanted vibration and rotation energy S:Adopted geometric incompatibilities principle and additional inner SLEs.
Chen & Guan, [38]	Deployable hexapod paraboloid antenna without locking mechanism during deployment	System stability	A:Geometry design S:Adopted geometric incompatibilities principle and additional inner SLEs.

Note: A-Analysis Findings ; S-Solution

It can be observed that the SMs in the application of spatial deployable structures mostly diagnosed the system problems in their final deployed configuration which means remain in stable state to sustain loads. For example, the additional tension wire was used to stiff the deployable structures become static at their final deployed configuration. Besides, additional inner SLEs also added as the secondary SLEs which used to lock the SMs become fixed and static. Some of the researchers also using design of geometrical constraints to fixed the system in their final configuration which called “self-stable method”. This self-stable method adopted geometric incompatible principle and additional secondary inner members design to achieve system stability during design stage [38]. It means that the system in their final deployed configuration can be stabilized by itself due to geometric constraints and secondary inner members lock into position for the system. Therefore, it is important for SMs in the application of spatial deployable structure for future research emphasis on the methods to stabilize the system in structural perspective which mean the deployable structures is stable as load bearing structures.

The others two matters such as initial geometry design stage is mostly determining their final architectural function in line with their kinematic motion based on their designated pathway during deployment stage. These geometry and kinematic motion is inter-related to avoid constraint during element transformation stage and not contributed to the deployable structure system stability and loads resistance. Thus, the final configuration stability of the SMs in the application of spatial deployable structures is the most important matters in structural perspective.



(a) Dome shape (b)Scissor details

Figure 4: Zeigler’s patented collapsible self-supporting dome shape scissor structure: dome and scissor details [23]

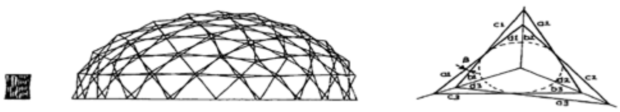


Figure 5: Trissor compact and deployed configuration of a hemispherical dome and top view by Clarke, 1984[24]

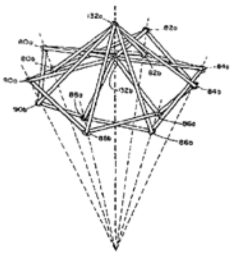


Figure 6: Hexagonal self-locking Pantographic unit by Krishnapillai 1992[25]

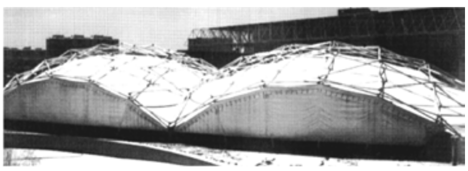


Figure 7: Deployable swimming pool cover in Seville, Spain[28]

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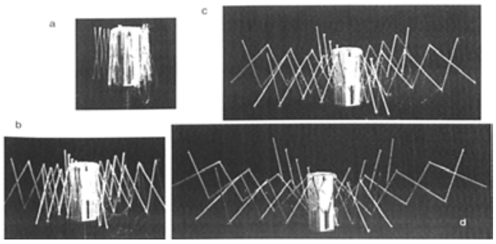
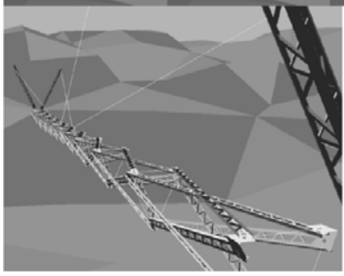


Figure 8: The deployment of the PDA from (a) the fully closed configuration to (d) the fully deployed configuration [17]



(a) 50 m span suspension bridge concept by applying vertical connection to horizontal like a balancing toy, it becomes foldable bridge easy to construct. The bridge is designed that to pull the suspension wire make it developed.

(b) The dome and the bridge in Park Hanamizuki in Japan

Figure 9: Atake's scissor structures[30]

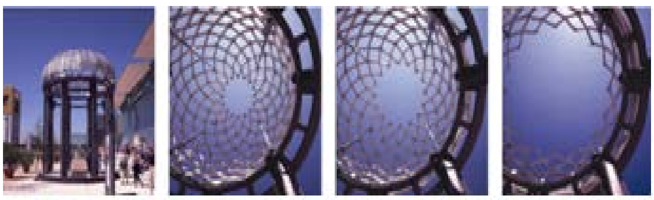


Figure 10: Iris dome or Hoberman Sphera in EXPO 2000[31]

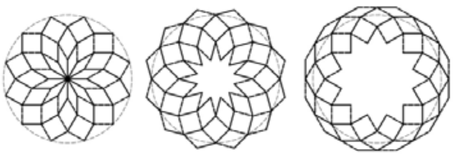


Figure 11: Deployable sequence of a ring structure developed by Z. You and S. Pellegrino [18]

