Generation of a New Type of Architectural Umbrella

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ABSTRACT: The essence of this paper is the proposal of an innovative type of architectural umbrella. The new umbrella consists of a new type of symmetric spatial one-degree of freedom platform mechanism, a flexible covering with ribs and a hollow cylindrical mast with rotational movement. The most distinctive features of the umbrella are the expansion process and the way input is applied. As for the conventional foldable umbrellas, the joints should permit certain controlled movements, which in their turn would cause the process of the open and closed configurations of the umbrella. Graphical synthesis method is used to design and develop the mechanism.

Key Words: transformable, adaptable, kinetic structure, spatial mechanism, umbrella.

1 INTRODUCTION

An umbrella is a transformable kinetic structure that is adaptable to the rapidly changing needs of the modern society. It meets meteorological changes with two opposite states, one closed and passive, one open and active. A conventional umbrella is a special type of planar sliding mechanism. It is constructed by connecting planar sliding mechanisms around a hollow circular joint. In the umbrella concept, changes in the form of the structure are achieved by sliding the hollow circular joint along a cylindrical mast. The mast is usually vertical and transfers the weight of the structure to the ground.

The main principle of the research presented here is developing a new architectural umbrella based on an innovative spatial mechanism principle. The new architectural umbrella consists of two main components. The first one is the innovative symmetric spatial expandable platform mechanism. It is central on the cylindrical mast and appropriate to assemble on any one because the need of height of the mast varies according to the activities. The second one is a flexible covering with its ribs. The ribs are assembled to the legs of the platform mechanism. Materials considered are lightweight aluminum for the spatial platform mechanism and the mast, flexible membrane for the covering. The structural components must be durable to withstand harsh conditions of the weather, and they should not collapse and be safe to use.

Graphical synthesis method is used to design and develop the architectural umbrella. In the design process, mechanical and structural functions are mutually reinforcing. An effort is made to present briefly critical aspects in the design process that are of interest to the architectural engineer. The design process is divided into two parts. First of all, the basic spatial platform mechanism is designed. Linkage topology and type of joints of the platform mechanism are determined. Visual Nastran Desktop 4D is used to analyze the performance of the architectural umbrella. At the second part of design process, covering material and its attachment method is designed. Final step is the building process of a 1/1 scale physical model to demonstrate the umbrella.

2 GENERATION OF THE EXPANDABLE PLATFORM MECHANISM

From the viewpoint of structural engineering, the key element of the umbrella is platform mechanism, which provide the capability to change the geometric configuration while carrying its own weight and the live load.
In the design process of the expandable platform mechanism, a well-known geometry has been followed. The hyper surface generation by moving a straight line (generator) upon two fixed curves or straight lines (directrices) has been known for a long time. When the generator is a straight line, dependant on its position in space in relation to the axis of rotation, typical surfaces of cone, hyperboloid or cylinder can be generated (Fig. 1). These are also defined as ruled surfaces. It is also well known that a cylinder can be transformed to a hyperboloid by rotating the top or bottom surface of the cylinder around its vertical axis (Fig. 2). By following this geometric feature, it is possible to obtain a three-dimensional expandable platform mechanism with four legs to cover a square area. Mechanism can transform from a cylinder in closed configuration to a hyperboloid in open configuration. Graphical method is used to design the suitable mechanism to achieve the required performance given above.

The first step is the determination of the linkage topology and type of joints to construct the mechanism with 1 degree of freedom. In its simplest forms Figure 3 shows two extreme positions, the open and closed configurations of the concept of new mechanism. The closed configuration is defined when the structure spans the minimum distance. This distance is denoted $R_{\text{min}}$. Similarly the open configuration is defined when the structure spans the maximum distance. This distance is denoted $R_{\text{max}}$. It is obvious that this is a symmetrical platform mechanism with four legs.