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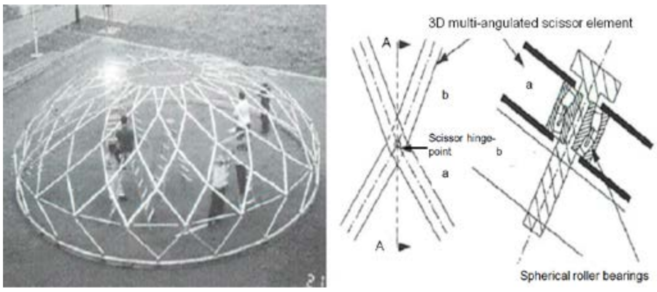

Figure 12: Retractable dome opening on the spherical surface with telescopic ring, plan view and section of its scissor hinge [32]

C. Recent research development on SMs deployable structures

The recent research development on SMs deployable structures is more concentrated on the structural dynamic characteristic [39] and geometrical configurations [40, 41] which focuses on their expanded performance during deployment stage. In 2006, [42] has successfully demonstrated deployable space application for building assemblies in achieving compact folding while maintaining the maximum expansion for building. Besides, Arnouts et al., (2018) studied also mentioned that hinge joint dimension and misalignment highly influence the deployable structure behaviour and cause imperfections. As mentioned earlier, the main disadvantage of SMs is it needs additional actuator for stabilization [9] and presents researches can be seen lack studied conducted on the restraint methods for SMs deployable structures. Stabilization is the critical manner for SMs to sustain load in vertical configuration. The stabilization is depends on the model shape and function where in principle can provide simple, fast, practical and sustainable approach solution to restraint the system.

Moreover, the previous research on SLEs deployable structures tends to solve the problems such as inconsistency perimeter [19], wind effects [40] and loose hole due to different direction of hinge and hole axes [40]. All these perimeter variation problems may lead to the geometric constraints and finally cause instability to the deployable structures. The solutions for these geometric problems were solved by introduce secondary mechanism such as slide radial joint[19], pin jointed support by Kokawa, fixed point rotation by Kassabian and hybrid of scissor hinge and common hinge by Kovacs [40]. The deployable structure stabilization studies currently also attract the researcher's attention. The studied on SLEs column instability for critical buckling load under its own weight by [6] indicated that this stability influences by three parameters such as number of elements, deployment angle and bar length. The gravity effect is the counterbalance by snap-through magnitude and the vertical force was needed to fold the curve structure [9].

The current development trend challenges are towards sustainable engineering approach [43] which considering environment, social and economic aspects towards sustainable development [44]. With this principle in mind, the transformable structures with capable to change shape is a novel architecture currently towards better use of natural energy resources, better occupant comfort, space use and building function flexibility[44]. Therefore, the deployable lattice structures with pantographic principle using scissor mechanism will be the focus since this structures transformable, speedily construction, easily transported, high material and energy efficiency, unlimited energy resources, operation and maintenance optimization, minimal installation cost, minimal impact on human health, enables indoor environmental quality enhancement and maximal usage of natural energy resources [44]. However, scissor-like deployable structures need additional elements so called locking system to ensure stability in

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the final deployed configuration [9], avoiding necessary cables or other additional tensile elements [44]. Therefore in overall, the fastest assemblies with sustainable approach and faster restraint in position method inventors will lead the prefab transformable structure industry in future.

III. SMs deployable structures analysis methods

Generally, the structure analysis may refer to the analysis of the structures itself to resist load applied and remain stable during service period or under it self-weight. In the past, the researchers have focused on explaining the structural, geometric and kinematic behaviors of SMs by various analytical, numerical and geometrical methods in the development of new mechanisms [3]. In fact, the analysis methods for designing both planar and spatial SMs have been developed using simple geometric approaches based on trigonometric, analytic or matrix methods. The structures analysis methods adopted in calculation and analysis of deployable structures were showed in Table 3.

Table 3: SMs deployable structures analysis

Author(s)	Analysis methods	Parameters measured	Remarks
Esther, [1]	Matrix calculation	Stress and displace-ment	The analysis conducted at deployed configuration.
Langbec-ker, [12]; Zanardo, [45]	Geometric principle	Displace-ment	Investigate the planar scissor systems to determine the foldability of translational, cylindrical and spherical configurations.
Patel & Ananthasuresh, [46]	Geometric principle and kinematic	Displace-ment	Explained angulated elements and plates
Kaveh & Daravan, [47]; Nagaraj et al., [48] ; Zhao & Feng, [49]	Matrix-based analysis	Stress and displace-ment	Studies the geometric and kinematic for planer, spatial scissor unit and simple grids.