To construct this structure, it is better to look closely the simplest form of the mechanism to determine the types of joints. Figure 4 shows two extreme positions of one leg/bar. Pairing elements at A0 and A1 points are two different joints, which connect the bar to the circular fixed base and to the rotational circular platform. The distance between these pairing elements is L. Pairing elements at A0 and A1 points can be described by two quantities. They allow relative motion between the platform, the base and the bars. These pairing elements with two quantities can be determined easily from left and front views of the mechanism. Front view shows relative rotation between the base and the bar by $\omega$ and again relative rotation between the platform and the bar by $\beta$. Left view shows relative rotation between the base and the bar by $\omega_1$ and again relative rotation between the platform and bar by $\beta_1$. At the same time, pairing element at point A1 moves to the point AJ while the platform rotates. This rotation changes the distance between the pairing elements from $L$ to $L_1$. It is determined that there is a sliding motion between the bar and the rotational platform. After these graphic analysis it is understood that two quantities (R-R) are...
necessary to describe the relative motion between the
bar and the base and three quantities (R-R-P) are
necessary to describe the relative motion between the
bar and platform. Figure 5 shows a proper joint
between the leg and the base with R-R quantity. Figure
6 shows the proper joints between the leg and the
platform with R-R and P quantity.

The final step of the platform mechanism design is
the determination of the input driver. The mast of the
mechanism will be the input driver at the same time. It
consists of two hollow cylinders, one inside the other.
The base of the mechanism is the top face of the outer
cylinder, which is fixed to the ground. The platform is
the top face of the inner cylinder, which is linked to
the base through a revolute joint. Input is the inner
cylinder than can be lengthened close to the ground to
be driven manually. The rotational movement of inner
cylinder about z-axis is transmitted to the mechanism
and to the ribs of the covering, thus opening or closing
the umbrella. However, during the computer
visualization process to evaluate the overall geometric
and kinematic conception of the mechanism, vN4D
displays an error on the geometry of the prismatic joint
shown in Figure 6. It is realized that prismatic joint
must allow rotation too. It must have two degrees of
freedom (P-R). The link numbered 3 in Figure 8
should be a circular bar to allow rotation (Fig. 7).

After all the topological and type of joint synthesis,
it is possible to draw the kinematic diagram of the
mechanism. Figure 8 shows the kinematic diagram in
a sketch form (proportional but not exactly to scale).
According to the kinematic diagram, platform
mechanism with proper joints is modeled again (Fig.
9). Visual Nastran 4D does not give any error message
for the kinematic topology or the type of joints.

3 STRUCTURAL FORMULA
As it is mentioned before, the desired degree of
freedom is 1 to perform all geometric configurations
in a predictable manner. A proper structural formula is
needed to check the degree of freedom of the platform
mechanism. Many scientists described structural
formulas to find degree of freedom (DOF) of complex
mechanisms. F. Freudenstein and R. Alizade described a structural formula for complex mechanisms.

\[ W = \sum_{i=1}^{h} f_i - \sum_{j=1}^{l} \lambda_j \]  

(3.1)

Where

- \( W \): degree of freedom of the mechanism,
- \( \sum_{i=1}^{h} f_i \): sum of degrees of freedom of the joints,
- \( \sum_{j=1}^{l} \lambda_j \): sum of degrees of freedom of the spaces, within which the closed loops operates,
- \( h \): number joints connecting \( n \) links.
- \( L \): number of independent loops.

In 1988, R. Alizade presented a new structural formula, in which platform types, number of platforms, number of branches between platforms and so were included along with mobility of kinematic pairs. Kinematic chains that form a platform (or base) are usually hexagons, pentagons, quadrilaterals and triangles. Now the theorem will be formulated, establishing the connections joining the platforms via intermediate branches.

Total number of linear independent closed loops is defined as the difference between the total number of joints in platforms and total number of platforms, intermediate branches:

\[ L = N - C - B \]  

(3.2)

Where

- \( L \): number of independent loops,
- \( N \): total number of joints on the moveable platforms,
- \( C \): total number of intermediate branches between moveable platforms
- \( B \): total number of moveable platforms

So, we can write sum of degrees of freedom of the spaces within which the closed loops operates as:

\[ \sum_{j=1}^{l} \lambda_j \]  

(3.3)

By using equations (3.1) and (3.3) we can find a new equation:

\[ W = \sum_{j=1}^{h} f_i - \lambda (N - C - B) \]  

(3.4)

By using the R. Alizade equation, it is possible to find
the degree of freedom of the expandable bar structure.

\[ W = ? \]

Where,

\[ \sum_{i=1}^{n} f_i = 25, \quad \lambda = 6, \quad N = 5, \quad C = 0, \quad B = 1 \]

\[ W = \sum_{i=1}^{n} f_i - 1 (N - C - B) \]

\[ W = 25 - 6 (5 - 0 - 1) = 25 - 24 = 1. \]

4 PARAMETERS OF THE STRUCTURE

The main parameters influencing the R max of the umbrella are as follows. d is the diameter of the inner cylinder of the mast. h is the distance between the platform and the base.