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Li et al., [50]	Experimen-tal	Joint clearance and link flexibility.	Analyzed the effects of clearance size and gravity on the dynamic characteristics of the deployable space structures.
Sun et al., [51, 52]	Screw theory	Displace-ment & mobility	Analyse the dynamics and mobility of scissor-like element deployable structures.
Li et al., [39]	Gonthier nonlinear force model & LuGre model.	Joint clearance	Evaluate the effect of clearance joint on dynamic performance of the deployable structure scissor mechanisms.
Yan et al., [53]	Dynamic equation model	Deployment angle & impact force magnitude	Joint clearance will disturb the deployment angle while the member's flexibility will reduce the magnitude of impact force for deployable structures.

Based on the past research deployable structures analysis methods adopted, the analysis methods for designing both planar and spatial SMs have been developed using simple geometric approaches based on geometric, kinematic motion, screw theory, experimental, force model, dynamic equation and matrix methods. The parameters measured mostly regarding the SMs deployable structures displacement, stress, joint clearance, link flexibility, deployment angle and dynamic performance. Anywhere, the concerned on the SMs deployable structures is their deployability condition which can fulfills their architectural function, meaning to say that the system can be deployed and folded smoothly and stable in their final deployed configuration to sustain loads.

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IV. Discussions

Based on the reviewed findings, SMs with pantographic principle is the basic module used for spatial deployable structures. It consists of two beam connected with pivot at middle point and hinge at end nodes where shapes flexibility may be achieved by altering the pivot location and it behave as mechanism during deployment and load bearing at their final deployed configuration. Anywhere, the deployment control for SMs required additional locking devices for stabilization at deployed configuration to enable the system stable to carry loads. Therefore, the deployability conditions and basic scissor unit types must be examined in term to understand their geometric design principles.

There are three types of basic scissor units used to assemble the deployable structures based on SLEs principle namely translational unit, polar unit and angulated unit. The translational scissor unit uses rectilinear motion to transform the structure elements (Upper and lower) with same distance along two parallel straight lines and remain the same during and after deployment. For scissor polar unit, the system form curvilinear motion where the structure elements travels along a curved path and scissor hinge, top and bottom of the system lie on the concentric circles. While for the scissor angulated unit, it consist of two identical angulated bars to deploy closed-loop structures radially and capable of retracting to their own perimeters. These three types of scissor units can be analyzed using geometric principle such as trigonometry method to solve the unknown parameters of the system. Therefore, it is important to determine the type of scissor unit used in initial design stage based on the structures profiles and their architectural function.

Generally, the SMs in the application of deployable structures mainly possess stabilization problems since SMs characteristics required additional locking device to fix the system in stable configuration. The past SMs deployable structure problems have been solved separately based on their design, shape and architectural function by introducing additional secondary stabilization mechanism such as tension cable or wire, additional inner SMs members with rigid bars, hinges, fixed support points for rotation, geometric constraints design, spring, sliding joint, combined SLEs and hinges to fix outer ring and spherical roller bearing. Anywhere, all these proposed stabilization methods must be simple, practical, vertical motion and embracing sustainability.

The geometric constraints design and additional secondary inner SMs members in stabilizing the system called “self-stable” design approach [35] is the method to fix the system automatically once at deployed configuration. This stabilization tools embracing sustainable principle but another approach may turn to the nature of gravity loads principle. This is because in civil engineering applications, gravity loads are always present depending on the structure types and its orientation such as vertical folded direction [9]. Therefore, gravity loads possess the potential influence for SMs stabilization with the combination of others parameters such as structures geometry shape, motion direction and joint dimension in line to construct sustainable stable and rigid deployable structures based on scissor concept. Furthermore, all deployable structures covered area size changed during the transformation process but the overall crucial part is its geometric design since their geometric shape and basic unit type’s selection will influence the deployability condition, load carrying capacity and structure stability. This is because SMs deployable structure shapes is a mechanism which can basically be converted during deployed and contracted configurations.

The SMs deployable structures analysis methods for designing both planar and spatial SMs have been developed

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using simple geometric approaches based on trigonometric, analytic or matrix methods. Generally, the past researchers have focused on explaining the structural, geometric and kinematic behaviors of SMs by various analytical, numerical and geometrical methods in the development of new mechanisms [3]. The analysis conducted is aims to ensure the system developed stiff and stable to resist load in dynamic motion stage and during static configuration.

V. CONCLUSION

Based on the literature review's findings, there are some conclusions that can be drawn for the studies as stated below;

i. Scissor mechanisms (SMs) is a pantographic principle based mechanism with revolute joint. It need additional locking devices for stabilization before able to resist loads and altering the pivot location may achieved geometry shapes flexibility purpose.

ii. There are three basic scissor units namely translational, polar and angulated which these scissor unit used to assemble difference profiles of the deployable structures and related to deployment behaviours.

iii. The final deployed configuration stability is the main problem for SMs deployable structures and various stabilization methods used based on their structures profiles and geometric principle.

iv. Self-stable approach and gravity loads stabilization method possess a potential in embracing sustainable SMs spatial deployable structure design and practices.

v. The simple geometric approaches based on trigonometric, analytic or matrix methods have been used to analyze the SMs deployable structures.

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