The open configuration is reached when the legs touch the inner cylinder while expanding. To compare the R max of various configurations, two parameters are introduced. These parameters are the diameter (d) of the inner cylinder and the height (h) of the platform from the base as shown in Figure 10.

Having defined the parameters within which the Rmax varies. Table 1 shows the results for 60 ≤ d ≥ 120 and 250 ≤ h ≥ 350. The legs are 200cm long. It has been found that Rmax increases when d and h decreases.

<table>
<thead>
<tr>
<th>d (mm)</th>
<th>60</th>
<th>290</th>
<th>291</th>
<th>292</th>
<th>293</th>
<th>302</th>
<th>307</th>
<th>312</th>
<th>317</th>
<th>321</th>
<th>326</th>
<th>331</th>
<th>335</th>
<th>340</th>
</tr>
</thead>
<tbody>
<tr>
<td>h (mm)</td>
<td>350</td>
<td>351</td>
<td>352</td>
<td>353</td>
<td>354</td>
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<td>356</td>
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<td>361</td>
<td>362</td>
<td>363</td>
</tr>
<tr>
<td>Rmax</td>
<td>284</td>
<td>285</td>
<td>286</td>
<td>287</td>
<td>288</td>
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<td>290</td>
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A physical model has been built to demonstrate the kinetic architectural umbrella. All of the structural elements and joints were constructed with metal (Fig. 11). Height of the platform from the base (h) is 350mm and the diameter of the inner cylinder (d) is 120mm. The legs are 150 cm long. It was found that the maximum distance is 185cm. As it is shown in Table 1, it is possible to provide more enclosure by reducing the d and h variables.

5 DEVELOPMENT OF THE COVERING

Expansion of the mechanism around z-axis should provide complete or partial enclosure defined by the umbrella. Sliding and rotating links against each other necessitates the redefinition of the covering and its attachment to the mechanism.

Two different types of materials are considered for covering the expandable platform mechanism to reach the final design of the architectural umbrella. The first type of covering material is a deployable rigid flat plate. The plates could be fiber-reinforced plastics (FRP). They can be linked to each other with cylindrical joints and to the legs of the mechanism with revolute joints. Special shapes of the straight-edged plates and the deployment methods are investigated for which the plates do not overlap or interfere during the expansion of the platform structure. The covering in Figure 12 has simple deployment process and provides a square enclosure in its open configuration. Square umbrella units can be joined together to form covered areas of any size.

However, rigid flat panels can cause problems in practical use. The umbrella could be under extreme wind force because of the wide surface of the rigid flat plates in the closed configuration. In reality, covering may not be durable to withstand the harsh conditions of the weather in closed or open configurations.
The second type of covering material is a flexible membrane. Flexible membrane can be attached to the legs with a separate supporting bar structure (ribs). Ribs deploy and prestress the membrane. The construction method is replacing the rigid flat plates with four ribs, which are connected to the legs with revolute joints. Membrane is tied to the ribs; thus there need for additional simple rope mechanisms to tension the membrane. These construction types of the ribs and attachment method of the flexible cover make the covering technically a simpler deployable system.

Ribs are assembled to the platform mechanism without the covering to show the final design (Fig.13). Ribs span 500cm and provide 25m² enclosure. It is assumed that conversion between two extreme configurations does not take much time because movement will not affect the membrane directly. If extreme weather conditions are considered, another advantage of the membrane is to be a gatherable material. New emerging technologies and flexible materials can offer ideas for covering kinetic, which will eventually affect the overall conception of transformable structures.

6 CONCLUSION
The most distinctive features of the umbrella are the expansion process and the way input is applied. The convenience in spatial expansion is very outstanding. It is also distinguished by having an input driver involving only pure rotational movement about z-axis, which is lacking in the conventional umbrellas. Such feature allows positioning the input anywhere on the mast. Besides the computer systems, umbrella could
be controlled manually when the input is close to the ground.

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8 REFERENCES